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Economic and Policy Challenges of the Energy Transition in CEE Countries

Edited by

Jacek Kamiński

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Editor

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Contents

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Article

Assessing the Effects of Uncertain Energy and Carbon Prices on the Operational Patterns and Economic Results of CHP Systems

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Abstract: In the power and heat sectors, the uncertainty of energy and carbon prices plays a decisive role in the rationale for decommissioning/repurposing coal-fired CHP (combined heat and power) systems and on investment decisions of energy storage units. Therefore, there is a growing need for advanced methods that incorporate the stochastic disturbances of energy and carbon emission prices into the optimization process of an energy system. In this context, this paper proposes an integrated method for investigating the effects of uncertain energy and carbon prices on the operational patterns and financial results of CHP systems with thermal energy storage units. The approach combines mathematical programming and Monte Carlo simulation. The computational process generates feasible solutions for profit maximization considering the technical constraints of the CHP system and the variation of energy and carbon emission prices. Four scenarios are established to compare the operational patterns and economic performance of a CHP system in 2020 and 2030. Results show that in 2020, there is an 80% probability that the system's annual profit will be less than or equal to €30.98 M. However, at the same probability level, the annual profit in 2030 could fall below €11.88 M. Furthermore, the scenarios indicate that the incorporation of a thermal energy storage unit leads to higher expected profits (€0.74 M in 2020 and €0.71 M in 2030). This research shows that coal-fired CHP plant operators will face costly risks and potentially greater challenges in the upcoming years with the increasing regulatory and financial pressure on CO_2 emissions and the EU's plan of phasing out fossil fuels from electricity and heat generation.

Keywords: combined heat and power; optimization; thermal energy storage; uncertainty; district heating

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1. Introduction

The ability to meet the demand for electricity and heat in energy systems is an important component of energy security. Consequently, energy security has become one of the main pillars of the European Union's energy policies. However, the achievement of this policy goal must also take into account different aspects, such as local market conditions and environmental issues. As a result, mechanisms for increasing the efficiency of primary energy use have gained significant attention in recent years, especially mechanisms that support the development of highly efficient cogeneration systems. In the EU heating sector, the deployment of new combined heat and power plants (CHPs) and the modernization of existing CHP installations have become vital for maintaining energy security.

However, with the rising CO_2 emission allowance prices, the uncertain situation on the fuel market, and the high volatility of the wholesale electricity prices, CHP plant owners and operators now face major financial and operational challenges; this is particularly true for systems with low operational flexibility and powered by fossil fuels. In this regard, several European countries have implemented new financial support schemes targeted to mitigate the inherent uncertainties of contemporary energy markets. An example of such schemes is the capacity market introduced in the United Kingdom and Poland or ancillary markets in Italy and the United States, in which CHP units can actively participate [1–3]. Yet, even after the implementation of such support schemes, relatively high levels of uncertainty remain for CHP plant operators. For example, in forward capacity markets, depending on the contracted volume of the capacity obligation in relation to the installed capacity of a given CHP plant, the fulfillment of the capacity contract can be considered an element of risk, but also an additional source of financial support.

Nowadays, operators of CHP installations are looking for solutions that will allow, at least partially, to mitigate the risk related to rising CO_2 emission allowances prices and the volatility of the wholesale electricity prices. One of such solutions is the investment in thermal energy (TES) storage technologies, such as tank storage systems or seasonal thermal storage units. As discussed in [4–7], the use of thermal energy storage in CHP plants has a direct impact on the system's financial performance. This is mainly due to the potential reduction of fuel consumption and CO_2 emissions costs as well as the increase in revenues from electricity sales. However, the operational management of the CHP generation and the opportunity to maximize profit while meeting all technical and environmental constraints is a complex task that requires the use of appropriate methods and computational tools.

Traditionally, researchers have evaluated the impact of uncertain parameters on the operation and financial performance of combined heat and power plants using discrete scenarios and simple sensitivity analyses. For instance, the authors of [4] used an optimization model to investigate the impact of market conditions on the operational pattern and revenue of a CHP plant. The study assessed discrete scenarios based on different electricity price profiles and fuel costs. Similar aspects were investigated in Ref. [5]. Using a mixed-integer programming approach and case-based scenarios (e.g., "low-price", "high-price"), the authors showed the positive financial effects of implementing heat accumulators in the district heating system of Berlin. In Ref. [6], the authors developed a model to optimize a medium-sized combined heat and power plant. The study assessed the economic performance of two energy systems using a set of discrete scenarios. In Ref. [7], a mathematical model was developed to optimize the district heating system based on RES units with thermal energy storage. The optimization aimed to minimize the overall net acquisition costs for energy under four CHP-DH system scenarios. The authors of Ref. [8] assessed the flexibility and operational strategy of an energy system comprised of four CHP plants, heat pumps, rooftop PV systems, and a power-to-hydrogen conversion system. Their study explored four discrete scenarios that considered possible developments in market prices and energy trends, renewable energy supply, and climate change. Other works have also investigated the operational planning of CHP systems and the optimization and sizing of the CHP systems with thermal storage systems using case-based scenarios and sensitivity analyses with discrete events [9,10].

Despite the advances in computational resources and modeling techniques, the use of Monte Carlo methods to evaluate the effects of uncertain parameters on the financial and optimal operational patterns of energy systems remains rather limited. Moreover, to date, there are very few studies that propose combined methods capable of optimizing the operation of CHP plants and at the same time consider the nature of uncertainty in economic parameters that describe current and future energy market conditions. One of such studies can be found in [11]. The authors used a deterministic model to find the optimal operating conditions of a small-scale CHP unit in a medical facility. In the study, a technique for clustering months to seasons and hours to intraday periods was employed. This reduced the complexity of the problem and enabled the authors to solve the MILP model for 1000 replications. In Ref. [12], the authors proposed a mathematical model with a Monte Carlo simulation approach to optimize electricity generation in district heating systems. The stochastic parameters investigated were electricity prices in day-ahead, intraday, and balancing market. In Ref. [13], the authors developed an optimization-based methodological approach for the optimal planning of a power system. The approach captured the uncertainty of hydro and renewable availability, unavailability factors, fuel prices, and carbon mission prices with a Monte Carlo method. More recently, the authors of Ref. [14] developed a Monte Carlo simulation and a multi-objective optimization criterion to investigate the influence of uncertainties on the optimal size and annual costs of a CHP system. The study focused on evaluating three different operational strategies of the energy system. In Ref. [15], the optimal design and operational planning of a residential and urban energy network using a Monte Carlo-based framework was investigated. The analysis explored the effects of uncertainty in heat demand with two probability distribution types. In Ref. [16], the author proposed a mixed-integer linear programming model integrated with a Monte Carlo simulation method to investigate the uncertainties of electrical and thermal demand as well as the intermittency of PV arrays and wind turbined on the operation and sensitivity of a microgrid with CHP units. In the abovementioned studies, the effects of possible future carbon emission and coal and electricity prices on the operational and financial behavior of CHP systems were ignored.

Taking into account the above-described circumstances of EU energy markets and the limited literature on the study of long-term uncertainties associated with energy and carbon prices, the main purpose of this article is to investigate the impact of uncertain parameters on the financial and operational patterns of large-scale coal-fired CHP systems coupled with thermal energy storage units. To achieve this goal, this paper develops a computational framework based on a mathematical programming method and a Monte Carlo technique. In this regard, this paper contributes to the literature by:

(i) Proposing a computational approach based on mathematical programming and a Monte Carlo technique to facilitate understanding and evaluation of stochastic parameters that affect the dynamic behavior of CHP systems.
(ii) Exploring the impact of observed and projected energy and EUA prices (for 2020 and 2030) on the financial and operational patterns of a stand-alone CHP system and an integrated CHP-TES system.

With this scope in mind, the remainder of this paper is organized as follows. Section 2 details the method developed to investigate the effects of stochastic energy and carbon prices on the economic performance and operational patterns of CHP systems with thermal energy storage units. Section 3 describes the case study, data, and research scenarios. Section 4 presents the results obtained from the application of the method. Section 5 concludes.

2. Materials and Methods

This work proposes a combined method to investigate the effects of uncertain energy and carbon prices on the optimal operation of a coal-fired CHP system with thermal energy storage. The approach combines mathematical programming and a Monte Carlo computational technique as a way to incorporate the stochastic disturbances of energy and carbon emission prices into the optimization process of the energy system. A flowchart of the proposed method is shown in Figure 1.

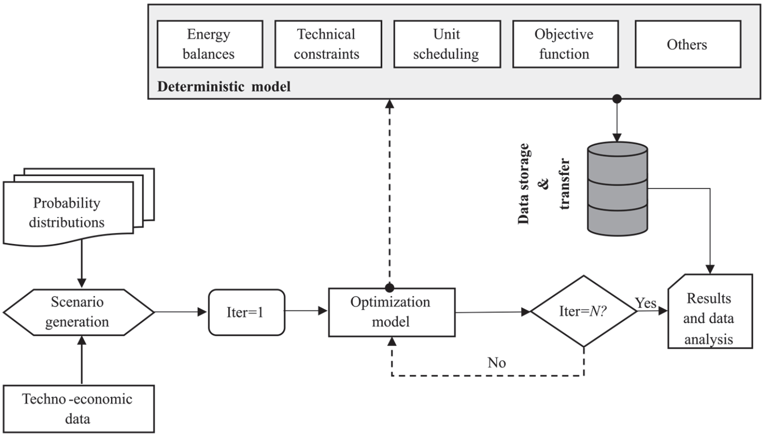

Figure 1. Overview of the proposed method.

2.1. Stochastic Simulation

In the power and heat sectors, the uncertainty of energy and carbon prices plays a decisive role in the rationale for decommissioning/repurposing coal-fired CHP systems and on investment decisions of energy storage units. Therefore, there is a growing need for combined methods that consider the stochasticity of specific parameters and facilitate understanding the financial implications of future electricity, coal, and carbon emission prices.

In this context, the approach proposed in this work considers the uncertainty of sensitive parameters through the application of a Monte Carlo method. Monte Carlo is a state-of-the-art computational technique for investigating the effects of uncertain parameters on the behavior of energy systems [14]. Thus, this method is applied in the present study to generate scenarios, taking into consideration a set of inputs chosen from random samples drawn from independent continuous probability distributions.

Unlike previous works that account for uncertainties as simple sensitivity analysis with discrete scenarios (case-based scenarios representing possible changes (e.g., low, mid, and high), this study incorporates a significant larger proportion of scenarios with stochastic inputs contained within minimum and maximum projected values of energy and carbon emission prices. The projected prices adopted as parameters for the distributions are based on the results of global transition scenarios generated by the International Energy Agency [17] and European Scenarios published by ENTSO-E [18].

The process employed for modeling and generating the Monte Carlo scenarios follows the guidelines outlined by [14,19]. It involves multiple steps that can be summarized as follows:

- Identification of model parameters that are considered uncertain and data collection from various information sources—the data consist of historical and projected values for the uncertain model inputs (i.e., electricity, coal, and carbon emission prices).
- Data analysis and selection of probability density functions for each model input.
- Generation of N random samples from probability density functions. The random samples are then converted into a set of possible inputs or Monte Carlo scenarios (coal, electricity, and carbon emission prices), which are subsequently transferred to the deterministic model. In this study, the deterministic model is a mixed-integer linear programming model.
- Deterministic calculations with input datasets (Monte Carlo scenarios). The optimization model is solved N number of times until the mean value and standard deviation of the objective function stabilizes.

- Analysis of model outputs with statistical indicators.

It is worth highlighting that the approach proposed in this study is particularly valuable for CHP-plant and district heating network operators, since it enables the testing of new operation strategies and the comprehensive analysis of the system's dynamic behavior considering multiple sources of uncertainty.

2.2. Energy System Model

As described in Section 1, this work expands the scope of our previous study [20] by (a) modeling and incorporating energy and electricity prices uncertainties and (b) investigating the economic and operational impacts of future energy and carbon prices on the operation of a coal-fired CHP system with thermal energy storage. Furthermore, the model used in the present study is an adapted version of the mixed-integer linear programming approach described in [21,22]. In our previous work, the feasible operating region of the combined heat and power plant equipped with an extraction-condensing steam turbine was modeled as a combination of convex points that represented the hourly thermal and electrical power generation. Using binary variables to represent the bounded polyhedron can be a major drawback, since it considerably increases the difficulty of finding an optimal solution. Therefore, in the present work, the model has been improved in several points. First, the modeling of the feasible operating region is based on a linear formulation that does not require binary variables and leads to shorter computation times. Second, the mathematical formulation of the storage thermal energy losses to the surroundings is modeled using a constant loss factor and predefined charge/discharge limits, which considerably simplify the problem. Consequently, the proposed formulation is much more efficient and allows the model to be used in an integrated stochastic approach based on a Monte Carlo method.

In addition, modeling the uncertainty of the future energy and carbon emission prices with a Monte Carlo technique allows to investigate the dynamics of the objective function and decision variables at the temporal resolution defined in the deterministic programming model. Generally, optimization models implemented in a Monte Carlo framework are markedly reduced and simplified to overcome the computational expense encountered during the iterative process. One standard method to reduce the computational burden is to find a subset of representative operating periods (e.g., daily, weekly, seasonal). However, a drawback of this method is that the results may lose their chronology and the thermal cycling of the storage units is not well represented [23]. Consequently, this study differs from previous ones in two aspects. First, the system CHP system is optimized for one year at hourly intervals, therefore retaining the chronology. Second, the short-term thermal variation of the energy storage modeled for one year makes it possible to quantitatively measure the contribution of the TES in reducing the mismatch of energy production and demand.

For the sake of brevity, the following subsections describe only some important features of the constraints and model. The equations of the optimization model can be grouped into four categories: objective function, thermal power balance, combined heat and power plant, auxiliary boilers, and thermal energy storage. Appendix A provides a description of the sets, parameters and variables used in the model.

2.2.1. Objective Function

The objective function concerns the maximization of the total system profit (P_r). It is defined as the sum of the hourly revenues from heat and electricity sales (R_{tot}) minus the sum of hourly costs (C_{tot}). The objective function reflects the operation strategy of a combined heat and power system exposed to a liberalized electricity market, and that can benefit from the possibility of selling electricity to the grid.

$$\max P_r = R_{tot} - C_{tot} \tag{1}$$

The total revenue (R_{tot}) consists of the income collected from electricity and heat sales. In Equation (2), p_t^{EC} indicates the electrical power output of the CHP plant, $C_t^{Electricity}$ stands for the electricity price at hour t, Q_t^{Demand} is the heat demand at hour t, and C_t^{Heat} is the heat price at time t:

$$R_{tot} = \sum_t p_t^{EC} \times C_t^{Electricity} + \sum_t Q_t^{Demand} \times C_t^{Heat} \tag{2}$$

Equation (3) describes the total costs of the system (C_{tot}), which can be decomposed into fuel costs, emission costs, variable operating costs, and start-up costs. Please note that formulation of Equation (3) excludes capital and non-variable costs, since the model is constructed and intended for the generation scheduling of a CHP system:

$$\begin{aligned} C_{tot} = \sum_t f_t^{EC} \times \quad & C_f^{EC} + \sum_t \sum_p \left(p_t^{EC} + q_t^{EC}\right) \times E_p^{EC} \times C_p \\ & + \sum_t \left(p_t^{EC} \times C_{VOM}^{EC-E}\right) + \left(q_t^{EC} \times C_{VOM}^{EC-Q}\right) + \sum_{t,b} \tau_{t,b}^B \times C_f^B \\ & + \sum_t \sum_b \sum_p q_{t,b}^B \times E_p^B \times C_p + \sum_{t,b} q_{t,b}^B \times C_{VOM}^B \\ & + \sum_t \sum_b z_{t,b}^B \times C_{SU}^B \end{aligned} \tag{3}$$

where f_t^{EC} stands for the fuel consumption of the CHP in hour h, C_f^{EC} is the fuel cost of the CHP, q_t^{EC} is the thermal power output of the CHP, E_p^{EC} is the emission factor of pollutant p related to the power output of the CHP, and C_p is the emission cost of pollutant p. Variable O&M costs related to the thermal and electrical output of the CHP are described by C_{VOM}^{EC-Q} and C_{VOM}^{EC-E}. Moreover, $\tau_{t,b}^B$ is the slack variable used for modeling the heat-only boiler fuel consumption and C_f^B is the fuel cost of the heat-only boiler in hour h. The emission factor of pollutant p related to the power output of the heat-only boiler (HOB) is described by E_p^B and the variable O&M cost of the HOB by C_{VOM}^B. Lastly, the $z_{t,b}^B$ is the binary variable used to model the start-up trajectory of the heat-only boiler and C_{SU}^B stands for the start-up costs of the HOB.

2.2.2. Thermal Power Balance

Equation (4) reflects the overall thermal power balance of the system. In the model, we assume that the thermal demand must be satisfied by the input sources (i.e., CHP plant, heat-only boilers, and discharged energy from the thermal energy storage $\left(Q_t^{TES,dis}\right)$) and balanced by the output sources (i.e., the energy directed to the thermal energy storage $\left(q_t^{TES,chr}\right)$). Q_t^{Demand} stands for the hourly heat demand of the district heating network:

$$q_t^{EC} + \sum_b q_{t,b}^B + q_t^{TES,chr} - Q_t^{TES,dis} = Q_t^{Demand} \qquad \forall t \tag{4}$$

2.2.3. Combined Heat and Power Plant

The operation of the CHP plant is modeled by Equations (5)–(13). Because the CHP plant is assumed to be equipped with an extraction-condensing steam turbine, the feasible operation zone (FOZ) is constructed as a two-dimensional region that describes the production possibility sets p_t^{EC} and q_t^{EC}. The production possibility sets are dependent on the power-to-loss ratio (β) and power-to-heat ratio (σ) [24,25]. Equations (5)–(9) express the FOZ considering the maximum thermal and electrical power output of the steam turbine. The fuel consumption of the pulverized coal-fired boilers supplying high-pressure steam to the turbine is given by Equations (10) and (11). Although condensing-extraction steam turbines provide high levels of operational flexibility, maximum ramping rates must be considered for the safety and stability of the system, as shown in Equations (12) and (13):

$$p_t^{EC} \leq \; P_t^{EC,Max} - \beta \times q_t^{EC} \qquad \forall t \qquad (5)$$

$$p_t^{EC} \geq \; P_t^{EC,Min} - \beta \times q_t^{EC} \qquad \forall t \qquad (6)$$

$$p_t^{EC} \geq \; \sigma \times q_t^{EC} \qquad \forall t \qquad (7)$$

$$p_t^{EC} \leq \; P_t^{EC,Max} \qquad \forall t \qquad (8)$$

$$q_t^{EC} \leq Q^{EC,Max} \qquad \forall t \qquad (9)$$

$$f_t^{EC} = m^{EC,Max} \times q_t^{EC} + b^{EC,\ Max} \qquad \forall t \qquad (10)$$

$$f_t^{EC} = m^{EC,Min} \times q_t^{EC} + b^{EC,\ Min} \qquad \forall t \qquad (11)$$

$$\left(p_t^{EC} + q_t^{EC}\right) - \left(p_{t-1}^{EC} + p_{t-1}^{EC}\right) \leq \Delta R_{Max} \qquad \forall t \qquad (12)$$

$$\left(p_t^{EC} + q_t^{EC}\right) - \left(p_{t-1}^{EC} + q_{t-1}^{EC}\right) \geq \Delta R_{Min} \qquad \forall t \qquad (13)$$

where $P_t^{EC,Max}$ and $P_t^{EC,Min}$ describe the maximum and minimum electrical power output of the CHP, the parameters $m^{EC,Max}$, $m^{EC,Min}$, $b^{EC,\ Max}$, and $b^{EC,\ Min}$ represent the slopes and intercepts of the linear functions adopted to model the fuel consumption of the steam boilers, and ΔR_{Max} and ΔR_{Min} are the maximum and minimum rate of change, respectively, of the combined power output of the CHP system.

2.2.4. Auxiliary Boilers

The operational strategy and technical limitations of the auxiliary boilers are described by Equations (14)–(19). The maximum power output and logical state of the boilers are given in Equations (14)–(16). The auxiliary boilers can enter operation when the thermal demand exceeds the thermal power output of the CHP system. The fuel consumption of the boilers is linearized considering the approach proposed in [26], as expressed in Equation (19):

$$q_{t,b}^{B} \leq u_{t,b}^{B} \times Q^{B,Max} \qquad \forall t, b \qquad (14)$$

$$q_{t}^{EC} \geq u_{t,i}^{b} \times Q^{EC,Max} \qquad \forall t, b \qquad (15)$$

$$q_{t}^{EC} + q_{t,b=\mathrm{B}-1}^{b} \geq u_{t,b=B-2}^{B} \times \left(Q^{EC,Max} + Q^{B,Max}\right) \qquad \forall t, b \qquad (16)$$

$$z_{t,b}^{B} \geq u_{t,b}^{B} - u_{t-1,b}^{B} \qquad \forall t, b \qquad (17)$$

$$z_{t,b}^{B} \geq -u_{t,b}^{B} + u_{t-1,b}^{B} \qquad \forall t, b \qquad (18)$$

$$\tau_{t,b}^{B} \geq fb_{j}^{B} + \left(fm_{j}^{B} \times q_{t,b}^{B}\right) \qquad \forall t, b, j \qquad (19)$$

where $Q^{B,Max}$ is the maximum power output of the heat-only boilers, $Q^{EC,Max}$ is the maximum power output of the CHP system, the commitment status of the heat-only boiler is given by the binary variable $u_{t,b}^{B}$, and the fuel consumption of the boilers is described by the slack variable $\tau_{t,b}^{B}$ and coefficients fb_{j}^{B}, fm_{j}^{B}.

2.2.5. Thermal Energy Storage

Equations (20)–(27) describe the operation of the thermal energy storage in each time period. The energy balance of the thermal energy storage is given in Equations (20) and (21). The mathematical formulation of the thermal energy storage unit considers a predefined capacity $\left(Q_{Cap}^{TES}\right)$ and C-factors $(Cf_{chr}^{MAX}, Cf_{dis}^{MAX})$ (i.e., upper and lower bounds of charge and discharge rates). As mentioned in Section 2, the thermal energy losses to the surroundings are modeled using constant loss factors (η_s), which simplifies the optimization problem:

$$q_{t}^{TES} = \eta_s \times q_{t-1}^{TES} + q_{t}^{TES,chr} \times \eta_{chr} - \frac{q_{t}^{TES,dis}}{\eta_{dis}} \qquad \forall t \qquad (20)$$

$$q_{t}^{TES} = q_{t}^{TES,chr} \times \eta_{chr} - \frac{q_{t}^{TES,dis}}{\eta_{dis}} \qquad \forall t = 1 \qquad (21)$$

$$q_{t}^{TES} \leq Q_{Cap}^{TES} \qquad \forall t \qquad (22)$$

$$q_t^{TES,chr} \leq Cf_{chr}^{Max} \times Q_{Cap}^{TES} \qquad \forall t \qquad (23)$$

$$q_t^{EC} \leq Q^{EC,Max} \qquad \forall t \qquad (24)$$

$$q_t^{TES,dis} \leq Cf_{dis}^{Max} \times Q_{Cap}^{TES} \qquad \forall t \qquad (25)$$

$$q_t^{TES,chr} + Q_{t-1}^{TES} \leq Q_{Cap}^{TES} \qquad \forall t \qquad (26)$$

$$q_t^{TES,dis} - q_{t-1}^{TES} \leq 0 \qquad \forall t \qquad (27)$$

where the thermal energy storage charge and discharge efficiencies are described by the parameters η_{chr} and η_{dis}.

3. Case Study

The combined heat and power plant examined in this study consists of two pulverized coal-fired boilers supplying high-pressure steam to an extraction-condensing steam turbine (120 MW_e and 205 MW_t). Additionally, two auxiliary coal-fired boilers (80 MW each, commonly referred to as "heat-only boilers") are installed to satisfy the thermal demand at peak load hours or during scheduled/unscheduled downtimes and unexpected breakdowns. The CHP-HOB system covers the thermal demand for space heating and domestic hot water of customers in a district heating network. A boxplot of the hourly heat load for different months of the year is depicted in Figure 2.

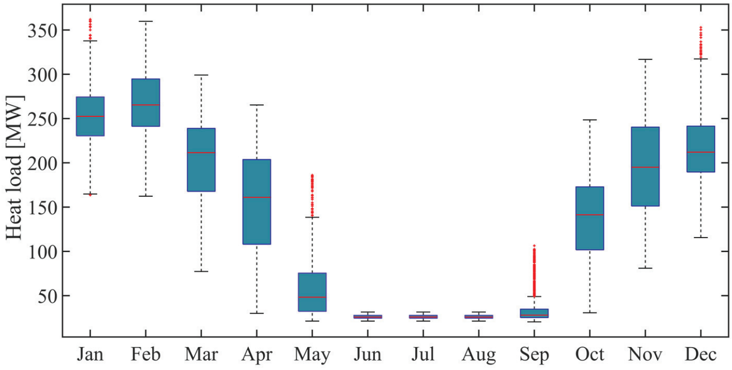

Figure 2. Boxplot of the hourly heat load for different months of the year.

Besides the heat-only boilers, the CHP plant is connected to a tank thermal energy storage unit (TES). This type of storage technology is generally designed for short-term applications. Consequently, in this study, the storage capacity is limited to one-week thermal cycles; in other words, the TES must charge and discharge to the initial conditions of the storage capacity within 168 h of operation. The total storage capacity of the tank is

400 MWh. Because the CHP plant operators aim to maximize the expected profit from the electricity traded at the day-ahead power market, the storage unit is used to avoid thermal load imbalances and acts as a thermal energy buffer. Figure 3 shows the schematic of the CHP system.

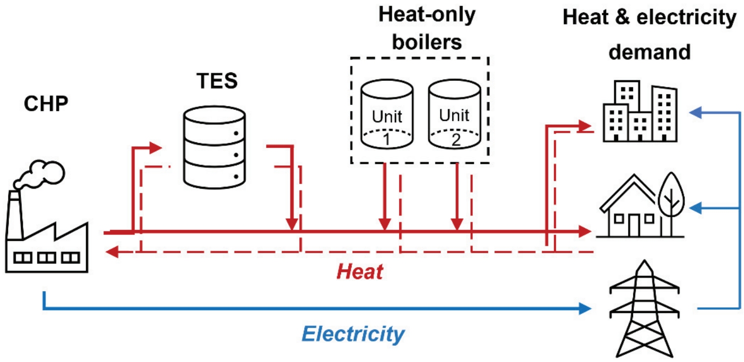

Figure 3. Combined heat and power system.

3.1. Data and Research Scenarios

Four scenarios are designed to investigate the economic effects of uncertain energy and carbon emission prices on the financial performance of a coal-fired combined heat and power system. Scenario I and Scenario II aim to illustrate the effects of the commodity prices observed in 2020 (1 January 2020 to 31 December 2020) on the dynamic performance of the CHP system configuration. Scenario I considers the case of the stand-alone CHP-HOB system, while Scenario II describes the same system integrated with a 400-MWh tank thermal energy storage unit.

As future electricity, coal, and carbon emission allowance prices are uncertain, the present study investigates two additional scenarios. Scenario III and Scenario IV explore the impact of energy and EUA prices in 2030 on the financial and operational performance of the stand-alone CHP system and integrated CHP-HOB-TES system. Possible future energy and carbon emission prices reported by the International Energy Agency [17] and ENTSO-E [18] are used to define the bound and parameters that describe the probability distributions. Table 1 summarizes the scenarios under which the CHP system is evaluated.

Table 1. Summary of research scenarios.

	Year	Energy System	
		CHP-HOB System	**CHP-HOB-TES System**
Scenario I	2020	●	
Scenario II	2020		●
Scenario III	2030	●	
Scenario IV	2030		●

In the present set of scenarios, a special case of Beta distribution was used to model the potential ranges of future energy and EUA prices. This type of continuous distribution—commonly referred to as PERT—uses three estimators: minimum, maximum, and most likely value. This distribution was selected since it has been extensively used in several fields to model projections and expectations of commodity prices [11,19]. Moreover, it constructs a smooth curve and emphasizes the most likely value, which is of outstanding importance in exploratory studies (research that accounts for possible versions of the future).

The data used to estimate the distribution parameters were collected from multiple information sources, and are summarized in Table 2. Data for coal prices in 2020 were obtained from the Polish Steam Coal market index [27]. Coal price projections for 2030 were extracted from the most recent World Energy Outlook (WEO 2021) [17]. In the case of electricity day-ahead prices for 2020, the data were taken from the Polish Power Exchange and the Transmission System Operator [28]. Electricity price projections for 2030 were obtained from the most recent ENTSO-E Ten-Year Network Development Plan (TYNDP 2022) [18]. Prices of CO_2 emission allowances for 2020 were extracted from the Quandl [29], whereas price projections for 2030 were taken from the WEO 2021 [17]. It is assumed that heating prices are regulated with a single tariff for the one-year period in all scenarios. The tariff for 2020 was estimated from heat prices reported by the Energy Regulatory Office of Poland [30]. Heat prices for 2030 were projected by extending the upward trend in local municipal heat prices observed in recent years.

Table 2. Distributional assumptions.

Parameter	Unit	Scenario I and II (2020)	Scenario III and IV (2030)
Coal price	€/Mg	PERT(57.1; 59.1; 60.4)	PERT(45.6; 50.9; 57.9)
Electricity price	€/MWh	PERT(26.9; 47.2; 69.2)	PERT(62.0; 64.0; 66.0)
EUA price	€/Mg	PERT(15.2; 24.8; 33.3)	PERT(87.8; 105.3; 114.1)
Heat price	€/MWh	Constant(26.7)	Constant(39.6)

Note: PERT(A; B; C)—Beta-PERT distribution with a λ (lambda) parameter of 4; A—lowest possible value, B—most likely value, C—highest possible values.

Figure 4 illustrates the distributions of energy and carbon emission prices for 2020. The bounds of the distributions reflect the observed coal and electricity prices in Poland and carbon emission prices in the European Union.

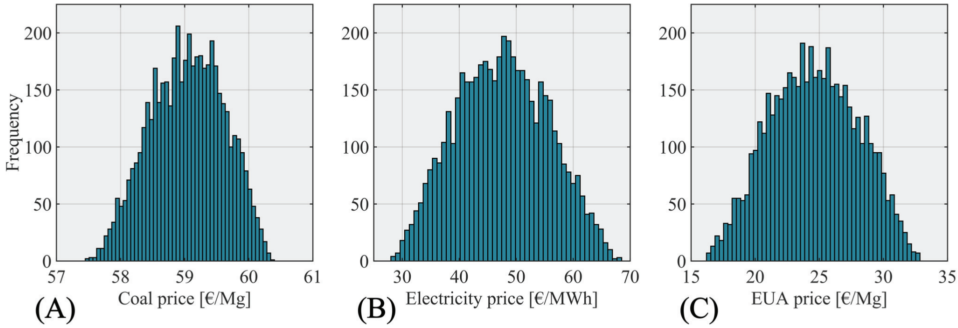

Figure 4. Distributional assumptions for 2020. (**A**) Coal price (**B**) Electricity price (**C**) EUA price.

Figure 5 shows the distributions of energy and carbon emission prices for 2030. The bounds of the distributions were defined from projected coal and carbon emission prices by the International Energy Agency [17] and electricity prices by ENTSO-E [18].

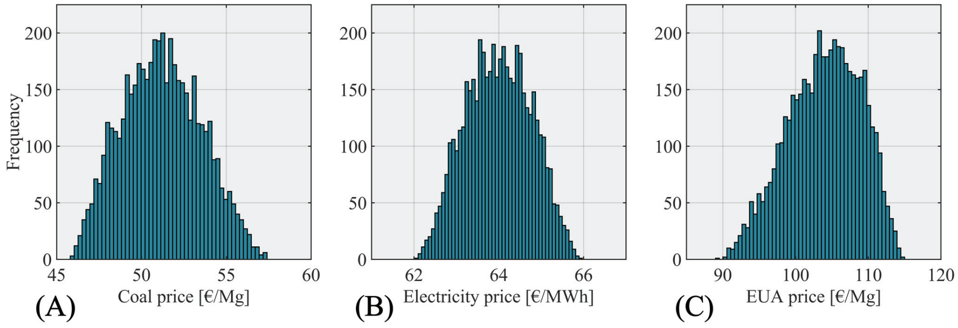

Figure 5. Distributional assumptions for 2030. (**A**) Coal price (**B**) Electricity price (**C**) EUA price.

3.2. Model Implementation

The proposed computational framework was coded in the General Algebraic Modeling Systems (GAMS) and soft-linked to MATLAB. Random samples from PERT distributions for each input parameter were generated with MATLAB using the Statistics and Machine learning toolbox. The mixed-integer linear programming model was implemented in GAMS and solved using CPLEX 20.1 in a desktop computer with 46 GB of RAM and an Intel Core i7-8086 4.0 GHz.

4. Result

As described in Section 2, the method involved solving the optimization model *N* number of times until the average value and standard deviation of the expected profit stabilized. For each of the Monte Carlo scenarios, the optimization model was run for a full year. Each scenario consisted of a set of possible coal, electricity, and carbon emission prices. Figure 6 shows the results of the Monte Carlo simulation for Scenarios I and III after 1200 replications. From the figure, it can be observed that the average value and standard deviation stabilized at approximately 1000 sample sets.

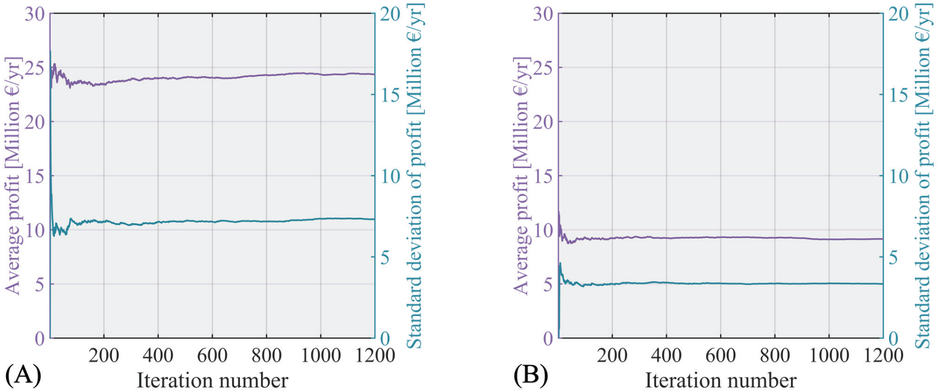

Figure 6. Convergence of mean profit and standard deviation: (**A**) Scenario I; (**B**) Scenario III.

It is worth noting that the addition of the energy storage in Scenarios II and IV increased the solution times significantly. This was mainly due to the relatively higher number of binary variables used for modeling the behavior of the thermal energy storage unit. Table 3 summarizes the results obtained after 1200 iterations. Additionally, it shows the fluctuations that occurred between the first two hundred iterations and the evolution of the mean profit as the total number of iterations increases.

Table 3. Monte Carlo simulation results.

Iteration	Scenario I (2020)			Scenario II (2020)			Scenario III (2030)			Scenario IV (2030)		
	$P_r(Mean)$(M€)	$P_r(SD)$(M€)	$t(Mean)$(s)	$P_r(Mean)$(M€)	$P_r(SD)$(M€)	$t(Mean)$(s)	$P_r(Mean)$(M€)	$P_r(SD)$(M€)	$t(Mean)$(s)	$P_r(Mean)$(M€)	$P_r(SD)$(M€)	$t(Mean)$(s)
1	24.78	17.66	0.84	25.49	17.68	29.00	11.67	0.04	0.82	12.38	0.01	15.96
200	23.49	7.17	0.79	24.22	7.18	17.61	9.22	3.32	0.72	9.93	3.31	23.51
400	23.97	7.16	0.79	24.71	7.17	17.86	9.24	3.42	0.72	9.95	3.41	20.78
600	24.07	7.16	0.79	24.81	7.17	17.72	9.32	3.37	0.72	10.03	3.36	21.34
800	24.29	7.18	0.79	25.03	7.18	17.71	9.25	3.35	0.72	9.96	3.35	20.46
1000	24.35	7.35	0.79	25.09	7.35	17.76	9.12	3.38	0.72	9.83	3.37	19.95
1200	24.34	7.31	0.79	25.08	7.31	17.80	9.15	3.33	0.72	9.86	3.32	19.59

Note: *SD* stands for standard deviation; *t* represents computation time.

The iterative computational process generates feasible solutions for profit maximization considering the technical constraints of the CHP system and the variation of energy and carbon emission prices. The solutions can be described in the form of histograms and used to assess the variation in profit and the financial contribution of the thermal energy storage unit.

Figure 7 provides a visual comparison of the four scenarios examined in this study. The results showed that integrating a short-term thermal energy storage unit increased the profitability of the system and helped reduce the risk associated with fluctuating energy prices. This can be observed in Figure 7b,d, which show an increase in profit of approximately €0.74 M in 2020 and €0.71 M in 2030.

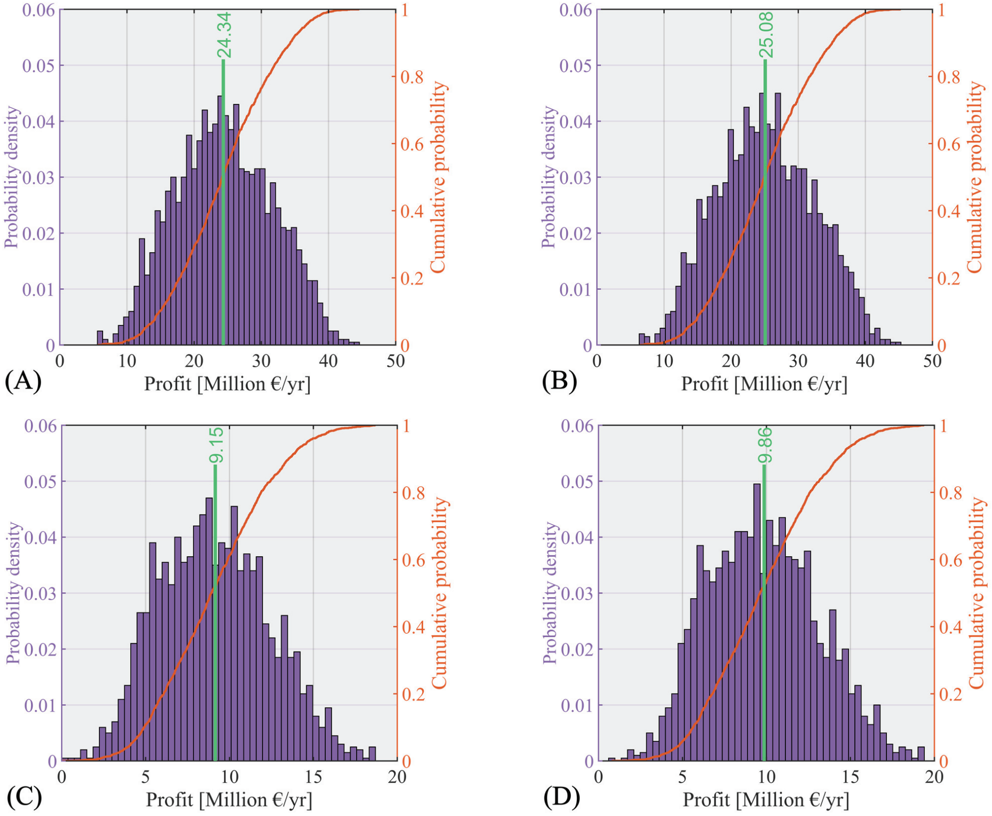

Figure 7. Probability density functions and cumulative probability functions: (**A**) Scenario I, (**B**) Scenario II, (**C**) Scenario III, (**D**) Scenario IV.

Furthermore, based on the outcomes of Scenario II (2020, CHP-HOB-TES) and Scenario IV (2030, CHP-HOB-TES), it can be noticed that in 2030 coal-powered CHP systems will face the risk of very low returns. This risk is mainly triggered by the continued upward movement in EUA prices.

The distributions of the different outcomes also allowed to estimate the probability of the potential annual profits. For the case of the stand-alone CHP system operating in the market scenario of 2020, the results showed that there is an 80% probability that the annual profit will be less than or equal to €30.98 M. On the other hand, with the installation of a tank thermal energy storage unit, the cumulative probability of 80% was at €31.72 M. Based on the cumulative distribution functions (CDFs) of Scenarios III and IV (2030), it can be stated that there is a 95% probability that the annual profit of the stand-alone and the integrated CHP-HOB-TES system will be below €14.64 M. Furthermore, the analysis of these two scenarios showed that the thermal energy storage increases the chances of receiving additional profits. There is an 80% probability that in 2030, the annual profit of the stand-alone CHP system will be less than or equal to €11.88 M, while for the integrated CHP-HOB-TES system, the profit may be less than or equal to €12.6 M. The findings above are particularly important for potential investors in new cogeneration systems and thermal energy storage units, since they offer valuable insights into the economic consequences of integrating the two technologies.

During each iteration, the optimization model solves the coal-fired CHP system's operational planning problem, taking into account the scenarios drawn by the Monte Carlo procedure. This computational process allows monitoring and collecting information about the system's economic performance in each hour of the simulated year. Figure 8 illustrates the hourly generation costs and revenues from electricity sales for one week in 2030. The stochastic simulated time series capture the variability in generation costs and revenues from electricity sales of the stand-alone and the integrated CHP system. The large variation envelope in generation costs indicated that coal and carbon emission prices have a more significant impact on the optimal behavior of the system as compared to the variation in electricity prices.

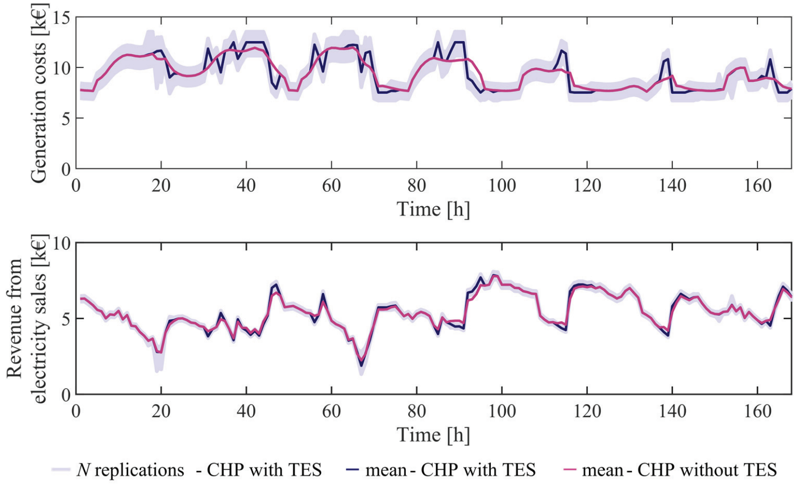

Figure 8. CHP system economic performance. (**Top**): Generation costs (Scenario III and IV). (**Bottom**): Revenue from electricity sales (Scenario III and IV).

The average annual results obtained from the Monte Carlo procedure for 2020 and 2030 are illustrated in Figure 9. The figure breaks down the estimates into three separate components: revenues, costs, and profits. The total annual revenue of the stand-alone

CHP increased from nearly €72 M in 2020 to €102 M in 2030, representing a rise in revenue of approximately 40%. However, because of the projected increase in carbon emission allowances prices, the average annual generation costs for the same CHP system configuration nearly doubled. Despite the higher revenues in 2030, the substantial increase in generation costs resulted in a drop in expected profits from €24 M to €9.15 M, or approximately 62%. Similar variations were observed for the scenarios that incorporate a tank thermal energy storage unit. These findings indicate that coal-fired CHP plant operators will face costly risks and potentially greater challenges in the upcoming years with the increasing regulatory and financial pressure on CO_2 emissions and the EU's plan of phasing out coal and other fossil fuels from electricity and heat generation.

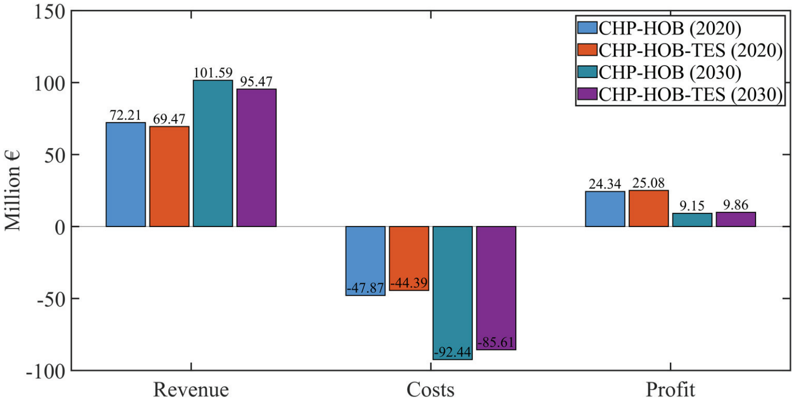

Figure 9. Comparison of annual average results.

5. Conclusions

The main goal of the study was to investigate the effects of uncertain energy and carbon prices on the operation and financial performance of CHP systems with thermal energy storage. This objective was achieved by developing a stochastic approach composed of a mathematical programming method and a Monte Carlo technique. The approach was designed to deal with the uncertainty of fluctuating energy and carbon prices and assess the financial contribution of thermal energy storage. The proposed computational framework was coded in the General Algebraic Modeling Systems (GAMS) and soft-linked to MATLAB. The stochastic approach was applied to generate scenarios taking into consideration a set of inputs chosen from random samples drawn from independent continuous probability distributions.

In the study, four scenarios were investigated. Scenario I and Scenario II aimed to illustrate the effects of the commodity prices observed in 2020. Scenario III and Scenario IV explored the impact of energy and EUA prices in 2030. From the results, the following conclusions can be derived:

1. The iterative computational process generates feasible solutions for profit maximization considering the technical constraints of the CHP system and the variation of energy and carbon emission prices.
2. The distributions of the different outcomes allowed to estimate the probability of the potential annual profits. For the case of the stand-alone CHP system operating in the market scenario of 2020, there is an 80% probability that the annual profit will be less than or equal to €30.98 M.
3. There is an 80% probability that in 2030 the annual profit of the stand-alone CHP system will be less than or equal to €11.88 M, while for the integrated CHP-HOB-TES system, the profit may be less than or equal to €12.6 M.

4. Integrating a short-term thermal energy storage unit increased the profitability of the system and helped reduce the risk associated with fluctuating energy prices. Profit increased on average by €0.74 M (with the implementation of a TES) in 2020 and €0.71 M in 2030.

In the coming years, the operational patterns and economic results of CHP systems will be significantly affected by new electricity and heat consumption patterns and market changes. Moreover, further research challenges will arise because of the increasing penetration of renewable generation and large-scale electrical energy storage deployment. The issues mentioned above will require comprehensive models that consider multiple interdependent sources of uncertainty (e.g., short-term economic factors, environmental and operational aspects of renewable power technologies, power and heat consumption patterns, and thermal comfort levels, among others). In this regard, an important avenue for future research is the incorporation of wind and solar systems along with their high degree of uncertainty (wind speed and solar irradiation) into the proposed Monte Carlo-based method. Another direction for future research is the integration of new computational techniques such as deep learning (neural networks) to reduce the computational complexity of the Monte Carlo approach and the mixed-integer linear programming model.

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Abbreviations

CHP	Combined heat and power
EU	European Union
EUA	European Union Allowance
FOZ	Feasible operation zone
HOB	Heat-only boiler
MILP	Mixed-integer linear programming
TES	Thermal energy storage

Appendix A

Table A1. Indices and sets of the mathematical model.

Sets	Description
t	Hours, $t \in T$
b	Heat $-$ only boilers, $b \in B$
p	Pollutant, $p \in P$
j	Piecewise linear approximation breakpoints, $j \in J$

Table A2. Parameters of the mathematical model.

Parameters	Description
ΔR_{Max}	Maximum rate of change of combined power output, (MW)
ΔR_{Min}	Minimum rate of change of combined power output, (MW)
η_{chr}	Energy storage charge efficiency
η_{dis}	Energy storage discharge efficiency
η_{s}	Energy storage efficiency
C^{B}_{SU}	Start-up costs of HOB, (€)
C^{B}_{VOM}	Variable O&M cost of heat-only boiler, (€/MWh)
C^{EC-E}_{VOM}	Variable O&M cost related to the electrical output of the CHP, (€/MWh)
C^{EC-Q}_{VOM}	Variable O&M cost related to the thermal output of the CHP, (€/MWh)
C^{B}_{f}	Fuel cost of heat-only boiler in hour h, (€/Mg)
C^{EC}_{f}	Fuel cost of CHP, (€/Mg)
Cf^{Max}_{chr}	Maximum charge rate of TES (fraction of total TES capacity)
Cf^{Max}_{dis}	Maximum discharge rate of TES (fraction of total TES capacity)
C_{p}	Emission, (PLN/Mg)
$C^{Electricity}_{t}$	Electricity price, (€/MWh)
C^{Heat}_{t}	Heat price, (€/MWh)
E^{B}_{p}	Emission related to the power output of the HOB, (Mg/MWh)
E^{EC}_{p}	Emission related to the power output of the CHP, (Mg/MWh)
$P^{EC,Max}_{t}$	Maximum electrical output of the CHP, (MWh)
$P^{EC,Min}_{t}$	Minimum electrical output of the CHP, (MWh)
Q^{Demand}_{t}	Heat demand, (MWh)
fb^{B}_{j}	Coefficient Fb in segment j
fm^{B}_{j}	Coefficient Fm in segment j
β	Power-loss ratio
σ	Power-to-heat ratio

Table A3. Variables of the mathematical model.

Variables	Description
Continuous variables	
f^{EC}_{t}	Fuel consumption of CHP, (Mg)
p^{EC}_{t}	Electrical output of CHP, (MWh)
q^{TES}_{Cap}	TES installed capacity, (MWh)
$q^{B}_{t,b}$	Thermal output of HOB, (MWh)
q^{EC}_{t}	Thermal output of CHP, (MWh)
$q^{TES,chr}_{t}$	Energy charged to TES, (MWh)
$q^{TES,dis}_{t}$	Energy discharged from TES, (MWh)
q^{TES}_{t}	TES level, (MWh)
$\tau^{B}_{t,b}$	Slack variable-heat-only boiler fuel consumption, (Mg)

Table A3. *Cont.*

Variables	Description
Binary variables	
$u^B_{t,b}$	Commitment status of heat-only boiler
$z^B_{t,b}$	Start-up of heat-only boiler

References

1. Komorowska, A. Can decarbonisation and capacity market go together? The case study of Poland. *Energies* **2021**, *14*, 5151. [CrossRef]
2. Bracco, S.; Bianchi, E.; Bianco, G.; Giacchino, A.; Ramaglia, A.; Delfino, F. On the participation of small-scale high performance combined heat and power plants to the Italian ancillary services market within Virtually Aggregated Mixed Units. *Energy* **2021**, 122275. [CrossRef]
3. Ahn, H.; Miller, W.; Sheaffer, P.; Tutterow, V.; Rapp, V. Opportunities for installed combined heat and power (CHP) to increase grid flexibility in the U.S. *Energy Policy* **2021**, *157*, 112485. [CrossRef]
4. Beiron, J.; Montañés, R.M.; Normann, F.; Johnsson, F. Combined heat and power operational modes for increased product flexibility in a waste incineration plant. *Energy* **2020**, *202*, 117696. [CrossRef]
5. Christidis, A.; Koch, C.; Pottel, L.; Tsatsaronis, G. The contribution of heat storage to the profitable operation of combined heat and power plants in liberalized electricity markets. *Energy* **2012**, *41*, 75–82. [CrossRef]
6. Król, J.; Ocłoń, P. Economic analysis of heat production in existing medium size combined heat and power plant, with respect to the CO_2 allowances purchasing cost. *Energy Convers. Manag.* **2018**, *171*, 110–125. [CrossRef]
7. Wang, H.; Yin, W.; Abdollahi, E.; Lahdelma, R.; Jiao, W. Modelling and optimization of CHP based district heating system with renewable energy production and energy storage. *Appl. Energy* **2015**, *159*, 401–421. [CrossRef]
8. Daraei, M.; Campana, P.E.; Avelin, A.; Jurasz, J.; Thorin, E. Impacts of integrating pyrolysis with existing CHP plants and onsite renewable-based hydrogen supply on the system flexibility. *Energy Convers. Manag.* **2021**, *243*, 114407. [CrossRef]
9. Mollenhauer, E.; Christidis, A.; Tsatsaronis, G. Increasing the Flexibility of Combined Heat and Power Plants with Heat Pumps and Thermal Energy Storage. *J. Energy Resour. Technol.* **2017**, *140*, 020907. [CrossRef]
10. Jiménez Navarro, J.P.; Kavvadias, K.C.; Quoilin, S.; Zucker, A. The joint effect of centralised cogeneration plants and thermal storage on the efficiency and cost of the power system. *Energy* **2018**, *149*, 535–549. [CrossRef]
11. Mavrotas, G.; Florios, K.; Vlachou, D. Energy planning of a hospital using Mathematical Programming and Monte Carlo simulation for dealing with uncertainty in the economic parameters. *Energy Convers. Manag.* **2010**, *51*, 722–731. [CrossRef]
12. Dimoulkas, I.; Amelin, M. Monte Carlo simulation of district heating system short-term operation in electricity markets. *Energetika* **2017**, *63*, 93–104. [CrossRef]
13. Koltsaklis, N.E.; Nazos, K. A stochastic MILP energy planning model incorporating power market dynamics. *Appl. Energy* **2017**, *205*, 1364–1383. [CrossRef]
14. Urbanucci, L.; Testi, D. Optimal integrated sizing and operation of a CHP system with Monte Carlo risk analysis for long-term uncertainty in energy demands. *Energy Convers. Manag.* **2018**, *157*, 307–316. [CrossRef]
15. Koltsaklis, N.E.; Kopanos, G.M.; Georgiadis, M.C. Design and operational planning of energy networks based on combined heat and power units. *Ind. Eng. Chem. Res.* **2014**, *53*, 16905–16923. [CrossRef]
16. Rezaee Jordehi, A. Economic dispatch in grid-connected and heat network-connected CHP microgrids with storage systems and responsive loads considering reliability and uncertainties. *Sustain. Cities Soc.* **2021**, *73*, 103101. [CrossRef]
17. IEA. *World Energy Outlook 2021*; IEA: Paris, France, 2021.
18. ENTSO-E. TYNDP 2022—Draft Scenario Report; Belgium, 2021. Available online: https://2022.entsos-tyndp-scenarios.eu (accessed on 14 November 2021).
19. Zaroni, H.; Maciel, L.B.; Carvalho, D.B.; Pamplona, E.d.O. Monte Carlo Simulation approach for economic risk analysis of an emergency energy generation system. *Energy* **2019**, *172*, 498–508. [CrossRef]
20. Benalcazar, P. Optimal sizing of thermal energy storage systems for CHP plants considering specific investment costs: A case study. *Energy* **2021**, *234*, 121323. [CrossRef]
21. Benalcazar, P.; Kamiński, J. Optimizing CHP operational planning for participating in day-ahead power markets: The case of a coal-fired CHP system with thermal energy storage. *Math. Model. Contemp. Electr. Mark.* **2021**, 237–258. [CrossRef]
22. Benalcazar, P. Sizing and optimizing the operation of thermal energy storage units in combined heat and power plants: An integrated modeling approach. *Energy Convers. Manag.* **2021**, *242*, 114255. [CrossRef]
23. Collins, S.; Deane, J.P.; Poncelet, K.; Panos, E.; Pietzcker, R.C.; Delarue, E.; Ó Gallachóir, B.P. Integrating short term variations of the power system into integrated energy system models: A methodological review. *Renew. Sustain. Energy Rev.* **2017**, *76*, 839–856. [CrossRef]
24. Verbruggen, A.; Klemeš, J.J.; Rosen, M.A. Assessing Cogeneration Activity in Extraction–Condensing Steam Turbines: Dissolving the Issues by Applied Thermodynamics. *J. Energy Resour. Technol.* **2016**, *138*, 052005. [CrossRef]

25. Fang, T.; Lahdelma, R. Optimization of combined heat and power production with heat storage based on sliding time window method. *Appl. Energy* **2016**, *162*, 723–732. [CrossRef]
26. Short, M.; Crosbie, T.; Dawood, M.; Dawood, N. Load forecasting and dispatch optimisation for decentralised co-generation plant with dual energy storage. *Appl. Energy* **2017**, *186*, 304–320. [CrossRef]
27. TGE Polish Steam Coal Market Index. Available online: http://gpi.tge.pl/en/web/wegiel/47 (accessed on 1 March 2021).
28. PSE Day Ahead Wholesale Market Price of Electricity—PSE. Available online: https://www.pse.pl/web/pse-eng/data/balancing-market-operation/basic-price-and-cost-indicators/day-ahead-wholesale-market-price-of-electricity (accessed on 5 March 2021).
29. Instrat—Open Energy Data Platform EUA Certificate Prices. Available online: https://energy.instrat.pl/co2_prices (accessed on 14 March 2021).
30. URE Taryfy Opublikowane w 2020 r. Available online: https://bip.ure.gov.pl/bip/taryfy-i-inne-decyzje-b/cieplo/3913,Taryfy-opublikowane-w-2020-r.html (accessed on 3 March 2021).

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Capacity Market and (the Lack of) New Investments: Evidence from Poland

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Abstract: Capacity remuneration mechanisms operate in many European countries. In 2018, Poland implemented a centralized capacity market to ensure appropriate funding for the existing and new power generation units to improve long-term energy security. One of the declarations made while the mechanism was deployed was its beneficial influence on incentives for investments in new units. In this context, this paper aims to analyze the effects of the capacity mechanism adopted for investments in new power generation units that may be financed under the capacity market mechanism in Poland. The analysis is conducted for four types of capacity market units, the existing, refurbishing, planned, and demand-side response types, and includes the final results of capacity auctions. The results prove that the primary beneficiaries of the capacity market in Poland have been the existing units (including the refurbishing ones) responsible for more than 80% of capacity obligation volumes contracted for 2021–2025. Moreover, during the implementation of the capacity market in Poland, the planned units that signed long-term capacity contracts with a total share of 12% of the whole market were already at the advanced phases of construction, and the investment decisions were made long before the implementation of the capacity market mechanism. Therefore, they were not associated with the financial support from the capacity market. The study indicates that the capacity market did not bring incentives for investments in new power generation units in the investigated period.

Keywords: capacity market; energy transition; remuneration mechanism; power generation; new investments

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1. Introduction

Capacity remuneration mechanisms (CRMs) are proposed to solve capacity adequacy problems in the power system that have arisen due to the increase in the share of renewable energy sources. These units have an impact on the merit order effect resulting in a decrease in the revenues of thermal units. Consequently, thermal units cannot cover their operational costs, investors cannot have enough incentives, and the problem of missing capacity and even brownouts or blackouts may occur.

CRMs include a broad range of instruments, such as strategic reserve [1], capacity payments, capacity obligations, reliability options, and centralized and decentralized capacity markets [2–4]. They are implemented in many European countries (i.e., the United Kingdom [5], Germany [1,6], Italy [7], Ireland, and others [8–10]), as well as in the United States [11–14], and others throughout the world [15,16]. According to the literature and policymakers, their main goal should be to ensure appropriate investment incentives for power generation units [2,13,17] to secure stable and economically efficient power generation [18,19].

The Polish power system also faced the specter of the problem of missing capacity. Similar to other European countries, the energy-only market in Poland did not provide adequate price signals to maintain the required generation capacity in the system in the long-term perspective. Market prices did not provide economic conditions for continuing market participation by existing units or making decisions about building new investments. The Polish generation system is based mainly on fossil fuels, thus is vulnerable to climate policies and increasing carbon prices. Additionally, most generating assets in Poland are outdated, with numerous units over 30 years old [20]. Therefore, they should be refurbished or decommissioned in the coming years. On the other side, it is expected that electricity consumption will increase [21,22]. The final indication of the mounting difficulties was the lack of sufficient capacity in the system to meet the peak demand in August 2015 [23]. High temperature, unfavorable hydrological conditions, maintenance breaks in some units, and increased demand caused the introduction of restriction of electricity consumption for industry and large companies.

To address these problems and avoid the brownouts and economic losses, Poland deployed the centralized capacity market in 2018, with the parameters and regulations developed on solutions implemented in the United Kingdom. To the best of the authors' knowledge, Poland followed the British model as it had gone through the notification of the European Commission and because it was believed that it would be easier to follow the same path. Additional advantages of the British model over, for example, the US, resulted from the similarity of the British energy market to the Polish one:

- The relatively high share of conventional, coal-fired power units in the fuel mix (at the time of considering and introduction of capacity remuneration mechanism).
- A similar design of the energy market before implementation of capacity remuneration mechanism (one unified market, with one Transmission System Operator (TSO) in the country vs. several regional markets in the US, with several TSOs).

Before settling on the British model, numerous techno–economic analyses were carried out to compare various possible scenarios. The centralized capacity market was considered an optimal solution from the perspective of system reliability and minimization of electricity prices for consumers.

1.1. Literature Review

The influence of the capacity market for making incentives for building new power units was studied by Byers et al. (2018). However, the authors focused merely on theoretical possibilities for supporting new production units [24]. Mastropietro et al. (2017) delivered empirical evidence from the functioning of capacity remuneration mechanisms in the United Kingdom, the United States (Colombia, ISO New England, and PJM Energy Markets), and France [25]. Spees et al. (2013) analyzed the functioning of the capacity market mechanism in the United States [13]. Based on the results, they proposed recommendations for the mechanisms deployed in Europe. They noted that the capacity market does not generate market incentives that could be expected from its theoretical assumptions.

Fang et al. (2021) pointed out the current design of the capacity markets does not consider the difference in the flexibility of power units. The authors propose the new framework of capacity remuneration mechanism that would differentiate the characteristic of units and provide better incentives for peak load generation capacity [26]. Schäfer and Altvater (2021) also indicate that the capacity market does not provide the same chances for each power unit. The authors propose a new modification to the current design of CM and price markup depending on the carbon emissions of individual power plants. Consequently, the cleanest technologies could obtain the highest payments from the capacity markets [27]. McCullough et al. (2021) address the research question regarding the competitiveness in PJM. The results show that the solution is inefficient and allows one to use the market power of individual suppliers [28].

The Polish capacity market is a subject of numerous analyses. However, most studies cover techno–economic simulations of its operation in the long term. E.g., Komorowska et al. (2020) investigated the economic consequences of introducing the capacity market until 2030 [29]. Zamasz et al. (2020) compared support mechanisms for new combined heat and power plants assuming the time horizon of 2050 [30]. Komorowska (2021) presented the impact of the capacity market on the decarbonization process in Poland until 2040 [18]. Jeżyna et al. (2020) questioned 50 companies about their expectations and plans related to the participation in capacity marked compared to other DRS schemes [31].

1.2. Study Contributions

To the best of the authors' knowledge, there are no studies about the influence of the capacity market on incentives for investments in new units. Given that the Polish capacity market is a relatively new mechanism, it lacks detailed empirical analyses of its functioning and influence on generating market incentives for building power units. Since five capacity auctions have already been held (for 2021–2025 delivery years), the question is whether and to what extent the capacity market implemented in Poland generates appropriate signals for building new power generation units. That is why this paper significantly contributes to the related discussion.

Within this context, this paper contributes to the existing literature in the following ways: First, it provides a comprehensive analysis of results of capacity auctions held to date broken down into capacity market units. Second, it extends the current studies on the consequences of the operation of capacity remuneration mechanisms in European markets. Third, the results show that the capacity market does not meet its assumptions about creating market signals for building new units. Finally, the analysis provides the conclusions that may be used by countries considering the implementation of such a mechanism to their energy markets.

The authors are aware that the study has some limitations. The results of capacity auctions include only limited information about capacity units. Each unit was identified due to the authors' knowledge of the Polish power sector and their analyses about power companies. Although not all units were identified, their share is small enough to be neglected in this analysis without impacting the study results and conclusions.

In this context, the paper aims to analyze past capacity auctions to estimate the influence of adopted solutions on investment in new power generation units. The remainder of the paper is structured as follows: Section 2 presents the principles and functioning of the capacity market in Poland and includes a description of the method applied for the analysis. Section 3 presents the results, and Section 4 summarizes and concludes the discussion.

2. Materials and Methods

This section presents the essential principles of the capacity remuneration mechanism implemented in Poland (the centralized capacity market). Furthermore, it describes sources of information used in the analysis, general assumptions, and the methodology applied.

2.1. Capacity Market in Poland

Capacity remuneration mechanisms, including the capacity market, have been the subjects of numerous studies and publications [2,9,10,32,33]. Main conditions and principles regarding the centralized capacity market deployed in Poland under the act of 8 December 2017, Dz.U. 2018, item 9 [34] are presented in [18,29,30]. It needs to be highlighted that the capacity market deployment in Poland aimed to ensure middle- and long-term energy supply security that would be economically justified, nondiscriminatory, and respecting sustainable development principles.

According to the act, the capacity market deployed in Poland shall be technologically neutral and open for the existing, refurbishing, and new power generation units. Solutions stimulating the demand side's participation are promoted. Foreign units are also allowed to participate in the capacity market.

On the Polish centralized capacity market, transactions are made at the primary and secondary capacity markets (Figure 1).

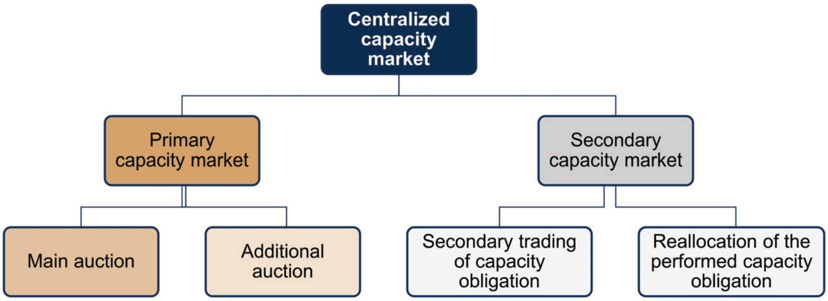


Figure 1. The general framework of the centralized capacity market implemented in Poland. Source: Own analysis based on [34].

Owners of power generation assets are obliged to participate in a certification procedure. After positive verification and passing the certification procedure, they can participate in the capacity auction for a specified delivery year. Stages conducted within the national capacity market are presented in Figure 2.

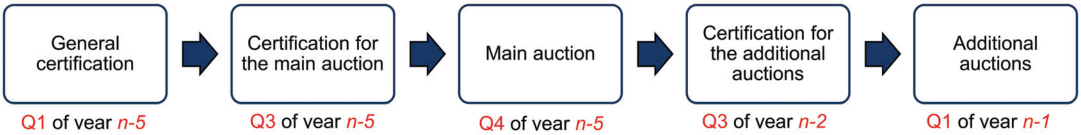


Figure 2. Main stages of the participation process in the capacity auctions for the ***n***–delivery year. Source: Own analysis based on [34].

In the Polish capacity mechanism, main auctions are held five years before a delivery period. An exception was 2018, when three auctions were held for the 2021, 2022, and 2023 delivery years. Additional auctions are held one year before a planned delivery period.

Capacity auctions held within the national capacity market are the descending clock auctions, that is, they consist of many rounds with decreasing prices [35]. In each round, a capacity provider offers a certified capacity obligation volume with a price equal [34] to:

- Exit price (when during a given or previous round there was an exit bid submitted),
- Starting price of another round (when a capacity provider did not bid an exit offer, and a given round is not the last round of the capacity auction) or
- Minimal price 0.2 Euro cents/kW/month (when a capacity provider did not submit an exit bid and a given round is the last round of the capacity auction).

Length of capacity contracts depends on the unit type and scale of investment:

- Existing and DSR units may sign contracts for one year,
- Refurbishing and DSR units (after meeting a criterion of the minimal level of investment) may sign contracts for five years, or
- New/planned units (after meeting a criterion of the minimal level of investment) may sign contracts for fifteen years.

Additionally, for high-efficiency cogeneration units, it is possible to extend the length of capacity contracts by two years (the so-called green bonus) in the case in which the units:

- Have an individual CO_2 emission factor lower than 450 kg CO_2/MWh of produced energy, and
- Sell at least half of produced heat to the heating network where hot water is a heat carrier.

A capacity auction ends in the round in which the total capacity obligation volume without exit bids is lower or equal to capacity demand, or in the case of finishing the last round. Consequently, capacity auctions are won by the capacity market units for which capacity providers offer the lowest price. An auction type is pay-as-clear that is expected to deliver lower prices than pay-as-bid auctions [36]. The costs of the capacity market are borne by the final consumers (mainly households and industry).

2.2. Method Applied

From the capacity market deployment in Poland from 2018 to October 2021, five main capacity auctions were held for delivery years 2021–2025. The analysis of the primary capacity market was conducted using the final results of the capacity auctions published by the President of the Energy Regulatory Office (ERO):

1. ERO President's Announcement No. 99/2018 of the Final Results of the Capacity Auctions for the Delivery Year 2021.
2. ERO President's Announcement No. 103/2018 of the Final Results of the Capacity Auctions for the Delivery Year 2022.
3. ERO President's Announcement No. 14/2019 of the Final Results of the Capacity Auctions for the Delivery Year 2023.
4. ERO President's Announcement No. 106/2019 of the Final Results of the Capacity Auctions for the Delivery Year 2024.
5. ERO President's Announcement No. 2/2021 of the Final Results of the Capacity Auctions for the Delivery Year 2025.

The documents include capacity provider's names, unit types, delivery periods, volumes of contracted capacity obligations, and the auction clearing price. Because of the lack of information directly identifying specific power generation units, technical parameters of existing, planned, and constructed power units were used.

The analysis concerns four types of capacity market units (CMUs):

1. Existing units which include mainly conventional coal-fired, gas-fired, and hydro-pumped storage power plants.
2. Refurbishing units, which, in contrast to the existing units, need to declare minimal investments before the first delivery period given in the capacity agreement.
3. New/planned units, which include all units that had not been commissioned before the general certification to a given capacity auction and meet the minimal level of investment criterion.
4. Demand-side response units (DSRs) which consist of mainly planned demand-side response units.

3. Results

Results presented in this section are divided into a general overview and detailed discussion, the former consists of key data on the concluded capacity auctions while the latter presents results related to the types of capacity market units, separately for each auction and at the aggregated level.

3.1. General Results

Table 1 summarizes the results of the main auctions held for delivery years 2021–2025. The highest clearing price of 57.1 EUR/kW/year was noted during the main auction held for the 2024 delivery year. A high price (52.8 EUR/kW/year) was also achieved in the first capacity auction. Both are characterized by the highest volume of planned power units. Relatively low prices were noted on auctions for 2022 and 2023 delivery years. These auctions were characterized by low or close to none contracted capacity volumes for new/planned units.

Table 1. Final results of the main capacity auction for 2021–2025 delivery years.

Parameter	Unit	2021	2022	2023	2024	2025
Auction price cap	EUR/kW/year	72.1	80.5	89.5	88.9	91.2
Market entry price of a new generating unit (CONE)	EUR/kW	65.5	67.0	68.8	68.4	70.1
Auction clearing price	EUR/kW/year	52.8	43.5	44.6	57.1	38.0
Capacity obligation purchased	MW	22,427.1	10,580.1	10,631.2	8671.2	2367.3
Total capacity obligations	MW	22,427.1	23,038.9	23,215.0	22,107.6	21,472.8
Planned capacity volume	MW	4022.3	0	852.6	1440.3	4.9
Final round number	–	5	7	8	5	7
Number of winning bids	–	160	120	94	103	55

Source: Own analysis based on [37–41].

3.2. Detailed Analysis of Capacity Auctions: New vs. Refurbishing vs. Existing vs. DSR Units

In this subsection, the results of each capacity auction are analyzed first, and then the aggregated results are discussed and summarized.

3.2.1. Main Capacity Auction for 2021 Delivery Year

Figure 3 presents the volume of capacity obligations contracted in the first capacity auction (for the 2021 delivery year). The chart shows that the capacity market supported the existing units with more than 10 thousand MW while the refurbishing ones with over 7.5 thousand MW. Units declared as planned contracted over 4 thousand MW in total. Nevertheless, the detailed analysis of the auction results offers a different conclusion. As previously indicated in the Polish capacity market principles description, the planned units include all units that passed the certification on participating in the capacity market but were not commissioned before the general certification for a given capacity auction. Given this, in the first capacity auction, power plants and combined heat and power plants (CHPs), for which investment decisions and construction itself had been initiated before adopting the Polish Act on the Capacity Market (in most cases, even several years earlier), were qualified as the planned units.

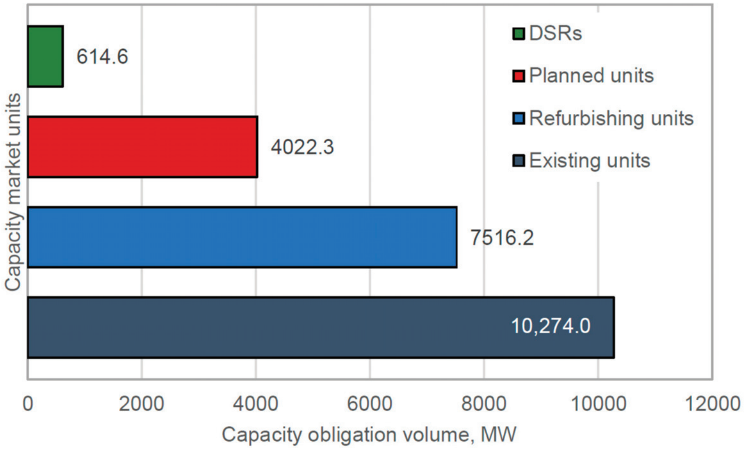


Figure 3. Capacity obligation volume contracted in main capacity auction for 2021 delivery year–break down by official (declared) assignments to capacity market units. Source: Own analysis based on [37].

Among the largest planned units that have made capacity agreements there can be indicated new generation units in coal-fired power plants in Opole (2 units, 900 MW each), Jaworzno (910 MW), Turów (496 MW), and gas-fired power generation units in CHPs in Stalowa Wola (450 MW), Płock (630 MW), and Żerań (499 MW).

The contract for building new hard coal-fired units in the power plant in Opole was signed at the beginning of 2014, and in the third quarter of 2018, 80 % of the investment was realized. The power plant case in Jaworzno was similar; the construction contract was signed in 2014, and in October 2018 (before the first main auction), reports stated 80% of investment completion. In 2014, other contracts were signed for building new units in the power plant in Turów and in the CHP in Płock. In the first case, the construction work was finished in November 2018, and the start-up phase began, while the gas unit in Płock was put into operation in June 2018 due to the shorter investment period. The construction of a combined cycle gas turbine (CCGT) unit in Stalowa Wola began at the end of 2012. Still, due to significant perturbations in the investment process, the commissioning occurred no sooner than September 2020. A delay was a matter of concern also for the CCGT unit investment in CHP in Żerań. Although the connection conditions of this investment were given in 2015 and the construction contract was signed in the third quarter of 2017, the unit was not commissioned in the assumed deadline, i.e., before the first delivery period given in the capacity agreement (2021).

Considering the described circumstances regarding the time of making investment decisions, beginning the construction of new units, and their advancement before the first capacity auction, it should be stated that the capacity mechanism operating in Poland was not a decisive factor for the realization of the new power generation units. That is why recognizing the investments within the category “capacity market’s planned units” may be misleading. Constructions of indicated units were not initiated due to the capacity market deployment.

The capacity obligation of planned units that were already under construction during the capacity market deployment in Poland (mainly at the very advanced stage of the investment) was over 3.9 thousand MW. In Figure 4, the volume of advanced projects was transferred to the existing units, which, after the change, accounts for more than 14 thousand MW. A comparison of the auction results for the 2021 delivery year (official vs. actual assignment) is well-presented in the chart with the percentage structure of contracts signed at the auction with a distinction into the types of capacity market units (Figure 5). The initial results (a) show that the planned units were almost 18% of the total volume contracted at the auction. However, after considering the proposed changes (b), the share of these units decreases to 0.4%. Simultaneously, the share of existing units increased from almost 46% (Figure 5a) to more than 63% (Figure 5b).

3.2.2. Main Capacity Auction for 2022 Delivery Year

In the case of the main auction for the 2022 delivery year, only the existing and refurbishing units signed capacity contracts for the total capacity obligation volume of over 9.8 thousand MW. DSR units also signed such contracts (761 MW) (Figure 6). It needs to be pointed out that the existing units were almost 92% of the total volume, DSRs were 7.2%, and the refurbishing units were slightly above 1% (Figure 7).

3.2.3. Main Capacity Auction for 2023 Delivery Year

The planned unit contracted the capacity obligation volume of 852.6 MW in the capacity auction for the 2023 delivery year (Figure 8). The highest volume of capacity obligations stipulated by capacity agreements were the existing units (almost 9 thousand MW). It needs to be noted that the decision to build that planned unit (a new coal-fired power generation unit in Ostrołęka with the capacity of 1000 MW) was made in 2016 (in the same year there was made another decision to sign a contract for fuel delivery). It means that also, in this case, the classification of the power unit to the new/planned category may be misleading. The structure of capacity contracts for the given types of CMUs, both the official (a) and actual assignments (b), are presented in Figure 9.

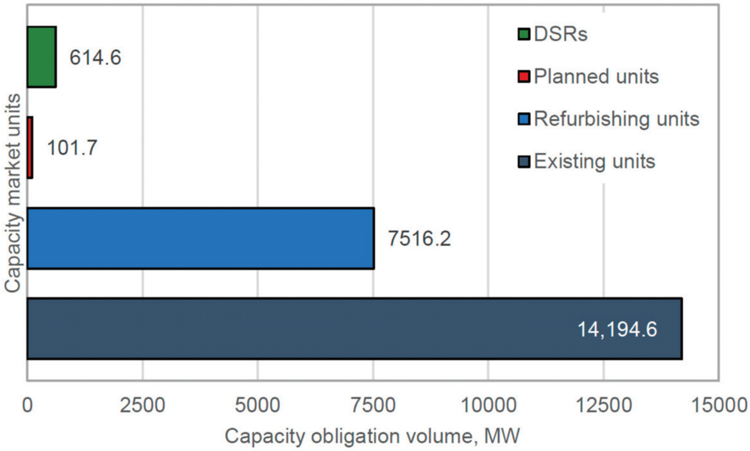
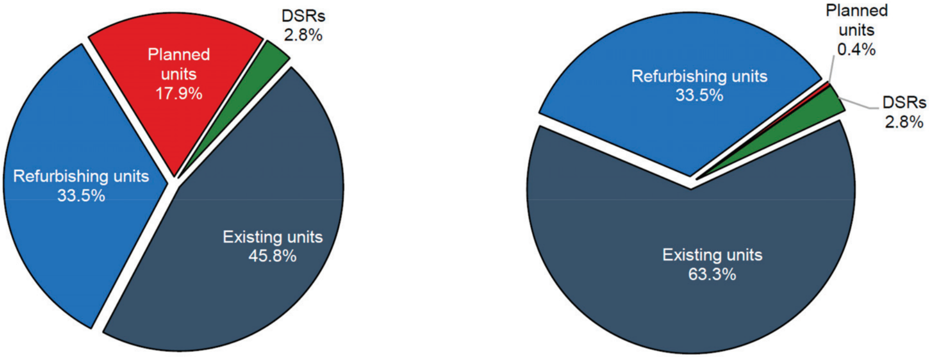


Figure 4. Capacity obligation volume contracted in main capacity auction for 2021 delivery year–break down by real status of capacity market units. Source: Own analysis based on [37].



(**a**) (**b**)

Figure 5. Structure of capacity obligation volumes contracted in main capacity auction for 2021 delivery year–break down by capacity market units: (**a**) official (declared) assignment; (**b**) actual status of capacity market units. Source: Own analysis based on [37].

Analyzing the results, one should consider the current state of investment in the new unit in Ostrołęka. Due to high prices for CO_2 emission allowances and the planned decarbonization of the Polish economy [42–44], the construction of this unit was withheld at the beginning of 2020. It was decided to partially dismantle already built structures and change the production technology, including the construction of the gas-fired unit. Until now (October 2021), there have been no final decisions in this matter.

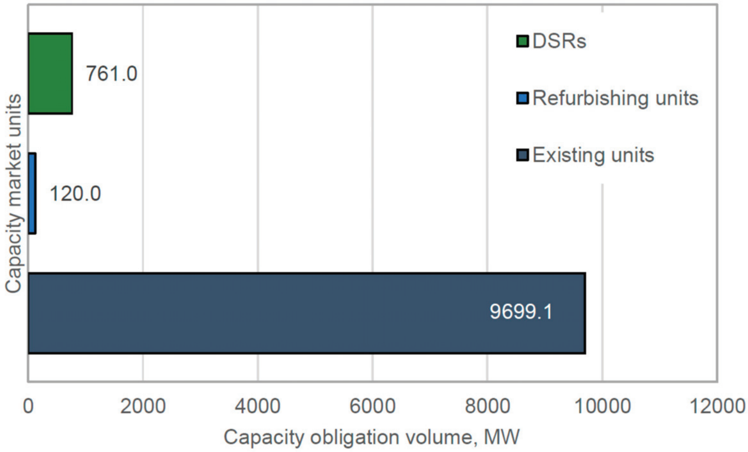


Figure 6. Capacity obligation volume contracted in main capacity auction for 2022 delivery year–break down by official (declared) assignments to capacity market units. Source: Own analysis based on [38].

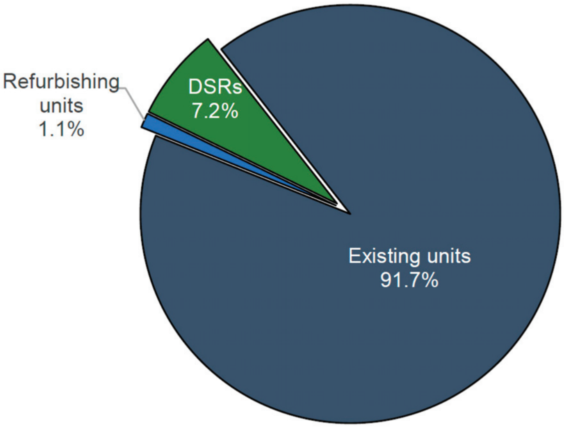


Figure 7. Structure of capacity obligation volumes contracted in main capacity auction for 2022 delivery year–break down by official (declared) assignments to capacity market units. Source: Own analysis based on [38].

3.2.4. Main Capacity Auction for 2024 Delivery Year

The capacity market auctions for a delivery period 2021–2023 were held in the same year (2018) and preceded by the standard process of certifications for the auctions. Subsequent capacity auctions are held five years before a delivery year they concern. The auction results for the 2024 delivery year are different from the previous auctions, mainly due to regulations implemented by the Regulation (EU) 2019/943 of the European Parliament and the Council of 5 June 2019 on the Internal Market for Electricity [45]. According to the regulation, capacity remuneration mechanisms may concern only the units that meet the CO_2 emission limit (550 kg CO_2/MWh of produced electricity), which, in practice, eliminates coal-fired power plants and CHPs from participating in the primary capacity market. The regulations concern all new units that have begun operation after 4 July 2019 and set a deadline for supporting the existing units, i.e., put into operation before 4 July 2019, for 1 July 2025. It means that the auction for the 2024 delivery year was the last on which the existing power generation units could sign a long-term capacity contract for the refurbishing capacity market units.

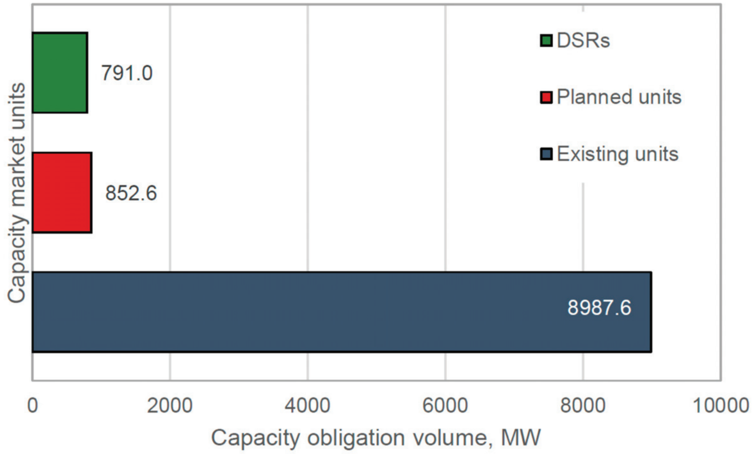
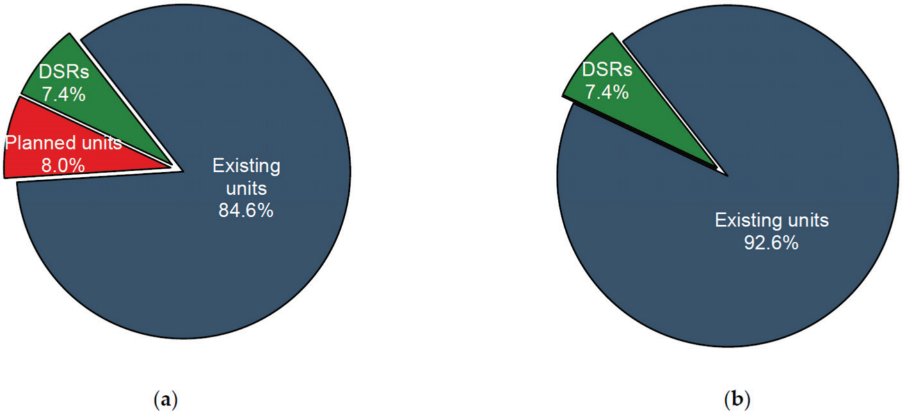


Figure 8. Capacity obligation volume contracted in main capacity auction for 2023 delivery year–break down by official (declared) assignments to capacity market units. Source: Own analysis based on [39].



(**a**)

(**b**)

Figure 9. Structure of capacity obligation volumes contracted in main capacity auction for 2023 delivery year–break down by capacity market units: (**a**) official (declared) assignment; (**b**) actual status of capacity market units. Source: Own analysis based on [39].

Given that situation, the highest contracted capacity obligation volume was for the refurbishing units–over 4.2 thousand MW (Figure 10), almost 49% of all contracts (Figure 11). The existing units came second (22.7%) with a volume of nearly 2.0 thousand MW. Moreover, 1.4 thousand MW were contracted for the planned units (16.5%; four gas-fired power units in total) and over 1000 MW for the DSRs (11.9%).

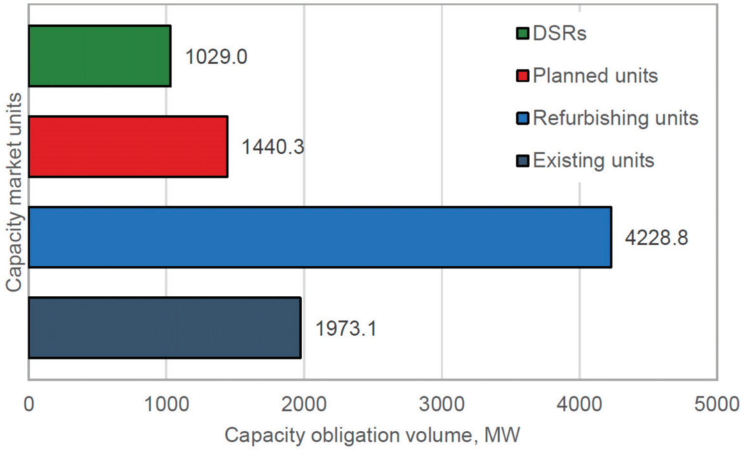


Figure 10. Capacity obligation volume contracted in main capacity auction for 2024 delivery year–break down by official (declared) assignments to capacity market units. Source: Own analysis based on [40].

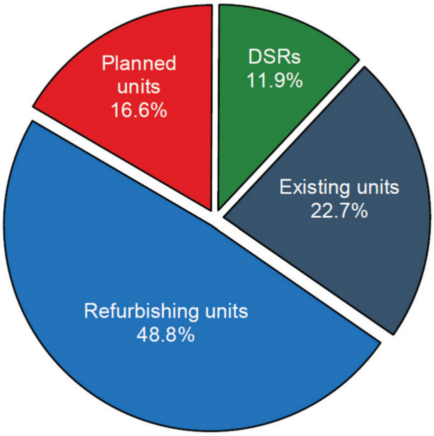


Figure 11. Structure of capacity obligation volumes contracted in main capacity auction for 2024 delivery year–break down by official (declared) assignments to capacity market units. Source: Own analysis based on [40].

3.2.5. Main Capacity Auction for 2025 Delivery Year

The main capacity auction for the 2025 delivery year is characterized by a very small capacity demand (Table 1). Approx. 2.3 thousand MW were bought in total, of which the highest volume (1.3 thousand MW) was the existing units (Figure 12). The capacity obligations of coal units were about 300 MW; their contracts will be valid until the half of 2025. The remaining existing units are mainly gas-fired power plants and CHPs, and hydro pumped storage. Moreover, a capacity contract was signed by the refurbishing units (161.6 MW) and DSRs, for which the total volume (949.0 MW) was over 40% of the total contracted capacity (Figure 13). Low-capacity demand, fierce competition, and the lowest clearing price among all main capacity auctions (Table 1) caused that the capacity agreement was signed only by one new unit, which reported capacity obligation was 4.9 MW–about 0.2% of the total volume.

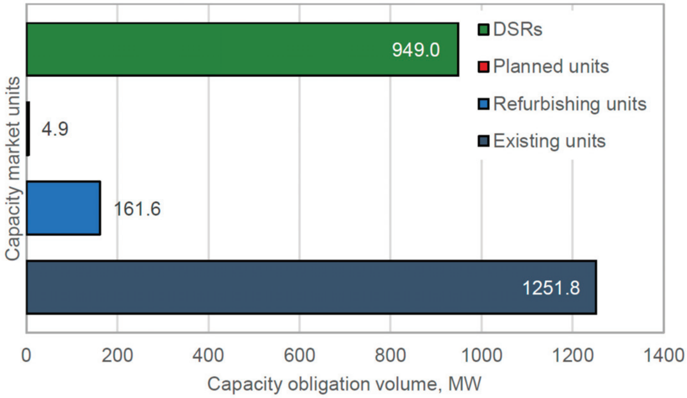


Figure 12. Capacity obligation volume contracted in main capacity auction for 2025 delivery year–break down by official (declared) assignments to capacity market units. Source: Own analysis based on [41].

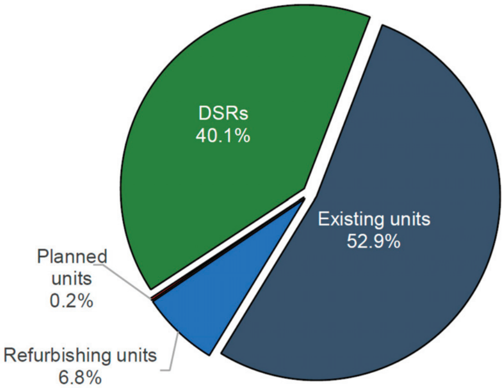


Figure 13. Structure of capacity obligation volumes contracted in main capacity auction for 2025 delivery year; break down by official (declared) assignments to capacity market units. Source: Own analysis based on [41].

3.2.6. Aggregated Results of All Main Capacity Auctions for 2021–2025 Delivery Years

Figures 14 and 15 present the aggregated results of all main capacity auctions for 2021–2025 delivery years with a distinction into the types of contracted units. The total volume of capacity obligations of the existing and refurbishing units supported by the capacity market was over 44 thousand MW (Figure 14), which is over 80% of the total contracted volume (Figure 16a). Units declared as new (planned), of which capacity obligation stipulated by the agreements was over 6.3 thousand MW, were almost 12% of the mentioned volume (it should be remembered that the planned units signed long-term agreements, mostly for 15 and 17 years).

It should also be noted that the beneficiaries of the capacity market are, to a relatively large extent, DSR units (over 4.1 thousand MW of contracted capacity obligation volume in years 2021–25). Based on the presented results (Figures 4, 6, 8, 10 and 12), an upward trend in the share of DSR units in the capacity market for the first four auctions can be observed. The volume of contracted capacity at the last capacity auction (for 2025 delivery year) decreased slightly and was related to the lowest auction clearing price (38.0 EUR/kW/year) among all past auctions. Apart from support from the capacity market, DSR units can also obtain additional revenues from the electricity balancing market, as well as take advantage of the interventional reduction of consumption scheme (a successor to the guaranteed, current, and simplified current DSR schemes available in the 2017–20 period). The Polish Transmission System Operator (TSO) implemented the latter mechanism, which takes the form of tenders, to cover capacity deficits with demand reduction services. On the other hand, there is also a strong expectation from the owners and aggregators of DSR units to introduce dynamic tariffs for electricity consumers in Poland based on real-time pricing. The results indicate that the centralized capacity market mainly supports the existing power generation units (mostly coal-fired ones and, to a much lesser extent, gas-fired units and hydro pumped storage) and does not generate sufficient incentives for investing in new power generation units.

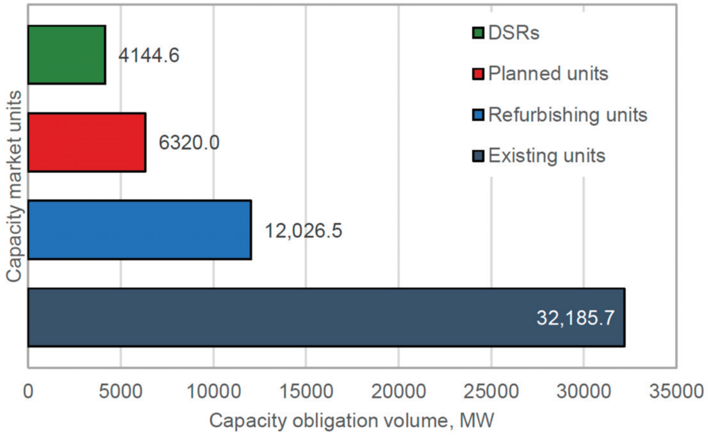


Figure 14. Capacity obligation volume contracted in main capacity auction for 2021–2025 delivery years; break down by official (declared) assignments to capacity market units. Source: Own analysis based on [37–41].

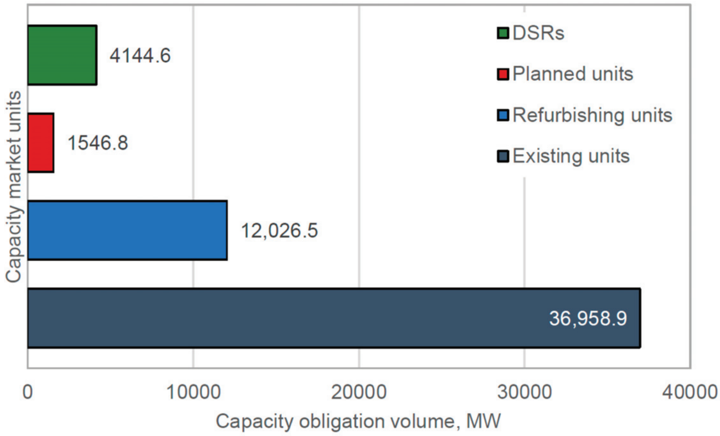


Figure 15. Capacity obligation volume contracted in main capacity auction for 2021–2025 delivery years–break down by actual status of capacity market units. Source: Own analysis based on [37–41].

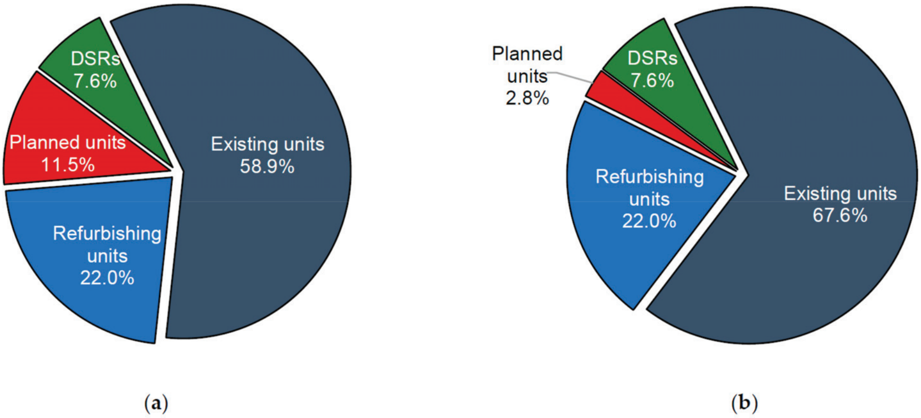


Figure 16. Structure of capacity obligation volumes contracted in main capacity auction for 2021–2025 delivery years–break down by capacity market units: (**a**) official (declared) assignment; (**b**) actual status of capacity market units. Source: Own analysis based on [37–41].

The change of unit arrangement based on the actual state (Figures 15 and 16b) only deepens our observation. In this case, almost 90% of the total contracted capacity obligation volume concerns the existing units, including the refurbishing ones and units under construction, before deploying the capacity remuneration mechanism in Poland in 2018. According to the actual results, the total volume for the planned/new units is merely 2.8% of all signed contracts (Figure 16b).

4. Conclusions

The main goal of this paper was to analyze the influence of the capacity market deployment on generating real incentives for investing in new power generation units based on the evidence from Poland. The investigation proves that the primary beneficiaries of the capacity market have been the existing and refurbishing units (mostly coal-fired ones) that together (according to the classification system) comprise more than 80% of the capacity obligation volumes contracted for 2021–2025. The detailed analysis allowed us to conclude that new/planned power generation units that signed long-term capacity agreements with a total share of 12% of all contracts were already in the advanced stage of construction when the capacity market was deployed in Poland. This means that investment decisions had been made much earlier and were not related to support that was possible to achieve from the capacity market.

In the analyses and with changing the unit types, the problem only deepened. In this case, the new and planned units were merely 2.8% of signed capacity agreements. The remaining volume of contracted capacity obligations was attributed mainly to the existing and refurbishing units (89.6%). The empirical case of the Polish power system proves that in the investigated period, the capacity market was not a sufficient incentive for building new power generation units and served mainly the financing of the existing and refurbishing, mostly coal-fired–units.

The analysis shows that although the capacity market in Poland results in the improvement of system reliability in the long term, the mechanism has not fulfilled its objectives in the context of creating market signals for new investors. However, the solution adopted allowed to address the capacity adequacy problem through supporting existing thermal units.

Introduction of changes in the principles for qualifying units for participating in the capacity market and excluding support for high-emission units at the European level (CO_2 emission limit 550 kg CO_2/MWh for electricity production) will have an impact on the results of the subsequent capacity auctions. Since there are many power plants and CHPs in the power system, their exclusion from the capacity auctions may cause an impulse for investing in new, low-emission power generation units. However, it is crucial to consider the current design of the Polish capacity market to avoid problems with different flexibility of power units [26].

Our results also confirm the need for modifications of the current design of existing capacity markets, as indicated by Schäfer and Altvater (2021) [27]. The concept of the introduction of emission standards from the beginning would allow cleaner technologies to compete with existing coal-fired units. Such classification could also create sufficient incentives to invest in low-emission technologies.

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Abbreviations

Name	Explanation
CCGT	Combined cycle gas turbine
CHP	Combined heat and power plant
CO	Capacity Obligation
CRM	Capacity Remuneration Mechanisms
CMU	Capacity Market Unit
CO_2	Carbon Dioxide
DSR	Demand-side response
ERO	Energy Regulatory Office
EU	European Union
RES	Renewable Energy Sources

References

1. Neuhoff, K.; Diekmann, J.; Kunz, F.; Rüster, S.; Schill, W.P.; Schwenen, S. A coordinated strategic reserve to safeguard the European energy transition. *Util. Policy* **2016**, *41*, 252–263. [CrossRef]
2. Cramton, P.; Ockenfels, A.; Stoft, S. Capacity market fundamentals. *Econ. Energy Environ. Policy* **2013**, *2*, 27–46. [CrossRef]
3. Neuhoff, K.; De Vries, L. Insufficient incentives for investment in electricity generations. *Util. Policy* **2004**, *12*, 253–267. [CrossRef]
4. Pollitt, M.G.; Haney, A.B. Dismantling a Competitive Electricity Sector: The U.K.'s Electricity Market Reform. *Electr. J.* **2013**, *26*, 8–15. [CrossRef]
5. Bhagwat, P.C.; Marcheselli, A.; Richstein, J.C.; Chappin, E.J.L.; De Vries, L.J. An analysis of a forward capacity market with long-term contracts. *Energy Policy* **2017**, *111*, 255–267. [CrossRef]
6. Ozdemir, O.; de Joode, J.; Koutstaal, P.; van Hout, M. Financing investment in new electricity generation capacity: The impact of a German capacity market on Northwest Europe. In Proceedings of the 2013 10th International Conference on the European Energy Market (EEM), Stockholm, Sweden, 27–31 May 2013; pp. 1–8.
7. Mastropietro, P.; Fontini, F.; Rodilla, P.; Batlle, C. The Italian capacity remuneration mechanism: Critical review and open questions. *Energy Policy* **2018**, *123*, 659–669. [CrossRef]

8. Hancher, L.; De Hauteclocquoe, A.; Sadowska, M. *Capacity Mechanisms in EU Energy Market*; Oxford University Press: Oxford, UK, 2015.
9. Cramton, P.; Ockenfels, A. *Economics and Design of Capacity Markets for the Power Sector*; Springer: Berlin/Heidelberg, Germany, 2012.
10. ACER. *ACER Marker Monitoring Report 2018—Electricity Wholesale Markets Volume*; ACER: Ljubljana, Slovenia, 2019.
11. Lin, J.; Vatani, B. Impact of capacity market design on power system decarbonization. In Proceedings of the 2017 14th International Conference on the European Energy Market (EEM), Dresden, Germany, 6–9 June 2017; pp. 1–6.
12. Bowring, J. Capacity Markets in PJM. *Econ. Energy Environ. Policy* **2013**, *2*, 47–65. [CrossRef]
13. Spees, K.; Newell, S.A.; Pfeifenberger, J.P. Capacity Markets—Lessons Learned from the First Decade. *Econ. Energy Environ. Policy* **2013**, *2*, 3–26. [CrossRef]
14. Pfeifenberger, J.P.; Spees, K.; Shumacher, A. *A Comparison of PJM's RPM with Alternative Energy and Capacity Market Designs*; The Brattle Group: Boston, MA, USA, 2009.
15. Galetovic, A.; Muñoz, C.M.; Wolak, F.A. Capacity Payments in a Cost-Based Wholesale Electricity Market: The Case of Chile. *Electr. J.* **2015**, *28*, 80–96. [CrossRef]
16. Ashokkumar Parmar, A.; Pranav, B.; Darji, B. Capacity market functioning with renewable capacity integration and global practices. *Electr. J.* **2020**, *33*, 106708. [CrossRef]
17. Roques, F.A. Market design for generation adequacy: Healing causes rather than symptoms. *Util. Policy* 2008. [CrossRef]
18. Komorowska, A. Can Decarbonisation and Capacity Market Go Together? *The Case Study of Poland. Energies* **2021**, *14*, 5151. [CrossRef]
19. Bhagwat, P.C. Security of Supply during the Energy Transition: The Role of Capacity Mechanisms. Ph.D. Thesis, Delft University of Technology, Delft, The Netherlands, 2016.
20. ARE SA. *Energy Statistics*. 2020. Available online: https://www.are.waw.pl/component/phocadownload/category/28-statystyka-elektroenergetyki-polskiej?download=104:statystyka-elektroenergetyki-polskiej-2020 (accessed on 8 August 2021).
21. Majchrzak, K.; Olczak, P.; Matuszewska, D.; Wdowin, M. Economic and environmental assessment of the use of electric cars in Poland. *Polityka Energetyczna-Energy Policy J.* **2021**, *24*, 153–168. [CrossRef]
22. Ministry of Climate and Environment Energy Policy of Poland until 2040. 2021. Available online: http://isap.sejm.gov.pl/isap.nsf/download.xsp/WMP20210000264/O/M20210264.pdf (accessed on 8 August 2021).
23. PSE SA. Report on the Reasons for the Introduction of Restrictions on the Supply and Consumption of Electricity in August 2015 in the Territory of the Country. 2015. Available online: https://www.pse.pl/biuro-prasowe/aktualnosci/-/asset_publisher/fwWgbbtxcZUt/content/pse-sa-opracowaly-raport-o-przyczynach-wprowadzenia-na-terenie-kraju-ograniczen-w-dostawach-i-poborze-energii-elektrycznej-w-sierpniu-2015-r-/exclusive?safeargs=696e686572 (accessed on 8 August 2021).
24. Byers, C.; Levin, T.; Botterud, A. Capacity market design and renewable energy: Performance incentives, qualifying capacity, and demand curves. *Electr. J.* **2018**, *31*, 65–74. [CrossRef]
25. Mastropietro, P.; Rodilla, P.; Battle, C. Performance incentives in capacity mechanisms: Conceptual considerations and empirical evidence. *Econ. Energy Environ. Policy* **2017**, *6*, 149–164. [CrossRef]
26. Fang, X.; Hu, Q.; Bo, R.; Li, F. Redesigning capacity market to include flexibility via ramp constraints in high-renewable penetrated system. *Int. J. Electr. Power Energy Syst.* **2021**, *128*, 106677. [CrossRef]
27. Schäfer, S.; Altvater, L. A Capacity Market for the Transition towards Renewable-Based Electricity Generation with Enhanced Political Feasibility. *Energies* **2021**, *14*, 5889. [CrossRef]
28. McCullough, R.; Weisdorf, M.; Ende, J.C.; Absar, A. Exactly how inefficient is the PJM capacity Market? *Electr. J.* **2020**, *33*, 106819. [CrossRef]
29. Komorowska, A.; Benalcazar, P.; Kaszyński, P.; Kamiński, J. Economic consequences of a capacity market implementation: The case of Poland. *Energy Policy* **2020**, *144*, 111683. [CrossRef]
30. Zamasz, K.; Kapłan, R.; Kaszyński, P.; Saługa, P.W. An Analysis of Support Mechanisms for New CHPs: The Case of Poland. *Energies* **2020**, *13*, 5635. [CrossRef]
31. Jezyna, B.; Lis, M.; Mesjasz-Lech, A. The DSR Scheme in the Capacity Market of Industrial Enterprises in Poland—Participation Determinants. *Energies* **2020**, *13*, 5462. [CrossRef]
32. ACER. *Capacity Remuneration Mechanisms and the Internal Market for Electricity*; ACER: Ljubljana, Slovenia, 2013.
33. Kirschen, D.; Strbac, G. *Fundamentals of Power System Economics*, 2nd ed.; John Wiley & Sons Ltd.: Hoboken, NJ, USA, 2019.
34. Ministry of Energy. *The Act of 8 December 2017 on Capacity Market (Dz.U. 2018 poz. 9)*; Ministry of Energy: Warsaw, Poland, 2018.
35. Carare, O.; Rothkopf, M. Slow Dutch Auctions. *Manage. Sci.* **2005**, *51*, 365–373. [CrossRef]
36. Saługa, P.; Kamiński, J. Rynek mocy w Polsce—aukcja jednocenowa vs. *aukcja dyskryminacyjna. Polityka Energ.-Energy Policy J.* **2017**, *98*, 167–176.
37. Energy Regulatory Office. ERO President's Announcement No. 99/2018 of the Final Results of the Capacity Auctions for the Delivery Year 2021. 2018. Available online: https://www.ure.gov.pl/pl/energia-elektryczna/rynek-mocy/informcjepure/8976,Informacja-nr-992018.html (accessed on 15 November 2021).
38. Energy Regulatory Office. ERO President's Announcement No. 103/2018 of the Final Results of the Capacity Auctions for the Delivery Year 2022. 2018. Available online: https://www.ure.gov.pl/pl/energia-elektryczna/rynek-mocy/informcjepure/8975,Informacja-nr-1032018.html (accessed on 15 November 2021).

39. Energy Regulatory Office. ERO President's Announcement No. 14/2019 of the Final Results of the Capacity Auctions for the Delivery Year 2023. 2019. Available online: https://www.ure.gov.pl/pl/energia-elektryczna/rynek-mocy/informcjepure/8973,Informacja-nr-102019.html (accessed on 15 November 2021).
40. Energy Regulatory Office. ERO President's Announcement No. 106/2019 of the Final Results of the Capacity Auctions for the Delivery Year 2024. 2019. Available online: https://www.ure.gov.pl/pl/energia-elektryczna/rynek-mocy/informcjepure/8971,Informacja-Nr-1062019.html (accessed on 15 November 2021).
41. Energy Regulatory Office. ERO President's Announcement No. 2/2021 of the Final Results of the Capacity Auctions for the Delivery Year 2025. 2021. Available online: https://www.ure.gov.pl/pl/energia-elektryczna/rynek-mocy/informcjepure?page=0 (accessed on 15 November 2021).
42. Drożdż, W.; Kinelski, G.; Czarnecka, M.; Wójcik-Jurkiewicz, M.; Maroušková, A.; Zych, G. Determinants of Decarbonization—How to Realize Sustainable and Low Carbon Cities? *Energies* **2021**, *14*, 2640. [CrossRef]
43. Mucha-Kuś, K.; Sołtysik, M.; Zamasz, K.; Szczepańska-Woszczyna, K. Coopetitive Nature of Energy Communities—The Energy Transition Context. *Energies* **2021**, *14*, 931. [CrossRef]
44. Wójcik-Jurkiewicz, M.; Czarnecka, M.; Kinelski, G.; Sadowska, B.; Bilińska-Reformat, K. Determinants of Decarbonisation in the Transformation of the Energy Sector: The Case of Poland. *Energies* **2021**, *14*, 1217. [CrossRef]
45. European Parliament and Council Regulation (EU). 2019/943 of the European Parliament and of the Council of 5 June 2019 on the Internal Market for Electricity. 2019. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32019R0943 (accessed on 8 August 2021).

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Application of Smart Technologies in Metropolis GZM to Reduce Harmful Emissions in District Heating Systems

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Abstract: Harmful emissions from heating installations have recently received public attention in Poland. Polish municipalities mainly take their heat from local district heating networks with large-scale coal-fired heat sources. Today, transition to nonemissive sources on this scale would be impractical. The easiest way to reduce carbon emissions is to limit heat consumption, but at the same time, to preserve thermal comfort, the application of smart technologies is necessary. Veolia operates on 71 district heating systems in Poland, including Warsaw, Lodz, and Poznan. Since heat consumption in Warsaw and Metropolis GZM is at a similar level, this is a case study of Hubgrade automation system application within the Warsaw district heating network. This paper also presents results of simulation of harmful emission reduction potential in Metropolis GZM. Simulation results show that there is a potential for saving approximately 275 kt of CO_2 for the whole Metropolis GZM.

Keywords: district heating; carbon emissions; decarbonization; energy efficiency; Hubgrade

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1. Introduction

The rapid industrialization process in Poland left a heavy burden on the environment. Despite consistent economic growth in recent years [1], today, in the COVID-19 era [2], the Polish economy needs to find a way forward, which would incorporate a promise of digital transformation [3] and take into account expectations of the stakeholders [4]. The energy sector is in the spotlight as it exemplifies both challenges and possibilities that the economy is facing [5]. In the past, energy under various forms was available without paying any attention to the environmental effort of such energy generation. The EU introduced three directives to tackle the air pollution problem: the LCP Directive, the MCP Directive, and the IE Directive. These directives are focused predominantly on decreasing relative values of emissions. This approach led to a significant drop in TSP emissions from 1156 kt in 1990 to 343 kt in 2019 overall. Greenhouse gases (GHG) emissions were 382 Mt in 1990 and 322 Mt in 2019. This paper presents how the Hubgrade solution contributes to harmful emissions reduction in the Warsaw district heating system and simulates how it could address emissions in the Metropolis GZM district heating system.

Metropolis GZM, in Polish "Górnośląsko-Zagłębiowska Metropolia", refers to an association of 41 municipalities located in southern Poland. Metropolis GZM was established to carry out regional tasks, which were to build a strong, industrial region in the national and international arena and to create an image of an attractive space for living, investing, and visiting. For the years 2018–2022, five priority strategic goals have been set [6]:

1. Create a metropolitan study. The study is a formal urban planning document. It supports the development of green cities, reduction of wastes, and consumption reduction of water and electricity.
2. Integrate public transport providers. It should include integration of tariffs and ticket systems, new intercity connections, and the purchase of zero-emission buses.
3. Support the implementation of tasks by the member states through subsidies from the Solidarity Fund and in projects related to the senior policy.
4. Promote the metropolitan association and its area. It should include building the metropolitan brand and identity among residents of the GZM.
5. Develop the Metropolitan Socio-Economic Observatory and a platform for good practices and internal management system.

All the goals can be achieved by various means, but they have to be simultaneous to meet the ambitious European Green Deal standards. However, there is a reason why climate neutrality was set as the first of the strategic goals. The historical culture of Silesia, mining and metallurgy, led to significant degradation of the region. Mining activity was dictated by huge coal seams located under the GZM and the surrounding areas. Access to cheap but unsustainable coal-based energy is the reason why local and national heat and electricity generation sources are strongly dependent on coal. This goal is also in line with the vision of The European Green Deal, which states that energy efficiency must be prioritized, and, at the same time, the EU's energy supply needs must be secure and affordable for consumers and businesses [7].

This can be accomplished by various activities. The concept of sharing economy may be a partial solution to minimize consumption of energy [8]. However, in order to meet the ambitious goals of The European Green Deal, all activities must be carried out simultaneously. One of these goals is to increase energy efficiency. Metropolis GZM, thanks to the relatively strong population density and an extensive network of district heating (DH) systems, creates a potential for savings through the use of intelligent technologies in DH systems.

To benefit from favoring geospatial conditions, a high level of coordination between stakeholders is necessary. GZM Metropolis can play a pivotal role in this process, which can result in the implementation of a smart city concept [9].

There is a necessity to develop suitable instruments in the decision-making process by the authorities, since the demand for intelligent solutions in service of operational cost reduction of the cities is growing. These instruments should include advanced technologies and social actions related to cooperation with residents and supporting social capital. In addition to advanced technologies, the importance of soft potentials is growing, including technology, talent, tolerance, and trust—jointly known as 4T. This 4T potential supports the intelligence, entrepreneurship, and innovation of a city. The presence of 4T in smart city management is a quality measure of the life of the inhabitants and its competitive position in the metropolis. Metropolis GZM had gone through a similar process before with the transportation network in which user experience improved through the integration of providers and smart technologies. District heating is another area in which creating soft potential, particularly in building trust among stakeholders, may transform into energy efficiency benefits and thus support the European Green Deal goals [10].

The effects of the implementation of smart technologies in the district heating network are not fully discussed in the existing literature, although there are some mentions [11,12]. This paper summarizes the application of smart solutions in the Warsaw district heating system, in which heat consumption is comparable to Metropolis GZM. Based on this summary, the authors simulated energy-saving opportunities and harmful emissions reduction potential in the GZM region. It is worth mentioning the fact that lack of competitiveness in the DHS sector has caused stagnation, and monopolistic conditions are natural to this branch, unlike in electric energy markets [13].

2. Generations of District Heating Systems

The development of technology and changes in urban evolution has caused modern district heating networks to not resemble those which were built 200 years ago [14]. To differentiate types of networks that exist, special nomenclature evolved as the district heating technology changed.

"First-generation" district heating systems started the existence of district heating at the end of the 19th century in the USA and Western Europe and used steam as a medium of heat carrier. The temperature of steam reached up to 150 °C.

In "second generation" heating systems, the heat carrier had been changed into pressurized water with a temperature above 130 °C, transmitted through steel pipes without good insulation which ran in concrete channels. This technology was used from the 1930s and was popular until the 1970s, especially in socialist countries, including Poland. Both of these technologies are characterized by high transmission losses.

The technology that is the most common in district heating systems at the moment of writing this paper are the "third-generation" systems (3G DHS) [11]. The main difference distinguishing this generation from the previous is the prefabricated technology in which pipes are built. Prefabrication means that pipes are produced integrated with insulation. Third-generation systems are supplied with pressurized hot water, whose temperature is often below 100 °C.

"Fourth generation" district heating systems (4G DHS) are difficult to characterize, and they are not very popular yet. As energy efficiency has become a global trend, it is impossible to stop the transformation of the state-of-the-art district heating technology. Future district heating systems will have to meet challenges, such as the ability to supply existing buildings as well as low-energy buildings at the same time, reduction of network losses, and the ability to integrate existing heat sources with renewable energy sources (RES) [15]. Thus, the fourth generation is expected to be supplied with low-temperature water that ranges from 30 °C−70 °C. To improve energy efficiency and meet the above-mentioned challenges, coordination of the performance of the buildings and the district heating system is required. Intelligent control of performance and smart metering of the network together with reasonably accurate weather forecasting may play a crucial role in the optimization of heat consumption. Intelligent algorithms and remote control of valves allows predicting the required need for heat and supplying the building with it without excess, and, as a result, maximizing energy efficiency. According to Li and Nord [12], smart district heating, thereby 4G DHS, consists of three essential parts: physical network (PN), Internet of Things (IoT), and intelligent decision system (IDS). Installation and integration of those three parts may be beneficial in terms of flexibility in the demands of the buildings, as the concrete structure of the building is used as a short-term heat storage system.

The idea of a "fifth-generation" system (5G DHCS: fifth-generation district heating and cooling) is not yet widespread. The main concept of 5G DHCS combines the system of district heating and district cooling. The carrier used in this technology is at ultra-low temperature. The use of RES is anticipated to be at the highest level guided by the principle of closing energy loops as much as possible [16]. The difference of heat carrier temperature in 3G DHS and 5G DHCS is significant enough that the return flow of 3G DHS may be a supply for 5G DHCS. Such a solution has been proposed in the urban renovation project for the district Hertogensite in Leuven (Belgium) [17].

2.1. Selected Projects Funded by the European Union Regarding Smart DH Systems

The European Union has allocated a great number of funds for research and innovation. Within the Horizon 2020 program, many scientific projects have been launched to increase energy efficiency and reduce the impact on the environment. Among projects in the DH field, the following can be mentioned [18]: FLEXYNETS [19], STORM [20], InDeal [21], and OPTi [22].

FLEXYNETS was an H2020 European Project that received funding under grant agreement no. 649820. The idea of the project was to integrate low-temperature heat sources, low-temperature waste heat, and RES with a DH network that works at neutral temperature of 15 °C−30 °C. The project mitigates heat losses resulting from the difference of ambient and the district heating network temperature, since the heat exchange drops as the temperature difference drops. Regarding the fact that the operating temperature of the network may be both a source of heat and a source of coolness, the idea is in line with the assumptions of 5G DHCS. Reversible heat pumps are used to enable heat exchange between internal building installation and the network [19].

STORM was an H2020 European Project that received funding under grant agreement no. 649743. As a part of the project, a special controller was designed and implemented. The goal of the implementation of the device was to increase the use of waste heat, RES, and boost energy efficiency at the district level. The STORM project was based on self-learning algorithms that operate on special designed smart network controllers. Two pilot projects have been launched and tested, unveiling the hidden potential of digitalization in the district heating field. Demonstration sites in Heerlen (The Netherlands) and Rottne (Sweden) proved the thesis of the research, with peak shavings (12.75% in Rottne), capacity improvements (42.1% in Heerlen), electricity purchase price reduction, and overall CO_2 emission reduction [20].

InDeal is an H2020 European Project that received funding under grant agreement no. 696174. InDeal was a multidisciplinary project whose selected objectives are as follows: development of a short-term weather forecasting tool, development of new insulation materials, development of storage management tool to monitor and control production, development of artificial intelligence metering, and development of web control platform. The InDeal system has been tested in real conditions at two pilot sites (the DH network in Vransko, Slovenia, and the DHC networks in Montpellier, France) [21].

OPTi is an H2020 European Project that received funding under grant agreement no. 649796. The project focused on the way DH is architected, controlled, and operated. The main goal was to reduce peak demand, lower supply temperature, optimize network operation, and reduce (very specific for the test site) geographic restrictions. By building a network simulation tool, forecasting weather conditions and heat demand tool, and creating a virtual valve mechanism that gives users control over their thermal comfort, the goal of the project has been achieved. The concept was analyzed at two demonstration sites: Luleå (Sweden) and Majorca (Spain) [22].

2.2. Selected Commercially Implemented Systems of Smart Managed District Heating Systems

Proof that intelligent solutions in the district heating field are no longer only in the research and development phases is the fact that there are commercial solutions. There are available proposals on the market that bring not only economic benefits but also environmental benefits. Selected examples of such solutions are mentioned below.

Building Energy Services-Hubgrade (BES-Hubgrade) is a service proposed by Veolia Energia Warszawa S.A. company (Poland) [23]. Through technical solutions, based on intelligent and remotely managed control devices, this service enables optimization of thermal energy consumption in connection to the service buildings. Continuous monitoring of parameters in the network, weather forecast analysis, multi-point temperature measurements, and a remote control system ensures the thermal comfort and simultaneous reduction of thermal energy consumption in the building, which translates into a lower carbon footprint in the heat production process and lower charges for citizens of the buildings. In addition, the system increases reliability and improves the efficiency of devices in the substation. Optimal energy consumption reduces the emission of gases harmful to the environment, since BES-Hubgrade is offered primarily in a region where approximately 90% of the heat comes from coal [24].

Smart Heat Grid Solutions™ and Smart Heat Building Solutions™ are intelligent management business proposals provided by NODA Intelligent Systems [25]. NODA Smart Heat Building is a solution that uses a self-learning and adaptive mathematical model that enables various scenarios, with sensors, which satisfy the system with continuous temperature monitoring, and enables calculation of the energy balance of the property and regulation of the existing control system of the heating substation. The solution is a comparable proposition to the BES-Hubgrade, pursuing similar goals with similar mechanisms. NODA Smart Heat Grid is a tool that allows reducing the use or eliminating the operation of peak heat sources during peak load periods. Thanks to the control of the interaction between the production conditions and the needs of consumers, NODA Smart Heat Grid is also able to cool the return water more, which translates into an increase in the efficiency of electricity generation in cogeneration systems with a steam turbine and thus increase in energy efficiency. In addition, the tool allows for the use of connected entities as virtual hot water tanks.

Smart Active Box (SAB) is a predictive maintenance system provided by Arne Jensen AB (Sweden) designed for managing the condition of district heating pipes [26]. The system is equipped with features different from previously mentioned systems. It is a device that collects specific data as acoustic vibrations (Delta-t®) to predict leakage in the district heating network. By using statistics, the system can monitor wear-down and corrosion levels and inform whether the line is to be replaced or not. Such a solution brings efficiency in maximization of the utilization of the pipes and thus minimization of the cost and carbon footprint, caused by the energy-consuming production process of pipes. However, the most important feature is that the system minimizes downtime. Sensors such as oxygen meters, temperature sensors, or flood sensors provide additional information about the situation in a heating chamber.

iSENSE™ is another smart solution for district heating networks, which is developed by Vexve Oy (Finland) [27]. The system consists of three monitoring solutions: iSENSE Opti for real-time monitoring and optimal control of the district heating network, iSENSE Pulse for leakage detection, and iSENSE Chamber for online monitoring of the conditions in a heating chamber.

3. Materials and Methods

3.1. GZM Boundary Assumption

In later references, GZM is understood as a collection of counties (second-layer units of local governments pol. "powiaty"). The list of assumed GZM counties is as follows:

- Powiat m.Bytom
- Powiat tarnogórski
- Powiat m.Piekary Śląskie
- Powiat m.Gliwice
- Powiat gliwicki
- Powiat m.Zabrze
- Powiat m.Katowice
- Powiat m.Chorzów
- Powiat m.Mysłowice
- Powiat m.Ruda Śląska
- Powiat m.Siemianowice Śląskie
- Powiat m.Świętochłowice
- Powiat m.Sosnowiec
- Powiat będziński
- Powiat m.Dąbrowa Górnicza
- Powiat m.Tychy
- Powiat bieruńsko-lędziński
- Powiat mikołowski

Powiat pszczyński was not included in the list, since only one municipality from this county (Kobiór) belongs to GZM, and data from bigger municipalities that belong to this county could significantly affect the quality of results.

Municipalities such as Krupski Młyn, Tworóg, Miasteczko Śląskie, Kalety (Powiat tarnogórski), Toszek, Wielowieś (Powiat gliwicki), Orzesze and Ornontowice (Powiat mikołowski) were included into GZM, although they do not belong to it, as they constitute a whole in a given county and it is not possible to exclude them from the data.

This concept is not fully covered in reality; however, the differences in boundaries are small, and the quality and availability of data in Statistics Poland's databases for GZM understood in this way is much greater.

3.2. Methodology of Calculating Heat Savings

Because weather conditions are unique for every year, and to provide an accurate and reliable measurement method, a special index of heat consumption was developed, which is calculated as follows:

$$KPI(n) = \frac{Q(n)}{HDD(n)} \tag{1}$$

where KPI(n) is an index of heat consumption over the reading period (n), Q(n) is heat consumption reading over the (n) period, and HDD(n) is the sum of the daily differences over the (n) period between the reference temperature of 18 °C and the average outdoor temperature during the day, expressed in °C, calculated for average daily temperatures less than or equal to 14 °C. In the case of an average daily outside temperature above 14 °C and in the months of June, July, and August, the HDD value is zero.

The heat consumption index in the following year is expressed by Equation (2).

$$KPI(n+1) = \frac{Q(n+1)}{HDD(n+1)} \tag{2}$$

Since, in many cases, accurate billing readings are not made on the first or last day of the month, a special formula has been developed that calculates consumption in a given month based on readings often performed in the middle of the month. In such cases, heat consumption in a given month Q(M) is calculated as the sum of the products of the heat consumption index for the first period KPI(n) and the number of heating degree days (from the beginning of the month to the moment of measurement) HDD(Ma) and the analogous product of the heat consumption index for the second period of the month KPI(n + 1) and the number of degree days (from reading point till the end of the month) HDD(Mb).

$$Q(M) = KPI(n) * HDD(Ma) + KPI(n+1) * HDD(Mb) \tag{3}$$

Theoretical base heat consumption $(Q)_{\text{base}}$ is calculated monthly as the product of the $\text{KPI(M)}_{\text{base}}$ heat consumption index in the base year and the number of HDD in the corresponding month. $\text{KPI(M)}_{\text{base}}$ is the average heat consumption $Q_{\text{ave}}(M)$ and $\text{HDD}_{\text{ave}}(M)$ over the previous five years.

$$KPI(M)_{base} = \frac{Q_{ave}(M)}{HDD_{ave}(M)} \tag{4}$$

$$Q(M)_{base} = KPI(M)_{base} * HDD(M) \tag{5}$$

In the end, heat savings achieved through intelligent management of the heating subsystem, are calculated as the difference between theoretical base heat consumption and actual heat consumption reading monthly.

$$\Delta Q = Q(M)_{base} - Q(M) \tag{6}$$

3.3. Comparison

Table 1 depicts that taking Warsaw DH system as a reference point is justified, because of the comparable length of the grid, which is 17% smaller in Warsaw, the cubature of the heated buildings, which is 37% higher in Warsaw than in GZM: the volume of the sold heat is 25% higher in Warsaw and, at the same time, the volume of the sold heat per 1 dam is 19% lower in Warsaw.

Table 1. Comparison of Warsaw DH system and aggregated data of GZM DH systems. Source: own elaboration based on [28–30].

Name of DH	Length of Heating Network	Cubature of Heated Buildings	Amount of Heat Sold
Warsaw DH system	1847 km (2019)	341,270 dam^3 (2018)	26,443 TJ (2019)
GZM DH systems (total)	2168 km (2019)	213,340 dam^3 (2018)	19,731 TJ (2019)

4. Calculations and Results

4.1. Number of Heating Degree Days in the Analyzed Period

As mentioned in Section 2.2, to compare the real impact of the adopted solutions, the following numbers of heating degree days were taken into account concerning the baseline, which is a base year. In Figure 1 the numbers of heating degree days between the years 2018 and 2020 are presented.

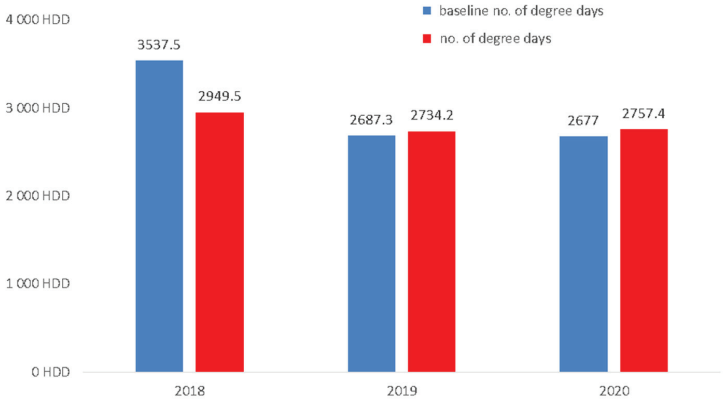


Figure 1. Number of heating degree days between 2018 and 2020.

It is visible that the number of heating degree days in 2018 is almost 20% lower than the baseline. In 2019, the number of heating degree days was 1.7% higher than the baseline, and in 2020, the number of heating degree days was 2.9% higher than the baseline. This implies the necessity of taking into account the number of heating degree days in the assessment of the achieved level of saving.

4.2. Hubgrade Performance Assessment

Assessment of the achieved level of savings began by rejecting incomplete data and choosing the complete dataset of consumption and savings between the years 2018 and 2020. The result is shown in Figure 2.

Then, the following question was posed: if the application of Hubgrade solution had contributed the level of savings or not. The calculated correlation coefficient of Hubgrade application concerning the achieved savings is close to 1, which implies that there is a tight relation between the application of Hubgrade and heating energy saving.

On average, between 2018 and 2020, heating energy saving was at the level of 13.8%. It is worth mentioning that the great majority of buildings in Warsaw that were taken into account have already undergone thermo-modernization.

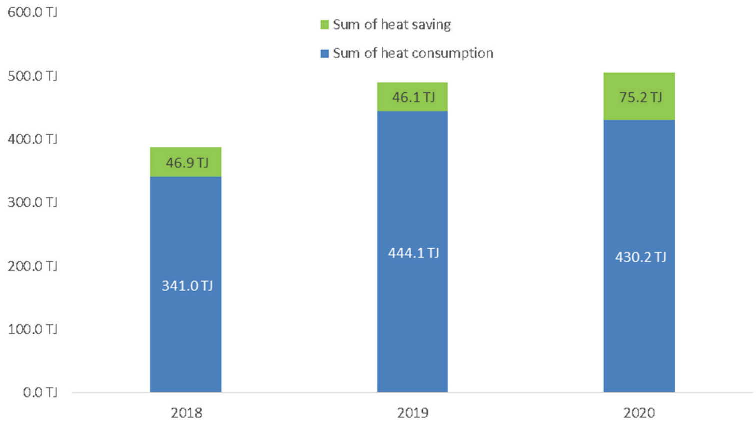


Figure 2. Consumptions and savings between 2018 and 2019 concerning baseline in the Warsaw DHN.

Basing on the achieved results and taking into account comparison of district heating systems in Warsaw and the one in GZM, the following thesis was assumed: both Warsaw and GZM have similar size and potential to apply Hubgrade solution, and, because both these systems are located in the same climate zone, it will be possible to achieve similar results. Figure 3 presents a simulation of the results of Hubgrade application in the whole GZM and Warsaw district heating systems.

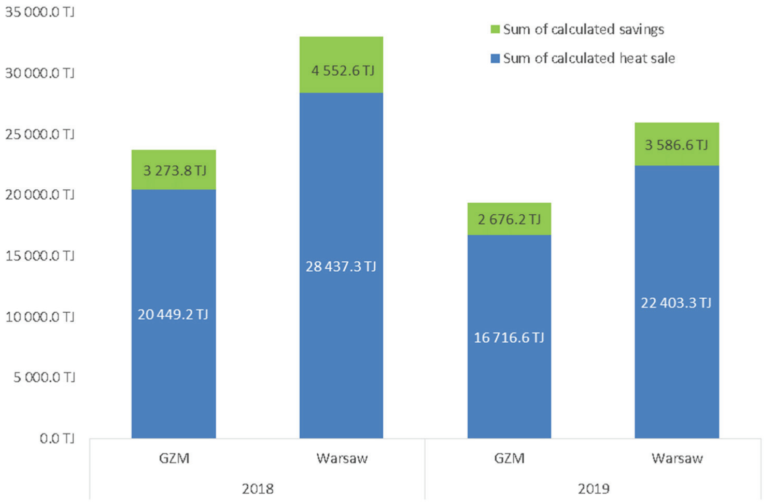
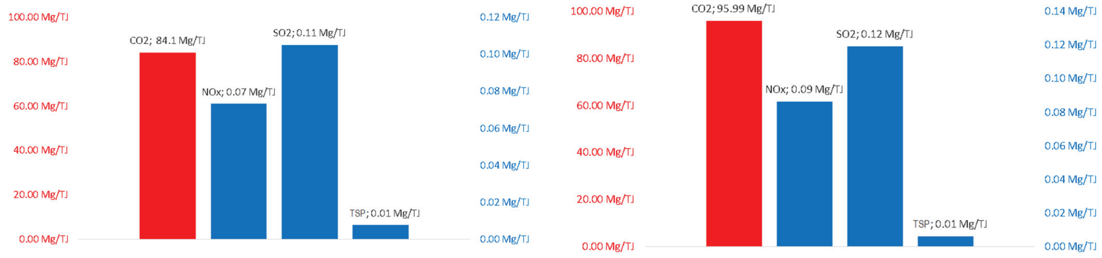


Figure 3. Simulation of results of Hubgrade application in the whole GZM and Warsaw district heating systems.

In total, this saving in GZM and Warsaw could reach up to 7044 TJ of heating energy, which is enough to supply heat to the whole of Chorzów city or the whole tarnogórski county.

4.3. Comparison of the Local Means of Energy Production to Forecast the Harmful Emissions Volume

In Figure 4, fuel mix from GZM and Warsaw is presented. Data for this figure were obtained from the official reports of the appropriate local heat suppliers, and they are as follows:



(**A**) (**B**)

Figure 4. Comparison of absolute values of emissions in GZM and Warsaw. (**A**) Emissions in GZM: absolute values. (**B**) Emissions in Warsaw: absolute values.

This would reflect emission reduction as presented in the Table 2:

Table 2. Calculated absolute values of emissions reduction potential for the GZM.

Emission	Unitary Emissions	Energy Saving in 2019	Emission Saving
CO_2	84.13 Mg/TJ	3273.8 TJ	275,424.8 Mg
SO_2	0.11 Mg/TJ		360.1 Mg
NO_x	0.07 Mg/TJ		229.2 Mg
TSP	0.01 Mg/TJ		32.7 Mg

The calculated emission savings show that there is a potential of decreasing emission by application of smart control on the local substation. Additionally, it shows that emission of TSP from central heat sources are at a low level in comparison to local unsupervised heat sources.

5. Conclusions

In Poland, there is still huge potential to adopt smart technologies in district heating systems to reduce harmful emissions. The simulated savings of 275 kt CO_2 show that it may reduce harmful emissions by 16%. The cost of application of Hubgrade is lower than the cost of changing heat production technology, while it produces significant environmental results without affecting the thermal comfort of the end-user.

Comparison of the two similar district heating systems suggests that there is also a huge diversity of energy production means, and, as a result, absolute values of emissions in one region of Poland can differ from emissions in the other. Results of the study carried out suggest that the absolute values of the GZM emissions are smaller than the ones in the Warsaw district heating system, but at the same time, the potential for emission reductions stays at a very high level.

In more distributed systems, reduction of harmful emissions can be even greater, but at the same time, the options of emissions reduction are greater, i.e., by application of the centrally supervised distributed heat pumps in combination with the existing district heating system. This will be the subject of further scientific investigation.

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original draft preparation, J.S., A.S. and K.C.; writing—review and editing, G.K., J.S., A.S. and P.B.; visualization, K.C., A.S. and P.B.; supervision, G.K. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

Abbreviation	Meaning
BES	Building energy services
DHCS	District heating and cooling system
DHN	District heating network
DHS	District heating system
EU	the European Union
GZM	Polish: Górnośląsko-Zagłębiowska Metropolia
H2020	Horizon 2020: an EU research and innovation programme with funding available over 7 years (from 2014 to 2020)
HDD	Heating degree days: no. of days when the average outdoor temperature is no greater than 14 °C
IDS	Intelligent decision system
IED Directive	Industrial Emissions Directive 2010/75/EU of the EU
IoT	Internet of Things
KPI	Heat consumption index
LCP Directive	Large Combustion Plant Directive 2001/80/EC of the EU
MCP Directive	Medium Combustion Plant Directive (EU) 2015/2193 of the EU
PN	Physical Network
RES	Renewable energy sources
SAB	Smart Active Box, a predictive maintenance system by Arne Jensen AB
STORM	Smart Freight Transport and Logistics Research Methodologies, an EU founded project
TSP	Total suspended particulate matter

References

1. Gorynia, M.; Matysek-Jędrych, A.; Mińska-Struzik, E. Poland on the path of competitiveness growth. In *Competitiveness and Economic Development in Europe*; Routledge: London, UK, 2021; ISBN 978-1-00-309536-1.
2. Dyduch, W.; Chudziński, P.; Cyfert, S.; Zastempowski, M. Dynamic Capabilities, Value Creation and Value Capture: Evidence from SMEs under COVID-19 Lockdown in Poland. *PLoS ONE* **2021**, *16*, e0252423. [CrossRef]
3. Jedynak, M.; Czakon, W.; Kuźniarska, A.; Mania, K. Digital Transformation of Organizations: What Do We Know and Where to Go Next? *J. Organ. Change Manag.* **2021**, *34*, 629–652. [CrossRef]
4. Wójcik-Jurkiewicz, M.; Czarnecka, M.; Kinelski, G.; Sadowska, B.; Bilińska-Reformat, K. Determinants of Decarbonisation in the Transformation of the Energy Sector: The Case of Poland. *Energies* **2021**, *14*, 1217. [CrossRef]
5. Malec, M.; Kinelski, G.; Czarnecka, M. The Impact of COVID-19 on Electricity Demand Profiles: A Case Study of Selected Business Clients in Poland. *Energies* **2021**, *14*, 5332. [CrossRef]
6. Strategy for Metropolis GZM. Available online: https://metropoliagzm.pl/en/stategia/ (accessed on 19 June 2021).
7. The European Green Deal. Available online: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en (accessed on 13 November 2021).
8. Wojcik-Jurkiewicz, M.; Lubicz-Posochowska, A.; Czarnecka, M.; Kinelski, G.; Sadowska, B. Legal Aspects of Sharing Economy: The Case of Games' Platforms. *Eur. Res. Stud. J.* **2021**, *XXIV*, 1196–1210. [CrossRef]

9. Zamasz, K.; Mucha-Kuś, K.; Sorychta-Wojsczyk, B.; Musioł-Urbańczyk, A.; Tchórzewski, S.; Kinelski, G.; Lis, M.; Wydawnictwo, A.M. *Project Management in Public Administration: The Case of Metropolis GZM*; Wydawnictwo Adam Marszałek: Toruń, Poland, 2020; ISBN 978-83-8180-323-6.
10. Drożdż, W.; Kinelski, G.; Czarnecka, M.; Wójcik-Jurkiewicz, M.; Maroušková, A.; Zych, G. Determinants of Decarbonization—How to Realize Sustainable and Low Carbon Cities? *Energies* **2021**, *14*, 2640. [CrossRef]
11. Grzegórska, A.; Rybarczyk, P.; Lukoševičius, V.; Sobczak, J.; Rogala, A. Smart Asset Management for District Heating Systems in the Baltic Sea Region. *Energies* **2021**, *14*, 314. [CrossRef]
12. Li, H.; Nord, N. Transition to the 4th Generation District Heating—Possibilities, Bottlenecks, and Challenges. *Energy Procedia* **2018**, *149*, 483–498. [CrossRef]
13. Pająk, K.; Kinelski, G. Competitive Market and Sources of Its Advantages in the Electric Energy Subsector. *Prog. Econ. Sci.* **2017**, *4*, 347–360. [CrossRef]
14. Kinelski, G. The Main Factors of Successful Project Management in the Aspect of Energy Enterprises' Efficiency in the Digital Economy Environment. *Polityka Energy Energy Pol. J.* **2020**, *23*, 5–20. [CrossRef]
15. Lund, H.; Werner, S.; Wiltshire, R.; Svendsen, S.; Thorsen, J.E.; Hvelplund, F.; Mathiesen, B.V. 4th Generation District Heating (4GDH). *Energy* **2014**, *68*, 1–11. [CrossRef]
16. Boesten, S.; Ivens, W.; Dekker, S.C.; Eijdems, H. 5th Generation District Heating and Cooling Systems as a Solution for Renewable Urban Thermal Energy Supply. *Adv. Geosci.* **2019**, *49*, 129–136. [CrossRef]
17. Buffa, S.; Cozzini, M.; D'Antoni, M.; Baratieri, M.; Fedrizzi, R. 5th Generation District Heating and Cooling Systems: A Review of Existing Cases in Europe. *Renew. Sustain. Energy Rev.* **2019**, *104*, 504–522. [CrossRef]
18. Loureiro, T.; Rämä, M.; Sterling, R.; Cozzini, M.; Vinyals, M.; Descamps, M.; Birk, W.; Unkaya, G.; Fuligni, F.; Doračić, B.; et al. District Energy Systems: A Collaborative Exchange of Results on Planning, Operation and Modelling for Energy Efficiency. *Proceedings* **2018**, *2*, 1127. [CrossRef]
19. Flexynets. Available online: http://www.flexynets.eu/en/ (accessed on 13 June 2021).
20. STORM. Available online: https://storm-dhc.eu/en (accessed on 13 June 2021).
21. InDeal. Available online: http://www.indeal-project.eu/ (accessed on 13 June 2021).
22. OPTi. Available online: http://www.opti2020.eu/ (accessed on 13 June 2021).
23. BES—Hubgrade (Building Energy Services—Hubgrade). Available online: https://energiadlawarszawy.pl/zarzadzanie-energia-cieplna-w-budynku/ (accessed on 13 June 2021).
24. The Structure of Primary Fuels Used to Generate Heat in 2020 for the Needs of the Warsaw District Heating System. Available online: https://energiadlawarszawy.pl/wp-content/uploads/sites/4/2021/04/Struktura-paliw-2020.pdf (accessed on 13 June 2021).
25. NODA Smart Heat Grid SolutionsTM & NODA Smart Heat Building SolutionsTM. Available online: http://noda-polska.pl/ (accessed on 13 June 2021).
26. SAB—Smart Active Box. Available online: https://www.smartactivebox.com/sab/ (accessed on 13 June 2021).
27. ISENSE. Available online: https://www.vexve.com/en/isense/ (accessed on 13 June 2021).
28. *Statistics Poland—Heating Network in Licensed Entities*; GUS: Warszawa, Poland. Available online: https://stat.gov.pl/ (accessed on 13 November 2021).
29. *Statistics Poland—Cubic Volume of Buildings with Central Heating by Location*; GUS: Warszawa, Poland. Available online: https://stat.gov.pl/ (accessed on 13 November 2021).
30. *Statistics Poland—Sale of Heating Energy during the Year by Location*; GUS: Warszawa, Poland. Available online: https://stat.gov.pl/ (accessed on 13 November 2021).

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Risk-Adjusted Discount Rate and Its Components for Onshore Wind Farms at the Feasibility Stage

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Abstract: The concept of risk is well known in the energy sector. It is normally recognized when it comes to price and cost forecasting, annual production calculation, or evaluating project lifetime. Nevertheless, it should be pointed out that the quantitative evaluation of risk is usually difficult. The discount rate is the only parameter reflecting risk in the discounted cash flow analysis. Therefore, knowledge of the discount rate along with the major components affecting its level is of fundamental significance for making investment decisions, capital budgeting, and project management. By referring to the standard coal-fired power generation projects the authors of the paper tackle the analysis of the composition of discount rate for onshore wind farm technologies in the Polish conditions. The study was carried out on the basis of a typical (hypothetical) onshore wind farm project assessed at the feasibility stage. To enable comparisons and discussions, it was assumed that the best reference point for such purposes is the real risk-adjusted discount rate, RADR, after-tax, in all equity evaluations (the 'bare bones' assumption); that is because such a rate reflects the inherent characteristics of the project risk. The study methodology involves the a priori application of the discount rate level and subsequently—in an analytical way—calculation of its individual components. The starting point for the analysis of the RADR's composition was the definition of risk, understood as the product of uncertainty and consequences. Then, the risk factors were adopted and level of uncertainty assessed. Subsequently, using the classical sensitivity analysis of IRR, the consequences (as slopes of sensitivity lines) were calculated. Consequently, risk portions in percentage forms were received. Eventually, relative risks and risk components within cost of equity were assessed. Apart from the characteristics of the discount rate at the feasibility stage, in the discussion section the study was supplemented with an analogous analysis of the project's cost of equity at the operating stage.

Keywords: onshore wind; risk assessment; cash-flows; discount rate; cost of capital; cost of equity

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1. Introduction

Due to the climate policy of highly developed countries around the world, including the European Union, investments in renewable energy sources are becoming an urgent necessity in Poland. In relation to the above, not only is there an emerging public awareness of off-shore farms as a potential zero-carbon source of electricity [1], but also a number of low-carbon investments were implemented in Poland in the last decade, including the onshore wind farms (currently approx. 60% of the total RES capacity) [2]. This is favoured by the fact that, from the point of view of the wind technology, the area of Poland is geographically relatively attractive and the most interesting regions are Pomerania (primarily West Pomerania, Wolin Island), as well as the belt of lowlands in central Poland: from Greater-Poland, through Masovia, up to Warmia (Ermland) and Masuria provinces [3]. Actually, in Poland are currently operating approx. 1200 wind energy installations with a total capacity of approx. 6.7 GW producing ~10% (15.7 TWh) of electricity [4]. The recent increase in the demand for electricity was covered primarily thanks to the existence of such farms [5].

In spite of the fact that the development of wind power was, in Poland, temporarily halted by the introduction of the so-called 'Distance Act' and by the growing popularity of small photovoltaic panels technology among Polish citizens [6], yet the unwavering interest in wind farms—primarily on account of the pressure of climate policy of the European Union and a drop in investment costs—have induced the government to mitigate the current legal regulations [7]. The number of wind projects allows for expecting a new flourish and intensified development of this technology [3].

Wind energy projects are generally long-term. The investment period ranges from 3 to 4 years, whereas the operational period stretches even up to 25 years [8] which means that investors often use indicators to try to calculate the future profitability of an investment, such as NPV, IRR, or DPP [9]. One can say that there is usually an agreement within energy sector on CAPEX, OPEX, production, capacity factors and, in consequence, resulting cash flow values. Nevertheless, projects of this type are usually encumbered with a significant risk, the expression of which are discount rates used by the investors to actualise the values of the future cash flows and establish investment criteria.

Every discount rate is selected as regards the risk of an individual project in reference to:

1. Industry expectations with respect to the project returns;
2. The risk factors associated with energy projects in general, and
3. The risk factors associated with the specificity of the project.

One of the basic approaches applied in the procedure encompassing determination of an adequate discount rate is searching for similar—in relation to the analysed project—'twin' investments. Due to this, a significant role in this process plays the investor's comprehensive knowledge about similar projects and assessment of their efficiencies [10]. This experience is invaluable due to the fact that—e.g., in the case of projects implemented in the energy sector—these components may fall within a relatively extensive range—from several to several dozen percent (nominal) [11–13]. Various studies [11,12,14–16] show that among low-carbon technologies, the most risky are the wave (floating) power plants, CCS, nuclear power plants, geothermal plants, tidal barrage, and tidal stream plants; on the other hand, the lowest risk projects are the CCGT generation technologies, hydro RORs, solar PVs, biomass plants, and onshore wind farms—the last ones are the subject of this paper.

We must emphasize that, however, among industry professionals and scholars appear different views on levels of the discount rate that should be used in the net present value evaluations.

There is a number publications on discount rates applied in the renewable energy sector, including onshore wind projects. Because the majority of those papers concentrate on distinct and specific issues, they generally cite amounts of discount rates and roughly describe ways of obtaining those percentages but often without any vital details.

Publications on the cost of capital (briefly reviewed below) feature then various forms and approaches to discount rates: nominal or real, pre- and after-tax, but often they not indicate that issues. Most of the papers focus on hurdle rates and the calculation of the weighted average cost of capital, WACC [11–13,17–19]. The information about the last ones would even be more interesting if they gave feedback about gearing/capital structure, but they did not.

The level of the discount rate in the economic evaluation of energy technologies should reflect the risk related to an individual project. However, the risk is recognised in the majority of publications is typically assigned to a company. Moreover, it is usually given as aggregated single value, thus it is rather impossible to figure out which uncertain project parameters primarily correspond to the discount rate selected. A question arises then: what is of the structure of that rate and, consequently, their risk components? No available publications regard this issue, so this is a research gap; an unexplored topic revealed during a literature search is also issue of discount rates at different stages of energy project development. Correspondingly, the purpose of the paper is to analyse this issue with respect to the cost of equity for onshore wind investments in the Polish conditions. According to that we propose methodology for the analysis of risk levels that estimates the constituent components of the cost of equity used in DCF calculations of onshore wind projects. We find it to be an important contribution to the issue of the economics of renewables.

2. Methods

To answer the question presented above, in reference to the specific technology (here: the onshore wind technology) it is necessary, first of all, to determine the level of the discount rate for a particular project development stage in a form convenient for further analyses and, secondly, the risk product related to the individual parameters influencing the efficiency of onshore wind investments [20]. The used methodology is analogous to the one applied in the work pertaining to the cost of equity in the coal power sector [21] based on the approach proposed by Smith in the base-metals industry [22].

The discount rate, most frequently analysed in publications, is the weighted-average cost of capital which, according to economic theory, is a suitable finance parameter [18,19,23–25]. Companies usually use a combination of equity and debt financing. The after-tax *WACC* is calculated according to the formula

$$WACC = CoE \times V_e + CoD \times (1 - tax) \times V_d \tag{1}$$

where: *CoE*—cost of equity ≡ risk-adjusted discount rate, RADR; V_e—proportion of equity in investment financing; *CoD*—cost of debt; *tax*—corporate tax rate; $(1 - tax)$ means the tax shield; V_d—debt share in investment financing. Of course, in the pre-tax version, there is no $(1 - tax)$ component in Formula (1).

The WACC rate, unfortunately, does not form a convenient basis for any comparisons due to the fact that is comprises the weighted debt rate. The range of debt financing is different in individual countries: for example, in the EU member states it ranges from 55% in Sweden and Romania to 85% in Ireland and Germany [26]; credit interest rates range from 1% in Germany to 11% in Greece. In Poland, the share of debt in investment financing is 65%, whereas the average credit interest rate ranges from 4% to 6.5% [27].

The interesting to us component of WACC is cost of equity (CoE), or risk-adjusted discount rate (RADR). CoE is the return that a company requires for an investment or project; it reflects the gratification the financial markets require in order to:

(1) own the asset and
(2) take on the risk of ownership

Cost of equity is higher than cost of debt, because equity capital is more expensive. Since cost of debt is an external factor, CoE is the only discount rate which can be profoundly analysed in terms of risk of a project.

Thus, when speaking about investments in wind farms, the nominal cost of equity in the European Union member states recently ranged between 4% in Germany to 15–20% in Latvia (Figure 1), whereas in Poland from 9% to 11%. According to Damodaran [28], the average cost of equity (and thus the level of risk) for the European companies from the sector defined as 'Green and Renewable Energy', where wind power has a significant share, is systematically dropping: from 10.27% in 2015 to 5.93% in 2020 (nominal). This cost for individual companies is calculated according to the CAPM formula

$$CoE = RADR = R_f + \left(R_m - R_f\right) \times \beta \tag{2}$$

where: *CoE*—cost of equity ≡ RADR—expected return from *i* assets, R_m—expected return from market, R_f—risk free rate, β—beta coefficient for asset *i*.

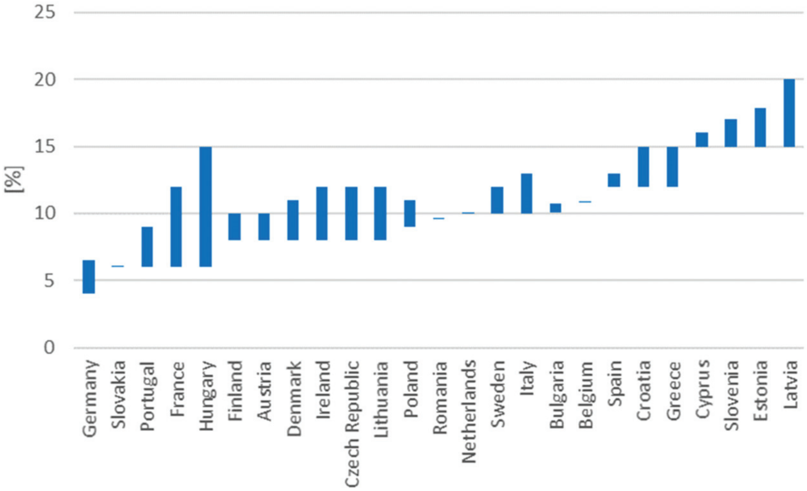

Figure 1. Cost of equity (2016) of an investment in wind energy in the European Union [26,27]. (Luxembourg and Malta—no data).

The risk-free rate, R_f, is calculated based of returns from risk-free securities (T-bills or/and T-bonds). The level of the rate changes along with the economic situation and monetary policy of individual EU member states.

The factor complicating the interest rate analyses of is inflation. Due to this, the authors of the paper decided to present these rates as real values.

Taking into account:

(1) the data referred to in the papers about discount rates [11–13,17,19–21,26,27,29–31],
(2) discussion with some renewable energy analysts,

the nominal cost of equity of onshore wind farm projects at the feasibility stage—in the Polish conditions—could be determined, on average, at the level of 10%.

All of the above-listed assumptions:

1. analysis of the investment at the feasibility stage;
2. 100% equity cash flows;
3. zero inflation,

allow for extracting a convenient substrate of the cost of equity ('bare bones') for all analyses and comparisons.

Bearing the above in mind, it is possible to analyse the structure of such rate and the range of individual uncertainties (risks) which are expressed in its components.

The risk-adjusted discount rate (CoE, RADR) comprises the following elements:

1. risk-free rate;
2. specific risk;
3. country risk;

In the case when the nominal discount rate is analysed, the result has to be increased by the rate of inflation, in line with Fisher's formula

$$R_n = [(1 + R_r)(1 + i)] - 1 \tag{3}$$

where: R_n—nominal interest rate, R_r—real interest rate, i—inflation.

The differences between the CoE/RADR rates presented in Figure 1 result from different specifics of individual EU member states with respect to adaptation of the wind technology and from various level of the risk-free rate in these countries.

It is worth underlying, that when adopting any financial-type parameters, it is necessary to take the future and not the past into account. However, the history may be a good point of reference for the future—in particular for long-term projects. Thus, when forecasting the risk-free rate in Poland for the upcoming decade, the relevant annual rates of return from 10-year bonds with annual average inflation rates according to Formula (3) were calculated. The long-term real risk-free rate, forecasted for the wind power plant lifetime and attained by averaging the results above, is on the level of 2.35%.

The expected real cost of equity of wind energy investments in Poland was calculated by reducing the nominal RADR in the amount of 10% by inflation (calculated as the long-term average) in line with Formula (3). The cost is on the level of 7.65% after-tax, which means that the real specific risk of onshore wind investments is on the level of 5.30%. Along with development of the project and information in-flow, the CoE/RADR (and thus the share of specific risk) will decrease: at the operating stage to the value of approx. 5.0–5.5% [32].

For the needs of the paper, a cash flow base case for a typical onshore wind farm project in Poland was developed, adopting the following premises:

1. installed capacity of the wind farm: 90 MW (45 wind turbines);
2. project lifetime: 25 years [5,29,32], where:
    - investment period: 3 years;
    - operating period: 22 years;
    - decommissioning: in the last (25th) year of the project life;
3. capital expenditures, CAPEX: 5.5 M PLN/MW [33,34]; distribution of CAPEX [17,24,35–37] as follow:
    - year 1–2% CAPEX;
    - year 2–18% CAPEX;
    - year 3–80% CAPEX;

    (CAPEX, after deducting the salvage (residual) value, were subjected to straight-line depreciation/amortization);
4. working capital: 6.03 M PLN (8.33% of annual revenues) [36]; spending—year ‘0’, recovery—year 25;
5. operating expenditures, OPEX: 0.1445 M PLN/MW [17,24,36–38]; given the high share of fixed costs, OPEX were compared not to the unit of produced energy but to 1 MW of installed capacity;
6. decommissioning cost: 0.6 M PLN per turbine [39];
7. salvage value: 0.288 M PLN per turbine [39,40];
8. capacity factor, CF: 0.36 [16,41,42]; the factor was selected in relation to the advancement in wind technology with an assumption that in reference to the reduction of power generated by the wind plant along with time and technical wear and tear [5], it is going to decrease from the 15th to 19th year of the project lifetime by 0.1 annually (and from the 19th to the 25th year by 0.2 annually—to the final value of 0.23).

When comes to the electricity prices, it must be emphasised that in Poland the auction system supporting the renewable energy sources has been functioning since 2015. The participants who offer the lowest energy price and whose bids jointly do not exceed 100% of the value or the amount of energy specified in the auction notice and 80% of the quantity of electricity covered by all of the submitted bids win the auction. The support is granted for 15 years, whereas the auctioned amount is indexed year by year with the annual consumer price index. The electricity prices in the project in question were defined according to own forecasts, taking the results of auctions from 2018–2020 into account [43]. The price, in constant zlotys, for the entire operating period was adopted at the level of PLN 255.00 per MWh.

Among the parameters mentioned above, the following key risk parameters of the project were identified:

1. CAPEX;

2. capacity factor (CF);
3. electricity price;
4. annual operating expenditures (OPEX);
5. project lifetime.

To estimate the volumes of the risk components within the cost of equity, an analogous methodology for determining the components of the risk-adjusted discount rate, RADR, for projects implemented in the traditional coal-fired technology was used [44].

The starting point of the methodology is the concept that a measure of risk is the product of uncertainty and consequences

$$Risk = UnCrnty \times CnSqnce \tag{4}$$

Uncertainty (‘*UnCrnty*’) is the state of ignorance that may be reduced as a result of attaining a greater amount of information and number of data. Naturally, if the parameters with greater variability strongly affect the project’s efficiency, it is said that they constitute significant risk factors. If, on the other hand, that influence is not great or the range of variability is narrow, then the risk related to such parameters is not high.

It is hard to precisely define the ‘*UnCrnty*’ factor, yet in the statistical sense, it may be understood as the spread or variance of the probability distribution. *UnCrnty* can be then expressed as the range of error or the level of accuracy of a parameter. On the other hand, consequences (‘*CnSqnce*’) are the effects of impact of a parameter on the measure of a project’s efficiency (here: internal rate of return, IRR—as this indicator is expressed as a percentage and may be directly referred to the cost of equity). *CnSqnce* may be measured by the tangent of the curve slope angle on the spider diagram in the classic sensitivity analysis. In case of strongly curved lines, it is possible to use the average tangent values of slopes of individual sections of the curve in the centre of the diagram.

The accuracy of assessment (*UnCrnty*) of key parameters was assumed as follows [32,34,45,46]:

1. CAPEX—±15%,
2. CF—±10%,
3. electricity price—±10%,
4. OPEX—±10%,
5. project lifetime—±5%.

3. Results

In the discounted cash flow spreadsheet, all calculations were made in constant Polish zlotys, PLNs, applying the real CoE/RADR in the amount of 7.65% (without country risk). It does not mean, of course, that 7.65% should be used for all onshore wind projects at the feasibility study—it was chosen just as a base.

Evaluation was made on all equity basis. The resultant net present value, NPV, in the base case amounts to 7.90 M PLNs, whereas the internal rate of return, IRR, is at 7.88%. Given that NPV > 0 and IRR > CoE/RADR, the project is feasible and thus should be implemented immediately.

Applying the proposed methodology, a sensitivity analysis was performed in line with the *Ceteris paribus* assumption to examine the change in the IRR in response to the changes of the key parameters adopted—in every case by ±10%, 20%, and 30%—and transferring the results to the spider diagram.

The results (Figure 2) indicate that the project’s IRR is most sensitive to changes of electricity prices and the capacity factor, whereas it is least sensitive to the changes in operating expenditures. High sensitivity of the IRR to changes in the CAPEX is interesting (more in the direction of potential falls than increments) along with very high sensitivity of the IRR to the downside changes of the lifetime as compared to very small sensitivity to upside changes. This is caused, to a significant degree, by the loss of efficiency of the wind turbines—especially in later years of the project lifetime. Consequently, the operators should not be induced to extend the lifetime of a wind project, but they should definitely eschew its decommissioning ahead of time.

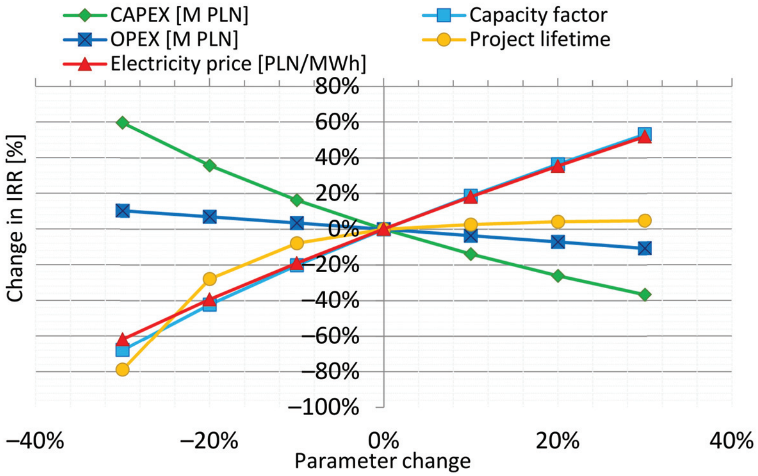

Figure 2. Sensitivity of IRR to key parameters of the typical wind project in Poland.

To calculate the *CnSqnce* values for individual variables, tangents of the slopes of sensitivity curves to the x-axis were calculated. Given the fact that the impact of individual risk factors is aggregate, all tangents of the slope of the sensitivity curves are adopted in the form of absolute values. By multiplying the values of *UnCrnty* and *CnSqnce* for every key variable, the value of risk was received and subsequently, by calculating the relative risk, the risk component in the cost of equity—i.e., the CoE/RADR—was received. The results of analysis of risk factors within the scope of the cost of equity are presented in Table 1 and in Figure 3.

Table 1. Analysis of risk components within a 7.65% real risk-adjusted discount rate of onshore wind projects in Polish conditions.

Risk Factor	*UnCrnty* (Assessment Accuracy)	*CnSqnce* (Slope)	Risk Product	Relative Risk	Risk Component
Risk-free rate (real)					**2.35%**
Capital expenditures, CAPEX (M PLNs)	15%	1.51	0.2269	0.323	1.71%
Capacity factor, CF	10%	1.94	0.1944	0.276	1.46%
Electricity price (PLN/MWh)	10%	1.86	0.1858	0.264	1.40%
Operating expenses, OPEX (M PLNs)	20%	0.35	0.0703	0.100	0.53%
Project lifetime	5%	0.52	0.0261	0.037	0.20%
Risk portion (SUM)			**0.7035**	**1.000**	**5.30%**
Cost of equity—risk-adjusted discount rate (real)					**7.65%**

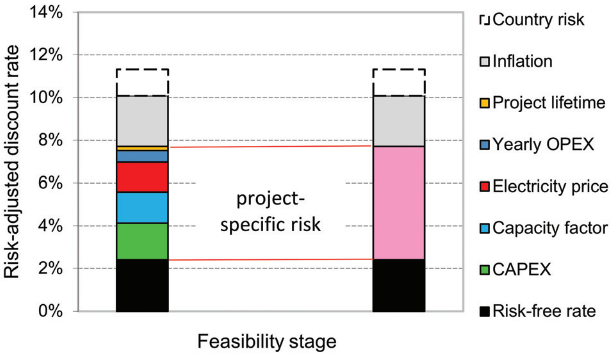

Figure 3. Key risk components of the risk-adjusted discount rate for Polish onshore wind projects at the feasibility stage.

With respect to the adopted assumptions the results show that the highest share within the specific risk of real cost of equity of onshore wind power projects in Poland (1.71%) have the capital expenditures, CAPEX, followed by—having a more or less equal share:

1. capacity factor, CF, (1.46%);
2. electricity price (1.40%).

The share of the remaining risk factors in the discount rate is slight: the component of operating expenses approximates 0.55% and the project lifetime is at 0.2%. When it comes to nominal values, the column would have to be increased by the rate of inflation, which would offer a nominal rate of 10.03%; a foreign investor would also increase such rate by the portion of the country risk (here: 1.2% [28]), which would eventually result in a nominal rate of 11.3%.

4. Discussion

The paper gives the answer as to what is the composition of risk within a 7.65% real discount rate of portions for Polish onshore wind projects at the feasibility stage. Crucial risk components are capital costs, capacity factor, and electricity price.

The obtained results provide useful information for decision-makers with respect to making decisions in the area of wind power: the greatest attention should be paid to the thought-through participation in the RES auctions and careful assessments of capital expenditures. It also implies that reducing CAPEX uncertainty investors might significantly change RADR structure, reducing risk within a discount rate mainly to combination of energy price and capacity factor risks.

As we mentioned above, risk-adjusted discount rate of 7.65% (real) is selected only as a base—it will vary over time, with risk-free rates and beta updates. It can be served, however, as a guide to make a ranking of different investment alternatives.

The concept that has been developed for the risk components analysis of a cost of equity at the feasibility study stage can be used for the evaluation of projects at other development stages—e.g., in reference to the results obtained, the analysis of the scope of the discount rate at the project's operating stage (5.5%) can be performed.

Discount rate in amount of 5.5% has been selected arbitrarily, taking into account discussion with energy companies—at this stage of the project development risk is significantly lower than at the feasibility stage. It can be assumed that at this level of project development the risk of capital expenses will resolve, whereas the assessment accuracy (*UnCrnty*) of the capacity factor, the price of electricity, the operating expenses, and the project lifetime will improve by half—the risk portions of these components will be reduced then as follows (Figure 4):

1. capacity factor—1.28%;

2. price of electricity—1.23%,
3. operating expenses—0.46%;
4. lifetime—0.17%;

altogether, with the risk-free rate, it amounts to 5.5%.

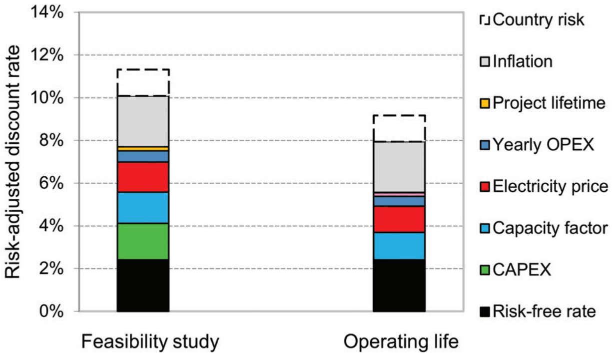

Figure 4. Key risk components of the risk-adjusted discount rate for Polish onshore wind projects at different development stages.

Then, the nominal rate will be 7.88% or, including the country risk—9.1%.

Similar analysis can be made for projects in scoping and pre-feasibility studies.

In reference to the analogous analyses carried out for traditional coal projects [23], it becomes clear that the risk factors within a similar CoE/RADR are distributed differently—in the case of traditional coal technology, the dominant component of specific risk within cost of equity was the electricity price (2.97%), which results from the fact that it is subject to market competition. Another significant portion is the price of CO_2 emission allowances (0.92%): the factor which does not occur in wind energy. The disparity of components of capital expenses is interesting: the risk portion (0.22%) related to this factor in reference to its weight in wind energy (1.71%) is slight, which is related to the amount, the technological advancement of capital assets and their significance for the efficiency of wind technology. Future research might involve gathering data that could help companies to estimate in detail the risk level of an individual project at various stages of a project. A very interesting challenge is also conducting similar studies for other renewable energy technologies.

5. Conclusions

Wind energy in Poland, in spite of the temporary inhibition of its development, has a significant growth potential, which may turn out to be invaluable when taking actions aimed at the transition to the modern low-carbon economy into account. One of the key issues that the investors have to face is the risk of the technology. Investors who put money into energy projects are expecting an adequately high interest rate, which would allow them to compensate for the minimum acceptable real rate of return from the market and the project's specific risk. That is reflected in the adopted discount rate, where the range of specific risk related to the technology used. The paper identifies key risk components within the cost of equity of onshore wind projects at the feasibility level.

In answering these questions, a decision was made to estimate the value of such a rate, and subsequently to present it in a form accessible for further research. It was decided that the analysis of the components of the discount rate is facilitated by the approach focusing exclusively on the cost of equity (risk-adjusted discount rate, RADR) after-tax. This rate reflects the real expectations of investors with respect to the project risk. It accounts for the risk-free discount rate, the project-specific risk and—depending on the purposes of the research—the inflation rate and the country risk. The analysis—assuming 100% equity in project financing—allows for concluding that the assessment refers to the inherent value of an energy project, not contaminated with the effects of benefits related to external financing.

To find out which onshore wind project parameters were the major factors of such risk, a relevant analysis of causes and effects was carried out, starting with the definition of risk understood as the product of uncertainty and consequences. Uncertainty was expressed as the assessment accuracy of key inputs, whereas consequence as the tangent of the slope of sensitivity curves of such variables (impact on changes in the IRR) on a spider diagram. Consequently, it was shown that the risk portions (real) in the cost of equity of onshore wind projects at the feasibility stage, in the amount of 7.65%, are as follows:

1. capital expenditures: 1.71%;
2. capacity factor: 1.46%;
3. electricity price: 1.40%;
4. operating costs: 0.53%;
5. project lifetime: 0.20%.

The analysis is supplemented by the assessment of risk portions within the rate characteristic for project's operating stage in the amount of 5.5%.

The research has some limits:

(1) results are rather indicative; *UnCrnty* and *CnSqnce* values should be determined for particular project individually;
(2) slopes of the sensitivity lines were averaged;
(3) variable assessment accuracies may be different for particular projects;
(4) identifying only a limited number of risk factors influencing a wind project;

Further work in this respect is of significant utility value—more extensive knowledge about the structure of cost of equity will allow for adequate commencement and more rational management of projects, as well as better understanding of cash flow evaluations and efficient risk control.

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References

1. Wójcik-Jurkiewicz, M.; Czarnecka, M.; Kinelski, G.; Sadowska, B.; Bilińska-Reformat, K. Determinants of Decarbonisation in the Transformation of the Energy Sector: The Case of Poland. *Energies* **2021**, *14*, 1217. [CrossRef]
2. PSE: Polish Power Network (Polskie Sieci Elektroenergetyczne). National Power System (KSE) Annual Report 2020. Available online: https://www.pse.pl/dane-systemowe/funkcjonowanie-kse/raporty-roczne-z-funkcjonowania-kse-za-rok/raporty-za-rok-2020 (accessed on 8 April 2021).
3. D'Angelo, M. Onshore Wind Energy Market Analysis of Sweden, Poland, and Romania. Master's Thesis, KTH School of Industrial Engineering and Management, Stockholm, Sweden, 2020. TRITA-ITM-EX 2020:469. Available online: http://kth.diva-portal.org/smash/get/diva2:1472686/FULLTEXT01.pdf (accessed on 7 April 2021).
4. GUS—Statistics Poland. Energy from Renewable Sources in 2019. Available online: https://stat.gov.pl/files/gfx/portalinformacyjny/pl/defaultaktualnosci/5485/3/14/1/energia_ze_zrodel_odnawialnych_w_2019_r.pdf (accessed on 8 April 2020).

5. Kotowicz, J.; Kwiatek, B. Analysis of Wind Farm Production Potential. *Rynek Energii Energy Mark. J.* **2019**, *4*, 38–47. (In Polish) Available online: https://www.cire.pl/pliki/2/2019/analiza_potencjalu_wytworczego_farmy_wiatrowej.pdf (accessed on 7 April 2021).
6. Drożdż, W.; Kinelski, G.; Czarnecka, M.; Wójcik-Jurkiewicz, M.; Maroušková, A.; Zych, G. Determinants of Decarbonization—How to Realize Sustainable and Low Carbon Cities? *Energies* **2021**, *14*, 2640. [CrossRef]
7. Sejm Rzeczypospolitej Polskiej [Polish Parliament]. Deputies' Bill on Amendments to the Act on Investments in Wind Plants. Available online: https://www.sejm.gov.pl/sejm9.nsf/PrzebiegProc.xsp?id=AF1614D32FD8858FC12584E90044AE8C (accessed on 27 April 2021). (In Polish)
8. DECC—Department of Energy & Climate Change. Electricity Generation Costs 2013. 2013. Available online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/223940/DECC_Electricity_Generation_Costs_for_publication_-_24_07_13.pdf (accessed on 7 April 2021).
9. Kinelski, G. The main factors of successful project management in the aspect of energy enterprises' efficiency in the digital economy environment. *Polityka Energetyczna Energy Policy J.* **2020**, *23*, 5–20. [CrossRef]
10. KPMG. Cost of Capital Study 2019. The Calm before the Storm—Rising Profits and Deflated Values? KPMG International Cooperative 2019. Available online: https://assets.kpmg/content/dam/kpmg/ch/pdf/cost-of-capital-study-2019.pdf (accessed on 16 April 2021).
11. Oxera. Discount Rates for Low-Carbon and Renewable Generation Technologies—Prepared for the Committee on Climate Change. April 2011. Available online: https://www.oxera.com/wp-content/uploads/2018/03/Oxera-report-on-low-carbon-discount-rates.pdf (accessed on 7 April 2021).
12. Hern, R.; Radov, D.; Carmel, A.; Spasovska, M.; Guo, J. Electricity Generation Costs and Hurdle Rates. Lot 1: Hurdle Rates Update for Generation Technologies, Report Prepared for the Department of Energy and Climate Change (DECC), NERA Economic Consulting. 2015. Available online: https://www.nera.com/content/dam/nera/publications/2016/NERA_Hurdle_Rates_for_Electricity_Generation_Technologies.pdf (accessed on 7 April 2021).
13. Zamasz, K. Discount Rates for the Evaluation of Energy Projects—Rules and Problems. Scientific Journal of Silesian University of Technology. *Organ. Manag. Ser.* **2017**, *101*, 571–584.
14. Mucha-Kuś, K.; Sołtysik, M.; Zamasz, K.; Szczepańska-Woszczyna, K. Coopetitive Nature of Energy Communities—The Energy Transition Context. *Energies* **2021**, *14*, 931. [CrossRef]
15. Smirnova, E.; Szczepańska-Woszczyna, K.; Yessetova, S.; Samusenkov, V. Supplying Energy to Vulnerable Segments of the Population: Macro-Financial Risks and Public Welfare. *Energies* **2021**, *14*, 1834. [CrossRef]
16. Hirth, L.; Steckel, J.C. The Role of Capital Costs in Decarbonizing the Electricity Sector. *Environ. Res. Lett.* **2016**, *11*, 114010. Available online: https://iopscience.iop.org/article/10.1088/1748-9326/11/11/114010 (accessed on 8 October 2021). [CrossRef]
17. Shrimali, G.; Nelson, D.; Goel, S.; Konda, C.; Kumar, R. Renewable Deployment in India: Financing Costs and Implications for Policy. *Energy Policy* **2013**, *62*, 28–43. [CrossRef]
18. Tagliapietra, S.; Zachmann, G.; Fredriksson, G. Estimating the Cost of Capital for Wind Energy Investments in Turkey. *Energy Policy* **2019**, *131*, 295–301. [CrossRef]
19. Steffen, B. Estimating the Cost of Capital for Renewable Energy Projects. *Energy Econ.* **2020**, *88*, 104783. [CrossRef]
20. Angelopoulos, D.; Brückmann, R.; Jirouš, F.; Konstantinavičiūtė, I.; Noothout, P.; Psarras, J.; Tesnière, L.; Breitschopf, B. Risks and Cost of Capital for Onshore Wind Energy Investments in EU Countries. *Energy Environ.* **2016**, *27*, 82–104. [CrossRef]
21. Saługa, P.W.; Kamiński, J. The Cost of Equity in the Energy Sector. *Polityka Energetyczna Energy Policy J.* **2018**, *21*, 81–96. [CrossRef]
22. Smith, L.D. Discount Rates and Risk Assessment in Mineral Project Evaluations. *Can. Inst. Min. Metall. Bull.* **1995**, *88*, 34–43.
23. Estache, A.; Steichen, A.S. Is Belgium Overshooting in Its Policy Support to Cut the Cost of Capital of Renewable Sources of Energy? De Boeck Supérieur. Reflets et Perspectives de la vie Économique 2015/1; Tome LIV. pp. 33–45. Available online: https://www.cairn.info/revue-reflets-et-perspectives-de-la-vieeconomique-2015-1-page-33.htm (accessed on 5 October 2021).
24. Partridge, I. Cost Comparisons for Wind and Thermal Power Generation. *Energy Policy* **2018**, *112*, 272–279. [CrossRef]
25. Egli, F. Renewable Energy Investment Risk: An Investigation of Changes over Time and the Underlying Drivers. *Energy Policy* **2020**, *140*, 111428. [CrossRef]
26. Brückmann, R. Cost of Capital for Onshore Wind in EU Member States—Some Good, Some Bad and Some Ugly News. Conference Presentation at Wind Europe Bilbao, 3 April 2019. Available online: https://ec.europa.eu (accessed on 11 April 2021).
27. Dukan, M.; Kitzing, L.; Bruckmann, R.; Jimeno, M.; Wigand, F.; Kielichowska, I.; Klessmann, C.; Breitschopf, B. Effects of Auctions on Financing Conditions for Renewable Energy: A Mapping of Auction Designs and Their Effects on Financing; DTU Library 2019. Available online: Orbit.dtu.dk (accessed on 11 March 2021).
28. Damodaran Online. Current and Archived Data. Discount Rate Estimation. Costs of Capital by Industry Sector (Europe). Website of Aswath Damodaran. 2021. Available online: http://pages.stern.nyu.edu/~adamodar/ (accessed on 15 April 2021).
29. Grant Thornton. Renewable Energy Discount Rate Survey Results—2018. A Grant Thornton and Clean Energy Pipeline Initiative. 2019. Available online: https://www.grantthornton.co.uk/globalassets/1.-member-firms/united-kingdom/pdf/documents/renewable-energy-discount-rate-survey-results-2018.pdf (accessed on 15 April 2021).
30. Bachner, G.; Mayer, J.; Steininger, K.W. Costs or Benefits? Assessing the Economy-Wide Effects of the Electricity Sector's Low Carbon Transition—The Role of Capital Costs, Divergent Risk Perceptions and Premiums. *Energy Strategy Rev.* **2019**, *26*, 100373. [CrossRef]

31. ARUP. Onshore Wind Financing. Cost of Capital Benefits of Revenue Stabilisation via a Contract for Difference. An Arup Report for Scottish Power Renewables. 2018. Available online: https://www.arup.com/perspectives/publications/research/section/onshore-wind-financing (accessed on 16 March 2021).
32. Deloitte. Establishing the Investment Case—Wind Power. 2014. Available online: https://www2.deloitte.com/content/dam/Deloitte/global/Documents/Energy-and-Resources/gx-er-deloitte-establishing-the-wind-investment-case-2014.pdf (accessed on 16 March 2021).
33. IRENA—International Renewable Energy Agency. Future of Wind—Deployment Investment, Technology, Grid Integration and Socio-Economic Aspects. A Global Energy Transformation Paper. 2019. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Oct/IRENA_Future_of_wind_2019.pdf (accessed on 16 April 2021).
34. Halleraker, E.E.; Skjefrås, B.H. Investment in Wind Power Development—A Comparative Study Between Norway, Denmark, and Sweden. Master's Thesis, UiS Business School, Faculty of Social Sciences, University of Stavanger, Stavanger, Norway, 2017. Available online: https://uis.brage.unit.no/uis-xmlui/bitstream/handle/11250/2456664/Halleraker_and_Skjefraas.pdf?sequence=4&isAllowed=y (accessed on 16 April 2021).
35. Łukaszewski, T.; Głoćko, W. An Assessment of Wind Farm Construction Efficiency Using the Real Option Method. *Folia Oeconomica Stetin.* **2016**, *16*, 84–102. [CrossRef]
36. Addessi, C. Planning and Valuation of Green Investments in the Energy Supply: A Wind Investment Valuation. LUISS Guido Carli—Libera Universita' Internationale Degli Studi Sociali, Department of Business and Management. 2014. Available online: https://tesi.luiss.it/11892/2/addessi-carlo-sintesi-2014.pdf (accessed on 20 April 2021).
37. Steffen, B. The Importance of Project Finance for Renewable Energy Projects. *Energy Econ.* **2018**, *69*, 280–294. [CrossRef]
38. Cloete, S. The Risks Related to Onshore Wind Power Investment. Energy Post. 2018. Available online: https://energypost.eu/the-risks-related-to-wind-power-investment/ (accessed on 16 April 2021).
39. Energy Ventures Analysis. Canisteo Wind Energy Center—Decommissioning Assessment. Prepared for: The Towns of Cameron, Canisteo, Greenwood, Jasper, Troupsburg, and West Union. 2019. Available online: http://documents.dps.ny.gov/public/Common/ViewDoc.aspx?DocRefId=%7B92CC174A-9E28-4394-AEAA-CDDCC8358484%7D (accessed on 16 April 2021).
40. Jensen, J.P. Evaluating the Environmental Impacts of Recycling Wind Turbines. *Wind Energy* **2019**, *22*, 316–326. [CrossRef]
41. Krohn, S.; Morthorst, P.E.; Awerbuch, S. (Eds.) The Economics of Wind Energy—A report by the European Wind Energy Association. EWEA 2009. Available online: https://www.ewea.org/fileadmin/files/library/publications/reports/Economics_of_Wind_Energy.pd (accessed on 16 March 2021).
42. Kroener, L. Economic Assessment of PV and Wind for Energy Planning. IRENA Global Atlas Spatial Planning Techniques—2-Day Seminar. 2014. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Events/2014/Jul/15/17_Economic_assessment_of_PV_and_wind_for_energy_planning_Lima_Peru-_EN.pdf?la=en&hash=D972733F4A10CE4AD3314060FFB97DFC8BA9DB9A (accessed on 22 April 2021).
43. URE—Energy Regulatory Office of Poland. Odnawialne Źródła Energii—Ogłoszenia i Wyniki Aukcji. Available online: https://www.ure.gov.pl/pl/oze/aukcje-oze/ogloszenia-i-wyniki-auk (accessed on 21 April 2021).
44. Saługa, P.W.; Szczepańska-Woszczyna, K.; Miśkiewicz, R.; Chłąd, M. Cost of Equity of Coal-Fired Power Generation Projects in Poland: Its Importance for the Management of Decision-Making Process. *Energies* **2020**, *13*, 4833. [CrossRef]
45. Montealegre, F.; Boutsikoudi, S. Wind Resource Assessment and Yield Prediction—Post Construction Analysis—Hoevensche Beemden, Laakse Vaart, Zwartenbergseweg. 2014. Available online: https://www.eneco.nl/~/media/files/e3/eneco/pdf/voorwaarden-en-brochures/hollandsewind-certificaten/windrapportecofys.ashx?la=nl-nl (accessed on 22 April 2021).
46. Wiser, R.; Rand, J.; Seel, J.; Beiter, P.; Baker, E.; Lantz, E.; Gilman, P. Expert Elicitation Survey Predicts 37% to 49% Declines in Wind Energy Costs by 2050. *Nat. Energy* **2021**, *6*, 555–565. [CrossRef]

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The Impact of Fleet Electrification on Carbon Emissions: A Case Study from Poland

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Abstract: Fleet electrification is one of the measures proposed for achieving climate neutrality in the coming years. The replacement of internal combustion engine vehicles with electric vehicles has a positive impact on carbon emission reduction in some countries. However, in countries highly dependent on fossil fuels, such a possibility requires examination with respect to the means of electricity generation and fuel mix used in their power systems. One such country is Poland, selected as an example of an economy strongly dependent on fossil fuels. The main objective of this paper is to investigate the impact of fleet electrification of an individual company located in Poland on the reduction of carbon emissions. The concept and calculations are based on historical data on the single-year mileage and fuel consumption of 619 cars used by this company. Even though the Polish power system is based on fossil fuels, fleet electrification could contribute to a reduction in carbon emissions of 24%. The decrease in operational costs by EUR 370 thousand/year is also significant. Apart from environmental and economic impacts, this paper provides valuable findings on the difference between catalogue and real-driving data application in the various analyses. With respect to Polish fuel mix in 2019, the application of data published by car producers shows that fleet electrification would increase carbon emissions by 14% in this company. This means that depending on the initial assumptions, different conclusions can be drawn by policymakers, regulatory bodies, academics, or other groups of interest.

Keywords: electromobility; electric vehicle; carbon emissions; fleet electrification; sustainable mobility; sustainable development; fleet management; energy mix

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1. Introduction

Electrification of transport is one of the key pathways towards energy transition [1]. Electromobility is also indicated as one of the solutions to achieving carbon neutrality in the European Union by 2050 [2]. However, the real impact of the electrification of transport on carbon emissions reduction is strongly dependent on the fuel mix of a given power system. Consequently, in countries where electricity is still mainly produced in coal-fired power plants, the impact of electrification is difficult to assess.

In the year 2019 in Poland, the total installed capacity in the power system was 46.8 GW, out of which, coal or gas-fired generation units stood for 74.3% (23.2 GW of hard coal-fired power plants, 8.4 GW of lignite-fired power plants, and 2.8 GW of natural gas-fired units). Electricity produced in these power plants amounted to 131.8 TWh (83.0% of total electricity production in 2019), of which 78.2 TWh was produced in hard coal-fired power plants, 41.5 TWh in lignite-fired power plants, and 12.1 TWh in natural gas-fired units [3]. The structure of electricity production in 2019 is shown in Figure 1. Additionally, because of the introduction of the capacity market, changes in electricity production structure are not expected to happen in the coming years [4–6].

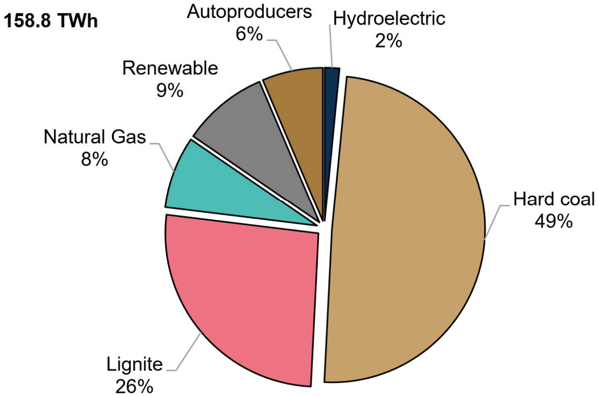

Figure 1. Electricity production in Poland in 2019.

1.1. Literature Review

Ref. [7] indicates that growth in electric vehicles leads to increased carbon emissions if electricity comes from hard coal-fired power plants. Studies conducted on the Chinese power system show that the indirect carbon emissions from BEVs are higher than from ICEVs (internal combustion engine vehicles) [8,9]. This issue is also presented in Ref. [10], where authors pointed out that indirect emissions from BEVs can be higher by 2.55–5.64 kg CO_2/day when compared to ICEVs in Poland. Ref. [11] provides the results of carbon emission reduction at the national scale as a function of fuel and electricity consumption under various scenarios of carbon emission factors in Poland.

The existing literature refers to large-scale issues and presents calculations for catalogue data only. The literature review indicates no studies based on actual data on fuel consumption and carbon emissions conducted for an individual company undergoing decarbonisation. Ref. [12] presents a fleet electrification example of a Brazilian taxi company, but is irrelevant for countries with a high share of fossil fuels in power systems.

Electromobility in Poland is a subject analysed in several papers and reports, and the number of studies is growing. None of these papers provides findings on carbon emissions reduction from the perspective of an individual company. Ref. [13] presents multiple aspects of electromobility introduction for one company located in Poland. Ref. [14] provides a general framework for the electrification of public transport and its environmental impact; they mainly focus on the current status of ICEV replacement instead of the quantitative reduction of carbon emissions. Ref. [15] presents only the economic consequences of public fleet electrification.

1.2. Study Contributions

This paper was inspired by the study conducted in Ref. [10], which presents an analysis of the replacement of nine ICEVs—the findings indicating that BEVs can provide even higher carbon emissions than petrol and diesel vehicles in countries with a high share of electricity produced in coal-fired power plants. The main objective of this study is to develop a method that could be applied to a company located in Poland and simulate the replacement of 619 ICEVs; it compares direct emissions from ICEVs and indirect emissions from BEVs. Emissions calculations for BEVs reflect the fuel mix of the Polish power system. We believe that this subject requires attention because company fleets are a substantial part of each country's vehicle base. Currently, companies often make decisions to try to improve their image as being environmentally friendly. We also believe that these findings will support decision makers in similar companies in their ICEV replacement process. If a positive net impact of fleet electrification on emissions is confirmed, the question of fleet conversion to BEVs (battery electric vehicles) comes down to the total cost of ownership only.

This paper also contributes to the existing literature by depicting the differences between fuel consumption and carbon emissions under real-world conditions, compared to the information provided by car producers.

Section 1 of this paper introduces the subject and explains how this paper contributes to the field. In Section 2 the methods and formulas for calculations are described. Section 3 of this paper presents the input data and numerical simulations; it also involves a discussion of the results of the study. Conclusions are presented in Section 4.

2. Materials and Methods

This paper aims to investigate the impact of fleet electrification on carbon emissions reduction in one company running its business in Poland. This company has 19 subsidiaries, and it operates mainly in the service and utility industry with diverse business profiles (among others, waste management, electricity, and heat production). To investigate the impact of fleet electrification, data from these subsidiaries (that altogether operated 619 cars fuelled by petrol or diesel) were collected and analysed.

The vehicles, which are used by the company, have been divided into six main categories (Table 1) representing the entire fleet, taking into consideration the variety of their applications. These categories include small (class A), medium (class B), and large (class C) passenger cars and SUVs. The remaining categories are cargo vans and commercial medium vehicles. The vehicles from the cargo vans category are intended for service activities, mostly within urban areas. The commercial medium vehicles are also intended for use predominantly in urban areas. Type of fuel is also provided as another distinguishing factor, namely petrol or diesel. The most numerous categories are the cargo vans—197 vehicles (of which 163 are diesel and 34 petrol), commercial medium cars—139 vehicles (all diesel), and B class passenger cars—98 vehicles (of which 35 are diesel and 63 petrol).

Table 1. Specification of ICE vehicles.

Category	**Fuel**	**Category Size**	**Number of Representative Cars per Category**	**Total Volume of Fuel Purchased in the Analysed Period, thous. dm^3**	**Engine Power, kW**	**Fuel Consumption, dm^3/km [1]**	**Carbon Emission, g/km [1]**
Passenger car—A class	Petrol	34	24	23.8	60–92	4.5–5.2	104–130
	Diesel	12	11	18.2	66–66	3.3–4.6	85–104
Passenger car—B class	Petrol	63	20	68.1	63–110	4.0–7.5	99–160
	Diesel	35	8	49.1	70–96	3.5–5.4	90–150
Passenger car—C class	Petrol	34	10	46.0	81–132	4.4–6.6	106–153
	Diesel	42	13	82.1	81–135	3.8–6.1	100–149
SUV	Petrol	55	46	47.1	96–165	4.4–7.6	107–177
	Diesel	8	2	13.6	88–133	3.8–9.2	103–215
Cargo van	Petrol	34	24	33.2	72–88	4.5–7.2	111–180
	Diesel	163	107	129.6	55–96	4.2–8.8	108–195
Commercial medium	Diesel	139	56	113.8	66–120	6.4–10.1	143–226
Total	-	619	321	624.6	-	-	-

[1] According to information published by producers. Based on: [16,17].

Table 1 shows the summary of specifications of ICE vehicles used in the company. Three hundred and twenty-one cars are chosen as representative cars, for which complete data on the total volume of fuel purchased were available over the analysed period. Based on the catalogue data of these vehicles, fuel consumption and carbon emissions per km were calculated. The ranges of results are also presented in this table.

2.1. Internal Combustion Engine Vehicles

In order to calculate the carbon emissions of each category of cars g with internal combustion engines, the average fuel consumption for each representative car per 100 km is required. Fuel consumption $FC_{g,\ rg,f}$ of representative car rg of group g and fuel f per 100 km in a period analysed is determined by Equation (1):

$$\bigwedge_{g\in G}\bigwedge_{rg\in RG}\bigwedge_{f\in F} FC_{g,\ rg,f} = \frac{FuelPurchase_{g,rg,f}}{CM_{g,rg,f}}\cdot 100 \tag{1}$$

where $FuelPurchase_{g,rg,f}$ means the total volume of fuel f purchased for representative car rg of group g, and $CM_{g,rg,f}$ is the total mileage of each representative vehicle considered.

Fuel consumption of a representative car of a group g is applied to Equation (2) to calculate the weighted average fuel consumption of each group $AFC_{g,f}$. To this end, the sum of the products of fuel consumption $FC_{g,\ rg,f}$ for representative car rg of a group g and fuel f per 100 km and weight factors $w_{g,rg,f}$, are divided by the total number of vehicles in the group g and fuel f of the same type as the representatives $TRGN_{g,f} = \sum\limits_{rg} w_{g,rg,f}$:

$$\bigwedge_{g\in G}\bigwedge_{f\in F} AFC_{g,f} = \frac{\sum_{rg}\left(FC_{g,rg,f}\cdot w_{g,rg,f}\right)}{TRGN_{g,f}} \tag{2}$$

where $w_{g,rg,f}$, means the number of vehicles in a group g with fuel f of the same type as the representative car model selected for each group g and fuel f.

Carbon emissions for representative car rg of a group g with fuel f over an analysed period is given in Equation (3). The average carbon emission factor in a group g with fuel f is calculated as given in Equation (4). The sum of the products of carbon emission factor $CO2ICE_{g,rg,f}$ for a representative car rg of a group g with fuel f and weight factors $w_{g,rg,f}$, is divided by the total number of vehicles in the group g with fuel f of the same type as the representatives $TRGN_{g,f} = \sum\limits_{rg} w_{g,rg,f}$:

$$\bigwedge_{g\in G}\bigwedge_{rg\in RG}\bigwedge_{f\in F} CO2ICE_{g,\ rg,f} = FC_{g,\ rg,f}\cdot\ CO2EF_f\cdot 10 \tag{3}$$

$$\bigwedge_{g\in G}\bigwedge_{f\in F} ACO2ICE_{g,f} = \frac{\sum_{rg}\left(CO2ICE_{g,rg,f}\cdot w_{g,rg,f}\right)}{TRGN_{g,f}} \tag{4}$$

where $CO2EF_f$ means carbon emission factor of fuel f.

Total average mileage $ACMTot_{g,f}$ for each group of cars g and fuel f is calculated as is shown in Equation (5):

$$\bigwedge_{g\in G}\bigwedge_{f\in F} ACMTot_{g,f} = FuelPurchaseTot_{g,f}\cdot\frac{100}{AFC_{g,f}} \tag{5}$$

where $FuelPurchaseTot_{g,f}$ is the total volume of fuel f purchased by all cars in a group g over an analysed period.

Total carbon emission for a group g with fuel f over an analysed period is given in Equation (6). It is a product of the total average mileage for a group of cars g with fuel f and average carbon emissions in a group of cars g with fuel f [18]. Consequently, the total emissions $CO2ICETot$ in the entire fleet with internal combustion engines are determined by Equation (7):

$$\bigwedge_{g\in G}\bigwedge_{f\in F} CO2ICETot_{g,f} = ACMTot_{g,f}\cdot ACO2ICE_{g,f}\cdot 10^{-6} \tag{6}$$

$$CO2ICETot = \sum_{g,f} CO2ICETot_{g,f} \tag{7}$$

2.2. Battery Electric Vehicles

In this paper, the authors assume that each car with an internal combustion engine is replaced with a battery electric vehicle. As a result, to calculate the carbon emission factor of the assigned electric vehicle to each group of cars g with fuel f, the electricity consumption and CO_2 emission intensity of electricity generation at the national level are considered. The formula is presented in Equation (8):

$$\bigwedge_{g\in G}\bigwedge_{f\in F} CO2BEV_{g,f} = \frac{CO2EmIntensity\cdot EC_{g,f}}{100} \tag{8}$$

where $CO2EmIntensity$ means carbon emission intensity of electricity generation, and $EC_{g,f}$ is the electricity consumption of the assigned battery electric vehicle of a group of cars g with fuel f per 100 km.

Total carbon emissions for a group g with fuel f in an analysed period is given in Equation (9). The carbon emission factor of the assigned battery electric vehicle of each group of cars and the total average mileage for a group of cars g with fuel f in the analysed period are taken into account. Consequently, the total emissions in BEVs are determined by Equation (10):

$$\bigwedge_{g\in G}\bigwedge_{f\in F} TotCO2BEV_{g,f} = CO2BEV_{g,f}\cdot ACMTot_{g,f}\cdot 10^{-6} \tag{9}$$

$$TotCO2BEV = \sum_{g,f} TotCO2BEV_{g,f} \tag{10}$$

Electricity consumption in BEVs corresponding to each group of cars g with fuel f is also used to calculate total electricity consumption depending on the average mileage for each group g and fuel f, as is given in Equation (11). The study assumes fleet electrification at the level of 100%:

$$\bigwedge_{g\in G}\bigwedge_{f\in F} TotEC_{g,f} = \frac{ACMTot_{g,f}\cdot EC_{g,f}}{100} \tag{11}$$

The total electricity consumption is used to calculate the total charging cost of electric vehicles corresponding to each group of cars g and fuel f, as is given in Equation (12):

$$TotalChargingCost_{g,f} = 0.8\cdot TotEC_{g,f}\cdot\left(1+\frac{ACLoss}{100}\right)\cdot ACCost + 0.2\cdot TotEC_{g,f}\cdot DCCost \tag{12}$$

where $ACLoss$ is the losses from AC charging, $ACCost$ means the cost of electricity (for the AC charging), and $DCCost$ is the charging service cost (for the DC charging).

Total cost of ownership (TCO) analysis has been conducted and compared between ICE vehicles and BEVs for two categories of cars (SUVs and B class). To this end, the following cost components were used in the analysis: cost of fuel or electricity, financial rate, and service rate.

2.3. Case Study Assumptions

The formulas presented in Section 2.2 were applied to the case study of a fleet of 619 ICE vehicles that were considered for replacement with battery electric cars in the coming years. Apart from economic reasons, the companies intended to reduce the carbon footprint of their business. That is why the impact of mobility on the group's carbon footprint and its potential reduction was of the utmost importance.

For the sake of representativeness of the results, a pre-covid period of one year between March 2019 and February 2020 was chosen. The analysis was conducted based on data on fuel consumption gathered from petrol retailers (fuel cards are the only form of fuel payments in the company). Additionally, since each employee is obliged to provide data on current mileage to the company's system with every fuel purchase, these data were also used in the study. The whole database constitutes fifty-nine thousand entries.

Due to the heterogeneity of the input data and their poor quality in some cases, concerning the number of kilometres travelled for business purposes, the data set was cleansed from obvious errors in the mileage reported by employees, non-fuel-related purchases at petrol stations, and empty entries. As previously mentioned, representative vehicles were chosen for each category, based on the number of vehicles of a given model in the category, the mileage, and continuity of usage over the analysed period. As a result, the analysis includes 22 vehicle models (two for each category), represented by 321 individual vehicles.

For each representative vehicle, average fuel consumption was calculated. The calculation was based on all available data for each representative car (not limited to the analysis period only). In order to estimate the real carbon emissions (g/km) for the representative cars, the tailpipe carbon emission factor for combustion of 1 dm^3 petrol and diesel was used, at the level of 2.3 and 2.6, respectively [19]. In order to compare real carbon emissions, adequate for Polish weather conditions, an average of combined real data for cold weather (worst case based on -10 °C and use of heating) and mild weather (23 °C and no use of air conditioning) was considered.

The analysis assumed that each vehicle from the categories listed in Table 1 could be replaced with a specific electric car model. The parameters of these BEVs, primarily in terms of size and possible applications, were similar to ICE vehicles from the corresponding categories. Data for these electric vehicles, including their engine power, electricity consumption per 100 km, and driving range with a fully charged battery, are presented in Table 2.

Table 2. Specification of battery electric vehicles.

Category	Model	Engine Power, kW	Electricity Consumption, kWh/km	Battery Capacity, kWh	Range, km
Passenger car—A class	Opel Corsa-e	100	16.7	50	330
Passenger car—B class	Nissan Leaf	110	14.5	40	270
Passenger car—C class	Volkswagen ID.3 Pro	107	15.6	62	420
SUV	Skoda ENYAQ iV 80	150	17.4	82	536
Cargo van	Citroën ë-Jumpy M	100	24.4	75	330
Commercial medium	Fiat E-Ducato	90	24.1	79	194

According to real-world data—except for cargo van and commercial medium categories for which no reliable real-world data was available, for which information published by the producer was used in this study. Based on: [20–25].

One of the main assumptions regarding the impact analysis of fleet electrification on carbon emissions was the CO_2 emission factor per unit of electricity production. Poland is an example of a country heavily dependent on fossil fuels—mainly hard coal and lignite. As a result, the CO_2 emission factor for electricity available for the end-user (i.e., produced in thermal power plants, including electricity supplied by RES units and including transmission losses and balance differences) amounted to 719 kg CO_2 per MWh in 2019 [26]. It was also one of the highest rates in the entire EU (Figure 2), which significantly influenced the final calculations of the possible fleet conversion effect.

However, Poland is undergoing a transition process towards a low-emission economy and decarbonisation of the power system [27]. According to the new Energy Policy of

Poland until 2040 (EPP2040), in 2040, the assumed fuel mix of electricity generation (i.e., 27.9% coal, 17.0% gas, 13.6% nuclear, 39.5% renewables, and 2.0% others [28]) might result in a reduction in the carbon intensity of electricity generation, to the level of 378 kg CO_2/MWh (own estimations).

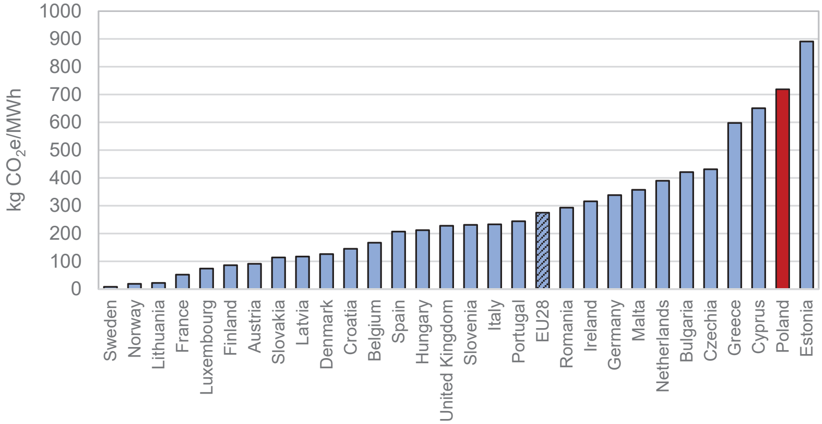

Figure 2. Greenhouse gas emission intensity of electricity generation (as a CO_2 equivalent) in EU countries in 2019. Source: own elaboration based on [29].

Another key assumption was that the entire fleet of ICE cars would be replaced with battery electric vehicles at the same time (100% conversion). Although the replacement of vehicles would be phased and spread over time, such an assumption allows one to calculate the maximum effects of fleet electrification. These findings are valuable from the perspective of company management because they provide the information needed to define or verify strategic goals.

As previously mentioned, in addition to investigating the impact of fleet electrification on CO_2 emissions, the work also provides the results of potential savings related to the purchase of petrol or diesel (for ICE cars) and battery-charging costs (for BEVs). Information on fuel consumption costs for each ICE category was assumed based on historical data from petrol retailers and fuel cards of the company's employees. In the case of BEVs, a model for charging electric vehicles was defined as follows: 80% of total electricity consumption is covered from AC chargers and 20% from high-power DC chargers [30,31]. Electricity costs for AC chargers and total fees related to charging the vehicle at stations equipped with DC chargers are given in Table 3. It is also worth noting that the process of charging electric vehicle batteries is not without losses. Therefore, based on the data presented in Ref. [31], charging losses were assumed at the level of 10% to reflect losses between electric vehicle supply equipment (EVSE) and transformers. Taking into account the current policy of car dealers in Poland of providing mobile AC chargers (usually 3.7 kW or 11 kW) free of charge or for a symbolic fee, the focus was on carbon emissions rather than TCO, and considering the negligible cost of such a charger compared to the TCO of a vehicle, authors decided to exclude AC charger capital expenditure from the analysis.

Table 3. Charging cost of electric vehicles.

Type	Unit	Value
AC charger	EUR/kWh	0.14
DC charger [1]	EUR/kWh	0.47

[1] For DC chargers, total unit cost includes costs and margin of the charging station owner. Based on: [31,32].

3. Results and Discussion

This section presents and discusses the results obtained from the employment of the mathematical formulas to the case study of an individual company. The average total monthly fuel consumption is shown in Figure 3. The analysis indicates that the fleet consumes more than 52 thous. dm^3 of fuel (18 thous. dm^3 of petrol and 34 thous. dm^3 of diesel) per month, corresponding to 135.7 Mg of CO_2. What is also noticeable, is that the largest share in the total monthly fuel consumption (and consequently in the carbon emission) was from the diesel-fuelled cars: cargo vans (20.7%), commercial medium vehicles (18.2%), and passenger C class vehicles (13.2%). These categories were the most significant in the electrification of the company's fleet. Replacing these ICEV groups with BEVs would give the best results for decreasing emissions from fuel combustion (NOx, SOx, VOC, CO, and PM), which are responsible for the phenomenon of low-stack emissions.

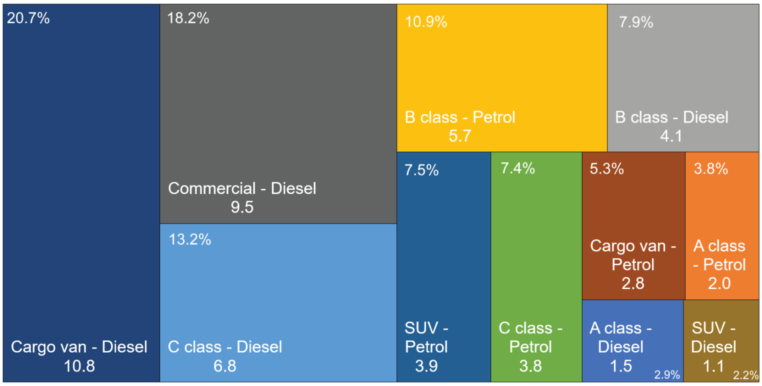

Figure 3. Average monthly fuel consumption for each category of ICE fleet, thous. dm^3.

3.1. Fuel Consumption and Carbon Emissions

As previously mentioned, two representative vehicles were chosen for each category (Table 1), taking into account the number of a given car model in each category. Then, vehicles were reviewed based on their mileage and continuity of mileage to find the most representative vehicles for a given category. Consequently, the fuel consumption of each group and level of carbon emissions was calculated and compared with the catalogue data published by the producers of the representatives considered. The results are presented in Figures 4 and 5, respectively.

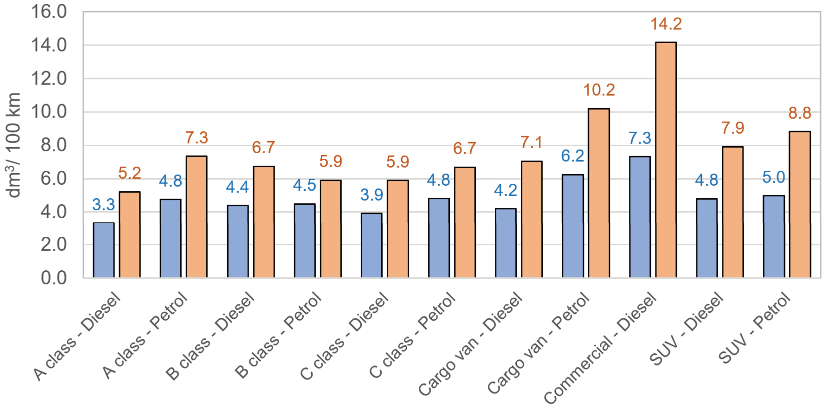

Figure 4. Comparison of fuel consumption (dm^3 per 100 km) of ICE cars—producers' data and fleet-specific measurements.

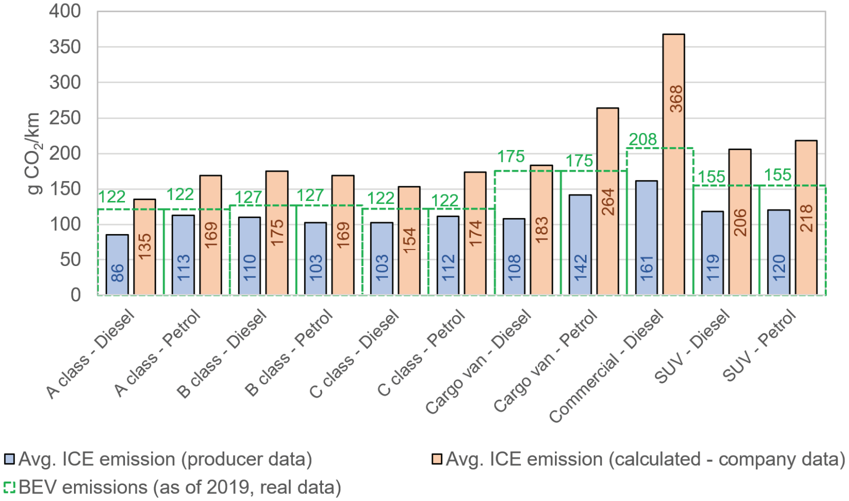

Figure 5. Comparison of carbon emissions (g CO_2/km) of ICE and BEV cars—producers' data, fleet-specific measurements and real usage data.

It can be noticed that real fuel consumption and carbon emission levels were higher across all categories in the case of ICE cars. Particularly:

- For commercial medium vehicles, fuel consumption increased by 94%, which can be attributed to prevalently urban usage (the Worldwide Harmonised Light Vehicles Test Procedure (WLTP) and similar fuel consumption tests assume mixed usage).
- For SUVs, the fuel consumption increase was observed at the level of 77%, making this category particularly interesting for further considerations in the context of a confidence level of the data on fuel consumption published by producers, conversion to BEVs and for introducing eco-driving training dedicated for SUV users.

3.2. Carbon Emissions from BEVs in 2019 and 2040

For each category (regardless of fuel type), a BEV analogue was assigned, chosen from car models currently available on the market. Due to the lack of reliable true usage data for commercial medium category emissions declared by producers, an increase of 20% was assumed.

As presented in Figure 5, for all categories, indirect BEV emission levels for the Polish energy mix of 2019 were higher than those declared by car producers and lower than actual emissions calculated for the category representatives. This is a significant finding, showing that for a power system which largely depends on fossil fuels, such as the Polish one, operational carbon emission levels for this particular fleet were in favour of BEVs back in 2019. A much greater effect could be obtained if the carbon intensity of the Polish power generation system was at the projected level for 2040 (47% reduction from 719 kg CO_2/MWh as in 2019 to 378 kg CO_2/MWh). Comparison of real data on carbon emission levels (in g CO_2 per one kilometre) for BEV cars between the energy mixes in 2019 and 2040 is presented in Figure 6.

For each category, total carbon emission levels were calculated for the current ICE and the purely BEV fleet under two scenarios: First, the structure of electricity generation in 2019 was considered (Figure 1). Second, the assumptions published in the Energy Policy of Poland (EPP2040) regarding the energy mix for the year 2040 were taken into account [28].

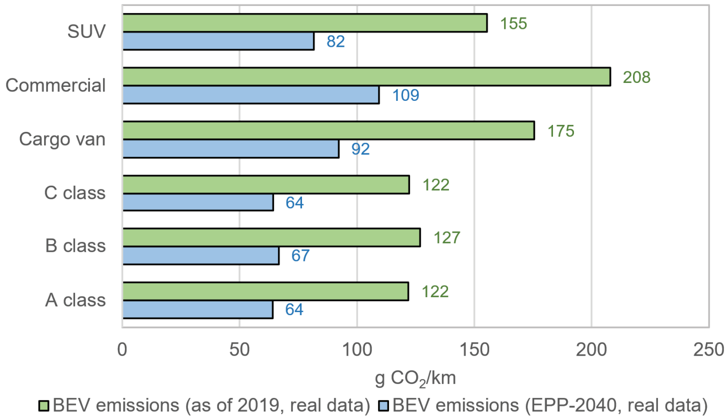

Figure 6. Emission levels for BEVs for each category—comparison based on the carbon intensity of the Polish power sector: fuel mix in 2019 vs. fuel mix in 2040 (EPP2040).

The carbon intensity of each group of ICE vehicles and BEVs is presented in Figure 7. The total emissions from ICE vehicles amounted to 1628 Mg. Their replacement with battery electric vehicles caused a reduction by 24% (to the level of 1231 Mg). The results also indicated that the carbon emissions calculated for the energy mix of 2040 were lower by as much as 47.4% in comparison to 2019. Therefore, charging cars with electricity using a structure similar to 2040 would cause a carbon emission reduction of 60% (even with a 44.9% share of fossil fuels).

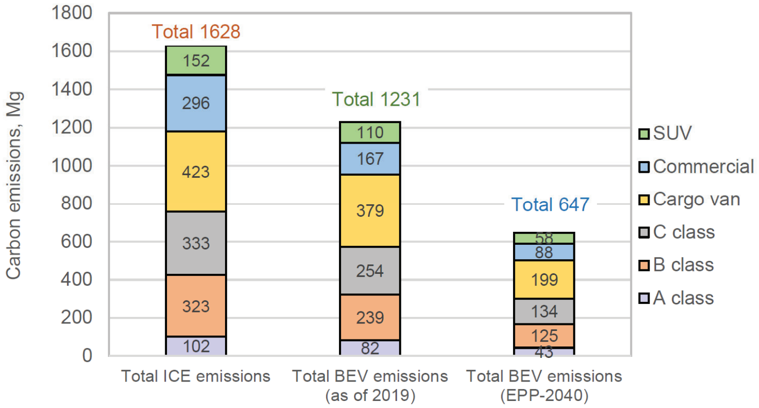

Figure 7. Comparison of total emission levels for ICE and BEV vehicle categories (Mg).

In Figures 8 and 9, a reduction in carbon emissions across categories is presented, along with emission reductions under the 2019 and 2040 Polish energy mix scenarios. It is perfectly justified to rely on a country’s energy mix while looking at fleet electrification at the national scale. However, in the case of a given company or single BEV user, the individual structure of electricity consumption should be considered. Supposing that the company considers using solely renewable electricity to charge its cars at their premises, offsetting carbon emissions for home charging by employees and purchasing electricity and charging services from companies using renewable sources. In this case, the mobility decarbonisation goals could be achieved much earlier than presented in national commitments.

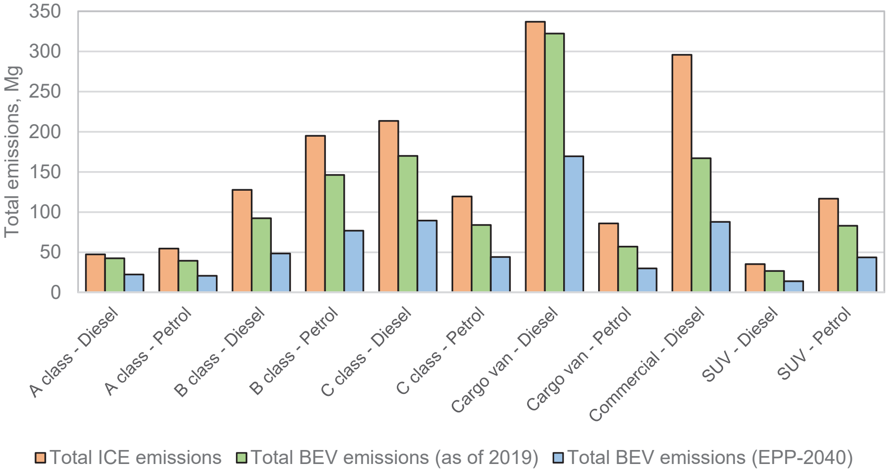

Figure 8. Breakdown of total carbon emissions (Mg) across vehicle categories of the Polish carbon intensity of electricity generation as of 2019 and in 2040 (EPP2040).

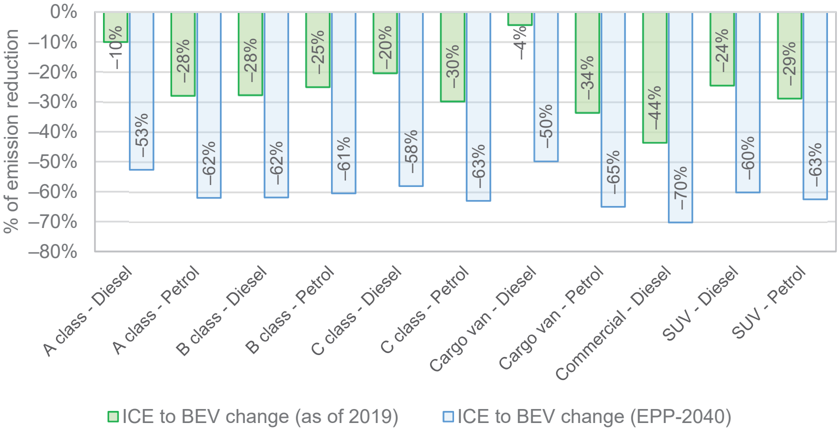

Figure 9. Breakdown of emission reductions (%) for the Polish carbon intensity of electricity generation as of 2019 and in 2040 (EPP2040).

3.3. Operational Costs and Savings

Apart from the comparison of carbon emissions in ICE vehicles and BEVs, a simplified analysis of fuel/charging costs was conducted. The main findings for all vehicle groups are presented in Table 4. The results indicate that total fleet electrification would result in reduction of fuel costs by 50%, allowing the company to generate monthly savings, which could contribute to an increase in lease fees.

In addition to analysis of the savings from the perspective of groups, a rudimentary total cost of ownership (TCO) analysis was conducted. The TCO for two pairs of car categories (SUV and B class) were calculated in two scenarios: an average monthly mileage of 2000 km and the mileage for which break-even is reached. The cost of vehicle insurance was excluded from the analysis due to a lack of complete data. Therefore, it should be noted that due to the higher BEV value, insurance premiums are higher, and, consequently, the presented values are slightly biased in favour of BEVs. The same assumptions regarding charging structure and cost were made for emission level calculations. It is clearly visible that the higher the monthly mileage is, the greater the use of the public charging infrastructure. Consequently, the generated savings will not be linear. For shorter ranges, almost all trips can be made using solely AC charging, limiting the cost. For the SUV category with a monthly mileage of 2000 km, electric vehicles were an economically viable solution, as presented in Table 5. Only below 600 km per month was the combustion model more profitable. In the case of B class vehicles, the situation was opposite—with a monthly mileage of 2000 km, the diesel representative was more economical, and the breakpoint occurred at a mileage of 3770 km per month, which is difficult to achieve in the majority of cases; this is depicted in Table 6.

Table 4. Operational costs and savings analysis for ICE to BEV conversion.

Category	Fuel	Consumption		Fuel/Charging Cost, €		Savings, €	
		Fuel, dm^3	Electricity, MWh	ICE	BEV	Total	Monthly per Vehicle
Passenger car—A class	Petrol	23,756	54.8	28,039.75	11,830.57	16,209.19	39.73
	Diesel	18,196	59.2	21,758.85	12,778.34	8980.51	62.36
Passenger car—B class	Petrol	68,090	203.3	80,356.18	43,897.55	36,458.63	48.23
	Diesel	49,119	128.5	58,653.10	27,737.57	30,915.53	73.61
Passenger car—C class	Petrol	45,967	116.7	54,277.41	25,205.72	29,071.68	71.25
	Diesel	82,145	236.5	98,230.19	51,063.96	47,166.23	93.58
SUV	Petrol	47,139	115.5	55,109.88	24,943.91	30,165.97	45.71
	Diesel	13,577	37.1	16,103.93	8005.29	8098.65	84.36
Cargo van	Petrol	33,197	79.4	38,667.66	17,144.48	21,523.18	52.75
	Diesel	129,586	448.3	153,807.38	96,790.97	57,016.42	29.15
Commercial medium	Diesel	113,780	232.3	134,804.71	50,160.00	84,644.71	50.75
Total	-	624,552	1711.6	739,809.05	369,558.36	370,250.69	49.85

Table 5. TCO comparison for the SUV category.

	Kodiaq 2.0TDI 150 Style AT	Enyaq iV 80	Kodiaq 2.0TDI 150 Style AT	Enyaq iV 80
Financial rate	€338.17	€400.88	€338.17	€400.88
Service rate	€77.32	€59.86	€77.32	€59.86
Fuel/Electricity cost	€73.15	€93.28	€73.15	€27.89
Total	€659.34	€554.01	€488.65	€488.72
Monthly mileage	2000 km	2000 km	600 km	600 km

Table 6. TCO comparison for the B segment category.

	Focus KB 1.5 TDCi 120KM	Leaf 62kWh N-Connecta AT	Focus KB 1.5 TDCi 120KM	Leaf 62kWh N-Connecta AT
Financial rate	€152.64	€333.29	€152.64	€333.29
Service rate	€76.76	€55.55	€76.76	€55.55
Fuel/Electricity cost	€160.81	€76.22	€302.12	€143.67
Total	€390.20	€465.06	€532.52	€532.51
Monthly mileage	2000 km	2000 km	3770 km	3770 km

It can be noticed that TCO is highly dependent on average monthly mileage. Taking into account that the scope of this article is on CO_2 emissions, it can be concluded that while planning a fleet transformation, a priority should be given to high-mileage cases within each category, which should provide benefits of both an environmental and economic nature.

3.4. Catalogue Data vs. Real-World Driving Data

The results of this study point out that there is a divergence in fuel consumption between (a) the catalogue data and (b) data collected from real-world driving (see Figure 10). The analysis conducted using producers' data indicated an increase in carbon emissions by 14% for the current fuel structure of the Polish power system. However, considering the data describing the historical mileage and fuel consumption of 619 cars, the results presented a reduction in carbon emission at the level of 24% for the same energy mix in the power system. Consequently, this paper confirms the existence of the fuel consumption gap that is discussed in detail in Ref. [33].

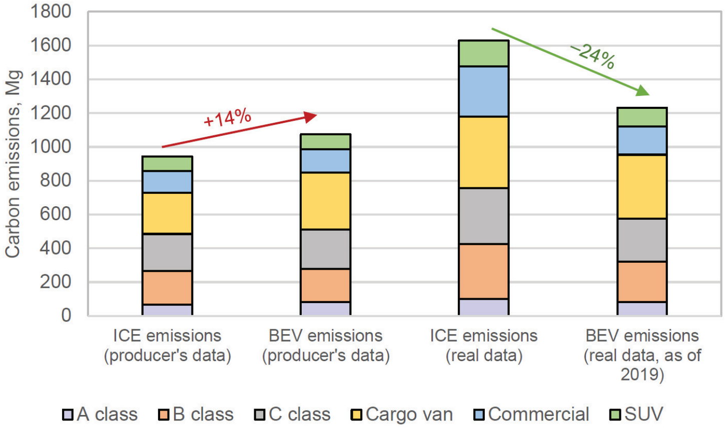

Figure 10. Differences between the impact of fleet electrification on carbon emissions using producers' data and case study results.

In the context of fuel/charging costs, as previously mentioned, fleet conversion resulted in a 50% reduction in fuel costs when real consumptions were compared to reference ICEVs and their BEV counterparts. As far as catalogue data are concerned, the difference was still in favour of BEVs, but it decreased to 30%. In case of no conversion of the fleet, the calculated savings achieved if ICE cars had consumed as producers had declared, reached 38% across all categories.

As a result, apart from the outcomes concerning carbon emission reduction and operational costs stemming from fleet electrification in an individual company, this work provides valuable findings on the divergence of the results depending on the method adopted. The selection of the different input data assumptions can cause different conclusions to be drawn. For instance, interest groups or lobbyists of ICE cars may use catalogue data in their analyses and provide completely different outcomes and findings than those presented here. Based on such analyses, fleet electrification in the company would cause an increase in carbon emissions. Therefore, the replacement of ICE vehicles with electric vehicles would be considered in the future with respect to forecasts of the fuel mix of the power system.

This is why decision-makers, and even policymakers or regulatory bodies, should rely on analysis based on real-driving data instead of catalogue data published on producers' websites.

4. Conclusions

The main aim of this paper was to investigate the potential of CO_2 emission reduction related to company fleet electrification in Poland, a European Union country, which is heavily dependent on fossil fuels for electricity generation. This paper also presents the results of the study of ICEV replacement with BEVs in a large international company. It provides valuable insights into the effects of this replacement on researchers, managers, and policymakers. These insights are valid not only in Poland but also in other countries with similar structures of power systems.

This paper also fills a research gap in the context of fleet electrification on a small scale using real-world data from a fleet of 619 vehicles operated across 19 subsidiaries of a resource management company located in Poland. The main conclusion is that even for a highly fossil fuel-dependant energy mix, indirect emissions for BEVs are lower than tailpipe emissions from ICE vehicles. The case study analysis shows that fleet electrification in the current fuel mix of the Polish power system (75% of electricity is still produced in coal-fired generation units, and 8% in natural gas-fired units) would decrease carbon emissions by 24%. These findings may support decision-making processes in companies when considering the replacement of ICE cars with electric vehicles due to environmental policies.

Case study analysis shows that fleet electrification also results in a decrease in operational costs; the annual expenditure on the purchase of electricity was EUR 370 thousand lower than on conventional fuel. Therefore, the replacement of combustion cars with electric ones may also generate financial savings. However, if the total cost of ownership (TCO) is analysed, the economic viability of electric vehicles is dependent on mileage. The TCO of SUVs is significantly lower for 2000 km per month but higher for mileage below 600 km. This is a consequence of the higher fraction of fixed costs. In the case of B class cars, the results are the opposite; the TCO of BEVs is lower at mileages over 3700 km when compared to ICEVs.

This study also provides a valuable insight into the implications of the methodological approaches used for similar analyses. Using the producers' data instead of real-world data produces entirely different results and different conclusions. The results indicate that using data published by producers gives an increase in carbon emissions of 14% instead of a decrease of 24%. This is why an appropriate method and input data assumptions are of the utmost importance in obtaining reliable outcomes.

Global companies perceive either moral obligation or economic value in becoming independent of energy utilities and their carbon footprint. Technological progress and increasing adoption of renewable sources, battery storage solutions and BEVs are constantly fuelling this trend towards economic break-even and resulting mass adoption.

The transition from ICE vehicles to BEVs is subject to heated public debate, misinformation and contradictory research results. In this context, this study provides valuable insight into the national and global debate as to whether fleet electrification in countries heavily dependent on fossil fuels is justified.

Although this article focuses on emissions reduction and associated fuel/charging costs, a transition towards BEV-based fleets constitutes a significant organisational, managerial and cultural challenge as habits and preferences are strong across all societies [34]. The authors plan to extend the concept and methods adopted here for future research. Firstly, the authors plan to prepare new business models for BEV fleet management as a tool for further reduction of emissions [35]. Secondly, the authors' aim is to expand the analysis of the total cost of ownership components [36], such as maintenance and failure costs [37]. Thirdly, the authors plan to compare the energy consumption of BEVs gradually introduced into company fleets with results published by OEMs and other BEV users. Finally, further research is needed to provide policy recommendations to assure a consistent regulatory framework. Current regulations in Poland tend to concentrate on individual users and public transport, with a relatively lower focus on company car fleets, which constituted more than 70% of new cars purchased in Poland in 2020 [38].

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original draft preparation, J.S., A.K. and P.K.; writing—review and editing, K.Z., J.S., A.K. and P.K.; visualisation, J.S., A.K. and P.K.; supervision, K.Z. All authors have read and agreed to the published version of the manuscript.

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Nomenclature

Name	**Unit**	**Explanation**
Sets		
g	-	Group of cars, $g \in G$ = {passenger cars: A, B, C class, SUV, cargo van, commercial medium}
rg	-	Representative car of each group g, $rg \in RG$
f	-	Fuel, $f \in F$ = {petrol, diesel}
Parameters		
$FuelPurchase_{g,rg.f}$	dm^3	Volume of fuel f purchased for representative car rg of a group of cars g
$CM_{g.rg.f}$	km	Total mileage of representative car rg of a group of cars g with fuel f
$TRGN_{g.f}$	-	Total number of vehicles in the group g with fuel f of the same type as the representatives; $TRGN_{g,f} = \sum_{rg} w_{g,rg,f}$
$w_{g,rg,f}$	-	Number of vehicles in the group g with fuel f of the same type as the representative car model selected for each group g and fuel f
$CO2EF_f$	kg/dm^3	Tailpipe carbon emission factor of fuel f
$FuelPurchaseTot_{g,f}$	dm^3	Total volume of fuel f purchased by all cars in a group g
$CO2EmIntensity$	g/kWh	Carbon emission intensity of electricity generation
$EC_{g,f}$	kWh/100 km	Electricity consumption of assigned battery electric vehicle of a group of cars g with fuel f per 100 km
$ACLoss$	%	Losses of AC charger
$ACCost$	EUR	Cost of electricity (for the AC charging)
$DCCost$	EUR	Charging service fees (for the DC charging)
Variables		
$FC_{g.\ rg.f}$	dm^3/100 km	Fuel consumption by representative car rg of a group of cars g with fuel f
$AFC_{g.f}$	dm^3/100 km	Average fuel consumption in a group of cars g with fuel f
$CO2ICE_{g.rg.f}$	g/km	Carbon emissions in representative car rg of a group g with fuel f
$ACO2ICE_{g.f}$	g/km	Average carbon emissions in a group of cars g with fuel f
$ACMTot_{g.f}$	km	Total average mileage for a group of cars g with fuel f
$CO2ICETot_{g.f}$	Mg	Total carbon emissions from ICE cars for a group of cars g with fuel f
$CO2ICETot$	Mg	Total carbon emissions from all ICE cars
$CO2BEV_{g,f}$	g/km	Carbon emission factor of the assigned battery electric vehicle of each group of cars g
$TotCO2BEV_{g.f}$	Mg	Total carbon emission from BEVs corresponding to a group of cars g with fuel f
$TotCO2BEV$	Mg	Total carbon emissions from all BEVs
$TotEC_{g.f}$	kWh	Total electricity consumption in BEVs corresponding to each group of cars g with fuel f, assuming fleet electrification at the level of 100%
$TotalChargingCost_{g.f}$	EUR	Total charging cost of battery electric vehicles corresponding to each group of a cars g and fuel f

Abbreviations

Name	**Explanation**
AC	Alternating Current
BEV	Battery Electric Vehicle
CO_2	Carbon Dioxide
DC	Direct Current
EPP2040	Energy Policy of Poland until 2040
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
GHG	Greenhouse Gas
ICEV	Internal Combustion Engine Vehicle
OEM	Original Equipment Manufacturer
WLTP	Worldwide Harmonised Light Vehicles Test Procedure

References

1. Wójcik-Jurkiewicz, M.; Czarnecka, M.; Kinelski, G.; Sadowska, B.; Bilińska-Reformat, K. Determinants of Decarbonisation in the Transformation of the Energy Sector: The Case of Poland. *Energies* **2021**, *14*, 1217. [CrossRef]
2. European Commission. The European Green Deal. 2019. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1588580774040&uri=CELEX%3A52019DC0640 (accessed on 7 July 2021).
3. Polish Power Grid Company. Summary of Quantitative Data on the Functioning of the National Power System in 2018. 2019. Available online: https://www.pse.pl/dane-systemowe/funkcjonowanie-kse/raporty-roczne-z-funkcjonowania-kse-za-rok/raporty-za-rok-2019 (accessed on 5 June 2020).
4. Komorowska, A.; Benalcazar, P.; Kaszyński, P.; Kamiński, J. Economic consequences of a capacity market implementation: The case of Poland. *Energy Policy* **2020**, *144*, 111683. [CrossRef]
5. Zamasz, K.; Kapłan, R.; Kaszyński, P.; Saługa, P.W. An Analysis of Support Mechanisms for New CHPs: The Case of Poland. *Energies* **2020**, *13*, 5635. [CrossRef]
6. Komorowska, A. Can Decarbonisation and Capacity Market Go Together? The Case Study of Poland. *Energies* **2021**, *14*, 5151. [CrossRef]
7. Kasten, J.P.; Bracker, M.H.; Purwanto, J. Electric mobility in Europe—Future Impact on the Emissions and the Energy Systems. Final Report of Task 2. 2016. Available online: https://www.electrive.com/study-guide/electric-mobility-in-europe-future-impact-on-the-emissions-and-the-energy-systems/ (accessed on 19 June 2021).
8. Xiong, S.; Ji, J.; Ma, X. Comparative Life Cycle Energy and GHG Emission Analysis for BEVs and PhEVs: A Case Study in China. *Energies* **2019**, *12*, 834. [CrossRef]
9. Yu, A.; Wei, Y.; Chen, W.; Peng, N.; Peng, L. Life cycle environmental impacts and carbon emissions: A case study of electric and gasoline vehicles in China. *Transp. Res. Part D Transp. Environ.* **2018**, *65*, 409–420. [CrossRef]
10. Sobol, Ł.; Dyjakon, A. The Influence of Power Sources for Charging the Batteries of Electric Cars on CO_2 Emissions During Daily Driving: A Case Study from Poland. *Energies* **2020**, *13*, 4267. [CrossRef]
11. Majchrzak, K.; Olczak, P.; Matuszewska, D.; Wdowin, M. Economic and environmental assessment of the use of electric cars in Poland. *Polityka Energetyczna Energy Policy J.* **2021**, *24*, 153–168. [CrossRef]
12. Teixeira, A.C.R.; Sodré, J.R. Impacts of replacement of engine powered vehicles by electric vehicles on energy consumption and CO 2 emissions. *Transp. Res. Part D Transp. Environ.* **2018**, *59*, 375–384. [CrossRef]
13. Drożdż, W.; Szczerba, P.; Kruszyński, D. Issues related to the development of electromobility from the point of view of Polish utilities. *Polityka Energetyczna Energy Policy J.* **2020**, *23*, 49–64. [CrossRef]
14. Połom, M.; Wiśniewski, P. Implementing Electromobility in Public Transport in Poland in 1990–2020. A Review of Experiences and Evaluation of the Current Development Directions. *Sustainability* **2021**, *13*, 4009. [CrossRef]
15. Pietrzak, O.; Pietrzak, K. The Economic Effects of Electromobility in Sustainable Urban Public Transport. *Energies* **2021**, *14*, 878. [CrossRef]
16. Motoreu.com. 2021. Available online: https://motoreu.com/ (accessed on 19 June 2021).
17. Wiki Automotive Catalogue. 2021. Available online: https://www.auto-data.net/en/ (accessed on 19 June 2021).
18. EIA. How Much Carbon Dioxide Is Produced from U.S. Gasoline and Diesel Fuel Consumption? 2021. Available online: https://www.eia.gov/tools/faqs/faq.php?id=307&t=11 (accessed on 19 June 2021).
19. Natural Resources Canada. Auto Smart. Learn the Facts: Fuel Consumption and CO_2. 2014. Available online: https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/oee/pdf/transportation/fuel-efficient-technologies/autosmart_factsheet_6_e.pdf (accessed on 19 June 2021).
20. Electric Vehicle Database: Operl Corsa-e. 2021. Available online: https://ev-database.org/car/1192/Opel-Corsa-e (accessed on 19 June 2020).
21. Electric Vehicle Database: Nissan Leaf e+. 2021. Available online: https://ev-database.org/car/1144/Nissan-Leaf-eplus (accessed on 19 June 2021).

22. Electric Vehicle Database: Volkswagen, ID.3 Pro. 2021. Available online: https://ev-database.org/car/1202/Volkswagen-ID3-Pro (accessed on 19 June 2021).
23. Electric Vehicle Database: Skoda Enyaq iV 80. 2021. Available online: https://ev-database.org/car/1280/Skoda-Enyaq-iV-80 (accessed on 19 June 2021).
24. UltimateSPECS: Citroen Jumpy 2016 e-Jumpy. 2021. Available online: https://www.ultimatespecs.com/car-specs/Citroen/122274/Citroen-Jumpy-2016-e-Jumpy-XL-75kWh.html (accessed on 19 June 2021).
25. E-Ducato broshuere. 2021. Available online: https://www.abz-nutzfahrzeuge.de/fileadmin/inhalte/Modelle_Fiat/Ducato/e-Ducato/E-Ducato-broschuere-englisch.pdf (accessed on 19 June 2021).
26. KOBiZE. CO2, SO2, NOx, CO and Total Dust Emission Indicators for Electricity Based on the Information Contained in the National Base on Emissions of Greenhouse Gases and Other Substances for 2019 (In Polish). 2020. Available online: https://www.kobize.pl/uploads/materialy/materialy_do_pobrania/wskazniki_emisyjnosci/Wskazniki_emisyjnosci_grudzien_2019.pdf (accessed on 19 June 2021).
27. Mucha-Kuś, K.; Sołtysik, M.; Zamasz, K.; Szczepańska-Woszczyna, K. Coopetitive Nature of Energy Communities—The Energy Transition Context. *Energies* **2021**, *14*, 931. [CrossRef]
28. Ministry of Climate and Environment. Energy Policy of Poland until 2040. 2021. Available online: http://isap.sejm.gov.pl/isap.nsf/download.xsp/WMP20210000264/O/M20210264.pdf (accessed on 8 August 2021).
29. European Environment Agency (EEA). *Greenhouse Gas Emission Intensity of Electricity Generation*; European Environment Agency: Copenhagen, Demark, 2020.
30. Funke, S.Á.; Sprei, F.; Gnann, T.; Plötz, P. How much charging infrastructure do electric vehicles need? A review of the evidence and international comparison. *Transp. Res. Part D Transp. Environ.* **2019**, *77*, 224–242. [CrossRef]
31. Apostolaki-Iosifidou, E.; Codani, P.; Kempton, W. Measurement of power loss during electric vehicle charging and discharging. *Energy* **2017**, *127*, 730–742. [CrossRef]
32. GreenWay Poland. Pricelist of Charging. 2021. Available online: https://greenwaypolska.pl/en/evdrivers/ (accessed on 20 June 2021).
33. Pavlovic, J.; Fontaras, G.; Ktistakis, M.; Anagnostopoulos, K.; Komnos, D.; Ciuffo, B.; Clairotte, M.; Valverde, V. Understanding the origins and variability of the fuel consumption gap: Lessons learned from laboratory tests and a real-driving campaign. *Environ. Sci. Eur.* **2020**, *32*, 53. [CrossRef]
34. Stęchły, J.; Stęchły, M.; Shahan, Z. *European and US Electric Vehicle Owner's Needs and Expectations Analysis. Conclusions for Poland (In Polish: Analiza Potrzeb i Oczekiwań Właścicieli Samochodów Elektrycznych w Europie i Stanach Zjednoczonych)*; Drożdż, W., Ed.; Electrobomility in the Development of Cities (In Polish: Elektromobilność w rozwoju miast): Warsaw, Poland, 2018; pp. 58–81.
35. Mucha-Kuś, K.; Stęchły, J.; Zamasz, K. The role of coopetition in development of electromobility. *Zesz. Nauk. Politech. Śląskiej Organ. Zarządzanie* **2018**, *21*, 357–369. [CrossRef]
36. Burnham, A.; Gohlke, D.; Rush, L.; Stephens, T.; Zhou, Y.; Delucchi, M.A.; Birky, A.; Hunter, C.; Lin, Z.; Ou, S.; et al. *Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains*; U.S. Department of Commerce: Alexandria, VA, USA, 2021.
37. Wróblewski, P.; Drożdż, W.; Lewicki, W.; Miązek, P. Methodology for Assessing the Impact of Aperiodic Phenomena on the Energy Balance of Propulsion Engines in Vehicle Electromobility Systems for Given Areas. *Energies* **2021**, *14*, 2314. [CrossRef]
38. IBRM SABAR. IBRM SAMAR Report—Registrations of Passenger Cars and Vans in July 2020 (In Polish: Raport IBRM SAMAR—Rejestracje Samochodów Osobowych i Dostawczych w Lipcu 2020). 2020. Available online: https://doi.org/10.1016/j.trd.2019.10.024 (accessed on 19 June 2021).

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The Future of the Polish Energy Mix in the Context of Social Expectations

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Abstract: Currently, Poland has been facing a process of intensive changes in the energy sector, motivated by the strengthening of the goals of the climate and energy policy at the European level. A key challenge for energy transition in Poland is to build an energy system that corresponds with social needs not only in terms of energy demand, but also environmental protection, with a strong role of local initiatives. The aim of this study is to present the expectations of the Poles regarding the optimal energy mix, especially representatives of local governments, and their awareness of the needs and expectations of their local communities. According to the authors, local governments are extremely important links, responsible for the development of the energy economy and energy security at the local level. The authors set themselves the task of verifying whether local authorities are prepared to create a substantive energy policy at the local level in accordance with the directions of the Polish energy policy and on the basis of local conditions, including the opinions of the inhabitants of a given region. The objective of this work was achieved by reviewing the available sources and the adopted survey method. A review of the literature, in particular in terms of the conducted research on the social acceptance in terms of energy policy, showed that there are no comprehensive surveys of the opinions of local government representatives. The results of study conducted by the authors showed that although the vast majority of respondents know the assumptions of the Polish energy policy until 2030, almost a quarter did not realize that the energy policy will be changed in the near future. At the same time, the vast majority of respondents believe that the Polish government should prepare a social campaign related to the energy policy. According to the authors, this proves the need to improve the awareness of this research group, which may bring benefits in the process of shaping the energy economy of the regions. The survey also showed preferences of the representatives of local governments for the optimal energy mix in Poland and their subjective assessment of the knowledge of public opinion in the region on the expected shape of the energy policy. From the findings, it can be concluded that more in-depth research is needed on the preparation of local governments to shape energy policy at the local level, including more detailed research on how opinions of the inhabitants of a given region and the specificity of a given region are taken into account while shaping local energy policy.

Keywords: Polish energy mix; energy transition in Poland; social acceptance; energy policy

1. Introduction

The transformation of the Polish energy sector has become a reality not only due to the need to keep pace with the path set out by the European Union's climate and energy policy, but also through support of society, which has created an impulse of initiatives and measures aimed primarily at increasing energy security at the local level and reducing the environmental pressures of the energy sector. An important reason for the growing interest of local communities in the energy sector is the increasing environmental awareness. The European Commission's 2014 study showed that most respondents associate the quality of their lives with the state of the environment and believe that environmental problems have a direct impact on their lives. People watch their governments more closely as regards their actions related to the energy sector, expressing their opinion and taking action in support of central action [1]. Despite income disparities between Poland and Western Europe, Poles also try to take action; hence, there is a growing number of prosumers as well as micro and small installations and community energy cooperatives in this country.

By 2040, Poland's electricity demand is expected to increase by up to 50%, to 240 TWh [2], which is a huge challenge for the energy sector. Achieving the objectives of the new energy policy, including the development of the renewable energy sector and reduction of the share of coal in power generation, will require effective measures, including those initiated at the local level. By 2032, approximately 12 GW of generation capacity is to be decommissioned in Poland, to be replaced by a similar new capacity in the energy system, approximately 32% of which is expected to come from wind sources [3]. Poland faces the risk of missing capacity, which may result in capacity shortages and difficulties in meeting a growing demand for energy [4].

The crisis caused by the COVID-19 pandemic will have an impact on the energy sector, and experts stress that the economy should recover in a sustainable manner, with as little impact as possible on the environment and natural resources. Recent IEA studies show that global energy demand will decrease by about 5% in 2020, which is directly linked to recent developments. However, economic recovery is likely to lead to considerable increases in energy demand, which needs proper preparation [5]. The European Green Deal climate actions and in particular the climate target plan's 55% net reduction target presented under the Fit for 55 package set the direction for the development of the European energy sector with its ambitious new goals: increasing the emission reduction target to 55% (compared to 1990 level), setting a target of spending 37% of the €750 billion NextGenerationEU recovery fund on Green Deal objectives, and increasing the RES share up to 38–40%.

On July 14, the European Commission announced the climate and energy legislative package—Fit for 55. In line with the EU's climate ambitions, greenhouse gas emissions are to be reduced by 55% by 2030 (compared to 1990). By 2050, the European Union aims to achieve zero net emissions. Such ambitious plans require changes in all areas of social and economic life. The European Green Deal sets out a detailed vision to make Europe the first climate neutral continent by 2050. The new climate target, along with the Fit for 55 package, are part of the European Green Deal adopted in December 2019. The European Commission's proposals must be approved by EU governments and the European Parliament. The package consists of 13 legislative proposals, some of which are new, others presenting changes to existing legislation. The current EU regulations are updated: revision of the EU Emissions Trading System (EU ETS), reform of the LULUCF regulation (Land Use, Land Use Change and Forestry), review of the Effort Sharing Regulation(ESR), amendment to the renewable energy directive (RED), amendment of the Energy Efficiency Directive (EED), revision of the Alternative Fuels Infrastructure Directive (AFID), amendment of the regulation defining CO2 emission standards for passenger cars and vans, and revision of the Directive on energy taxation. The new legislative proposals include the EU's new forest strategy, the Carbon Dioxide Limit Regulating Mechanism (CBAM), the Social Instrument for Climate Action, ReFuelEU Aviation (for sustainable aviation fuels), and FuelEU Maritim (for greening the European maritime space). The EU's goal of achieving net zero emissions by mid-century will require a massive increase in Europe's renewable energy generation capacity. The main aim of the reform will be to raise the RES targets for the EU. The current target for the share of renewable energy in the EU energy mix will be increased from 32 to 40 percent thanks to Fit for 55. All Member States will have to contribute to achieving this goal, which is an ambitious task for Poland and for the implementation of Polish energy policy. In addition, the directive will raise specific objectives, e.g., concerning the share of renewable energy sources in transport, heating, as well as the share of advanced biofuels. The issue of reducing emissions from the energy sector is one of the key problems of the Polish energy sector. The implementation of the fit for 55 package in Polish conditions will be difficult; however, the authors believe that the vision presented in the updated energy policy will support the ambitious European goals.

Therefore, the potential of local communities and special role of cities in the process of Poland's energy transition should not be overlooked [6]. The European Commission points to the phenomenon of 'community energy initiatives'. The Joint Research Centre (JRC) of the European Commission has examined the activities undertaken by "community energy initiatives" within the European Union. Research has shown that, owing to legislative support to community action, they undertake a number of initiatives—from power generation (mainly with RES) to energy saving and storage and electromobility [7]. This shows not only huge ambitions of communities for their place in the energy sector, but also how much support the EU and the governments of individual Member States should offer for this type of action. Local communities can play a significant role in the process of transformation of the energy sector in Poland; they can also actively participate in the EU energy market by generating electricity at the local level, using it or reselling it to the market. Furthermore, one of the tasks of the internal energy market is to strengthen the rights of consumers and citizen energy communities [8]. It is also important that regional energy planning is balanced and based on the available renewable raw materials, so as to take into account the constraints imposed by environmental requirements and natural conditions at the lowest cost [9].

A study conducted by the European Commission shows that, by 2030, energy communities could own about 17% of installed wind energy and 21% of solar capacity [10]. By 2050, almost half of EU households are expected to be producing renewable energy [11]. This shows that the potential of citizens is substantial, which, combined with increasing awareness and willingness to act and support from the government, can yield spectacular results, supporting the European and Polish climate and energy objectives.

Local governments are an important element of the complex system of shaping the energy policy in Poland, with their competencies in the field of:

- Identification of key energy resources and energy demand in the regions;
- Setting directions for the energy development of the regions based on a strategy defined at the national level (development of distributed energy, including RES, prosumers, etc.);
- Support for the development of intelligent solutions in the field of the energy systems in cities, including sustainable mobility, energy efficiency, education, smart cities concept, etc.;
- Supporting innovative initiatives and cooperation between local authorities, businesses, and research institutions;
- Shaping the local, sustainable energy economy, and supporting the goals of sustainable development;
- Building awareness of local communities.

The available research on public opinion about the expected shape of energy policy, conducted in Poland, lacks references to the perspective of local governments. The authors attempted to fill this gap by showing preferences of representatives of local governments for the optimal energy mix in Poland and assessing their preparation to create an energy policy at the local level. According to the authors, this preparation should take into account the knowledge of the preferences of the inhabitants of a given region, as well as an in-depth analysis of the implemented local initiatives (energy cooperatives, prosumers) and local energy resources. There are no in-depth analyses in this area in Poland. The authors emphasize the importance of shaping conscious attitudes in the local government environment, as well as building knowledge and skills and constantly improving the competences of local government employees in the field of energy policy and sustainable development.

2. Literature Review

2.1. Energy System in Poland in Figures

The specific nature of the Polish power system stems mainly from a high share of conventional, coal-based energy sources. In 2019, the installed capacity in the Polish Power System (PPS) amounted to 46,799 MW, while the generating capacity amounted to 46,991 MW, an increase by 1.9% and 2.9%, respectively, compared to 2018. The average annual demand for capacity was 23,082 MW, with a maximum demand of 26,504.4 MW (an increase by 1% and 0.2%, respectively, compared to 2018). The ratio of available generating capacity was 64.5%—a decrease by 1.6% compared to 2018 [3].

Figure 1 presents the structure of PPS's installed capacity in 2017–2019. In the last 3 years, there was a small increase in RES, which in 2019 accounted for approx. 16% of the entire capacity installed in the PPS. In total, approx. 47 GW of the capacity was installed in the PPS at the end of 2019 [12].

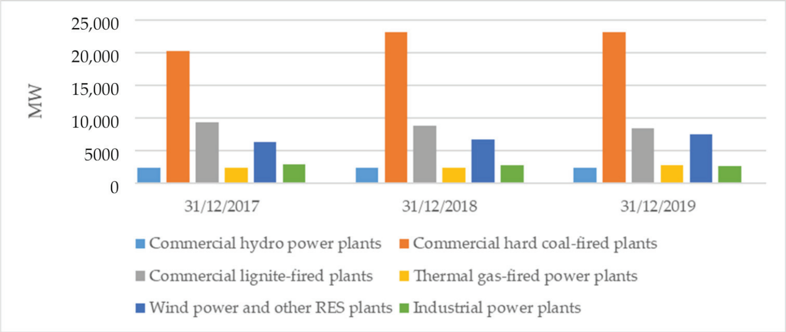

Figure 1. Structure of the Polish Power System's installed capacity in 2017–2019 [MW]. Source: developed by the authors, based on Reference [12].

In 2019, the average annual demand for capacity amounted to approx. 23.082 GW, while the maximum demand for capacity amounted to—approx. 26.5 GW [12]. Despite the fact that the highest historical level of the maximum demand for capacity was in 2019, the average annual demand for capacity in that year saw a slight decrease (by 0.9% compared to 2018). Due to the COVID-19 pandemic and the reduction in activity in certain sectors, the average annual demand for capacity is likely to follow the downward trend in 2020.

At the end of 2019, 9.5 GW was installed in RES, of which 1.5 GW in PV installations. Over the last two years, the development of RES has been supported by the development of prosumer installations. Wind energy clearly stands out among all RES—it has been developing dynamically from 2005, following the introduction of the support system (green certificates), until 2016, which is when the so-called a 'Distance Act' came into force (The Act of 20 May 2016 on wind farm investments) and the sector faced a major problem resulting from the oversupply of green certificates. This all led to the largest crisis in the history of the development of this sector in Poland, faced by both well-established companies and smaller investors [13]. At the end of 2019 the total installed capacity in onshore wind farms amounted to approx. 6 GW (Figure 2), which ranked Poland on the very high, 9th place in the European Union (Europe now has around 195 GW of onshore wind energy capacity installed) [14].

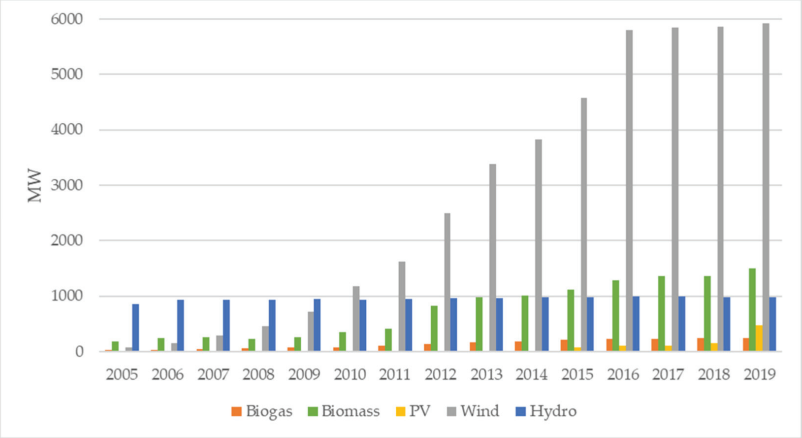

Figure 2. Renewable energy capacity installed in Poland in 2005–2019 [MW]. Source: developed by the authors, based on Reference [15].

Despite the increasing share of electricity generated from RES, this type of energy still accounts for only about 9% of Poland's electricity generation and covers approx. 8.5% of domestic electricity consumption (see Figure 3). According to the Polish National Renewable Energy Action Plan, prepared and submitted to the European Commission in 2010, by 2020, Poland is obligated to increase share of renewable energy in gross final consumption to 15%, but experts have pointed to the possible difficulties in achieving this target due to the specific nature of the Polish energy sector and the significant share of coal in energy production since its very adoption. In the last decade, the RES sector in Poland initially developed dynamically, increasing its share in the energy mix (mainly due to legislative changes and the introduction of the aforementioned support system in the form of green certificates). However, starting from 2012, large energy utilities have lobbied against RES, pointing to difficulties in balancing the power system and high costs of energy production, which resulted in annual RES capacity increases far from spectacular. The government's policies since 2015 have halted new investments, which threatened the achievement of the 2020 target [16].

Pursuant to Article 6a of the Act of 20 February 2015 on Renewable Sources, the President of the Energy Regulatory Office (hereinafter: ERO) shall prepare a report on the electricity fed into the grid by renewable energy prosumers and sold to the obligated seller referred to in Article 40(1) of the Act, which was generated from renewable energy sources in micro-installations and fed into the distribution grid, as well as informing about the type of micro-installations and their installed capacity [17]. This obligation has been in place for two years. The report prepared by the ERO President in 2020 [18] shows that there were 149,309 prosumers in Poland in 2019 (Table 1), and the total electricity fed into the grid by the prosumers amounted to 324,333.174 MWh, while the total amount of electricity fed into the grid by micro-installations was 47,896.048 MWh. In 2018 [19], the number of prosumers was 51,163 (the total electricity fed into the grid by prosumers in 2018 was 130,370.162 MWh), which means an increase by nearly 300%.

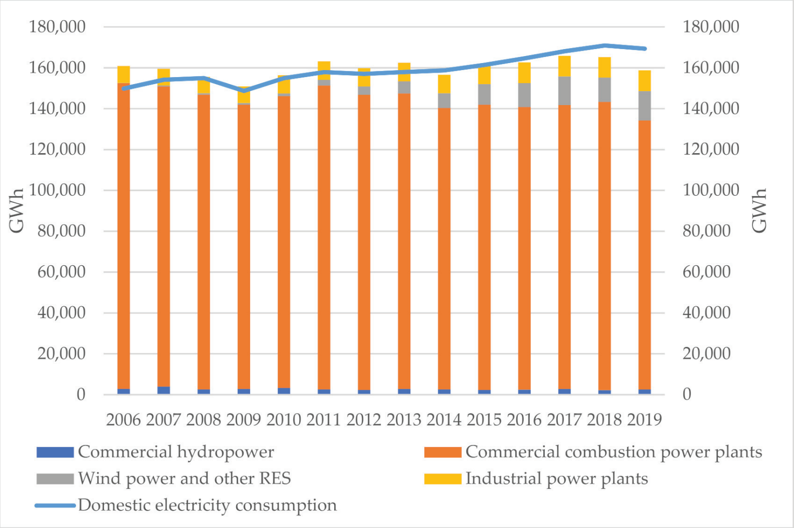

Figure 3. Domestic electricity production and consumption in Poland in 2006–2019 [GWh]. Source: developed by the authors, based on Reference [15].

Table 1. Number of micro-installations and total installed capacity in 2018–2019.

Type of Micro-Installation			**Total Capacity Installed [MW]**	
	2018	**2019**	**2018**	**2019**
Non-agricultural biogas	3	5	0.073	0.024
Agricultural biogas	16	25	0.42	0.665
Biomass	4	5	0.142	0.173
Solar	55.098	155.189	344.239	990.506
Solar/wind	29	40	0.181	0.359
Wind	68	73	0.37	0.384
Water	284	289	8.038	8.258
Total	55,502	155,626	353.463	1,000.369

Source: Developed by the Authors, Based on References [19,20].

The number of small installations has also been steadily increasing in Poland. In 2019, small energy producers generated energy in a total of 817 installations (one energy producer may hold several installations). Their total installed capacity was nearly 163 MW. In terms of the number (341) and installed capacity (51.5 MW), small hydropower plants were the most prevalent in Poland. They were followed by photovoltaic installations both in terms of the number of installations (247) and installed capacity (47.5 MW). The least popular, on the other hand, were small biomass power plants. At the end of 2019, there were only two such sources in Poland. Owners of small installations (697 entities) generated more than 342 GWh of energy in the previous year, of which 70% (238 GWh) was sold to the obliged sellers and 30% was used for own purposes or sold to other sellers. One year earlier, such installations generated 208 GWh of electricity, selling 142 GWh (more than 68% of the energy generated) to the obliged sellers to the distribution grid. The largest amount of energy—over 158 GWh—was produced by small hydropower plants—almost 46% of energy produced by all small RES installations came from this source. Biogas plants using non-agricultural biogas generated more than 102 GWh of energy, of which only 29 GWh were sold to the obliged sellers. Ranking third were small wind power plants, which generated more than 51 GWh of energy [21].

2.2. Energy Policy in Poland

The Energy Policy of Poland presents the government's long-term strategy for the energy and fuels sector. Such a document is required by Articles 13–15a of the Energy Law. The document currently in force in Poland was adopted by the Council of Ministers in 2009 and covers the perspective until 2030. Due to the fact that the conditions affecting strategic decisions in the energy sector have changed in the last decade, and the document currently in force takes into account neither European trends nor public expectations, the Ministry of Climate and Environment has developed a project titled 'Energy Policy of Poland until 2040'. As the Ministry stresses, the European Union's climate and energy policy, including regulations under the 'Clean energy for all Europeans' package, is important in the context of work on the new draft [22]. On 2 February 2021, 12 years following the adoption of the previous Policy, the Council of Ministers adopted the Draft. The experts pointed out that, given the current trends and directions of development, without updating the 2009 policy, it would be very difficult to anticipate the future shape of the energy mix in Poland, which is why the new draft energy policy was a long-awaited document [23].

On 10 November 2009, the Council of Ministers adopted the Energy Policy of Poland until 2030, a document which was supposed to address serious challenges faced by the Polish energy sector at that time. These challenges were mainly related to high energy demand, inadequate level of development of fuel and energy generation and transport infrastructure, significant dependence on external supplies of natural gas and nearly complete dependence on external oil supplies, as well as environmental commitments, including climate commitments [24].

For the purposes of developing the energy strategy for Poland, a forecast of fuel and energy demand until 2030 [25] was prepared. Following an analysis, it was concluded that the projected increase in the final energy consumption in 2030 would grow by around 29% compared to 2006, with the largest increase, i.e., by as much as 90%, expected in the services sector. A 15% increase was projected for the industry sector and a 64% increase for the transport sector [25].

Regarding the final energy demand by carrier, by 2030, the final electricity consumption is expected to increase by 55%, gas by 29%, district heating by 50%, petroleum products by 27%, and renewable energy by 60%. Particularly evident against this backdrop is the expected increase in the consumption of renewable energy, which, according to the authors of the forecast, will result from the fulfilment by Poland of its obligations under the European Climate and Energy Package [25].

Since 2005, there has been a steady increase in the generation of energy from renewable sources. The climate and energy package until 2020 assumed a 20% reduction in greenhouse gas emissions (from 1990 levels), a 20% share of renewable energy in total energy consumption in the EU, and a 20% increase in energy efficiency [26]. In 2007, targets were set for Member States, including the target of a 15% share of RES in gross final energy consumption for Poland. In 2014, the European Council approved new targets for the whole EU until 2030, which were then revised in 2018 [26]:

- A 40% reduction in greenhouse gas (GHG) emissions compared to 1990 (expressed as 2005 levels: −43% in EU ETS sectors and −30% in non-ETS sectors);
- At least a 32% share of renewable sources in gross final energy consumption;
- A 32.5% increase in energy efficiency;
- Completion of the EU internal energy market.

One of the main prerequisites for decision-making on energy policy is a forecast of national power supply. The government anticipates that gross domestic electricity demand in 2030 will be 217.4 TWh. By comparison, in 2006 it was 150.7 TWh. Due to EU requirements, a growing share of renewable energy is expected (see Figure 4). In this respect, the forecast net generation of power from renewable sources is set at 38 TWh, which accounts for 18.8% of the total forecast net power generation [25].

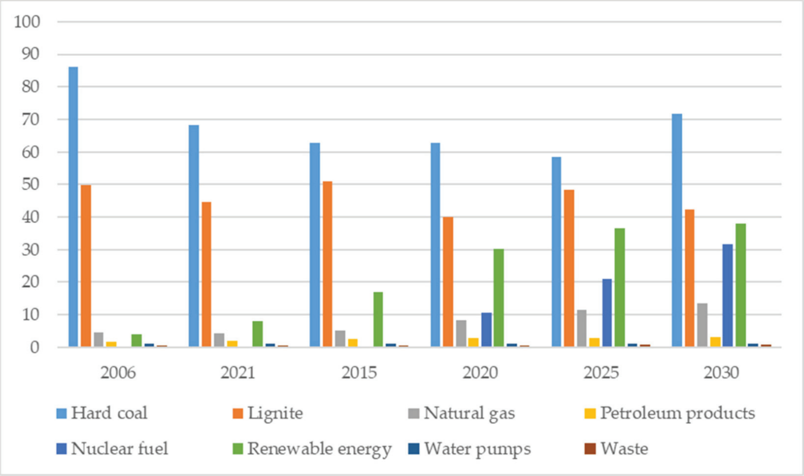

Figure 4. Net power generation by fuel in 2021–2030 [TWh]. Source: developed by the authors, based on Reference [25].

Among all renewable energy sources, wind sources play a dominant role, with an expected increase in capacity to almost 8 GW in 2030 [25].

Poland's specific and characteristic energy system has been the reason for adopting the following six interdependent directions in the Energy Policy until 2030: improving energy efficiency, increasing the security of fuel and energy supply, diversification of the energy generation structures by introduction of nuclear power, developing the use of renewable energy sources, including biofuels, developing competitive fuel and energy markets, and reduction of environmental impacts of the energy sector [24].

The development of renewable energy is vital in the context of achieving climate and energy targets, as well as improving energy security and reducing adverse environmental impacts of the energy sector. Bearing in mind the finiteness of fossil sources and their specific nature, renewable sources are an excellent alternative in the energy transition process of Poland. In addition, the development of distributed renewable energy sources reduces transmission losses and improves local energy security. Positive environmental effects associated with the production of energy from RES and socio-economic benefits that accompany their development are also important in this context. They lead to a steady increase in the support for RES, with growing popularity of local community initiatives aimed at growing the benefits of the local use of small renewable sources (energy cooperatives, development of prosumer energy generation) [24].

On 30 December 2019, the Minister of State Assets submitted to the European Commission the National Energy and Climate Plan for the years 2021–2030, thus fulfilling the obligation imposed on Poland by Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018, which sets out new climate and energy targets for Poland for 2030. These targets are presented in Figure 5.

The primary objective of the National Energy and Climate Plan for the years 2021–2030 is to act in five dimensions: improve energy security, create and operate the internal energy market, improve energy efficiency, reduce sectoral carbon footprint, and support research, innovation, and competitiveness [27].

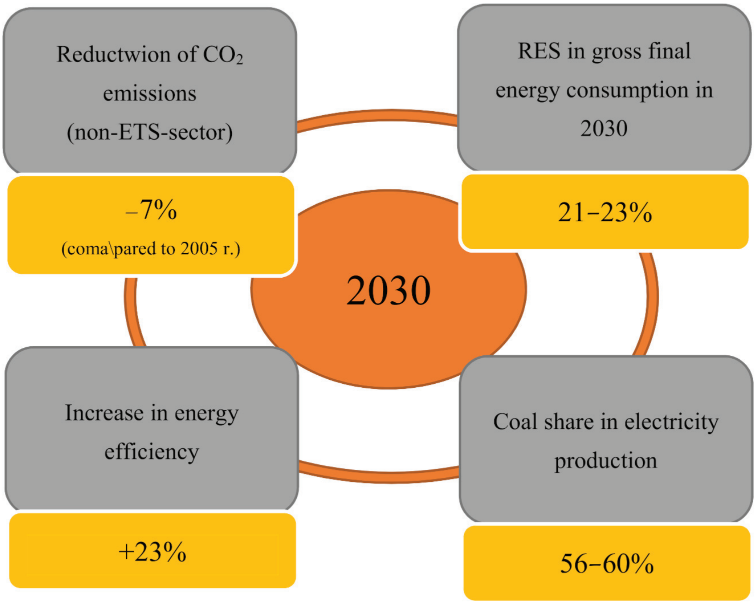

Figure 5. 2030 goals of the National Energy and Climate Plan for the years 2021–2030 for Poland. Source: developed by the authors, based on Reference [27].

The draft of the Energy Policy of Poland until 2040, adopted on the eve of the publication of this article [28], will define the long-term vision of the government for the energy sector. According to the Government's communication, the document will present a path towards the just transition of the energy sector, energy security, a stable labor market, sustainable development of the economy and strengthening its competitiveness, and recovery from the COVID-19 pandemic. Changes in the international context (Paris Agreement, so-called Katowice Climate Package, adoption by the EC of the 'Clean energy for all Europeans' package, and adoption of the European Green Deal) and global trends in climate and energy have forced Poland to revise the provisions of the already obsolete Energy Policy of Poland until 2030. These trends led to the revision of the objectives for the energy sector in Poland to support the European path to achieving climate neutrality by 2050 and to reduce adverse environmental impacts of the energy sector. The specific Polish energy sector, which is largely based on conventional, coal sources, requires continuous modernization of generation capacity and diversification of the energy generation structure, in particular while respecting the principle of just transition, which also takes into account its social context. The Polish government intends to allocate approx. PLN 200 billion from the EU and national funds under various mechanisms—such as the Cohesion Policy, the Recovery and Resilience Facility, the Just Transition Fund, and the Modernisation Fund or the Energy Transformation Fund—for the country's energy and climate transition by 2030 [28].

The new EPP 2040 is supposed to provide a foundation for the creation of a modern, sustainable, low-carbon energy system in Poland and is based on three pillars [28]:

I. Just transition, including: transformation of coal regions, reduction of energy poverty, and new industries related to RES and nuclear power;
II. Zero-emission energy system, including offshore wind energy, nuclear power, and local and citizen-based power generation;
III. Good air quality, including transformation of the heating system, electrification of transport, and Climate-Friendly Homes.

The specific objectives of EPP 2040 cover the entire energy supply chain, from raw material acquisition to energy generation and supply (transmission and distribution) to its use and sale.

For environmental reasons, the cost-optimal structure of power sources presented in EPP 2040, in line with the government's analysis, includes nuclear power plants, whose development is limited due to organizational and technical constraints. The Energy Policy of Poland until 2030 envisages that there will be three nuclear units with a total net power of 4.5 GW (4.8 GW gross) in operation by 2030 [29]. Today, we already know that this objective will not be achieved, although work on the implementation of the Polish Nuclear Power Programme is underway. Currently, the government maintains that in 2033, the first unit of the first nuclear power plant with a capacity of approx. 1–1.6 GW will be commissioned in Poland, with six nuclear reactors with a total capacity of approx. 6.6 GW operating in Poland by 2045. The share of nuclear power plants in electricity production is set to be 9% in 2035, increasing to 16% in 2040 and to 23% in 2045 [30].

The new scenario for the energy sector until 2040, presented as part of the update of the Energy Policy of Poland, assumes the development of offshore wind farms at approx. 1 GW per year starting from 2025, with the achievement of 8–11 GW in 2040 (a 19% share in the structure of power generation in 2040). The inclusion of the offshore wind energy sector in the draft EPP 2040 and the adoption of the Act on offshore wind energy generation are an important signal for enterprises from the industry (investors and suppliers), confirming the importance of this sector for the country's energy strategy. Offshore wind energy has a huge potential for shaping social and economic benefits for the countries that support it [31]. In addition, it has been assumed that energy generated using photovoltaics would grow to 10–16 GW (at least 5% share in power generation) and the amount of energy generated by onshore wind farms to at least 6.9 GW (at least 11% share in power generation) by 2040 [22].

The draft version of the Poland's new energy strategy also provides for the development of energy storage technologies, smart metering, and energy management systems, and the development of electromobility and alternative fuels and hydrogen-based technology. Electromobility in Poland is currently on the rise, as can be seen both in the development of charging infrastructure for electric vehicles and in the number of these vehicles on Polish roads (year-to-year increase in the number of vehicles is between 1.56 and 2.50) [11,29].

The Energy Policy of Poland until 2040 adopted the following indicators as a measure of achievement of the objective [18]:

- No more than a 56% contribution of coal in power generation in 2030;
- At least 23% of RES in gross final energy consumption in 2030;
- Adoption of nuclear power in 2033;
- A 30% reduction in GHG emissions by 2030 (compared to 1990);
- A 23% reduction of primary energy consumption by 2030 (compared to the consumption forecasts from 2007).

2.3. The Energy System of the Future—Analysis of Social Expectations Based on Secondary Data

The results indicate massive public support for the growth of renewable energy production, a strong policy supporting renewable energy, increasing energy efficiency, and greater active involvement of the Polish government in the efforts to reduce emissions in order to avoid dangerous changes. At the same time, support for coal, nuclear power, and other fossil fuels is much lower (Figure 6).

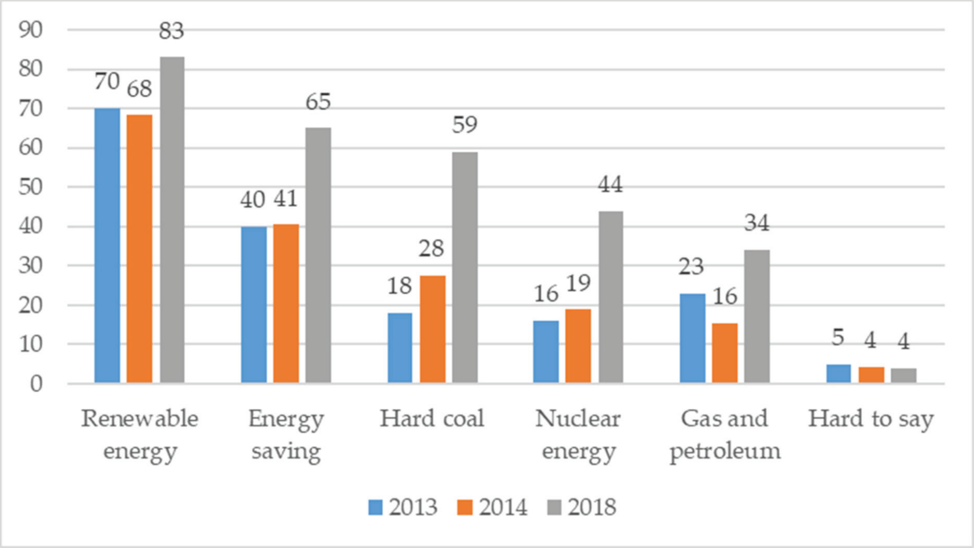

Figure 6. Type of energy that respondents believe should be developed in Poland in the near future (respondents could indicate two answers). Source: developed by the authors, based on Reference [32].

According to public opinion polls on RES carried out in Poland in 2015, one-third of the Poles knew about the existence of the RES Act, but only 7% were aware of what it addressed. A total of 11% of respondents were familiar with the term ‘prosumer’, but only 3% declared that they knew what exactly this term meant. The research also identified the investment potential of the Poles with regard to small RES installations. In 2015, 35% of respondents declared not only their support for the idea, but also their willingness to directly invest in RES, with 13% of respondents reporting willing to start using this technology within 2 years. At the same time, the percentage of those interested in the investment was significantly higher among those familiar with the RES Act (52%) and among those who felt informed about the possibilities of RES financing support (58%). Among those wishing to purchase RES installations, the main reason for such an investment was the willingness to reduce energy bills (over half of the respondents) and the possibility of enjoying cleaner air, as well as the convenience of using RES installations. Other reasons included the current opportunity of benefiting from subsidies, promotion of innovation or prestige, and improvement of one’s image due to the construction of such an installation [33].

Figure 7 summarizes the results of a survey of the opinions of Poles on various energy sources [32,34]. Solar and wind energy are definitely at the forefront of this summary—nearly 80% of respondents see their positive aspects. In that survey, conventional energy based on coal and nuclear sources enjoys the smallest support. The same study shows that in 2020, 75% of all respondents agree that the development of RES supports environmental protection and counteracts climate change. Slightly fewer, i.e., 70%, point to reduced dependence on energy imports and 68% of respondents say that it contributes to the creation of new jobs [34].

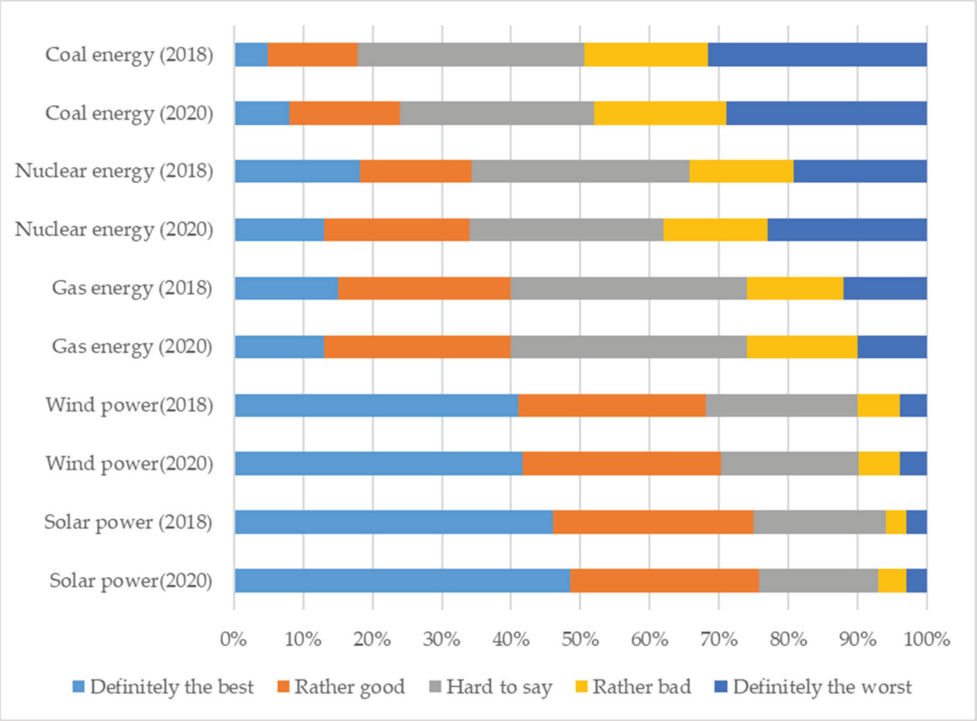

Figure 7. Comparative assessment of the different methods of power generation. Source: developed by the authors, based on References [32,34].

Despite the ambiguous dynamics of public support for RES initiatives, the declared level of support for pro-climate actions is relatively high and growing (Figure 8). In the 2018 social opinion polls [35], more than 80% of respondents agreed that Poland should support the European Union in its efforts to reduce carbon dioxide emissions. This percentage in 2018 was higher than in previous years. The results were similar for the question of whether Poland should support actions to help countries affected by the effects of climate change. At the same time, however, a significant number of people are concerned that Poland is too poor to afford special programs to combat climate change. In 2016, 48.9% of respondents thought so, while in 2018—37.3%. A significant proportion of respondents were also convinced that Poland's contribution to climate change was so low that its reduction would not significantly translate into global change. In 2016, 43.6% of respondents thought so, whereas in 2018 this percentage was lower, with only 37.3% of respondents saying 'yes'.

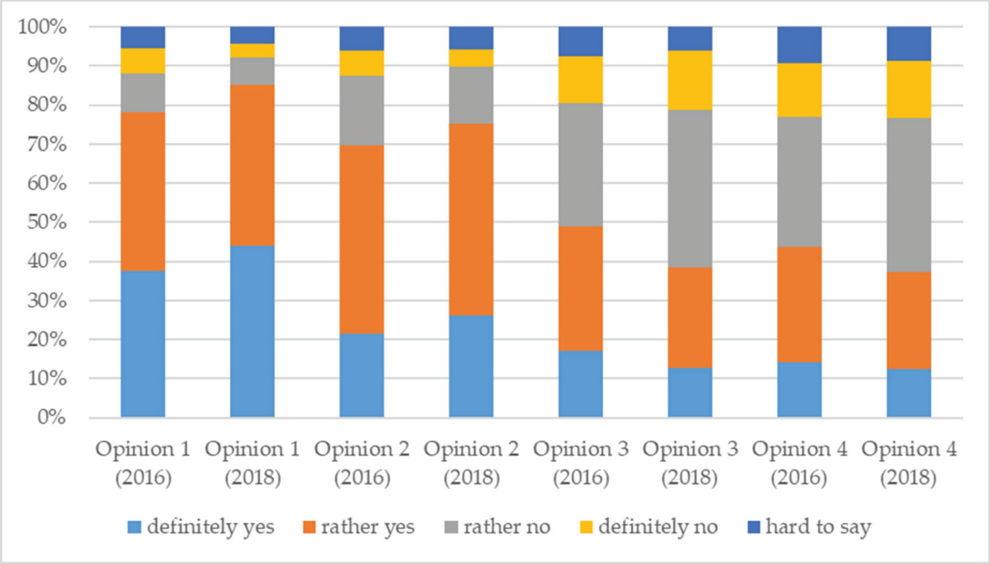

Figure 8. Support for the climate policy in Poland: Opinion 1: Poland should support the European Union in its efforts to reduce carbon dioxide emissions. Opinion 2: Poland should support actions to help countries that have been victims of climate change. Opinion 3: Poland is too poor to afford special programs aimed at combating climate change. Opinion 4: Poland's contribution to climate change is so small that the actions taken by Poland will change nothing. Source: developed by the authors, based on Reference [35].

3. Methods

The authors have used the diagnostic survey method and a critical literature review. This paper has been prepared based on the analysis of source materials such as documents and national and international regulations (in particular EU law), as well as secondary source data made available in reports prepared by energy sector entities, advisory companies, and research centers. To verify the results of the public opinion polls carried out in recent years, the available outcomes of these studies, conducted by renowned public opinion poll centers, were analyzed. The analysis seeks to answer the question of whether the energy policy implemented in Poland has met the expectations and how it has been received by the public, and to verify whether the research took into account opinions of local governments as the entities responsible for long-term anticipation of trends in the demand of the local community for fuels and energy.

The article analyzes the assumptions of the Energy Policy of Poland and changes in the Polish energy sector in recent years, in particular changes in the structure of power generation, based on reports published by Polskie Sieci Elektroenergetyczne S.A., a State-owned company, and then assesses the dynamics of these changes. Public expectations and opinions on energy policy are also analyzed using secondary data (reports on surveys conducted by leading marketing research agencies).

Due to the lack of information on the opinions of local governments in the available secondary data, which the authors deem a group of particular importance due to their contribution to the development of the energy policy—and energy security—at the local level, a survey was conducted in December 2020 involving a group of 274 respondents. The survey addressed current and general knowledge about the Energy Policy of Poland and the respondents' opinion on actions implemented by the local government, as well as the awareness of the needs and expectations of the local community. The respondents answered the questions in person (personal interview) or online.

4. Results

The study of the opinions of representatives of local government units was carried out in December 2020 in the form of a personal interview and an online survey. Answers were received from 274 respondents aged 28 to 62, most of whom were women (154, 56.30%). The age of the vast majority of respondents falls within the range of 36–45 years (111, 40.51%), followed by the range of 46–55 (84, 30.66%) and 23–35 years (68, 24.82%), with respondents aged 56–65 being the smallest group (11, 4.01%). No response was received from anyone aged over 65. The largest number of respondents represent urban municipalities [gmina miejska] (143, 52.19%), cities or towns with county rights [miasto na prawach powiatu] (60, 21.9%), or urban and rural municipalities [gmina miejsko-wiejska] (48, 17.52%), with rural municipalities being the least represented (23, 8.39%). Currently (as of 1 January 2021), Poland is divided into 16 voivodships, 314 poviats, and 2477 municipalities (302 urban municipalities, including 66 in cities or towns with county rights, 652 urban and rural municipalities, and 1523 rural municipalities) [36]. The feedback received covers 11% of all municipalities in Poland, including 47.35% urban municipalities, over 90% cities or towns with county rights, only 7.36% of urban and rural municipalities, and about 2% of rural municipalities.

Respondents were asked about their awareness of the Energy Policy of Poland until 2030. A total of 230 respondents said 'yes' (83.21%, of which 58.26% were residents from urban municipalities, 22.17% were from cities with country rights, 16.09% were from urban and rural municipalities, and 3.48% were from rural municipalities), while 44 responded said 'no' (16.06%, of which 20.45% were residents from urban municipalities, 20.45% were from cities with country rights, 25.00% were from urban and rural municipalities, and 34.09% were from rural municipalities). For the question for their knowledge of the EU climate and energy policy assumptions, 73 (26.64%) of respondents assessed their knowledge as very good, 43 (15.69%) as good, 87 (31.75%) as moderate, and 71 (25.91%) as poor (see Table 2 and Figure 9).

Table 2. Residents' knowledge of the EU climate and energy policy assumptions.

Place of Residence	Very Good	Good	Moderate	Poor	Total
Urban municipalities	53	19	51	20	143
Cities with country rights	12	16	17	15	60
Urban and rural municipalities	6	5	11	26	48
Rural Municipalities	2	3	8	10	23
Total	73	43	87	71	274

Source: Own Study.

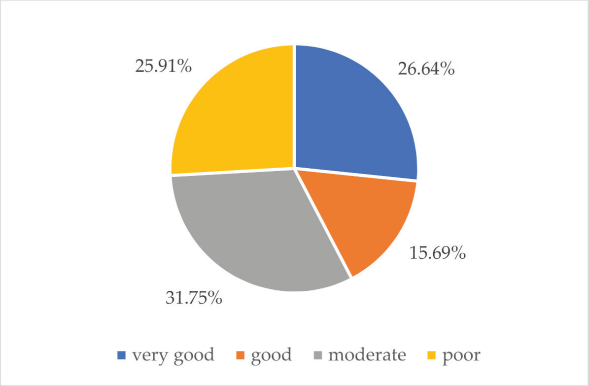

Figure 9. Knowledge of the EU climate and energy policy assumptions. Respondents could select only one answer. Source: own study.

Afterwards, respondents were also asked to assess their knowledge of the assumptions of the draft Energy Policy of Poland until 2040 (still in the project phase at the time of the survey). 63 respondents (22.99%) assessed their knowledge as very good, 85 (31.02%) moderate, and 71 (25.91%) poor. 55 (20.07%) respondents were not aware that the Energy Policy of Poland has been changing (see Table 3 and Figure 10).

Table 3. Residents' knowledge of the assumptions of the draft Energy Policy of Poland until 2040.

Place of Residence	Very Good	Moderate	Poor	Not Aware That the Energy Policy Has Been Changing	Total
Urban municipalities	38	54	41	10	143
Cities with country rights	21	18	10	11	60
Urban and rural municipalities	4	10	12	22	48
Rural Municipalities	0	3	8	12	23
Total	63	85	71	55	274

Source: Own Study.

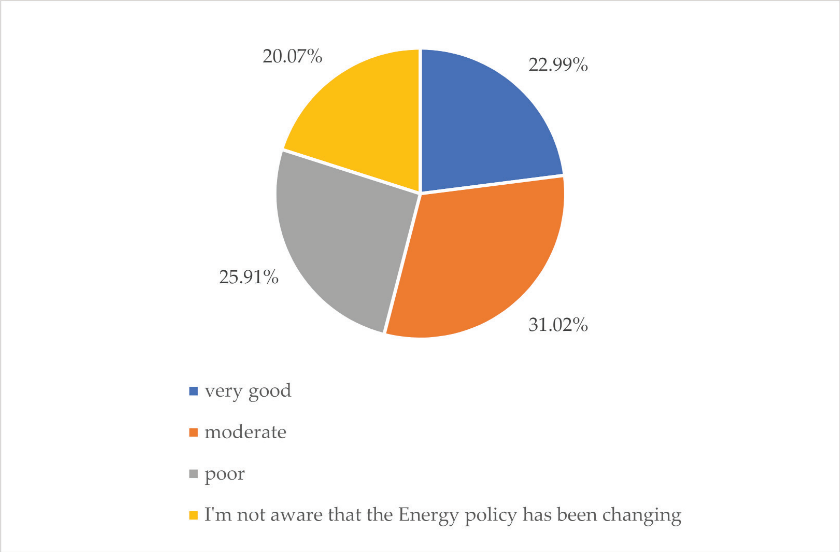

Figure 10. Knowledge of the assumptions of the Energy Policy of Poland until 2040. Respondents could select only one answer. Source: own study.

The respondents were also asked whether they knew what Poland's energy mix currently looks like, and their task was to tick the energy sources currently used in Poland (each respondent could select more than one answer). All respondents ticked hard coal (274, 100%) and almost all respondents (273, 99.64%) ticked lignite. A vast majority also ticked onshore wind energy (270, 98.54%), biogas (211, 77.01%), and biomass (194, 70.80%). A total of 150 (54.74%) respondents ticked gas and hydropower. Only 87 (31.75%) respondents selected photovoltaics and 67 (24.45%) ticked RES micro installations. Furthermore, 4 (1.46%) respondents ticked nuclear power, while 2 (0.73%) ticked offshore wind energy (see Figure 11).

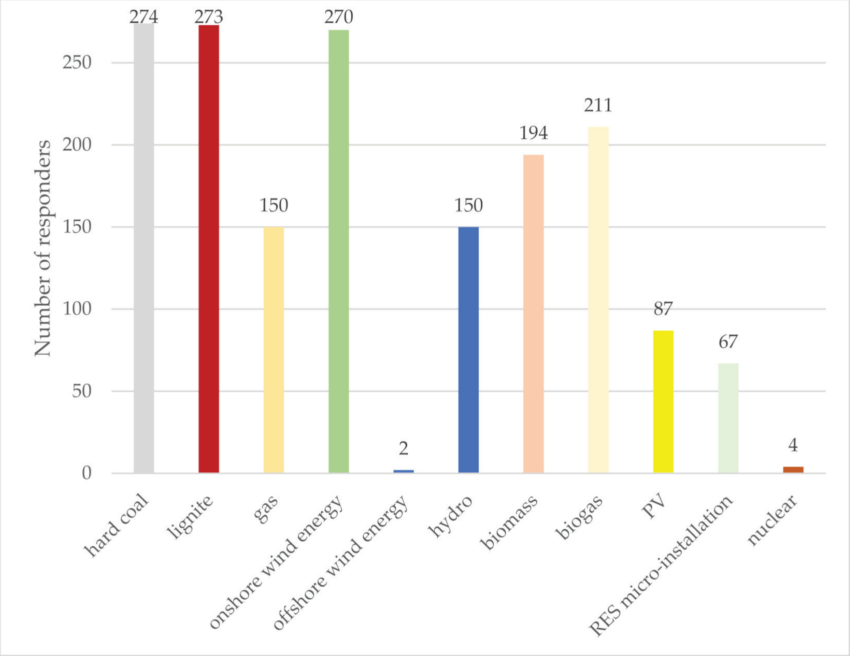

Figure 11. Energy sources currently used in Poland. Respondents could select more than one answer. Source: own study.

Respondents were also asked to express their opinion on what the optimal energy mix for Poland should look like, by indicating the relevant scenario (see Table 4 and Figure 12). Respondents could select only one answer. A total of 47 (18.29%) respondents indicated the scenario with a dominant role of RES, 45 (17%) respondents selected the scenario based mainly on coal, 15 (5.84%) opted for the scenario in which prosumers predominate, 10 (3.89%) indicated that the focus should be primarily on energy efficiency, and 5 (1.95%) selected the scenario based on nuclear power. A total of 118 (43%) respondents indicated that the optimal mix should be based on all previously indicated sources apart from nuclear power, while 34 (13.23%) were in favor of all previously indicated sources apart from RES.

Table 4. Residents' opinion on the optimal energy mix for Poland.

Place of Residence	Urban Municipalities	Cities with Country Rights	Urban and Rural Municipalities	Rural Municipalities	Total
Scenario based primary on coal	9	9	25	2	45
Scenario based solely on nuclear energy	0	3	2	0	5
Scenario based solely on RES	25	12	5	5	47
Scenario based solely on prosumer energy	9	5	1	0	15
Scenario based solely on energy efficiency	8	1	1	0	10
Coal, nuclear, prosumer, and energy efficiency scenario	15	14	5	0	34
Coal, RES, prosumer, and energy efficiency scenario	77	16	9	16	118
Total	143	60	48	23	274

Source: Own Study.

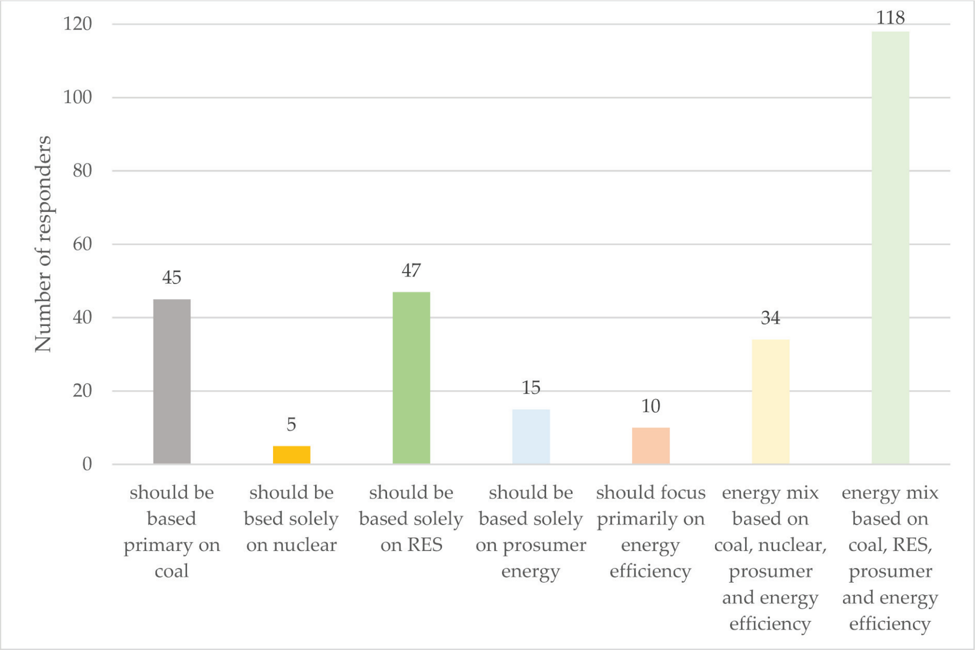

Figure 12. Opinion on the optimal energy mix for Poland. Respondents could select only one answer. Source: own study.

The respondents were also asked whether they knew what opinions the local community in their city/municipality had on the optimal energy mix (Figure 13). A total of 160 (58.39%, of which 41.25% were residents from urban municipalities, 25.63% were from cities with country rights, 23.75% were from urban and rural municipalities, and 9.38% were from rural municipalities) said yes, while 114 (41.61%, of which 67.54% were residents from urban municipalities, 16.67% were from cities with country rights, 8.77% were from urban and rural municipalities, and 7.02% were from rural municipalities) said no. Another question concerned the knowledge of the number of prosumers registered in the respondents' city/municipality (Figure 14). The vast majority (240, i.e., 87.59%, of which 59.17% were residents from urban municipalities, 24.17% were from cities with country rights, 15.42% were from urban and rural municipalities, and 1.25% were from rural municipalities) responded in the negative, while 34 respondents (12.41%, of which 2.94% were residents from urban municipalities, 5.88% were from cities with country rights, 32.35% were from urban and rural municipalities, and 58.82% were from rural municipalities) had knowledge on this figure. The respondents were also asked to say whether they had ever heard of energy cooperatives (Figure 15). A total of 150 respondents (54.74%, of which 42.67% were residents from urban municipalities, 27.33% were from cities with country rights, 20.00% were from urban and rural municipalities, and 10.00% were from rural municipalities) affirmed, while 124 (45.26%, of which 63.71% were residents from urban municipalities, 15.32% were from cities with country rights, 14.52% were from urban and rural municipalities, and 6.45% were from rural municipalities) had never heard of them.

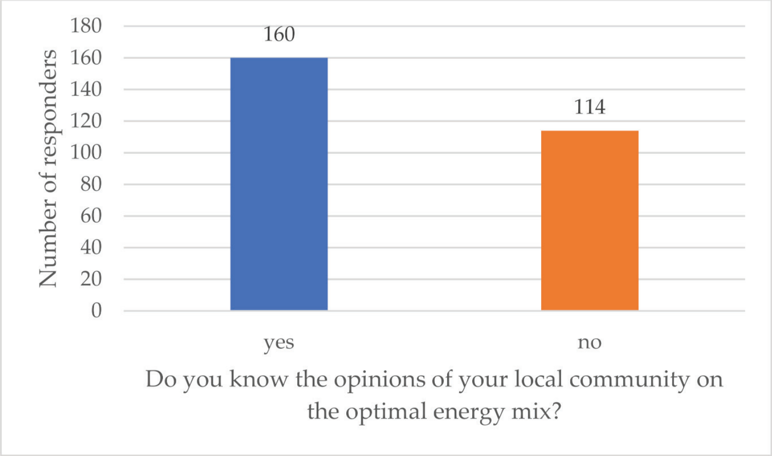

Figure 13. Knowledge of concepts and phenomena. Respondents could select only one answer—'yes' or 'no'. Source: own study.

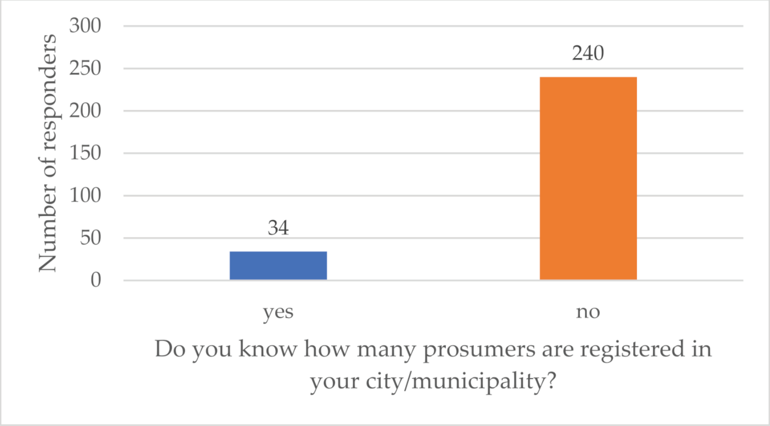

Figure 14. Knowledge of concepts and phenomena. Respondents could select only one answer—'yes' or 'no'. Source: own study.

Most respondents (112, 40.88%) had no concerns related to the implementation of EU climate and energy requirements in Poland (see Table 5 and Figure 16). A marginally smaller number of them (106, 38.69%) did have such concerns. A total of 56 respondents (20.44%) had no opinion on this.

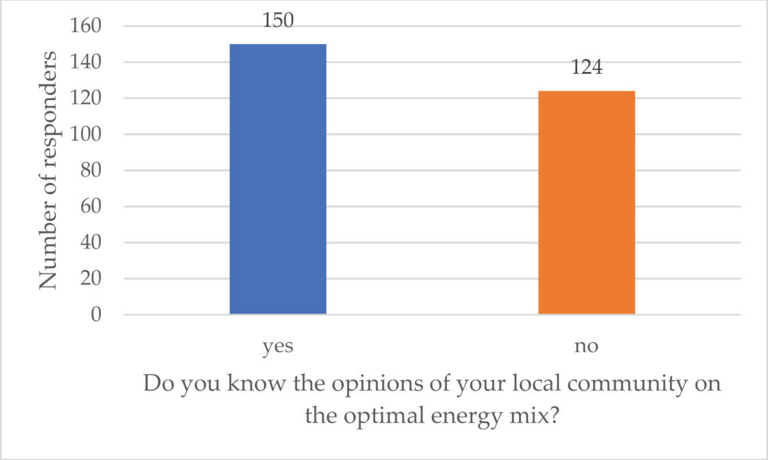

Figure 15. Knowledge of concepts and phenomena. Respondents could select only one answer—'yes' or 'no'. a—do you know the opinions of your local community on the optimal energy mix, b—do you know how many prosumers are registered in your city/municipality, c—have you heard the term 'energy cooperative'. Source: own study.

Table 5. Residents' concerns related to the implementation of EU climate and energy requirements in Poland.

Place of Residence	Yes	No	No Opinion	Total
Urban municipalities	35	80	28	143
Cities with country rights	35	4	21	60
Urban and rural municipalities	20	23	5	48
Rural Municipalities	16	5	2	23
Total	106	112	56	274

Source: Own Study.

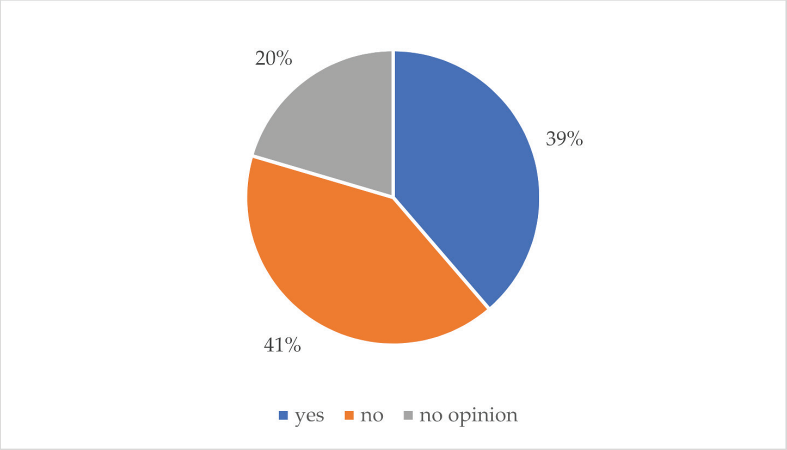

Figure 16. Concerns related to the implementation of EU climate and energy requirements in Poland. Respondents could select only one answer. Source: own study.

5. Discussion and Conclusions

Transformation of the energy sector in Poland is a current topic that has been developing before our very eyes. Both the Polish government and its citizens recognize the need to change the structure of power generation in Poland, and the path taken by the recently adopted draft Energy Policy of Poland until 2040 coincides with the expectations of Poles.

The authors made an attempt to check the development of the energy sector in Poland and verify the public opinion on the energy policy implemented in Poland. The authors also decided to check whether the available public opinion research include the expectations and knowledge of representatives of local governments, as a group particularly relevant from the point of view of their role in shaping energy policy and energy security at the local level.

The analysis of secondary data shows that the support for the European climate and energy policy among Poles is on the rise, as is the support for clean power such as solar and wind energy. There has been a slight decrease in the support for nuclear power, which may be due to the lack of a clear and consistent action plan and results. Social expectations are in line with the shape of the updated energy policy. As shown in [32–34], renewable energy sources, mainly wind and photovoltaics, are seen as the best ways of generating energy. Additionally, our own research showed that the optimal energy mix for Poland is expected to be based on RES or on RES together with prosumer initiatives and energy efficiency actions. This corresponds with the new goals of the energy policy in Poland, assuming no more than 56% of coal in power generation in 2030, at least 23% of RES in gross final energy consumption in 2030 a 30% reduction in GHG emissions by 2030 (compared to 1990).

Taking into account the information obtained in the survey, a majority of respondents have a moderate or low level of knowledge of the EU climate and energy package or the assumptions of the Energy Policy of Poland until 2040. At the same time, the vast majority of respondents know the assumptions of the Polish energy policy until 2030, but almost a quarter did not realize that the energy policy will be changed in the near future. According to the authors, the vast majority of respondents from this group come from rural areas, which may constitute a major barrier to initiatives taken by local governments or to the shaping of the local strategy for sustainable development due to the lack of knowledge of strategic paths for the development of the energy sector. The vast majority of respondents believe that the Polish government should prepare an awareness-raising campaign related to its energy policy and train local governments in this regard. The majority of respondents declare knowledge of the opinion of the local communities they represent—nearly 60% of them know their community's views on the optimal energy mix. It is worth emphasizing that 65% of the respondents from rural areas know the views of local communities. This shows that local governments in urban areas should take measures to better understand local communities and learn about their views on the preferred shape of energy policy. Given the current trends in the development of prosumer energy and support of the Polish government for the creation of energy cooperatives, it is also positive that a vast majority of respondents have heard of energy cooperatives. However, the lack of knowledge about the number of micro installations operating in a given city/municipality is unfavorable. The survey also showed preferences of representatives of local governments for the optimal energy mix in Poland and their subjective assessment of the knowledge of public opinion in the region on the expected shape of the energy policy. From the findings, it can be concluded that more in-depth research is needed on the preparation of local governments to shape energy policy at the local level, including more detailed research on how opinions of the inhabitants of a given region and the specificity of a given region are taking into account while shaping local energy policy.

Many local governments see RES as an opportunity for the development of their own region. The analysis of sectoral statistical data shows that both the share of renewable energy sources in the structure of power generation and the number of micro installations or prosumers have been gradually increasing, in line with the expectations of the public, as confirmed by the mentioned secondary research and the survey carried out by the authors.

This has a positive impact on energy security, also at the local level, and in the long term, it will reduce the adverse environmental impacts of the energy sector. It is known that caring for the natural environment is gaining importance because ecological products are available, the consumption and processing of plastic is reduced, and the waste segregation process is implemented. To help nature, the use of renewable energy sources is also being developed, i.e., those based on natural and inexhaustible resources. The developed methods of obtaining them guarantee not only emission-free electricity production, but also endless possibilities of its use. However, it should be noted that it will be very difficult to achieve a dominant role of RES in the power generation structure in Poland—not only due to the persisting belief of some citizens in the infinity of conventional resources, but mainly due to major technological, financial, or legal barriers. With growing adoption of RES technology in Poland, legal barriers are gradually reduced by the government, an example of which is the adoption of the Act on offshore wind energy generation in early 2021, which is expected to give impetus to the Polish renewable energy industry and form a part of Poland's energy security system.

A review of the literature, in particular of the conducted research on social acceptance in terms of energy policy, showed that there are no comprehensive surveys of the opinions of local government representatives. The authors point to the great role and responsibility of the local government in the context of building local energy strategies based on locally available energy resources, knowledge resources, and the level of activity of local communities. There is no in-depth research in Poland that would show not only the opinion of local government representatives, but also the existence and main assumptions of local energy strategies, as well as the way of creating these strategies. The survey showed that representatives of local governments, who mostly assess their knowledge of the EU's energy and climate policies as moderate or poor (the vast majority of respondents with poor knowledge come from rural areas), are not fully prepared to create energy plans for their regions. The authors emphasize, however, that for a thorough examination of this issue, a study covering a much larger research group and a wider range of issues is necessary. The authors also emphasize the importance of shaping conscious attitudes in the local government environment, as well as building knowledge and skills and constantly improving the competences of local government employees in the field of energy policy and sustainable development.

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References

1. Forum for Energy Analysis 2016. Polish Power Sector Riding on the Wave of Megatrends. Available online: https://forum-energii.eu/en/analizy/1-2 (accessed on 12 February 2021).
2. Berkenkamp, M.; Götz, P.; Heddrich, M.; Lenck, T. *Integration of European Energy Market. Poland and Baltic Sea Region (Integracja Europejskiego Rynku Energii. Polska i Region Morza Bałtyckiego)*; Advise2Energy: Frankfurt, Germany; Berlin, Germany, 2016.
3. Urząd Regulacji Energetyki. *Information on Investment Plans for New Generation Capacity in the Years 2018–2032 (Informacja na Temat Planów Inwestycyjnych w Nowe Moce Wytwórcze w Latach 2018–2032)*; Urząd Regulacji Energetyki: Warszawa, Poland, 2019; 14p. Available online: https://www.ure.gov.pl/pl/urzad/informacje-ogolne/publikacje/raport-plany-inwestycyj/8068,Raport-Plany-inwestycyjne-w-nowe-moce-wytworcze.html (accessed on 15 June 2020). (In Polish)

4. Polski Komitet Energii Elektrycznej (PKEE). *Capacity Market—How to Avoid Blackout. Analysis of the Legitimacy of Using the Comprehensive Application of the Capacity Market in Poland (Rynek Mocy Czyli Jak Uniknąć Blackoutu. Analiza Zasadności Wdrożenia Kompleksowego Mechanizmu Rynku Mocy w Polsce)*; PKEE: Warszawa, Poland, 2016; 44p. Available online: https://www.cire.pl/pokaz-pdf-%252Fpliki%252F2%252F2016%252Frynekmocy.pdf (accessed on 15 January 2021). (In Polish)
5. International Energy Agency. World Energy Outlook 2020. Available online: https://www.iea.org/reports/world-energy-outlook-2020 (accessed on 10 January 2021).
6. Drożdż, W.; Kurtyka, M. *Introduction: W: Red. Energy of Modern Cities*; PWN: Warsaw, Poland, 2021.
7. Caramizaru, E.; Uihlein, A. *Energy Communities: An Overview of Energy and Social Innovation*; Publications Office of the European Union: Luxembourg, 2020. Available online: https://publications.jrc.ec.europa.eu/repository/handle/JRC119433 (accessed on 15 January 2021).
8. Mróz-Malik, O.; Kopiczko, M. The role of electric vehicles in the future low-carbon energy system (Warszawa, 2021). In *Electromoblity as a Megatrend in National Economies*; PWN: Warszawa, Poland, 2021; pp. 143–158. (In English)
9. Drożdż, W.; Bilan, Y.; Kasperowicz, R.; Streimikiene, D.; Rabe, M. Sustainable regional energy planning: The case of hydro. *Sustain. Dev.* **2020**, *28*, 1652–1662. Available online: https://onlinelibrary.wiley.com/doi/epdf/10.1002/sd.2114 (accessed on 12 January 2021).
10. European Commission. Staff Working Document Impact Assessment Accompanying the Document Proposal for a Directive of the European Parliament and of the Council on the Promotion of the Use of Energy from Renewable Sources (Recast). 2016. Available online: https://ec.europa.eu/transparency/regdoc/rep/10102/2016/EN/SWD-2016-418-F1-EN-MAIN-PART-2.PDF (accessed on 25 January 2021).
11. Kampman, B.; Blommerde, J.; Maarten, A. *The Potential of Energy Citizens in the European Union*; CE Delft: Delft, The Netherlands, 2016; Available online: https://www.cedelft.eu/publicatie/the_potential_of_energy_citizens_in_the_european_union/1845 (accessed on 3 March 2021).
12. Polskie Sieci Elektroenergetyczne—Raport Roczny z Funkcjonowania KSE za Rok 2019. Available online: https://www.pse.pl/dane-systemowe/funkcjonowanie-rb/raporty-roczne-z-funkcjonowania-kse-za-rok/raporty-za-rok-2019#t1_1 (accessed on 2 January 2021).
13. The Polish Wind Energy Association. The State of Wind Energy in Poland in 2016. 2017. Available online: http://psew.pl/wp-content/uploads/2017/06/Stan-energetyki-wiatrowej-w-Polsce-w-2016-r.pdf (accessed on 12 February 2021).
14. Wind Energy in Europe 2020 Statistics and the outlook for 2021–2025. WindEurope 2021. Available online: https://windeurope.org/intelligence-platform/product/wind-energy-in-europe-in-2020-trends-and-statistics/ (accessed on 4 March 2021).
15. Urząd Regulacji Energetyki. Potencjał Krajowy OZE. Available online: https://www.ure.gov.pl/pl/oze/potencjal-krajowy-oze/5753,Moc-zainstalowana-MW.html (accessed on 14 January 2021).
16. Renewable Energy in Poland, Flanders Investment & Trade, June 2019. Available online: https://www.flandersinvestmentandtrade.com/export/sites/trade/files/market_studies/2019-Poland-Renewable_Energy.pdf (accessed on 10 January 2021).
17. Ustawa z Dnia 20 Lutego 2015 r. o Odnawialnych Źródłach Energii (Dz.U. 2015 Poz. 478). Available online: http://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20150000478 (accessed on 12 January 2021).
18. Raport Prezesa URE Zawierający Zbiorcze Informacje Dotyczące Energii Elektrycznej Wytworzonej z Odnawialnego Źródła Energii w Mikroinstalacji (w Tym Przez Prosumentów) i Wprowadzonej do Sieci Dystrybucyjnej w 2020 r. (art. 6a Ustawy OZE). Available online: https://bip.ure.gov.pl/bip/o-urzedzie/zadania-prezesa-ure/raport-oze-art-6a-ustaw/3793,Raport-dotyczacy-energii-elektrycznej-wytworzonej-z-OZE-w-mikroinstalacji-i-wpro.html (accessed on 20 March 2021).
19. Raport Prezesa URE Zawierający Zbiorcze Informacje Dotyczące Energii Elektrycznej Wytworzonej z Odnawialnego Źródła Energii w Mikroinstalacji (w Tym Przez Prosumentów) i Wprowadzonej do Sieci Dystrybucyjnej w 2019 r. (art. 6a Ustawy OZE). Available online: https://bip.ure.gov.pl/bip/o-urzedzie/zadania-prezesa-ure/raport-oze-art-6a-ustaw/3793,Raport-dotyczacy-energii-elektrycznej-wytworzonej-z-OZE-w-mikroinstalacji-i-wpro.html (accessed on 20 February 2021).
20. Raport Prezesa URE Zawierający Zbiorcze Informacje Dotyczące Energii Elektrycznej Wytworzonej z Odnawialnego Źródła Energii w Mikroinstalacji (w Tym Przez Prosumentów) i Wprowadzonej do Sieci Dystrybucyjnej w 2018 r. (art. 6a Ustawy OZE). Available online: https://bip.ure.gov.pl/bip/o-urzedzie/zadania-prezesa-ure/raport-oze-art-6a-ustaw/3793,Raport-dotyczacy-energii-elektrycznej-wytworzonej-z-OZE-w-mikroinstalacji-i-wpro.html (accessed on 20 February 2021).
21. Wytwarzanie Energii Elektrycznej w Polsce w Małych Instalacjach OZE. Raport Prezesa URE za 2019 Rok (Podstawa Prawna: Art. 17 Ustawy Odnawialnych Źródłach Energii). Warszawa. 2020. Available online: https://bip.ure.gov.pl/bip/o-urzedzie/zadania-prezesa-ure/raport-oze-art-17-ustaw/3556,Raport-zbiorcze-informacje-dotyczace-wytwarzania-energii-elektrycznej-z-odnawial.html (accessed on 12 February 2021).
22. Ministry of Climate and Environment. Available online: https://www.gov.pl/web/klimat/projekt-polityki-energetycznej-polski-do-2040-r (accessed on 12 December 2020).
23. Report on the Polish Power System. Version 2.0. Country Profile, Agora Energiewende. 2018. Available online: https://www.agora-energiewende.de/en/publications/report-on-the-polish-power-system-2018/ (accessed on 2 February 2021).
24. Energy Policy of Poland until 2030. Available online: https://www.iea.org/policies/325-polish-energy-policy-until-2030 (accessed on 12 December 2020).
25. Prognoza Zapotrzebowania na Paliwa i Energię Do 2030 Roku. Available online: https://www.gov.pl/web/klimat/polityka-energetyczna-polski-do-2030-roku (accessed on 10 December 2020).

26. European Commission. Climate Action—2020 Climate & Energy Package. Available online: https://ec.europa.eu/clima/policies/strategies/2020_en (accessed on 12 December 2020).
27. National Energy and Climate Plan for the Years 2021–2030. Available online: https://www.gov.pl/web/klimat/national-energy-and-climate-plan-for-the-years-2021-2030 (accessed on 20 January 2021).
28. Projekt Polityki Energetycznej Polski Do Roku 2040. Available online: https://www.gov.pl/web/klimat/polityka-energetyczna-polski (accessed on 15 January 2021).
29. Drożdż, W.; Szczerba, P.; Kruszyński, D. Issues related to the development of electromobility from the point of view of Polish utilities. *Polityka Energetyczna Energy Policy J.* **2020**, *23*, 49–64. [CrossRef]
30. Program Polskiej Energetyki Jądrowej. Available online: https://www.gov.pl/web/polski-atom/program-polskiej-energetyki-jadrowej-2020-r (accessed on 2 January 2021).
31. Drożdż, W.; Mróz-Malik, O.J. Challenges for the Polish energy policy in the field of offshore wind energy development. *Polityka Energetyczna Energy Policy J.* **2020**, *23*, 5–18. [CrossRef]
32. Badanie Opinii Polaków Na Temat Różnych Źródeł Energii. Indicatior 2018. Available online: http://psew.pl/wp-content/uploads/2020/01/Badanie-opinii-Polak%C3%B3w-nt.-r%C3%B3%C5%BCnych-%C5%BAr%C3%B3de%C5%82-energii-Indicator.pdf (accessed on 12 November 2020).
33. Co Polacy Sądzą o OZE. Badanie TNS Polska. Available online: https://www.gramwzielone.pl/trendy/20081/co-polacy-sadza-o-oze-badanie-tns-polska (accessed on 8 November 2020).
34. Badanie Opinii Polaków Na Temat Różnych Źródeł Energii. Indicator 2020. Available online: https://stowarzyszeniepv.pl/2020/05/10/badanie-opinii-polakow-na-temat-roznych-zrodel-energii/ (accessed on 12 November 2020).
35. Wójcik, A.; Byrka, K. Raport z Badań Opinii Społecznej Dotyczącej Energetyki w Polsce. Energia od Nowa 2018. Available online: https://energiaodnowa.wwf.pl/wp-content/uploads/2019/04/RAPORT-Z-BADAN-SONDAZOWYCH-OPINII-SPOLECZNEJ-DOTYCZACEJ-ENERGETYKI-W-POLSCE-luty-2018.pdf (accessed on 13 November 2020).
36. Website of the Ministry of Internal Affairs and Administration; Database of Local Government Units. Available online: http://administracja.mswia.gov.pl/adm/baza-jst/843,Samorzad-terytorialny-w-Polsce.html (accessed on 11 October 2020).

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The Impact of COVID-19 on Electricity Demand Profiles: A Case Study of Selected Business Clients in Poland

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Abstract: The COVID-19 pandemic has caused changes in electricity demand and, consequently, electricity consumption profiles. Given the rapid changes in energy prices, it is significant from the perspective of energy companies, and forecasting consumed energy volume. A necessity for accurate energy volume planning forces the need for analyzing consumers' behaviors during the pandemic, especially under lockdowns, to prepare for the possibility of another pandemic wave. Many business clients analyzed in the paper are economic entities functioning in sectors under restrictions. That is why analyzing the pandemic's impact on the change in energy consumption profiles and volume of these entities is particularly meaningful. The article analyzes the pandemic and restrictions' impact on the total change of energy consumption volume and demand profiles. The analysis was conducted basing on data collected from a Polish energy trading and sales company. It focused on the energy consumption of its corporate clients. Analyzed data included aggregated energy consumption volumes for all company's customers and key groups of economic entities under restrictions. The analysis demonstrates the influence of pandemic restrictions on energy consumption in the group of business clients. Significant differences are observable among various sectors of the economy. The research proves that the largest drops in energy consumption are related to shopping centers and offices. Altogether, the restrictions have caused a 15–23% energy consumption drop during the first lockdown and a maximum 11% during the second against expected values.

Keywords: COVID-19 pandemic; lockdown; electricity demand profiles; energy consumption

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1. Introduction

The outbreak of the COVID-19 pandemic in 2020 was unexpected and began many new challenges for the global and national economies [1]. The situation has significantly impacted numerous industries, including production, agriculture, transport, financial services, education, and healthcare [2]. Some of its consequences were changes in the electricity demand profiles of consumers representing various branches of the economy. Has the situation significantly impacted the energy sector, in which the correct forecasting of electricity consumption is one of the key factors guaranteeing power plants' stability works and continuous financial income? It concerns energy production, transfer, and supply [3,4]. The International Energy Agency (IEA) indicates that the change in energy demand in 2020 was the largest in the last 70 years. In 2020, the pandemic decreased the global GDP by 4.4%. This value was significantly higher than the GDP decrease of 2009 (0.1%) that resulted from the global economic crisis. Forecasts indicate that in 2021, global production will recover to the level of 2019 due to an economic boom in large developing countries, particularly China and India. However, it is expected that developed economies will not recover to the levels they had before the pandemic [5]. During the pandemic, in most countries, demand for electricity supply decreased significantly. It results in large uncertainty for all energy companies in the world. The pandemic makes predicting the situation's development impossible. Because of the lockdowns, limiting many life, economy, construction, and production activities decreased global demand for energy. Undeniably, the decrease has caused damage to the energy industry, which, in consequence, led at least nineteen American energy companies to bankruptcy [6].

Because of how the virus spreads, the main way to fight against it was to limit human interactions locally and globally. Depending on the country, the level of restrictions was related to an adopted strategy of fight against the pandemic and infection numbers [7]. One should pay attention to governments introducing restrictions undoubtedly influencing electricity consumption by consumers in many sectors. Unquestionably, politicians making decisions had taken energy security and the necessity for maintaining some economic sectors into account before restrictions were implemented. However, they did not know forecasts of possible consequences. Introducing restrictions usually had far-reaching consequences for energy companies. The lack of scenarios of restrictions' influence on energy consumption was significant in production planning and energy transfer organizing. However, the most severe consequences were observable in the electricity trade.

Introducing the first lockdown in March 2020 to respond to the SARS-CoV-2 spread was an entirely new situation for individual and business electricity consumers. In consequence, freezing many branches of the economy has led to considerable decreases in the first half of 2020 energy consumption. Compared to May 2019, energy consumption in 2020 was 8% lower [8].

Gradual unfreezing of the economy in the second half of 2020 caused successive equalization of energy consumption levels compared with the previous year. Sometimes, it was even higher than the year before. The rapid increase in 2020 energy consumption occurred in September. New restrictions of October–November 2020 did not change the increasing trend. At the beginning of December 2020, the electricity consumption level was circa (ca.) 14.5 TWh, 200 GWh more than in December 2019 [9,10].

In this context, it is essential to learn how to operate in case of a crisis. It is necessary to consider and adjust to aspects of a crisis and restrictions imposed by law. More than that, there is a need to be aware that a similar situation may happen again. It may refer to possible waves of the pandemic as well as other crises potentially impacting energy consumption for different hours, situations, and various branches of the economy. The energy sector has to be prepared for such situations. That is why an analysis of electricity consumption profiles is an absolute necessity. Uncertainty also impacts investment decisions in the energy sector, which is another reason behind the need for analysis [11,12].

As mentioned, the energy sector situation was disturbing for energy trading companies that carry out transactions on the stock exchange [13,14]. Electricity prices on the commodity market are conditioned mostly by production and environmental costs [15]. They are also strongly related to fuel prices, in Poland, it still is coal [16].

Given the energy prices fluctuation on the wholesale market, an accurate forecast is essential for energy trading and sales companies [17,18]. An adequate assessment of energy demand in particular hours of the day allows for correcting a contract position at the right time, maximizing the company's benefits, and minimizing its losses [19]. A key challenge from the perspective of energy trading companies was the changes in the consumption schedules and deviations in consumers' profiles. That is why the analysis of consumed energy volumes may enable an appropriate reaction to adopt accurate coefficients correcting consumption schedules, dependent on imposed restrictions.

The article analyzes energy consumption by a particular group of customers of a national energy trading and sales company. The research is focused on the restrictions' impact on the changes in electricity consumption volumes. Results were obtained through measurements taken during the lockdowns (the periods of limited mobility and activity of society) and compared with values obtained in the comparable period in 2019 and before the pandemic. The analysis concerns the total electricity consumption volumes and energy consumption profiles of clients from the key sectors. Besides the comparative analysis of energy consumption in 2019 and 2020, the article employs basic statistical measurements for the volatility analysis. Furthermore, the study includes the assessment of the ratio of expected to actual energy consumption based on trends from before the pandemic.

The remainder is organized as follows. Section 2 presents a review of current research on the influence of the COVID-19 pandemic on the energetic sector. Section 3 presents the schedule of introducing and lifting restrictions by the Polish government in 2020. Section 4 includes computing methodology. Section 5 includes results. Section 6 presents a discussion and the most important conclusions.

2. Literature Review

Undoubtedly, demand for electricity radically decreased during the lockdowns because governments have forced isolation and implemented numerous limitations on movement and transport. Consequently, the load structure and its daily profile have also changed, which was incredibly difficult for energy producers and sellers to balance. Changes have also been visible in national energy mixes. The share of energy produced from renewable resources has increased, while the total production of electricity has decreased [20]. The new situation in the balance of power and the increased uncertainty of demand have put pressure on system operators and caused problems with maintaining voltage in the power grid and other challenges for system management [21]. Thus, the pandemic has generated unprecedented distortions in almost every element of the energy market. In [22], it was proven that data on electricity markets with high granularity and frequency might be used for the causal estimation of the COVID-19 pandemic's short-term influence on the economy by delivering information important for future lockdown politics [22].

The pandemic's impact on the European electricity markets has been immense, especially in countries with rich energy supplies and nearly non-existent marginal production costs, such as France. The author of [23] presented the quantitative assessment of the crisis's influence on the French electro-energetic sector. During the lockdown, France experienced an unprecedented decrease in demand (−11.5%) and energy prices decline (−40%), which caused losses for the market participants estimated at 1.2 bln € (−45%) [23]. The COVID-19 pandemic's impact was also visible in decreasing GDP. For example, in Italy, it decreased about 30% [22]. The change in primary energy consumption in 20 European countries with the highest GDP was also discussed in [24].

In 2020, the only huge economy with a higher demand for electricity was China. However, the 2% increase was much lower than the values from previous years of about 6.5%. The other main electricity consumers, including the United States, India, Europe, Japan, South Korea, and South-Eastern Asia, noted a decrease in the scale of the whole year [1].

Nearly 42% of global demand for electricity is generated by industry and 22% by commercial and public services. That is why economic activity and electricity consumption are tightly related. In developed economies, the share of these sectors is more or less equal, about 32%. In developing countries dominated by industry, this sector needs about half of the final demand, while services use about 14% [5].

An accurate assessment of energy demand fluctuation based on constantly updated data is urgently required to analyze changes in the energy sector, production planning, and energy transportation. It is because investments and global energy supply chains have been distorted [25]. Load curves, especially electricity consumption peaks, have also changed. Noticeable changes in demand (consumption) in the macro- and microeconomic levels presented in the body of literature include:

1. Short-term demand decreases when the restrictions are introduced [26], but it is expected that demand will gradually recover after lifting them [27].

2. The peak of electricity demand changes. Studies based on electricity consumption in Canada indicate that the highest demand before the pandemic was in the second half of the week (from Wednesday to Friday), while after the pandemic, it has been observed at the week's beginning (from Monday to Tuesday) [28].
3. Demand for electricity decreases in the morning peak [29].
4. A change in society's behavior is visible, e.g., in using public transport. A total of 56.3% of respondents have limited its usage during and after the COVID-19 pandemic [30].
5. Demand for electricity decreases in industry and commerce but increases in households [10].

In the body of literature, there are studies of the impact of the pandemic on electricity consumption in various groups of end-consumers based on real measurements. Such research was conducted among households' inhabitants, an important group of consumers, who have changed electricity demand during the pandemic [31]. Other similar works present studies of the COVID-19 pandemic's influence on household electricity consumption in China [32], Spain [33], and Canada [34].

The other analyzed sector was healthcare. In these studies, authors review various changes in healthcare in different countries and their impact on the energy sector and environment. They present conclusions on the impact of the COVID-19 pandemic on these three sectors regarding climate change and the change in environmental emissions to which also healthcare has contributed [35].

Undoubtedly, new practices and social behaviors acquired during the pandemic influenced the need for electricity and its consumption. It has been proven that even though general demand for electricity during the pandemic decreases, quantitative and time differences are complex, and the return to usual consumption in various regions is not equivalent [36].

Studies demonstrate that the pandemic has had a particular effect on commerce. Analyses of the retail trade indicate that in March and April 2020, the highest decreases in the European Union countries were noted for gasoline and commodities bought in department stores and shopping malls. The situation stabilized in June 2020. The second period of decrease was observed from November 2020 to January 2021 [37].

Studies [5,27] indicate that changes in electricity consumption were independent of the region and the highest in commerce and services. The only difference was a period in which they occurred: the first quarter of 2020—China; the second quarter of 2020—Argentina (South America), Spain, and the United Kingdom (Europe); the second and the third quarter of 2020—the US (North America). Only in South America, the changes were also observed in the industry. Studies demonstrate that in the sector of households, significant changes in energy consumption were not noted in the analyzed regions.

Data presented in the European Parliament's report indicate that differences in the functioning of various industries were significant, which was another reason behind the change in their energy consumption. In EU countries, the results of the pandemic were primarily felt in the digital and healthcare sectors. The chemical industry, construction, and food production now go out of the crisis, which is best represented by the "V" curve, they recover to the production level before the pandemic. The automotive and textile industries are in a similar situation. Despite decreases, they are now recovering their positions before the first lockdowns. Sectors dependent on direct contact and human interactions, such as culture, environment, and air transport, have suffered from the crisis the most. They will be coping with its consequences for a long time. However, it has been proved that the pandemic increased the awareness of the benefits of digital and ecological transformation, which have to be associated with respective political investments and motivations [38].

Studies also indicate that from the perspective of the energy sector, the most direct consequences concerned the levels of power consumption, production mix structure, and electricity market price. Electricity consumption decreased by 15% in relation to previous years, and one could observe changing energy demand profiles in the states that introduced more rigorous restrictions than others, e.g., Italy, France, and Germany. In the states with less rigorous limitations (e.g., Sweden), significant changes in energy consumption were not noted [39]. In the context of the pandemic's influence on energy companies' functioning, particular attention deserves studies concerning the companies' financial outcomes [40]. Authors in [41] demonstrated that even though the lockdowns decreased mean energy prices in Italy by 45%, the transmission costs increased by 73% for the analogous period from the previous years. Thus, investments in power grids and the development of demand management technology are indispensable. Simultaneously, the growing share of renewable energy sources may increase the costs of maintaining a reliable power grid [42]. The COVID-19 pandemic has negatively influenced energy production, causing a rapid drop in income. Companies did not regulate fixed costs and expenses, which led them to lose value [43]. As mentioned in the introduction, some were even forced to declare bankruptcy [6].

The number of works evaluating the impact of restrictions on energy consumption from the perspective of an energy trading and sales company, which produces, distributes, and sells energy, is still very low. Such studies were conducted in the context of the possibility of implementing additional enhancements to energy consumption forecasting tools [44,45]. Understanding the changes in electricity demand and their influence on forecasting consumption is essential for maintaining reliable power grid operation and realizing tasks of energy trading companies with the best possible financial outcome. The change of consumers' behavior during the pandemic negatively impacts the predictability of demand schedules, which is critical for energy trading companies.

3. The Pandemic in Poland—A Course (Chronology)

In Poland, the first restrictions resulting from the COVID-19 pandemic were introduced by the Regulation of the Minister of Health on the Announcement of the State of Epidemic Emergency on the Territory of the Republic of Poland dated 13 March 2020. In practice, the state of the epidemic has been functional in Poland since 20 March 2020, after amending the announcement [46].

The regulation issued on 13 March introduced restrictions related to the functioning of many activities. The list of restricted entities was provided in the regulation following the Polish Classification of Activity. The restrictions introduced in the first period were gradually tightened. Since 25 March, there was a ban on movement except for strictly defined cases. April 1 introduced a ban on the operation of cosmetic and hairdressing salons and additional limitations to commerce. Lifting them began on 20 April, though their first effects were visible on 4 May. Eventually, the first stage of restrictions ended on 6 June. Since then, some recommendations on personal protection have been maintained. The limitations from March and April were called a "hard lockdown."

Since 8 August, in the country, there were regional restrictions. The state was divided into "yellow" and "red" zones. Districts were classified into them based on the number of confirmed infections. The second period of significant restrictions began on 24 October, though more limitations were added two weeks later. Some of them were lifted on 27 November 2020. The third state of restrictions was called a "national quarantine" and began on 28 December 2020 (Figure 1). The authors analyzed the impact of the pandemic on the change of energy demand profiles in 2019 and 2020. That is why "national quarantine" restrictions implemented in 2021 are not discussed in this article.

Figure 1. Graphical representation of COVID-19's restrictions from 2020 [46].

4. Methodology and Data

4.1. Data Characteristics

The analyzed dataset included the electricity consumption volumes of the customers of one of the national trading companies. The data were collected in hourly resolution for each hour in 2019 and 2020. The data were delivered in a day $n + 2$ by the Balance Responsible Party (Administrator) based on data coming from the Distribution System Operator. In case of detecting measurement errors, the Balance Party and the Operator revised them within 2 following days (Figure 2).

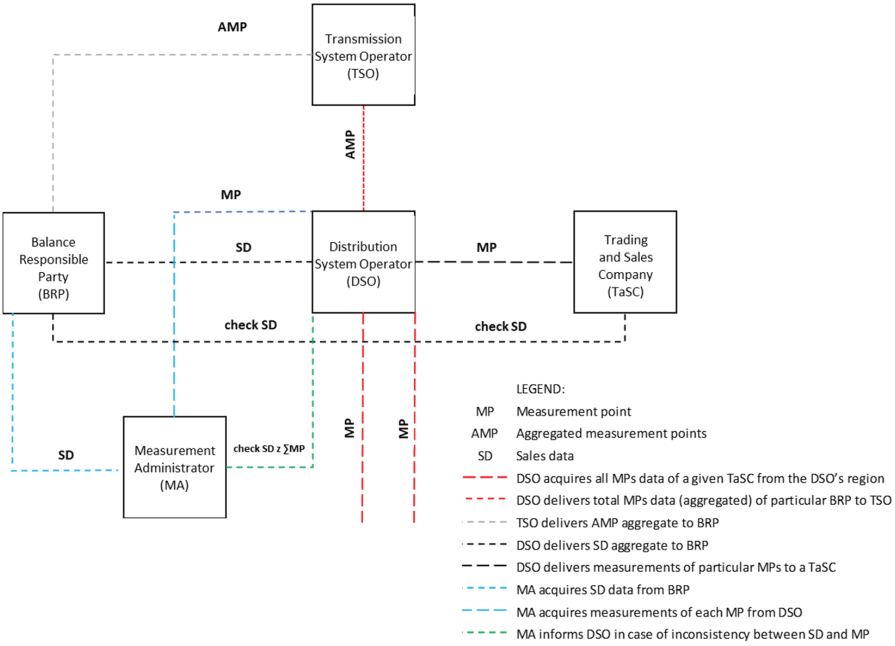

Figure 2. Collection and verification of measurement data—diagram.

Consumers belonging to the analyzed set represented various economic entities, e.g., production, service, and commercial companies operating in the territory of the whole country. The biggest clients were, among others, companies producing and distributing electricity, gas, and steam, ca. 35%, industrial consumers (food processing, electromechanical, and wood industries), ca. 30%, real-estate market companies (e.g., shopping malls), ca. 15%, and agriculture, ca. 7%. The total volume of energy consumed in 2019 was ca. 1.65 GWh. The Balance Responsible Party was obliged to create aggregates, including measurement points indicated by the Trading and Sales Company. The balancing positions of clients or shopping groups were appointed based on these points, but after an energy trading and sales company creates an energy consumption schedule. Such a plan must include all situations that may affect energy consumption (a day of the week, days off, unusual days, and nontypical phenomena). Parallelly, a considerable hardship for trading companies was verification and possible plan corrections due to an inertia period lasting 3 days. Actual consumption data were published on day $n + 2$ after 10:00, and SPOT trading on the Day-Ahead Market had to be submitted on the current day until 10:00 to the Polish Power Exchange.

The aim of the paper is to analyze the impact of the COVID-19 pandemic on the total electricity consumption and consumption profiles of clients representing key economic sectors. However, the authors are aware of certain limitations that may have an additional impact on energy consumption, such as the temperature difference occurring in the analyzed years or the difference in the level of companies' production. Due to measurement points' dispersion (several hundred recipients located in places of various longitude and latitude of Poland) and the lack of information about the production levels, introducing additional assumptions would adversely affect the presentation of the results, which could ultimately lead to a misinterpretation of the impact of lockdowns on the electricity consumption.

4.2. Methodology

4.2.1. Comparative Analysis

As mentioned, the data were collected in hourly resolution for each hour in 2019 and 2020. For the sake of other analyses, the dataset was arranged into daily, weekly, and monthly values. In the comparative analyses, it was decided to adjust the values of 2020 for one day. Thus, working days and days off overlapped to enable the comparison of daily differences in consumption volumes. The conducted analysis focused on differences in consumed energy volumes in hourly, daily, weekly, and monthly intervals in 2 subsequent years: in 2019, without restrictions associated with the COVID-19 pandemic; and 2020, during the pandemic.

Furthermore, the article analyzed energy demand profiles in 3 key groups of consumers. They were consistent with the Polish Classification of Activity, i.e., the set of the types of socio-economic activities undertaken by economic entities. The analyzed sections included: manufacturing (Section C), electricity, gas, steam, and air conditioning supply (Section D), and real estate activities, including the operation of shopping malls (Section L) [47].

4.2.2. Coefficient of Variation

This part analyzed the daily and weekly values of consumed energy. Volatility analysis was employed for investigating total consumption values. The analyses used weekly intervals (the subsequent weeks of the analyzed years), a selected working day (Tuesday), and one of the days off (Saturday). In the subsequent weeks, after computing mean and standard deviation values, total volatility was estimated for the selected variables in 2019 and 2020.

The measure of volatility was the coefficient of variation defined as the ratio of volatility absolute measure to mean values. Most often, it is the ratio of a mean analyzed value to the value of mean standard deviation [48].

$$V = \frac{S}{M} \cdot 100\% \quad (1)$$

where V—coefficient of variation, S—standard deviation (from the sample), M—mean (from the sample).

The coefficient of variation indicates a degree of differentiation of the analyzed sample (sample's features). Depending on the results, one can conclude about the level of volatility, but this coefficient is a relative measure. It is commonly recognized that a coefficient of variation lower than 10% indicates the statistical insignificance of the tested relation [49].

4.2.3. Forecast (Trend) and Difference Calculation

The last stage of the analysis was to compute a difference between energy consumed in subsequent weeks and the expected values of consumption. The latter was estimated using simple regression (linear regression) based on weekly values of consumption in the 4 weeks before introducing the first and second waves of restrictions. The analyzed period included both lockdowns.

5. Results

This section presents the results of the analysis of energy consumption by the business clients of the studied trading and sales companies in 2019 and 2020. Tables and charts highlight differences in the values of consumed energy in the annual perspective and in detail for the lockdowns. Additionally, the consumption volumes in three sections representing the key groups of consumers were analyzed. The following parts present the volatility analysis' results with the coefficients of variation estimated in the quarterly and yearly scales. Finally, after employing linear regression, there was estimated a trend of weekly energy consumption volume during the lockdowns based on the collected data.

Figure 3 presents the comparison of electricity consumption volumes in 2019 and 2020. The blue line marked consumption volumes in the hourly resolution in 2019; the red line represents values for 2020. The differences (only positive values, indicating lower energy consumption volumes in 2020) between volumes for 2019 and 2020 were presented as a black line. The mean hourly consumption volume for the whole of 2020 was 2 MWh higher, but during the lockdowns, the mean consumption was 14 MWh and 1 MWh lower in the first and second lockdown, respectively (Figures 4 and 5).

The confirmation of a significant decrease in the volume of energy consumption in the first lockdown is also visible in the analysis of total consumption for individual months (Figure 6). The first restrictions announced on 14 March 2020, caused a change of the expected increase in the energy consumption trend, observed before, e.g., in February. The following months of the first lockdown have brought additional declines. Compared with 2019, they were 13% in April and 4% in May when the strictest limitations were lifted. In June, the consumption volume was similar to the previous year. A significant increase in the consumption volume could be observed in the third quarter in the absolute values and relation to the same period in 2019. Another drop overlaps with the second wave of introducing severe restrictions. In October, the year-on-year value was even higher, even though the increasing energy consumption trend of 2019 was not maintained. In November 2020, the energy consumption was 1% lower than in the previous year, and the downward trend became clearly visible. The lifting of Another restriction (27 November) definitely impacted the consumption increase in December.

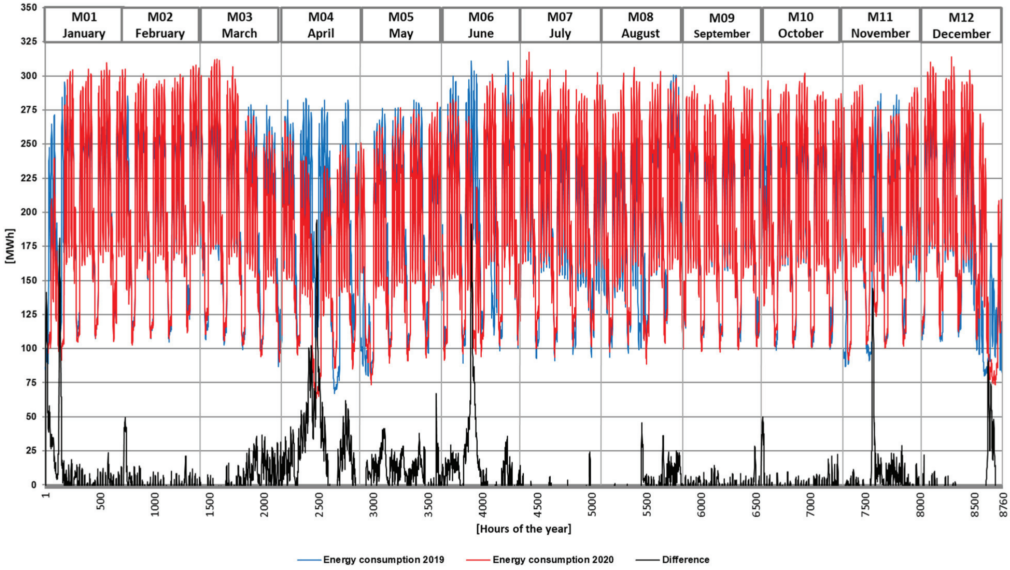

Figure 3. Comparative analysis of energy consumption in 2019–2020.

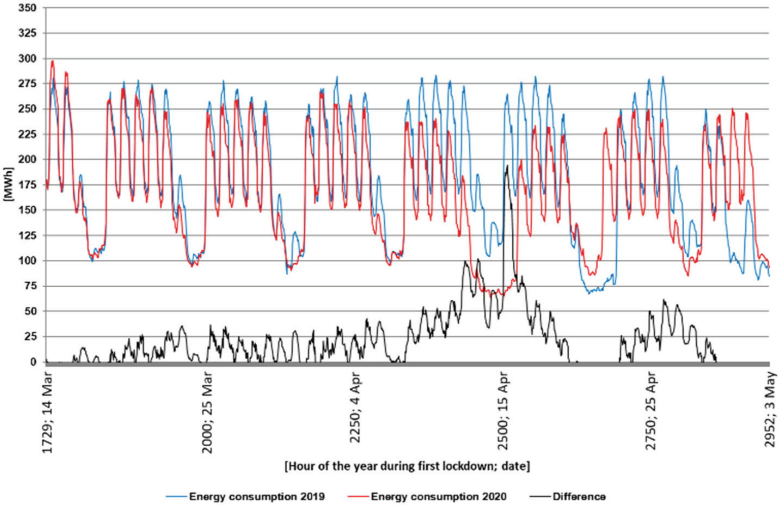

Figure 4. Comparative analysis of energy consumption 14 March–3 May (the first lockdown).

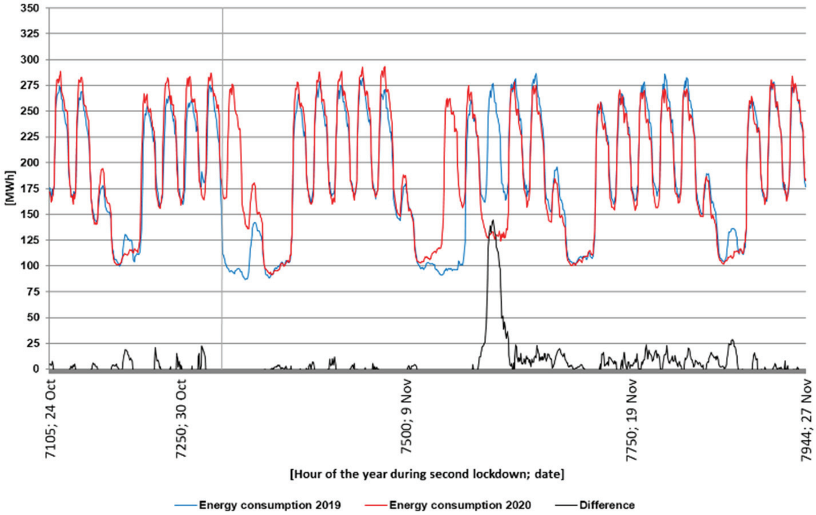

Figure 5. Comparative analysis of energy consumption 24 October–27 November (the second lockdown).

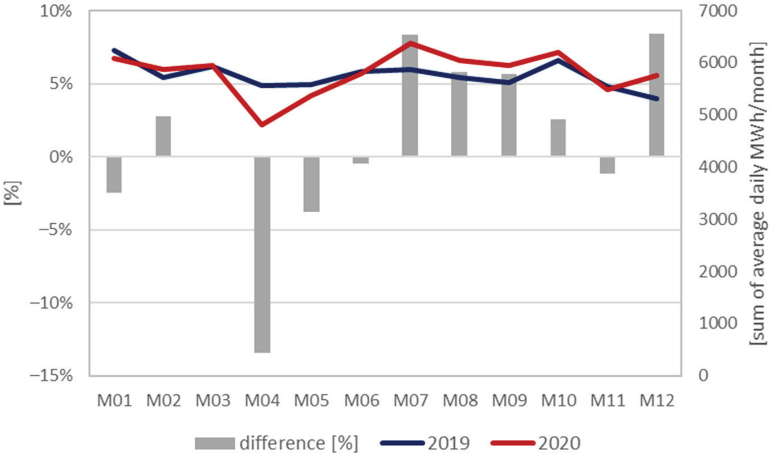

Figure 6. Comparison of energy consumption in 2019 and 2020 (difference 2019–2020).

Charts in Figure 7 present weekly electricity consumption profiles (W—week) in the groups of trading and sales company's key clients during the first and second lockdowns. The dashed line marks the period without restrictions (W10–11) and (W42–43) while the solid line the lockdown periods (W13–W18) and (W44–W48). The consumption values for the weeks W16, W18, and W46 are distorted because of the official days off, Easter Days (12–13 April), Labor Day, and 3 May Constitution Day (1–3 May), also Polish Independence Day (11 November).

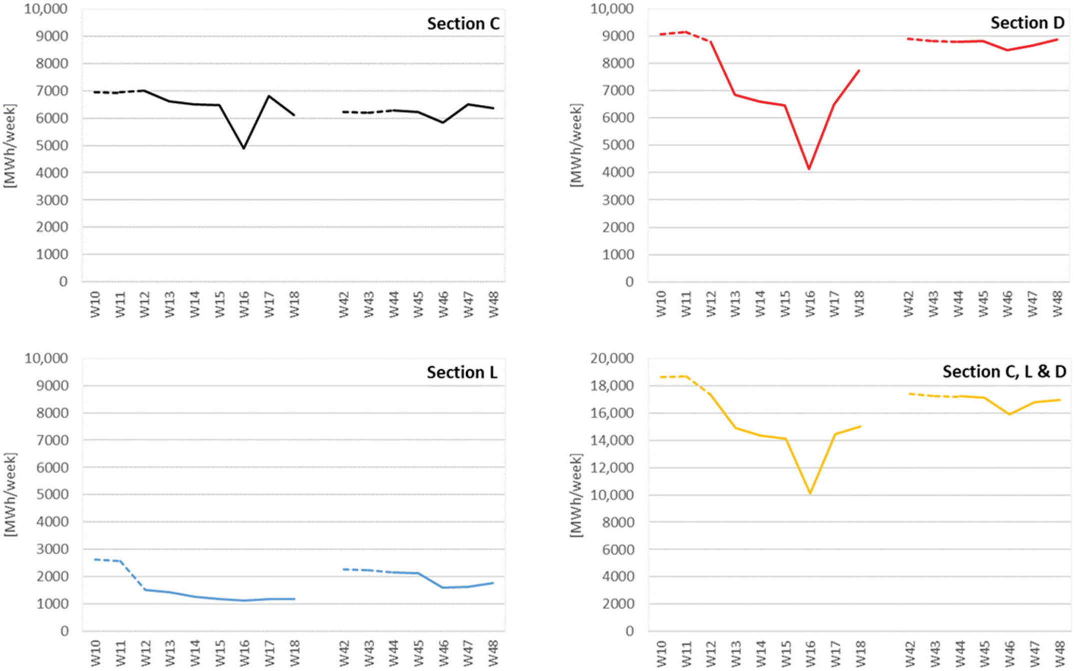

Figure 7. Weekly profiles of energy consumption for key sectors.

The analysis indicates that during the lockdown, the consumption volumes of Section C clients (manufacturing) have not changed drastically, but the volume decline was visible (400 MWh in the first week and 600 MWh/week in two others). The second lockdown did not significantly reflect on the volume of energy consumed by clients belonging to this section. Furthermore, during the lockdowns, for Section D clients (electricity, gas, steam, and air for air-conditioning supply), the energy consumption decrease was significant (400 MWh in the first week and more than 2000 MWh/week in the other three). However, the second lockdown did not impact the consumption value as much as the previous one. Besides trading real estates, Section L entities also service trading-office-entertainment complexes (shopping malls), which was clearly reflected in the electricity consumption volumes during the lockdowns. Yet, in the first lockdown, the volume of consumed energy decreased by 1000–1300 MWh per week, which was ca. 50% of the total decline in that group. In the second lockdown, there is clearly visible the second wave of restrictions (associated with the limitations imposed on shopping malls), in the period W46–W48, the consumption volumes were decreasing by ca. 500 MWh per week.

Another step was conducting the volatility analysis. The tables demonstrate the computed coefficients of variation for energy consumed by the clients. They are supplemented by standard deviation and mean values. The tables include the calculations of energy consumption volumes for weeks (Table 1), a selected working day, Tuesday (Table 2), and a selected day off, Saturday (Table 3). In all cases, the volatility of consumption volumes in 2020 did not change significantly compared to 2019. However, the noticeable changes in total values were related to the pandemic limitations.

Table 1. Results of volatility analysis—coefficients of variation (Energy consumption—week).

Parameter		Unit	Year	IQ	IIQ	IIIQ	IVQ
Energy consumption—week (2019)	Mean	[MWh/week]	31,775	33,590	31,383	31,340	30,788
	Standard deviation	[MWh/week]	3031	1157	3613	1873	4112
	Coefficient of variation	[%]	10%	3%	12%	6%	13%
Energy consumption—week (2020)	Mean	[MWh/week]	32,125	33,001	29,484	33,558	32,459
	Standard deviation	[MWh/week]	3435	3306	3 566	758	4023
	Coefficient of variation	[%]	11%	10%	12%	2%	12%

Table 2. Results of volatility analysis—coefficients of variation (Energy consumption—a working day).

Parameter		Unit	Year	IQ	IIQ	IIIQ	IVQ
Energy consumption—working day (Tuesday 2019)	Mean	[MWh/week]	5313	5565	5267	5140	5296
	Standard deviation	[MWh/week]	324	111	435	317	203
	Coefficient of variation	[%]	6%	2%	8%	6%	4%
Energy consumption—working day (Tuesday 2020)	Mean	[MWh/week]	5328	5526	4995	5474	5320
	Standard deviation	[MWh/week]	446	334	536	161	500
	Coefficient of variation	[%]	8%	6%	11%	3%	9%

Table 3. Results of volatility analysis—coefficients of variation (Energy consumption—a day off).

Parameter		Unit	Year	IQ	IIQ	IIIQ	IVQ
Energy consumption—day off (Saturday 2019)	Mean	[MWh/week]	3712	3841	3636	3722	3650
	Standard deviation	[MWh/week]	348	211	522	262	364
	Coefficient of variation	[%]	9%	5%	14%	7%	10%
Energy consumption—day off (Saturday 2020)	Mean	[MWh/week]	3648	3868	3143	3756	3842
	Standard deviation	[MWh/week]	454	298	521	297	182
	Coefficient of variation	[%]	12%	8%	17%	8%	5%

The volatility analysis for weekly electricity consumption values (Table 1) shows that the variation in the whole year was insignificantly higher. In the analysis of shorter (quarterly) intervals, it increased significantly only in the first quarter (from 3% to 10%), which could be caused by introducing the first restrictions at the end of the quarter. Despite the lockdowns, in the second and fourth quarters, the variation in 2019 and 2020 was ca. 12%. It was influenced by the restrictions and periods with the expected total change in energy consumption values (Easter, May weekend, II quarter, All Saints' Day, and Christmas, IV quarter).

In the case of energy consumption values for a selected working day, Tuesday (Table 2), the analysis indicates a minimal increase of volatility in the yearly scale (from 6% to 8%) and individual quarters with the restrictions. In the first quarter it increased from 2% to 6%, in the second from 8% to 11%, and in the fourth from 4% to 9%, respectively. 1 January 2019 (New Year) was a day off, which is why the analysis omits the consumption values for that date.

The volatility analysis of energy consumption in the selected day off, Saturday (Table 3), indicates that in 2020, the variation was insignificantly higher than in 2019. Unlike for the values for working days, the higher variability of electricity consumption could be observed in the first, second, and third quarters.

Tables 4 and 5, Figures 8 and 9, present the analysis of weekly energy consumption volumes during the first and second lockdowns in relation to the trend outlined based on four weeks before introducing restrictions.

In the first lockdown, decreases of the actual electricity consumption compared to expected values were large. Only at the first stage of implementing restrictions (since 14 March), the decrease of consumption in the subsequent weeks was 11%, 16%, and 15%. The consequences of limiting commerce, closing shopping malls, and restrictions imposed on industry were tangible. After introducing new restrictions (1 April), one could observe an additional decrease in the weekly energy consumption values. However, the following weeks of the first lockdown could not be analyzed in detail because of the Easter holidays (21–22 April 2019 and 12–13 April 2020).

The second lockdown analysis concerned the five restricted weeks. During that period, there was no limitation on movement and entire suspending services and commerce. The differences to the appointed trend were 2%, 2%, 11%, 6%, and 2% in subsequent weeks. The second wave of restrictions is clearly marked by the moment of closing shopping malls (from W46). As in the first lockdown, the difference to the appointed trend in the first week of the restrictions was 11%. However, actual energy consumption values were lower than expected.

Table 4. Analysis of energy consumption in relation to the forecast trend (the first lockdown).

Number of Week		**Date**	**Energy Consumption**	**Values Calculated in Line with (W8–W11) Trend**	**The Difference Value in Reference to the Trend**	
					Volume	**%**
[-]		[-]	[MWh/week]	[MWh/week]	[MWh/week]	[%]
NO LOCKDOWN	W8	15–21 February 2020	35,051	35,051	0	0%
	W9	22–28 February 2020	36,060	36,060	0	0%
	W10	29 February–6 March 2020	36,169	36,170	0	0%
	W11	7–13 March 2020	34,689	34,688	0	0%
LOCKDOWN	W12	14–20 March 2020	31,407	35,345	3938	−11%
	W13	21–27 March 2020	29,432	35,247	5816	−16%
	W14	28 March–3 April 2020	29,832	35,150	5318	−15%
	W15	4–10 April 2020	26,995	35,052	8057	−23%

Table 5. Analysis of energy consumption in relation to the forecast trend (the second lockdown).

Number of Week		**Date**	**Energy Consumption**	**Values Calculated in Line with (W40–W43) Trend**	**The Difference Value in Reference to the Trend**	
					Volume	**%**
[-]		[-]	[MWh/week]	[MWh/week]	[MWh/week]	[%]
NO LOCKDOWN	W40	26 September–2 October 2020	33,400	33,400	0	0%
	W41	3–09 October 2020	33,527	33,527	0	0%
	W42	10–16 October 2020	33,995	33,995	0	0%
	W43	17–23 October 2020	33,465	33,465	0	0%
LOCKDOWN	W44	24–30 October 2020	33,126	33,763	637	−2%
	W45	31 October–6 November 2020	33,127	33,829	702	−2%
	W46	7–13 November 2020	30,040	33,896	3856	−11%
	W47	14–20 November 2020	31,772	33,962	2190	−6%
	W48	21–27 November 2020	33,312	34,029	717	−2%

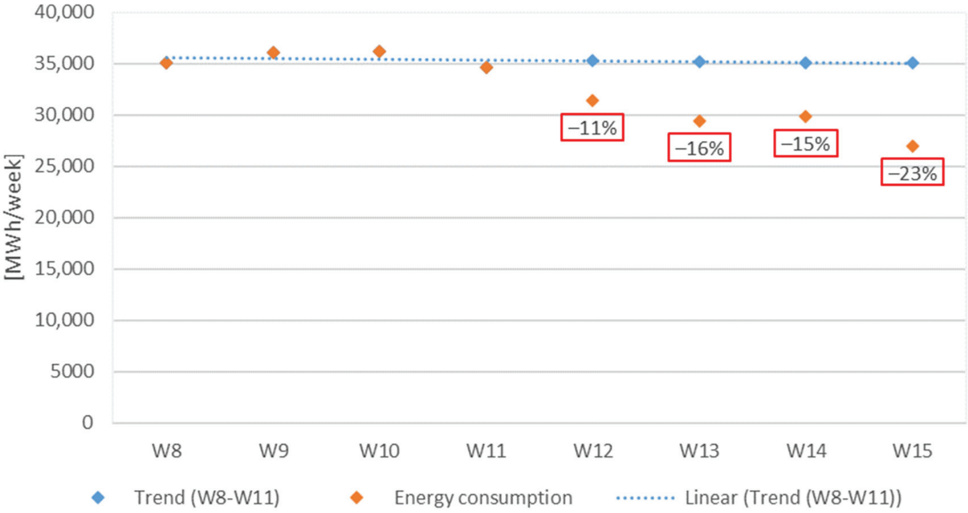

Figure 8. Analysis of energy consumption in relation to the forecast trend (the first lockdown).

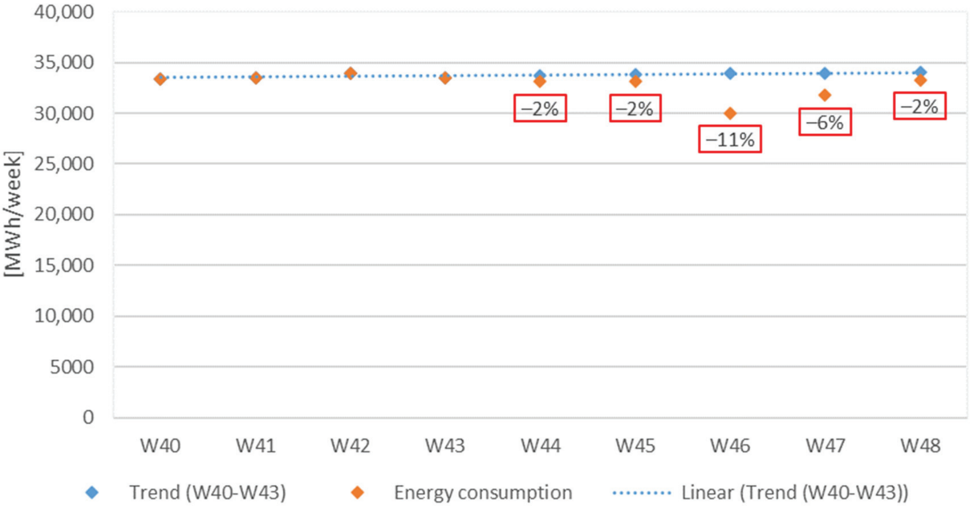

Figure 9. Analysis of energy consumption in relation to the forecast trend (the second lockdown).

6. Conclusions

The analysis confirmed an evident decline in energy consumption volumes during the lockdowns compared to values for 2019 and from several weeks before introducing new limitations. The changes are evident in the first stage of the pandemic. Beyond the lockdowns, energy consumption volumes in 2020 were several percent higher than in 2019.

The analysis of electricity consumption volumes of the key clients from the manufacturing and electricity, gas, steam, and air conditioning supply sections showed that the values were significantly lower only during the first lockdown while in the section real estate activities, each restriction related to closing shopping malls caused noticeable changes in energy consumption.

Restrictions imposed on the functioning of shopping malls cause a substantial decrease in the volumes of consumed energy in the analyzed group of clients, although the total value of their consumption is only ca. 15%. Moreover, energy demand profiles reflect additional limitations related to movement, commerce, and services (the so-called beauty industry).

To summarize, the restrictions caused a 15–23% decline in energy consumption during the first lockdown and a maximum of 11% during the second, against expected values. The conducted analysis demonstrates that in the context of the decline, the most significant aspect for the investigated group of clients was the limitation of commerce (including the closing of shopping malls). That and other restrictive regulations caused a ca. 9–11% decrease in energy consumption against the expected value in both periods of restrictions. The results should be verified based on data from lockdowns introduced in 2021.

The analysis demonstrates that additional restrictions (ban of movement, limiting commerce, and services) cause a higher drop in consumed energy volumes. The collected data are insufficient for concluding about exact values because some limitations were employed only one time.

The second lockdown caused changes in energy consumption profiles in the analyzed group of clients. Undoubtedly, it was impacted by the type of restrictions. During the second lockdown, there were no limitations on movement and no entire closing of commerce and services. Moreover, safety protocols used by industries have not entailed the necessity for limiting or canceling production.

The conducted volatility analysis proved that consumption volumes in 2020 did not change dramatically compared with 2019. However, the temporal increase of the coefficient of variation during the lockdowns was observed. The impact was seen particularly in analyzing energy consumption on a typical working day (Tuesday) for the first, second, and fourth quarter of the year and a day off (Saturday) for the first and second quarters.

The results are adequate to an energy trading and sales company having in its portfolio client groups mentioned in the paper (industry, services, commerce). It is possible that the implemented restrictions influenced various business activities differently. That observation justifies the need for conducting detailed analyses of the restrictions' impact on energy consumption in different branches of the economy.

The conducted research and further detailed analyses are required to improve the methods of forecasting customer energy consumption. Due to the dynamically changing electricity prices, the accurate forecasting of energy volumes significantly impacts the finances of energy trading and sales companies.

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References

1. *Electricity Market Report*; International Energy Agency (IEA): Paris, France, 2020. Available online: https://www.iea.org/reports/electricity-market-report-december-2020 (accessed on 21 May 2021).
2. Nikola, M.; Alsafi, Z.; Sohrabi, C.; Kerwan, A.; Al-Jabir, A.; Iosifidis, C.; Agha, M.; Agha, R. The socio-economic implications of the coronavirus pandemic (COVID-19): A review. *Int. J. Surg.* **2020**, *78*, 185–193. [CrossRef]
3. Szczepańska-Woszczyna, K. *Management Theory, Innovation, and Organisation: A Model of Managerial Competencies*; Routledge: Oxfordshire, UK, 2020; p. 206.
4. Kinelski, G. The main factors of successful project management in the aspect of energy enterprises' efficiency in the digital economy environment. *Polityka Energetyczna Energy Policy J.* **2020**, *23*, 5–20. [CrossRef]

5. *COVID-19 Impact on Electricity*; International Energy Agency (IEA): Paris, France, 2020. Available online: https://www.iea.org/reports/covid-19-impact-on-electricity (accessed on 20 May 2021).
6. Crider, J. COVID-19 Bankrupts 19 Energy (Oil & Gas) Companies. 2020. Available online: https://cleantechnica.com/2020/08/05/covid-19-bankrupts-19-energy-oil-gas-companies (accessed on 20 May 2021).
7. Baker, M.G.; Wilson, N.; Blakely, T. Elimination could be the optimal response strategy for covid-19 and other emerging pandemic diseases. *BMJ* **2020**, *371*. [CrossRef]
8. Czosnyka, M.; Wnukowska, B.; Karbowa, K. Electrical energy consumption and the energy market in Poland during the COVID-19 pandemic. In *2020 Progress in Applied Electrical Engineering (PAEE)*; IEEE: Piscataway, NJ, USA, 2020; pp. 1–5. [CrossRef]
9. Polish Power System-PSE-Reports. Available online: https://www.pse.pl/web/pse-eng/data (accessed on 12 May 2021).
10. Kaźmierska, M. Zużycie Prądu w Polsce. Jaki Wpływ Lockdownu? 2020. Available online: www.enerad.pl (accessed on 3 February 2021). (In Polish).
11. Saługa, P.W.; Szczepańska-Woszczyna, K.; Miśkiewicz, R.; Chłąd, M. Cost of Equity of Coal-Fired Power Generation Projects in Poland: Its Importance for the Management of Decision-Making Process. *Energies* **2020**, *13*, 4833. [CrossRef]
12. Mucha-Kuś, K.; Sołtysik, M.; Zamasz, K.; Szczepańska-Woszczyna, K. Coopetitive Nature of Energy Communities—The Energy Transition Context. *Energies* **2021**, *14*, 931. [CrossRef]
13. Kinelski, G. Two-way market and the existence of its competitiveness in the electrolygenic subsector. Rynek dwutowarowy i istota jego konkurencyjności w sektorze elektroenergetycznym. *Zesz. Nauk. Inst. Gospod. Surowcami Miner. I Energią Pol. Akad. Nauk.* **2018**, *102*, 277–299. (In Polish)
14. Wójcik-Jurkiewicz, M.; Czarnecka, M.; Kinelski, G.; Sadowska, B.; Bilińska-Reformat, K. Determinants of Decarbonisation in the Transformation of the Energy Sector: The Case of Poland. *Energies* **2021**, *14*, 1217. [CrossRef]
15. Łabinowicz, K.; Bujalski, W. Extracting main factors influencing spot electricity prices with application of statistical methods. Wyodrębnienie głównych czynników kształtujących ceny energii elektrycznej na Rynku Dnia Następnego z wykorzystaniem metod statystycznych. *Rynek Energii* **2015**, *6*, 15–21. (In Polish)
16. Malec, M. Impact of the volatility of coal prices in the international markets and it's impact on the volatility of domestic fuel and electricity prices. Wpływ zmienności cen węgla kamiennego na rynkach światowych na zmienność cen paliw i energii elektrycznej w Polsce. *Polityka Energetyczna Energy Policy J.* **2017**, *4*, 39–54. (In Polish)
17. Nowotarski, J.; Weron, R. Recent advances in electricity price forecasting: A review of probabilistic forecasting. *Renew. Sustain. Energy Rev.* **2018**, *81*, 1548–1568. [CrossRef]
18. Maciejowska, K.; Nitka, W.; Weron, T. Day-ahead vs. Intraday—Forecasting the price spread to maximize economic benefits. *Energies* **2019**, *12*, 631. [CrossRef]
19. Edoli, E.; Fiorenzani, S.; Vargiolu, T. Optimal Trading Strategies in Intraday Power Markets. In *Optimization Methods for Gas and Power Markets*; Palgrave Macmillan: London, UK, 2016; pp. 161–184. [CrossRef]
20. Ghenai, C.; Bettayeb, M. Data analysis of the electricity generation mix for clean energy transition during COVID-19 lockdowns. *Energy Sources Part A Recover. Util. Environ. Eff.* **2021**, *43*. [CrossRef]
21. Zhong, H. Implications of COVID-19 for the Electricity Industry: A Comprehensive Review. *CSEE J. Power Energy Syst.* **2020**, *6*, 489–495. [CrossRef]
22. Fezzi, C. Real-Time Estimation of the Short-Run Impact of COVID-19 on Economic Activity Using Electricity Market Data. *Environ. Resour. Econ.* **2020**, *76*, 885–900. [CrossRef] [PubMed]
23. Benatia, D.; Feron, O.; Alasseur, C. *Ring the Alarm! Electricity Markets, Renewables, and the Pandemic*; USAEE Working Paper No. 20-473; USAEE: Dayton, OH, USA, 2020. Available online: https://ssrn.com/abstract=3703117 (accessed on 10 May 2021).
24. Mirnezami, S.R.; Rajabi, S. Changing primary energy consumption due to covid-19: The study 20 european economies. *Int. J. Energy Econ. Policy* **2021**, *11*, 615–631. [CrossRef]
25. Castan Broto, V.; Kirshner, J. Energy access is needed to maintain health during pandemics. *Nat. Energy* **2020**, *5*, 419–421. [CrossRef]
26. Elavarasan, R.M.; Shafiullah, G.M.; Kannadasan, R.; Mudgal, V.; Arif, M.T.; Jamal, T. COVID-19: Impact analysis and recommendations for power sector operation. *Appl. Energy* **2020**, *279*, 115739. [CrossRef]
27. *Global Energy Review 2020: The Impacts of the COVID-19 Crisis on Global Energy Demand and CO_2 Emissions*; International Energy Agency (IEA): Paris, France, 2020. Available online: https://www.iea.org/reports/global-energy-review-2020 (accessed on 22 May 2021).
28. Abu-Rayash, A.; Dincer, I. Analysis of the electricity demand trends amidst the COVID-19 coronavirus pandemic. *Energy Res. Soc. Sci.* **2020**, *68*, 101682. [CrossRef]
29. Chen, C.F.; de Rubens, G.Z.; Xu, X.; Li, J. Coronavirus comes home? Energy use, home energy management, and the social-psychological factors of COVID-19. *Energy Res. Soc. Sci.* **2020**, *68*, 101682. [CrossRef]
30. Sui, Y.; Zhang, H.; Shang, W.; Sun, R.; Wang, C.; Ji, J. Mining urban sustainable performance: Spatio-temporal emission potential changes of urban transit buses in post-COVID-19 future. *Appl. Energy* **2020**, *280*, 115966. [CrossRef]
31. Bielecki, S.; Skoczkowski, T.; Sobczak, L.; Buchoski, J.; Maciąg, Ł.; Dukat, P. Impact of the Lockdown during the COVID-19 Pandemic on Electricity Use by Residential Users. *Energies* **2021**, *14*, 980. [CrossRef]
32. Cheshmehzangi, A. COVID-19 and household energy implications: What are the main impacts on energy use? *Heliyon* **2020**, *6*, e05202. [CrossRef]

33. Santiago, I.; Moreno-Munoz, A.; Quintero-Jiménez, P.; Garcia-Torres, F.; Gonzalez-Redondo, M.J. Electricity demand during pandemic times: The case of the COVID-19 in Spain. *Energy Policy* **2021**, *148*, 111964. [CrossRef]
34. Rouleau, J.; Gosselin, L. Impacts of the COVID-19 lockdown on energy consumption in a Canadian social housing building. *Appl. Energy* **2021**, *287*, 116565. [CrossRef]
35. Jiang, P.; Klemeš, J.J.; Bee, Y.M. More is not enough: A deeper understanding of the covid-19 impacts on healthcare, energy and environment is crucial. *Int. J. Environ. Res. Public Health* **2021**, *18*, 684. [CrossRef]
36. Jiang, P.; Fan, Y.V.; Klemeš, J.J. Impacts of COVID-19 on energy demand and consumption: Challenges, lessons and emerging opportunities. *Appl. Energy* **2021**, *18*, 684. [CrossRef]
37. Eurostat Report—Impact of COVID-19 Crisis on Short-Term Statistics. 2021. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Impact_of_Covid-19_crisis_on_short-term_statistics (accessed on 30 May 2021).
38. European Parliament Report—Impacts of the COVID-19 Pandemic on EU Industries. 2021. Available online: https://www.europarl.europa.eu/ (accessed on 2 June 2021).
39. Bompard, E.; Mosca, C.; Colella, P.; Antonopoulos, G.; Fulli, G.; Masera, M.; Poncela-Blanco, M.; Vitiello, S. The Immediate Impacts of COVID-19 on European Electricity Systems: A First Assessment and Lessons Learned. *Energies* **2021**, *14*, 96. [CrossRef]
40. Fu, M.; Shen, H. COVID-19 and Corporate Performance in the Energy Industry. *Energy Res. Lett.* **2020**, *1*, 12967. [CrossRef]
41. Graf, C.; Quaglia, F.; Wolak, F.A. (Machine) learning from the COVID-19 Lockdown about Electricity Market Performance with a large share of renewables. *J. Environ. Econ. Manag.* **2021**, *105*, 102398. [CrossRef]
42. Kuzemko, C.; Bradshaw, M.; Bridge, G.; Goldthau, A.; Jewell, J.; Overland, I.; Scholten, D.; Van de Graaf, T.; Westphal, K. COVID-19 and the politics of sustainable energy transitions. *Energy Res. Soc. Sci.* **2020**, *68*, 101685. [CrossRef] [PubMed]
43. Aruga, K.; Islam, M.; Jannat, A. Effects of COVID-19 on Indian energy consumption. *Sustainability* **2020**, *12*, 5616. [CrossRef]
44. Gomez-Omella, M.; Esnaola-Gonzalez, I.; Ferreiro, S. Short-Term Forecasting Methodology for Energy Demand in Residential Buildings and the Impact of the COVID-19 Pandemic on Forecasts. In *International Conference on Innovative Techniques and Applications of Artificial Intelligence*; Bramer, M., Ellis, R., Eds.; Springer: Cham, Switzerland, 2020. [CrossRef]
45. Alasali, F.; Nusair, K.; Alhmoud, L.; Zarour, E. Impact of the COVID-19 Pandemic on Electricity Demand and Load Forecasting. *Sustainability* **2021**, *13*, 1435. [CrossRef]
46. COVID-19 in Poland. Governments Actions. Available online: https://www.gov.pl/web/koronawirus/dzialania-rzadu (accessed on 22 April 2021). (In Polish)
47. Code List of Classification of Business Activities in Poland (PKD Classification). Available online: https://ec.europa.eu/eurostat/ramon/nomenclatures/index.cfm?TargetUrl=LST_NOM_DTL&StrNom=NACE_REV2&StrLanguageCode=EN&IntPcKey=&StrLayoutCode=HIERARCHIC&IntCurrentPage=1 (accessed on 1 June 2021).
48. Subrahmanya Nairy, K.; Aruna Rao, K. Tests of Coefficients of Variation of Normal Population. *Commun. Stat. Simul. Comput.* **2003**, *32*, 641–661. [CrossRef]
49. Forkman, J. Estimator and Tests for Common Coefficients of Variation in Normal Distributions. *Commun. Stat. Theory Methods* **2009**, *38*, 233–251. [CrossRef]

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Article

Can Decarbonisation and Capacity Market Go Together? The Case Study of Poland

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Abstract: In recent years, numerous countries have introduced or considered capacity markets as remuneration mechanisms for long-term capacity adequacy. Since adequacy is frequently linked with thermal power generation, there is an ongoing debate as to whether this instrument could impact decarbonisation. In this context, the paper presents a quantitative assessment of the consequences of introducing a capacity market on decarbonisation pathways. The Polish power system is taken as an example due to its heavy dependence on fossil fuels. To this end, a computable model of the Polish power system is developed and applied to the study of two research scenarios. The first scenario presents the power system without introducing a capacity market, while the latter considers the system with a capacity market in place. The analysis shows that the introduction of a capacity market delays the decarbonisation of the power system and has a negative impact on carbon neutrality. Even though coal-fired units are phased out, they are mainly replaced by natural gas. The method and model developed within this study can be applied to countries where a capacity market is being discussed, and fossil fuels continue to play a dominant role.

Keywords: decarbonisation; energy transition; capacity market; capacity adequacy; linear programming

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1. Introduction

Decarbonisation of power systems is one of the solutions to the problem of climate change [1]. The phasing-out of conventional power plants and their replacement with renewable generation sources results in a significant decrease in greenhouse gas (GHG) emissions. Although the environmental impact of decarbonisation is noticeable, the energy transition in systems with high penetration of fossil fuels has to consider other factors. The policymakers, transmission system operators, and regulatory bodies are required to ensure energy security [2]. As a result, the decarbonisation processes are different in different countries [3]. Although in Refs. [4,5] the authors indicate that fulfilling the requirements for zero-carbon electricity is possible by 2050, there is a need to investigate the potential in individual countries.

Another trend that has been observed in recent years is ensuring the adequacy of capacity. Apart from the advantages of energy liberalisation [6], the current electricity market design also has numerous failures. The following causes are indicated in the literature [7–9]:

- Specific features of electricity compared with other tradable commodities: As energy storage technologies are still costly, demand must be constantly balanced with supply.
- Low short-run price elasticity of demand: Lack of sufficient response of consumers to hourly price fluctuations.
- Increase in renewable capacity, mainly in wind and solar power generation units: Power in these units is generated at lower operating costs than in the case of conventional power plants. In favourable weather conditions, renewable electricity meets the real-time demand in priority. Consequently, the conventional generation units (coal- or gas-fired) generate losses, and market signals do not offer sufficient incentives to come to investment decisions.

- Price cap regulations: The price increase during periods of peak demand is administratively constrained. Therefore, fewer potential market signals occur in these periods than would be expected.

Global experience indicates that energy liberalisation has not met its major ends, and power companies do not receive sufficient revenues to cover their operational and capital costs. The situation where the electricity market revenues are too low to cover the total costs of power generation units is referred to as the missing money problem [10]. The market signals also do not provide a sufficient incentive for investors to build new power units. The lack of investment signals may result in missing capacity in the power system and, consequently, have serious implications for the entire economy and society.

1.1. Capacity Market

To this end, numerous countries have introduced or considered capacity remuneration mechanisms (CRMs), including the capacity market [11]. CRMs are energy policy instruments designed to ensure long-term capacity adequacy [12]. They provide additional remuneration for power companies in compensation for electricity generation in peak demand. They are also considered as instruments that ensure the stability of the power system during decarbonisation [13]. CRMs stimulate not only generation companies but also encourage consumers to reduce their electricity consumption in periods of peak demand. There are two essential categories of CRMs: (i) based on price: capacity payments and (ii) based on volume: strategic reserve, reliability options, capacity obligations, and capacity auctions. These mechanisms are discussed in detail in Refs. [8,10,12,14,15]. These instruments provide additional remuneration for power companies in compensation for electricity generation in peak demand. However, they may extend the economic lifetime of obsolete, usually carbon-intensive, power units.

Authors of Ref. [16] indicate that capacity mechanisms unintentionally favour peaking technologies like coal, oil and gas over wind, solar, or nuclear technologies. In Ref. [17], the authors investigate the impact of the capacity market design on power system decarbonisation in PJM (Pennsylvania-New Jersey-Maryland). The results show that the existing model of the capacity market does not specially target low-emission technologies but can be modified to fulfil the goals of power system decarbonisation. In Ref. [18], the authors review the support policies for renewable energy. Although they list numerous instruments (auctions, feed-in tariffs, and others), they do not mention any capacity remuneration mechanisms. Authors of Ref. [19] also emphasise that current designs of capacity markets do not provide incentives for intermittent renewable generation sources. The study presents a mathematical model that allows one to consider the specific characteristics of renewables in the design of capacity remuneration mechanisms. In Ref. [20], the authors analyse the consequences of the introduction of a capacity market in Poland but focus solely on the economic results. They present the impact of the mechanism on electricity prices.

The literature review indicates that there have been papers analysing the impact of capacity market design on decarbonisation. However, they mainly focus on the benefits of this mechanism to various technologies, especially carbon and non-carbon ones. Moreover, since previous studies mostly concern the short-term (up to five years) effects of capacity market operation, there is a limited number of studies on the long-term (more than ten years) consequences of the introduction of the capacity market, particularly in countries dependent on fossil fuels.

The Polish power system is an interesting case study to investigate the impact of the capacity market operation on the progress of decarbonisation. The capacity market is a relatively new mechanism in Poland, and its impact on hard coal and lignite consumption has not so far been studied. In 2019 the capacity installed in thermal power plants was 34.3 GW (73.4% of total installed capacity), of which the capacity of coal-fired units accounted for 31.5 GW [21]. As a result, the power system is sensitive to climate policies that emphasise the significance of decarbonisation and increasing renewable generation [22]. On the one hand, the policymakers have made decisions supporting the development of renewables [23], energy storage, electromobility, and other concepts aimed at achieving climate neutrality by 2050 [24]. On the other, the government introduced the capacity market to ensure long-term capacity adequacy. Therefore, there is a question of the long-term impact of the introduction of such an instrument on the efficiency of the energy transition of power systems with a high penetration of fossil fuels.

1.2. Study Contributions

In this context, the main objective of the study is to conduct a quantitative assessment of the introduction of the capacity market on hard coal and lignite consumption for electricity generation in the Polish power system up to 2040. For this purpose, a techno-economic model of the Polish power system was developed. The model was formulated as a linear programming problem and implemented in MATLAB software. The impact is assessed by examining and comparing the outcomes under two scenarios: (i) with and (ii) without the operation of the capacity market. The following results are compared and discussed: (i) coal-fired generation capacity in the power system, (ii) electricity generation from coal-fired power generation units, and (iii) the quantity of coal consumption for electricity generation. The changes in electricity prices over the period 2021–40 are also examined.

With this in mind, the study fulfils the research gap identified as a lack of studies on the long-term consequences of the introduction of a capacity market on the decarbonisation of coal-dependent power systems. The work contributes to the existing literature in the following ways. First, it provides a quantitative analysis on the influence of a capacity remuneration mechanism on the fuel mix of power systems with a high penetration of fossil fuels. Second, it provides the findings of the role of a capacity market in the decarbonisation process in such systems. Third, it extends the current studies on the consequences of the operation of a capacity market with a case study of Poland. Finally, the findings contribute to a discussion on the reasonability under environmental regulations of operating a capacity market in power systems dominated by coal-fired generation.

Poland is taken as an example due to the dominant share of fossil fuels in its electricity generation. However, the concept of the study and mathematical formulae can be applied to other countries where fossil fuels are prevalent and capacity remuneration mechanisms are considered or introduced. The main findings can also support the decision-making process in pursuit of carbon neutrality in such power systems.

The author is aware that the study has some limitations. The most important ones are described in this paragraph. The parameters used in the model were chosen as single points based on current reports and the best knowledge of the author. The model is a deterministic model and does not consider the probability distributions for uncertain input data [25,26]. The next step of the study will be to employ the probability distribution of each input parameter and provide ranges of results and the probability of their occurrence.

The study does not consider the adequacy indices (among others, Load of Load Probability (LOLP), Loss of Load Hours (LOLH), or Expected Energy Not Served). The power demand in the entire period of analysis (2021–2040) is based on the Polish Energy Policy until 2040. The document presents the values that include margins required to ensure power system security. However, these indices have been already studied in the previous paper [20] to investigate the economic consequences of introducing the capacity market in Poland.

The remainder of the paper is organised as follows. In Section 2, the approach and mathematical formulae applied in this study are described. This section also shows the scenarios and the assumptions regarding the input data. Section 3 presents the results of the study and discusses the main findings. Finally, conclusions are drawn in Section 4.

2. Materials and Methods

Linear programming is used in this study to assess the impact of the introduction of a capacity market on the decarbonisation of the power system [27]. Section 2.1 describes the methodology developed and employed. This section also presents the conceptual model of the Polish power system. Section 2.2 describes two formulated scenarios and their key assumptions. Section 2.3 presents the transposition of the conceptual model to the mathematical model: equations and inequalities are presented and described. Finally, in Section 2.4, the key assumptions of the input data are shown.

2.1. Methodology

The mathematical model, developed to quantify the influence of the capacity market, reflects the operation of the wholesale energy market. A schematic diagram illustrating the methodology employed is shown in Figure 1. The figure presents the inputs and outputs of the model equations and inequalities (green blocks in the scheme). For example, the objective function is related to the following parameters (grey blocks): fuel prices, CO_2 European Emission Allowances, environmental charges, variable operations and maintenance costs, CO_2 and pollutants emission factors, and net efficiency. Solving this equation together with all the others presented in the scheme (green blocks) results in the following outputs (brown blocks): power generated by individual units, the total variable cost of power generation, and electricity price. These values are used in the post-optimisation calculations, in line with Figure 1. The calculations are finished if all generation units have a positive profit (the "end" block). The scenarios are described in detail later in the paper.

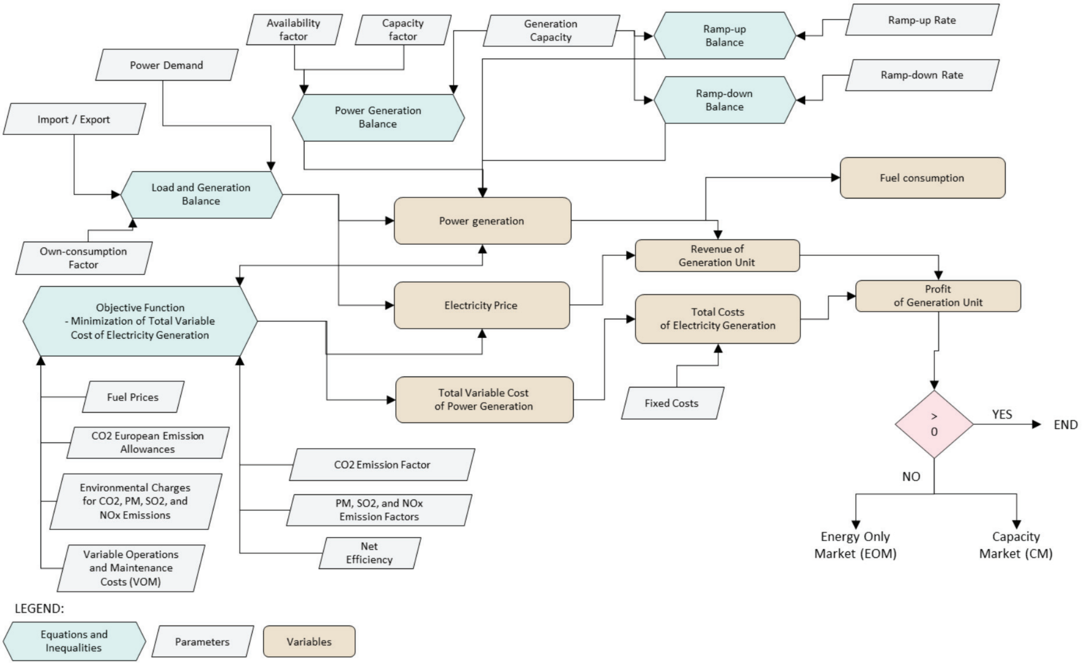

Figure 1. The methodology employed in the study.

The model is formulated as a partial equilibrium model of the Polish electricity and capacity markets using the Economic Dispatch Problem (EDP) approach. The EDP approach is widely used to simulate the operation of an electricity market to calculate the optimal generation structure at the lowest total operating cost [8]. Bids submitted by generating units are ranked according to their variable costs (merit order), and the market clearing price is equal to the short-term marginal cost of the system, subject to constraints. It is assumed that the electricity market operates as a competitive market.

The model is a short-term model with a time horizon of one year and hourly intervals. The analysis period is 2021–2040, which is in line with the time horizon assumed in the Polish Energy Policy [28]. The calculation procedures presented in Section 2.2 are executed individually for each year.

Two research scenarios (described in detail in Section 2.2) are formulated to quantitatively assess the impact of the capacity market on coal consumption:

- An energy only market (EOM) scenario, reflecting the operation of the energy market without a capacity remuneration mechanism.
- A capacity market (CM) scenario, reflecting the operation of a two-commodity market: the capacity market operates in parallel to the energy market.

As previously mentioned, the price elasticity of electricity demand is low because consumers do not make their consumption dependent on hourly prices. Therefore, the study assumed that power demand is a parameter based on the hourly forecast demand in the power system. The values of demand also include network losses.

Power generation units are reflected in the model in the following ways:

- Individual power generation units: (i) centrally dispatched power generation units (coal-fired, gas-fired, hydro pumped storage) and (ii) centrally dispatched combined heat and power (CHP) plants with a generating capacity of more than 99 MW.
- Clustered by fuel type (hard coal-fired, lignite-fired, natural gas-fired, biomass, biogas, and other): (i) centrally dispatched CHPs with a generating capacity of 50–99 MW and below 49 MW, (ii) other public and industrial CHPs.
- Clustered by technology: (i) renewable generation (onshore, offshore, solar, hydro run-of-river), (ii) demand-side response (DSR), (iii) energy storage.

The power generation units (individually or clustered) are described by their technical and economic parameters. The parameters are, e.g., net electrical capacity, net electrical efficiency, own-consumption factor, availability factor, capacity factor, ramp-up and ramp-down rates, fuel, CO_2, SO_2, NO_x, PM emission factors, and variable operations and maintenance (VOM) cost. The input data also includes information on the year of the decommissioning of the power generation units. In the case of refurbished units, the year, the planned increase in the generation capacity, and changes in the techno-economic parameters are included. New power generation units are considered individually in accordance with their investment schedule and techno-economic specification.

The remaining data assumed in this study are as follows:

- Power demand in hourly intervals.
- Fuel prices (hard coal, lignite, natural gas, biomass, biogas, uranium).
- CO_2 European Emission Allowances.
- Environmental charges for CO_2, PM, SO_2, and NO_x emissions.
- Hourly generation profiles of CHP plants.
- Hourly generation profiles of the following technologies: onshore, offshore, solar, and hydro run-of-river.
- Value of Lost Load (VoLL).

The model of the Polish power system is formulated as a linear programming problem. The objective function is to minimise the total annual variable cost of electricity generation. The cost consists of the following components: (i) fuel costs, (ii) environmental costs, and (iii) VOM costs. The methodology presented can also be applied to investigate the operation of power systems in other countries and described by different input data.

The main constraints implemented in the model are as follows:

- Load and generation balance: Each hour, the power generation volume (decreased by the own-consumption factor) must be equal to the power demand increased by export and decreased by import.
- Power generation balance: Each hour, power generation units cannot generate more power than the product of their maximum generation capacity and availability factor.

- Ramp-up balance: Each hour, the increase in the power generation volume in the power generation unit (compared to the previous hour) cannot be greater than the product of maximum generation capacity and ramp-up rate.
- Ramp-down balance: Each hour, the decrease in the power generation volume in the power generation unit (compared to the previous hour) cannot be greater than the product of maximum generation capacity and ramp-down rate.

In order to mimic the impact of the reserve margin on electricity prices, the system marginal cost is adjusted proportionally to the level of the reserve margin.

The next step of the methodology presents the calculation of (i) the annual revenues of the individual (or clustered) power generation units, (ii) the estimated total annual costs (variable and fixed) of the individual unit, and consequently, (iii) the annual profit from the sale of electricity on the wholesale market.

2.2. Scenario Assumptions

Since the study aims to quantify the impact of introducing the capacity market on the decarbonisation of the power system, two research scenarios were formulated (Figure 2). The electricity market operation is simulated in the same way for both scenarios, in line with the methodology presented in Section 2.1. The calculation of missing money is also carried out according to the same criteria for both market structures. The differences between the scenarios embrace the operation (or not) of power generation units with insufficient revenues from the sale of electricity (missing money).

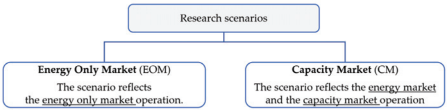

Figure 2. Research scenarios.

2.2.1. Energy Only Market (EOM)

The EOM scenario assumes that the power generation units that do not meet the economic efficiency criterion (missing money problem) are decommissioned. In order to ensure energy safety and sufficient generation capacity in the power system, new power generation units are commissioned. The new units are selected based on economic criteria. As a result, a new structure of the power system is simulated. Then, the entire calculation procedure is repeated for the new structure. Iterations are repeated until each power generation unit in the power system has a positive financial result.

Nonetheless, it is assumed that the number of decommissioned units cannot be greater than five due to the technical and security conditions in each year. Furthermore, it is assumed that units commissioned to the power system from 2018 onwards are not decommissioned in the entire analysis period, regardless of their financial results. The calculation procedure under the EOM scenario is shown in Figure 3.

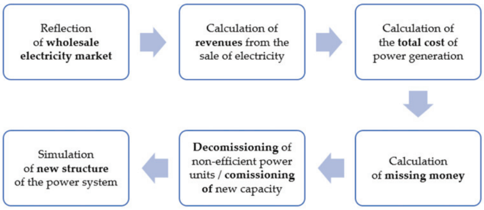

Figure 3. Calculation procedure under the EOM scenario.

2.2.2. Capacity Market (CM)

The CM scenario assumes that the power generation units that do not meet the economic efficiency criterion (missing money problem) can participate in the capacity auction. If the units win the auction, they can sign a capacity agreement and remain in the power system. The CM scenario also reflects the real capacity auction results conducted for 2021–2024 [29]. Additionally, according to the Regulation of the European Parliament and Council [30], the study assumes that coal-fired units cannot be the beneficiaries of capacity market support from 2025.

The scenario assumes that renewable generation sources may receive more favourable financial support from the auctions dedicated strictly to renewable technologies. Since double financial support from public funds is not allowed in Poland, the study assumes that an increase in renewable generation capacity is adopted according to the Project of the Polish Energy Policy [28].

The reserve margin in the power system in the CM scenario is assumed to be 30.91%. The level is estimated based on historical capacity auctions for 2021–2024. Therefore, the generation capacity demand is the product of the maximum demand and the coefficient of 1.31. In the case of insufficient generation capacity, new capacity is added.

Finally, a simulation is made of the wholesale electricity market. Units with missing money problems and without capacity agreements are decommissioned. In the case of insufficient generation capacity, new power generation units are commissioned (selected based on economic conditions). As a result, the power system has a new technological structure.

Similar to the EOM scenario, the number of decommissioned units cannot be greater than five each year (due to the technical and security conditions). The exception is 2025, when the decommissioning of a maximum of ten units is allowed. The exception stems from the fact that information about the lack of financial support for the coal-fired units is available several years ahead. The generation companies can implement appropriate procedures and decommission additional units earlier. Moreover, the decommissioning of the greater number of units will not affect energy security because, as a consequence of the results of capacity auctions for 2021–2024, the reserve margin is at the level of 39.1% for that year. The assumption of units commissioned from 2018 onwards is similar to the EOM scenario–regardless of their financial results, they remain in the power system. The calculation procedure under the CM scenario is shown in Figure 4.

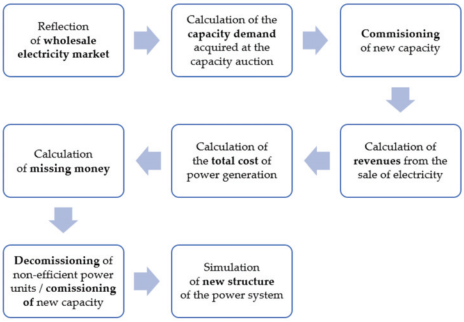

Figure 4. Calculation procedure under the CM scenario.

2.3. Mathematical Model

This section presents the description of the mathematical model developed. Symbols of sets, parameters, and variables used in the equations and inequalities are presented in Table 1.

Table 1. Symbol of sets, parameters, and variables used in the model.

Name	Explanation
	Sets
pp	Generation unit or group of units, $pp \in PP$
f	Fuel, $f \in F$
p	Pollutants and carbon dioxide, $p \in P = \{SO_2,\ NO_x, PM,\ CO_2\}$
h	Hours, $h \in H$
	Parameters
$Index_{pp,f}$	Incidence matrix–assignment of fuel f to generation unit or group of units pp (1–if fuel f is used by generation unit or group of units pp, 0–otherwise)
C_{pp}	Generation capacity of a generation unit or group of units pp (MW)
OCF_{pp}	Own-consumption factor of a generation unit or group of units pp
$AF_{pp,h}$	Availability factor of a generation unit or group of units pp at hour h
$MaxRampUpRate_{pp}$	Ramp-up rate of a generation unit or group of units pp
$MaxRampDownRate_{pp}$	Ramp-down rate of a generation unit or group of units pp
CF_{pp}	Capacity factor of a generation unit or group of units pp
EF_{pp}	Net electrical efficiency of a generation unit or group of units pp
FP_f	Price of fuel f (EUR/MWh)
$ER_{pp,p}$	Emission factor of pollutants or carbon dioxide p in a generation unit or group of units pp (kg/MWh)
EP_p	Environmental charges for emissions of pollutants and carbon dioxide p and CO_2 European Emission Allowances (EUR/kg)
VOM_{pp}	Variable operation and maintenance (VOM) cost of a generation unit or group of units pp (EUR/MWh)
D_h	Power demand at hour h (MW)
Im_h	Power import at hour h (MW)
Ex_h	Power export at hour h (MW)
Dur_h	Duration (1–in the case of a model with hourly intervals) (h)
	Variables
$PG_{pp,h}$	Power generation by a generation unit or group of units pp at hour h (MW)
$TVGC$	Total variable cost of a power generation in the power system (billon EUR)
	Parameters used in post-optimisation calculations
FC_{pp}	Fixed cost of a generation unit or group of units pp per 1 MW (million EUR/MW)
SMP_h	System marginal price at hour h (EUR/MWh)
$UpLift_h$	Margin at hour h
Q_f	Calorific value of fuel f (MJ/Mg or MJ/thousand m^3)
	Variables calculated in post-optimisation calculations
MCP_h	Market clearing price at hour h (EUR/MWh)
$Revenue_{pp,h}$	Revenue of a generation unit or group of units pp at hour h (million EUR)
$TotalCost_{pp}$	Total cost of a power generation in the generation unit or group of units pp (million EUR)
$Profit_{pp}$	Profit of a generation unit or group of units pp (million EUR)
$MissingMoney_{pp}$	Missing money of a generation unit or group of units pp (million EUR)
$ChemEnDemand_{pp}$	Chemical energy demand of a generation unit or group of units pp (GJ)
$HardCoalConsumption_{pp}$	Hard coal consumption in a generation unit or group of units pp (thousand Mg)
$TotalHardCoalConsumption$	Total hard coal consumption for electricity generation in the power system (million Mg)
$LigniteConsumption_{pp}$	Lignite consumption in a generation unit or group of units pp (thousand Mg)
$TotalLigniteConsumption$	Total lignite consumption for electricity generation in the power system (million Mg)

The objective function of the model, the total annual operational variable cost of electricity generation ($TVGC$), is given in Equation (1). The $TVGC$ is equal to the sum of the following components:

- The variable fuel cost, being the product of (i) the power generation $PG_{pp,h}$ by a unit or group of units pp at hour h, (ii) the fuel price FP_f divided by the net electrical efficiency EF_{pp}, and (iii) the duration Dur_h.

- The variable environmental cost, being the product of (i) the power generation $PG_{pp,h}$ by a unit or group of units pp at hour h, (ii) the emissions factor of pollutants or carbon dioxide $ER_{pp,p}$, (iii) the environmental charges for emission of pollutants and carbon dioxide and the CO_2 European Emission Allowances EP_p, and (iv) the duration Dur_h.
- The variable operations and maintenance (VOM) cost, being the product of (i) the electricity generation $PG_{pp,h}$ by a unit or group of units pp at hour h, (ii) the variable operation and maintenance cost VOM_{pp}, and (iii) the duration Dur_h.

$$\begin{aligned} TVGC = \sum\nolimits_{pp,h}\left(PG_{pp,h} * \left(\frac{\sum_f\left(Index_{pp,f} * FP_f\right)}{EF_{pp}} * Dur_h\right)\right) + \sum\nolimits_{pp,p,h}\left(PG_{pp,h} * ER_{pp,p} * \; EP_p * Dur_h\right) \\ + \sum\nolimits_{pp,h}\left(PG_{pp,h} * VOM_{pp} * Dur_h\right) \end{aligned} \tag{1}$$

The load and generation balance is given in Equation (2). The sum of power generation $PG_{pp,h}$ by a unit or group of units pp at hour h (decreased by an own-consumption factor OCF_{pp}) must be greater or equal to power demand D_h increased by the export Ex_h and decreased by the import Im_h.

$$\bigwedge\nolimits_{h \in H} \sum\nolimits_{pp}\left(PG_{pp,h} * \left(1 - OCF_{pp}\right)\right) \geq D_h + Ex_h - Im_h \tag{2}$$

The power generation balance is given in Equation (3). The power generation $PG_{pp,h}$ by a unit or group of units pp at hour h must be lower or equal to the product of the generation capacity C_{pp} and the availability factor $AF_{pp,h}$.

$$\bigwedge\nolimits_{pp \in PP} \bigwedge\nolimits_{h \in H} PG_{pp,h} \leq C_{pp} * AF_{pp,h} \tag{3}$$

The ramp-up balance is given in Equation (4). Each hour the increase in the volume of the power generation $PG_{pp,h}$ by a unit or group of units pp (compared to the previous hour) cannot be greater than the product of generation capacity C_{pp} and the ramp-up rate $MaxRampUpRate_{pp}$.

$$\bigwedge\nolimits_{pp \in PP} \bigwedge\nolimits_{h \in H} \; PG_{pp,h} - PG_{pp,h-1} \; \leq C_{pp} * \; MaxRampUpRate_{pp} \tag{4}$$

The ramp-down balance is given in Equation (5). Each hour the decrease in the volume of the power generation $PG_{pp,h}$ by a generation unit or group of units pp (compared to the previous hour) cannot be greater than the product of the generation capacity C_{pp} and the ramp-down rate $MaxRampDownRate_{pp}$.

$$\bigwedge\nolimits_{pp \in PP} \bigwedge\nolimits_{h \in H} \; PG_{pp,h-1} - PG_{pp,h} \; \leq \; C_{pp} * MaxRampDownRate_{pp} \tag{5}$$

The power generation constraint is given in Equation (6). The sum of the power generation $PG_{pp,h}$ by a unit or group of units pp at hour h divided by the sum of the generation capacity C_{pp} cannot be greater than their capacity factor CF_{pp}.

$$\bigwedge\nolimits_{pp} \frac{\sum_h\left(\; PG_{pp,h} * Dur_h\right)}{\sum_h\left(C_{pp} * Dur_h\right)} \leq \; CF_{pp} \tag{6}$$

The market clearing price is calculated using Equation (7). The market clearing price MCP_h at hour h is a product of the hourly system marginal price SMP_h and the hourly margin $UpLift_h$.

$$\bigwedge_{h \in H} MCP_h = SMP_h * UpLift_h \tag{7}$$

The revenue from the power generation $Revenue_{pp,h}$ of a unit or group of units pp is a product of the power generated $PG_{pp,h}$ by them at hour h, the market clearing price MCP_h, and the duration Dur_h.

$$\bigwedge_{pp\in PP} \bigwedge_{h\in H} Revenue_{pp,h} = PG_{pp,h} * MCP_h * Dur_h \tag{8}$$

The total cost of power generation $TotalCost_{pp}$ in a unit or group of units pp is given in Equation (9). The total cost is equal to the sum of (i) the variable cost of power generation, and (ii) the product of the fixed cost FC_{pp} and the generation capacity C_{pp}. The variable cost consists of the following elements: fuel, environmental, and VOM costs. The components are also presented in Equation (1).

$$\begin{aligned}\bigwedge_{pp\in P} TotalCost_{pp} = \Bigg(\Bigg(\sum\nolimits_h \Bigg(PG_{pp,h} * \Bigg(\frac{\sum_f \left(Index_{pp,f} * FP_f\right)}{EF_{pp}} * Dur_h\Bigg)\Bigg)\Bigg) + \sum\nolimits_{p,h} \Big(PG_{pp,h} * ER_{pp,p} * \; EP_p * Dur_h\Big) \\ + \sum\nolimits_h \Big(PG_{pp,h} * VOM_{pp} * Dur_h\Big) \Big) * 10^{-6}\Big) + \left(FC_{pp} * C_{pp}\right)\end{aligned} \tag{9}$$

The profit from power generation $Profit_{pp}$ of a generation unit or group of units pp is calculated as the difference between (i) the sum of the revenues $Revenue_{pp,h}$ of a unit or group of units pp at hour h, and (ii) the total cost of power generation $TotalCost_{pp}$ (Equation (10)).

$$\bigwedge_{pp\in PP} Profit_{pp} = \sum\nolimits_h \Big(Revenue_{pp,h}\Big) - TotalCost_{pp} \tag{10}$$

The missing money $MissingMoney_{pp}$ of a generation unit or group of units pp is a quotient of (i) its $Profit_{pp}$ and (ii) the product of the capacity generation C_{pp} (decreased by an own-consumption factor OCF_{pp}) and the availability factor $AF_{pp,h}$ (Equation (11)). The missing money is calculated exclusively for the units or group of units pp that do not make a profit from electricity generation.

$$\bigwedge_{pp\in PP} MissingMoney_{pp} = \frac{Profit_{pp}}{C_{pp} * \left(1 - OCF_{pp}\right) * AF_{pp}} \tag{11}$$

The chemical energy demand $ChemEnDemand_{pp}$ that is required for power generation in a unit or group of units pp is calculated using Equation (12). $ChemEnDemand_{pp}$ is equal to a quotient of (i) the product of power generation $PG_{pp,h}$ and the duration Dur_h, and (ii) the unit conversion rate 3.6.

$$\bigwedge_{pp\in PP} ChemEnDemand_{pp} = \frac{\sum_h \Big(PG_{pp,h} * Dur_h\Big)}{3.6} \tag{12}$$

The hard coal consumption $HardCoalConsumption_{pp}$ in a generation unit or group of units pp is a product of the chemical energy demand $ChemEnDemand_{pp}$, and the calorific value of the fuel Q_f used for power generation (Equation (13)). Therefore, the total hard coal consumption in the power system $TotalHardCoalConsumption$ is equal to the sum of the hard coal consumption in all hard coal-fired generation units or groups of units (Equation (14)).

$$\bigwedge_{pp\in PP} HardCoalConsumption_{pp} = ChemEnDemand_{pp} * Q_f * Index_{pp,f} \tag{13}$$

$$TotalHardCoalConsumption = \sum\nolimits_{pp} \left(HardCoalConsumption_{pp}\right) * \; 10^{-3} \tag{14}$$

The lignite consumption $LigniteConsumption\ _{pp}$ in the generation unit or group of units pp is a product of the chemical energy demand $ChemEnDemand_{pp}$, and the calorific value of the fuel Q_f used for power generation (Equation (15)). Therefore, the total lignite consumption in the power system *TotalLigniteConsumption* is equal to the sum of the lignite consumption in all lignite-fired generation units or groups of units (Equation (16)).

$$\bigwedge_{pp \in PP} LigniteConsumption_{pp} = ChemEnDemand_{pp} * Q_f * Index_{pp,f} \tag{15}$$

$$TotalLigniteConsumption = \sum_{pp} \left(LigniteConsumption_{pp} \right) * 10^{-3} \tag{16}$$

2.4. Input Data Assumptions

2.4.1. Power Demand

The hourly electricity demand curve of the reference year (2018) is shown in Figure 5. The total electricity demand was 171.2 TWh. The power demand curves for consecutive years of the study (2021–2040) are developed from the shape of the curve in the reference year and the average annual growth rate (1.5%) forecast by the Ministry of Energy [28]. The assumptions for specific years are shown in Table 2. The volume of power demand published in the Polish Energy Policy includes the reserve margin that is required to ensure power system security.

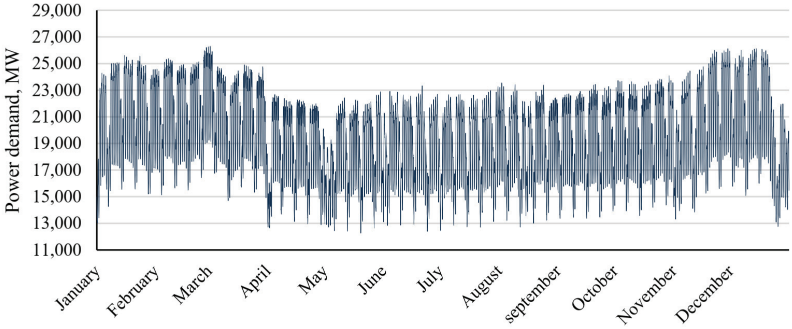

Figure 5. Power demand in the Polish power system in 2018 (based on [31]).

Table 2. Electricity demand in 2018–2040.

Parameter	Unit	2018	2021	2025	2030	2035	2040
Electricity demand	TWh	171.1	178.9	190.0	204.6	220.4	237.4

Source: Own analysis based on [28,31].

2.4.2. Import and Export

The study considers the volume of imported and exported electricity from neighbouring countries. The Polish power system has (i) synchronous connections with the German, Czech, and Slovak power systems and (ii) non-synchronous connections with the Swedish, Lithuanian, Ukrainian, and Belarusian power systems. The conditions of these connections are discussed in Ref. [32]. The total electricity import and export amounted to 13.8 TWh and 8.1 TWh in the reference year (2018).

Due to the complexity of estimating the electricity prices in European electricity markets, the study assumes that the rate as a percentage of cross-border exchange of electricity between Poland and the neighbouring countries is the same in each year of the analysis. As a result, net import (the difference between import and export) constitutes 3.30% of the total electricity demand each year.

2.4.3. Power Generation Units

The power generation units are characterised by their technical, economic, and environmental parameters. The data is sourced from governmental and international agency databases and reports. The main sources are the Transmission System Operator, the Energy Market Agency, the Energy Regulatory Office, the Central Statistical Office, the ENTSO-E platform, and databases managed by the Mineral and Energy Economy Research Institute of the Polish Academy of Sciences (MEERI PAS).

The public information on commissioning and decommissioning power generation units is also considered in the study. Additionally, the study assumes the commissioning of three nuclear power units of 1.3 GW in 2033, 2035, and 2038 [28]. Since uranium is not mined in Poland, the total volume is imported. Additionally, the study assumes that the nuclear units work as base-load due to their high start costs.

Electricity generation by CHP plants in 2021–2040 is based on the generation profile from the reference year (Figure 6). Industrial CHP plants supply the same volume of electricity to the power system every hour of the year.

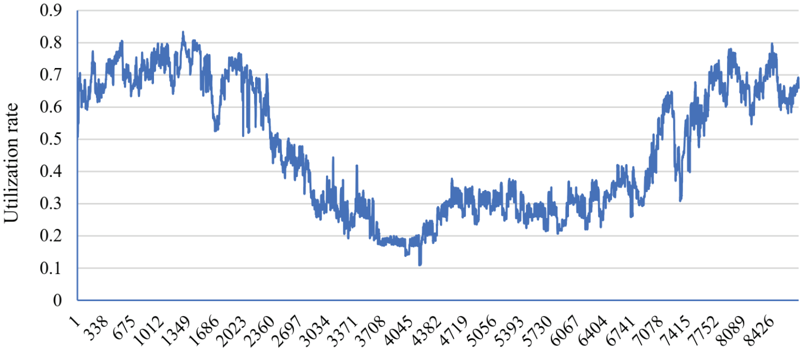

Figure 6. The average utilisation rate of CHP plants in 2018 (based on [33]).

The generation capacity of intermittent renewable units (solar, onshore, offshore, and hydro run-of-river) is assumed based on Ref. [28] (Figure 7). Electricity generation in 2021–2040 considers the generation profile of each technology in the reference year. As no offshore wind farms were operating in Poland in 2018, the generation profile was based on the German units (due to the weather conditions being similar to Poland) [34]. The study assumes that renewable generation sources are price-takers in the electricity market due to the low variable costs of generation.

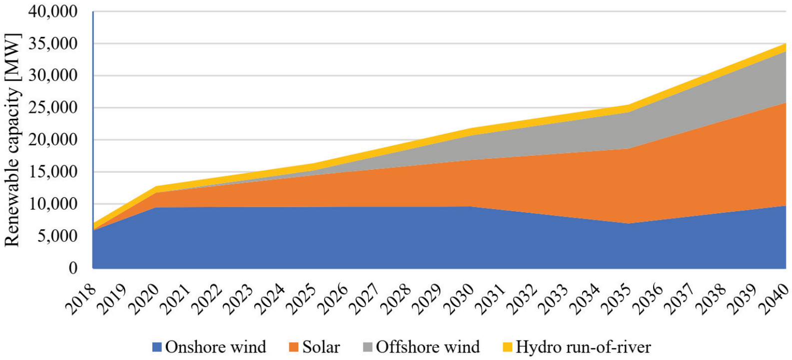

Figure 7. Renewable capacity in 2018–2040 (based on [28]).

The share of the demand-side response is assumed at a different level under the scenarios examined. The EOM scenario assumed that the share of DSR is at the level of 0.85% of maximum electricity demand. The capacity numeration mechanism supports these units. Therefore, the share of DSR in the CM scenario is greater and is different in each year of analysis (see subsection: Capacity market).

Finally, the study assumes that CHP plants, industrial power plants, and renewable generation sources sell their electricity generation in the electricity market in priority. Centrally dispatched power generation units cover the remaining demand (based on merit order).

2.4.4. Fuel Prices

Hard coal and natural gas price forecasts until 2040 are developed according to the Current Policies Scenario (CPS) of the World Energy Outlook Report [35]. As there are no long-term forecasts of lignite and biomass prices, they were calculated based on hard coal prices and the historical price relationship between them and hard coal prices. The fuel price assumptions are shown in Figure 8.

Uranium prices are assumed based on long-term contract prices (73.74 €/kgU in U_3O_8) and the forecast presented in Ref. [36].

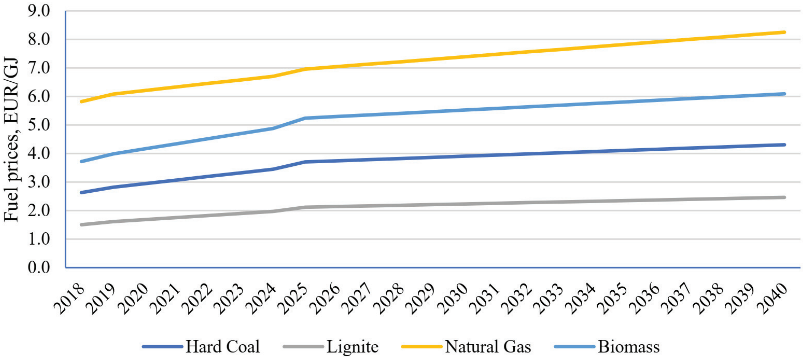

Figure 8. Fuel prices in 2019–2040 (based on [35,37,38]).

2.4.5. Environmental Charges

A forecast of CO_2 European Emission Allowances has been prepared according to the Current Policies Scenario (CPS) of the World Energy Outlook Report [35]. The results are shown in Figure 9. The calculation also includes environmental charges for the emission of pollutants (NO_x, SO_2, PM) and carbon dioxide. They are assumed according to national regulations and adjusted by the inflation rate each year of the analysis.

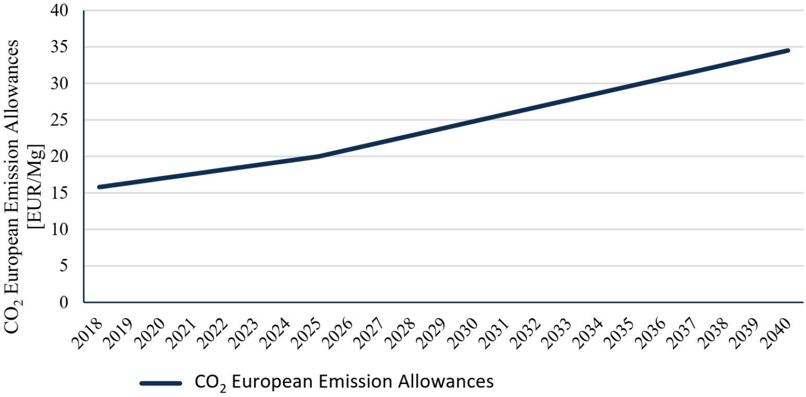

Figure 9. CO_2 European Emission Allowances in 2018–2040 (based on [35,39]).

2.4.6. Capacity Market

As previously mentioned, the average annual growth rate of power demand is 1.5% in the EOM scenario (36.36 GW in 2040). In the CM scenario, demand is calculated as a product of the forecast power demand and a coefficient of 1.31 (reserve margin). The assumptions are shown in Table 3. The generation structure is developed individually for each year of analysis based on the outcomes of the previous years.

Table 3. Power demand in the CM scenario until 2040.

Year	Power Demand [GW]
2021	27.4
2025	37.5
2030	41.0
2035	44.2
2040	47.6

Source: Own analyses based on [28].

The study assumes that the TSO acquires the entire required capacity in the main auction (auxiliary auctions are ignored in the analysis). Existing units may sign capacity agreements for one year and new units for fifteen years. In some cases (specified in Ref. [40]), capacity agreements can be signed for a period longer by two years (the green bonus). Moreover, according to the current regulations, coal-fired units cannot participate in the capacity auction from July 1, 2020 [30].

The capacity remuneration mechanism encourages demand-side response to participate in the market. Therefore, the study assumes that the volume of DSR capacity will increase from 0.6 GW in 2018 (2.25% of total power demand) to 3.1 GW in 2040 (6.56%).

Energy storage can also participate in the capacity auction. However, it has exclusively been pumped hydro storage (PHS) that has participated in the auctions conducted so far (for the supply years 2021–2024). Forecasts published by the Polish government do not assume an increase in the generation capacity of PHS technology but assume the growth in other technologies of energy storage systems (EESs) [28]. The study assumes that the capacity in EESs will increase by 20% each year due to decreasing capital expenditure [41,42]. Therefore, the EESs' capacity will increase from 90.9 MW in 2021 (0.33% of total power demand) to 2.5 GW in 2040 (5.48%). These values exclude generation capacity in PHS (approx. 1.7 GW throughout the period). Power generation units deployed in adjacent power systems did not participate in the capacity auction for 2021–2024. The study assumes that this will continue throughout the analysis period.

2.4.7. Other Assumptions

Value of Lost Load (VoLL) is assumed at EUR 3000/MWh [43]. The assumed prices and costs (e.g., fuel prices, environmental charges, VOM costs, fixed costs, and VoLL) are adjusted for inflation [44].

The study does not assume any constraint on the supply of hard coal. Hard coal can be acquired from domestic producers or be imported. However, in the case of lignite, the demand cannot exceed the maximum current and forecast production of domestic mines [45].

3. Results and Discussion

This section presents and discusses the results of the study. Since the Polish power system is heavily dependent on fossil fuel-based generation from hard coal and lignite, the changes related to these fuels are mainly discussed in the following subsections. Results regarding other energy sources in terms of installed capacity and electricity production are provided in Annex 1.

Key measures are used to analyse and compare results between the EOM and CM scenarios in order to adequately address the research question of this study:

- Coal-fired power generation capacity (Section 3.1).
- Electricity generation from coal-fired units (Section 3.2).
- Coal consumption for electricity generation (Section 3.3).

Additionally, the section presents electricity prices under two research scenarios (3.4. Electricity Prices).

3.1. Coal-Fired Power Generation Capacity

The total generation capacity in the Polish power system was 42.4 GW in the reference year (2018). The share of coal-fired generation capacity was almost 70% of total capacity installed and over 93% of capacity installed in carbon technologies (20.6 GW of hard coal-fired power generation units and 8.7 GW of lignite-fired units).

In the following years of the analysis (2021–2040), the total generation capacity in the Polish power system increases regardless of the scenario analysed; however, the volume is higher each year under the CM scenario (Figure 10). This effect is a consequence of guaranteeing a reserve margin in the case of capacity market operation. The greatest difference between scenarios is observed in 2021–2024 (10.4–14.7%). In these years, numerous inefficient, hard coal-fired units that are decommissioned under the EOM scenario are financially supported in the CM scenario. The difference follows a decreasing trend over the next four years, and from 2028 to the end of the analysed period, it remains at the level of 6.0%.

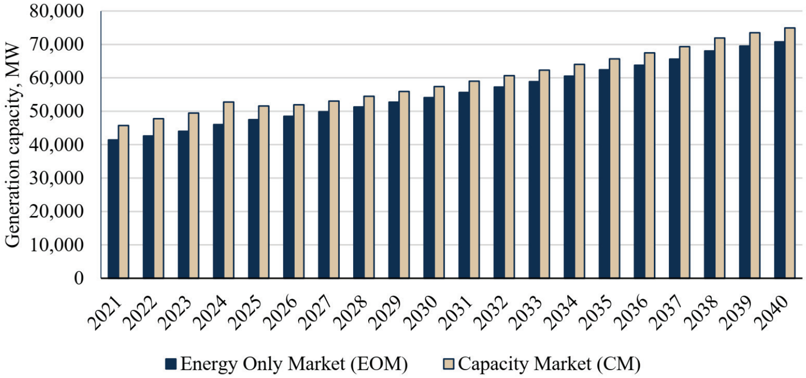

Figure 10. Generation capacity in the power system under the EOM and CM scenarios in 2021–2040.

Figures 11 and 12 show the hard coal-fired and lignite-fired generation capacity under the EOM and CM scenarios in 2021–2040. The extensive generation structures of the power system in the reference year (2018) and specific years of analysis (2021, 2025, 2030, 2035, and 2040) are presented in Appendix A (Table A1).

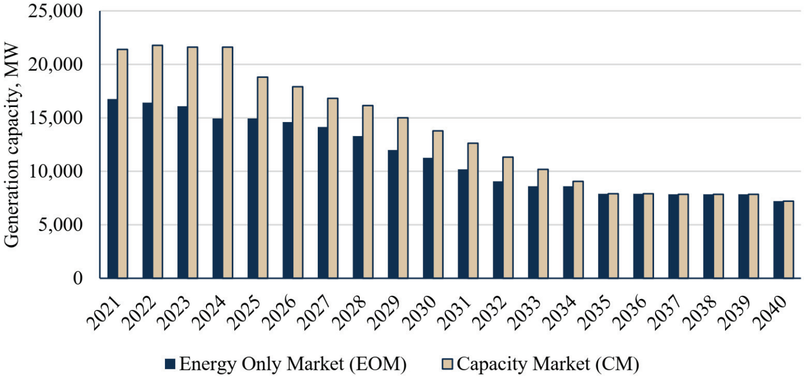

Figure 11. Hard coal-fired generation capacity under the EOM and CM scenarios in 2021–2040.

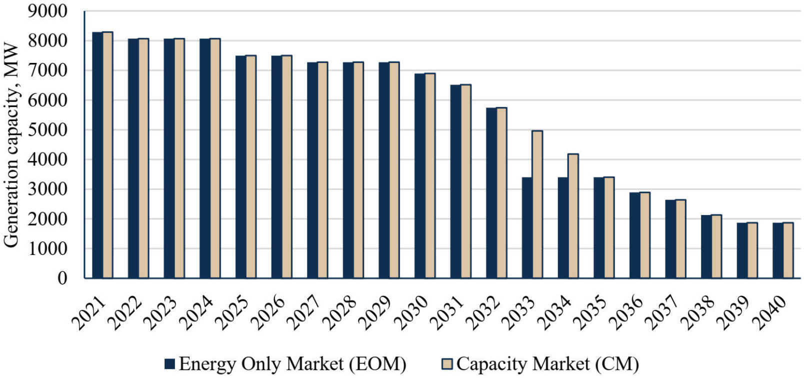

Figure 12. Lignite-fired generation capacity under the EOM and CM scenarios in 2021–2040.

Although hard coal-fired generation capacity decreases over the entire time horizon of analysis regardless of the research scenario, the volume of capacity is different in specific years in the EOM and CM scenarios (Figure 11). The results indicate that the greatest difference between scenarios is in 2021–2024. The difference stems from the fact that a significant number of coal-fired power generation units have insufficient profits from the energy only market, and in consequence, missing money problems occur. In the CM scenario, these units received additional income from the capacity market. Therefore, they are maintained in the system.

As previously mentioned, hard coal-fired units cannot be supported by public funds from 2025. Additionally, environmental charges have an increasing influence on the total generation cost of electricity. Under those circumstances, the difference between the scenarios decreases to 2034. After this year, the generation capacity is almost the same under both scenarios examined by the last year of analysis (units commissioned to the power system after 2018). Therefore, according to the assumptions, they are not decommissioned from the power system regardless of their financial outcomes.

Table 4 presents the generation capacity in hard coal-fired units in specific years. The table also includes information about changes compared to the reference year (2018).

Table 4. Generation capacity in hard coal-fired power generation units.

	Energy Only Market (EOM)		**Capacity Market (CM)**	
2018	**20.6 GW**			
	Generation capacity	Changes compared to 2018	Generation capacity	Changes compared to 2018
2021	16.8 GW	↓ 18.6%	21.4 GW	↑ 3.9 %
2025	14.9 GW	↓ 27.5%	18.8 GW	↓ 8.6%
2030	11.3 GW	↓ 45.3%	13.8 GW	↓ 33.1%
2035	7.9 GW	↓ 61.6%	7.9 GW	↓ 61.6%
2040	7.2 GW	↓ 65.0%	7.2 GW	↓ 65.0%

Unlike the generation capacity of hard coal-fired units, the difference in the lignite-fired generation capacity is not that significant (Figure 12). The costs of electricity generation in lignite-fired power units are significantly lower. Consequently, these units are base-load under both scenarios in the first years of the analysis (2021–2032). The decrease in the generation capacity in these years is a consequence of the decommissioning of certain units due to technical, not economic reasons.

The difference between the EOM and CM scenarios is only observed in 2033–2024 because of the long-term capacity agreement of the two units. The increasing environmental charges result in a missing money problem in units that are decommissioned in the EOM scenario.

The decrease in the generation capacity in both scenarios is still observed in 2035–2038. In the two last years of analysis, the generation capacity is at the same level in both scenarios (only units commissioned to the power system after 2018).

Table 5 shows the generation capacity in lignite-fired units in specific years. The table also includes details of the changes compared to the reference year (2018).

Table 5. Generation capacity in lignite-fired power generation units.

	Energy Only Market (EOM)		**Capacity Market (CM)**	
2018	**8.7 GW**			
	Generation capacity	Changes compared to 2018	Generation capacity	Changes compared to 2018
2021	8.3 GW	↓ 4.9%	8.3 GW	↓ 4.9%
2025	7.5 GW	↓ 14.0%	7.5 GW	↓ 14.0%
2030	6.9 GW	↓ 20.9%	6.9 GW	↓ 20.9%
2035	3.4 GW	↓ 61.0%	3.4 GW	↓ 61.0%
2040	1.9 GW	↓ 78.6%	1.9 GW	↓ 78.6%

As previously mentioned, the general structure of the power system is presented in Table A1, Appendix A. The table shows the study results in 2021, 2025, 2030, 2035, and 2040. It can be observed that the share of coal-fired units decreases. According to the developed research concept, in the case of insufficient capacity in the system, new capacities (with the lowest investments cost) are added, which enable balancing the demand and supply in the power system. Under the EOM scenario, the volume of commissioned power is 700 MW in 2021. On the other hand, under the CM scenario, the total capacity available in the power system is sufficient. Therefore, new generation capacities are not commissioned. In 2021, the capacity in renewable units (biomass, biogas, water, wind, and photovoltaic units) is 11.3 GW, which is a 21.7% increase compared to 2018. Under the EOM scenario, the share of renewable units is 27.2%, while under the CM scenario, it is 24.6%.

In 2025, under both scenarios analysed, the total capacity in the power system is sufficient in each of the analysed years (2022–2025). Therefore, no new units are added. In 2025, the capacity available in renewable units amounts to 18.5 GW, which is a 63.9% increase when compared to 2021. Under the EOM scenario, the share of renewable units is 38.9%, while under the CM scenario, it is 35.8%. In 2025, the first offshore wind farms are commissioned to the power system.

In 2026–2030, due to the lack of sufficient capacity meeting the economic efficiency criterion in the system, new units with a total capacity of 5.3 GW are added under the EOM scenario and 5.2 GW under the CM scenario. In 2030, the capacity available in renewable units amounts to 23.9 GW, which is a 29.7% increase compared to 2025. Under the EOM scenario, the share of renewable units is 44.3%, while under the CM scenario, it is 41.7%.

In line with the adopted assumptions, under both scenarios, two nuclear units are commissioned to the system with a generating capacity of 1,300 MW each. The first unit is put into operation in 2033, and the second in 2035. In 2031–2035, new generating units with a total capacity of 6.2 GW are added due to the lack of sufficient capacity in the system under the EOM scenario. Under the CM scenario, natural gas units with a total generating capacity of 8.0 GW are added. In 2035, the capacity available in renewable units is 30.0 GW, which is a 25.5% increase compared to 2030. Under the EOM scenario, the share of renewable units is 48.1%, while under the CM scenario, it is 45.7%.

In 2038, another 1,300 MW nuclear unit is commissioned to the power system under both scenarios. Under the EOM scenario, the lack of sufficient capacity in the system occurs in 2036–2037 and 2040. In the remaining years, the capacity available in the power system is sufficient to balance the demand. Under the CM scenario, gas capacities are added in the same years. In 2036, 600 MW of new capacity is commissioned, while 400 MW in 2037 and 150 MW in 2040. In 2040, the capacity of renewable units is 36.9 GW, which is a 22.7% increase when compared to 2035. Under the EOM scenario, the share of renewable units is 52.1%, while under the CM scenario, it is 49.2%.

3.2. Electricity Generation from Coal-Fired Units

Figures 13 and 14 present volumes of hard coal-fired and lignite-fired electricity generation under the EOM and CM scenarios in 2021–2040. The extensive structures of electricity production in the reference year (2018) and specific years of analysis (2021, 2025, 2030, 2035, and 2040) are presented in Appendix A (Table A2). The figures present the key changes in the years ahead.

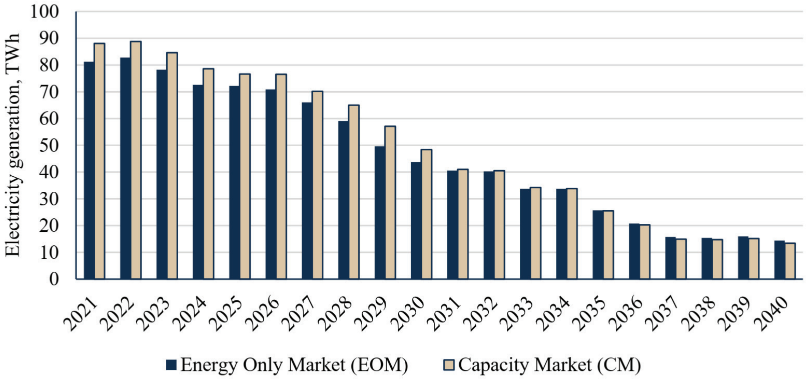

Figure 13. Electricity generation from hard coal-fired units under the EOM and CM scenarios in 2021–2040.

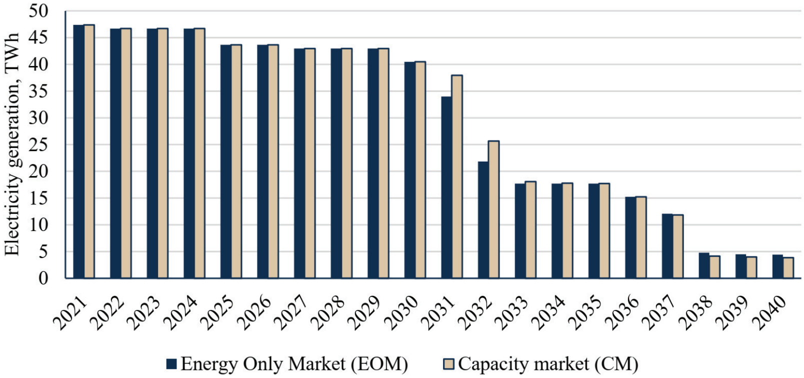

Figure 14. Electricity generation from lignite-fired units under the EOM and CM scenarios in 2021–2040.

Similar to the results of the generation capacity, electricity production from hard coal-fired power units also decreases throughout the period of analysis, regardless of the scenario and the assumptions adopted (Figure 13).

The greatest difference between the EOM and CM scenarios is observed over the period 2021–2030. The difference stems directly from the technology structure. The share of hard coal-fired units in the EOM scenario is lower. Therefore, a lower volume of electricity is generated by these units.

Between 2031 and 2036, electricity production is at a similar level in both scenarios because hard coal-fired units gradually reduce their share in the total generation of the power system. Additionally, the increasing environmental charges mean that electricity is mostly generated in other units. The renewable, natural gas-fired, and nuclear units are characterised by lower generation costs, and consequently, they have priority to access the transmission grid.

In 2037–2040, the quantity of electricity generated in hard coal-fired units is greater in the EOM scenario. The trend is changing due to the fact that the hard coal-fired units have a greater share in the power system. On the other hand, in the CM scenario (in which the reserve margin is secured), the capacity of natural gas-fired units and demand-side response is greater. These units meet the power demand first.

Table 6 provides detailed information about changes in the electricity generation from hard coal-fired units over the period analysed and scenarios examined.

Table 6. Electricity generation in hard coal-fired power units.

	Energy Only Market (EOM)		**Capacity Market (CM)**	
2018	**83.2 TWh**			
	Electricity generation	Changes compared to 2018	Electricity generation	Changes compared to 2018
2021	81.2 TWh	↓ 2.4%	88.0 TWh	↑ 5.9%
2025	72.2 TWh	↓ 13.2%	76.6 TWh	↓ 7.9%
2030	43.7 TWh	↓ 47.4%	48.4 TWh	↓ 41.8%
2035	25.7 TWh	↓ 69.1%	25.5 TWh	↓ 69.3%
2040	14.4 TWh	↓ 82.7%	13.4 TWh	↓ 83.9%

There is no significant difference in electricity generation from lignite-fired power units up to 2030 under the scenarios examined (Figure 14). These are base-load units due to the low generation cost. The decrease in electricity generation in 2025 and 2030 stems from the decommissioning of certain units due to their technical condition, not due to the missing money problem.

A difference between the EOM and CM scenarios is observed in 2031–2032. Increasing environmental charges result in an increase in generation costs in lignite-fired power units. After this year, the share of natural gas-fired units, commissioning of nuclear units and increasing share of renewables result in decreased electricity production from lignite in both scenarios examined.

From 2038, the quantity of electricity generated in lignite-fired units is greater in the EOM scenario. Similar to the hard coal-fired units, the change in the trend is due to the fact that the lignite coal-fired units have a greater share in the power system under this scenario. On the contrary, in the CM scenario (in which the reserve margin is secured), the capacity of natural gas-fired units and demand-side response is greater, and these units sell electricity before more expensive ones.

Table 7 provides information about changes in the electricity generation from lignite-fired units over the period analysed and scenarios examined.

Table 7. Electricity generation in lignite-fired power units.

	Energy Only Market (EOM)		**Capacity Market (CM)**	
2018	**45.7 TWh**			
	Electricity generation	Changes compared to 2018	Electricity generation	Changes compared to 2018
2021	47.4 TWh	↑ 3.6%	47.4 TWh	↑ 3.6%
2025	43.7 TWh	↓ 4.5%	43.7 TWh	↓ 4.5%
2030	40.5 TWh	↓ 11.5%	40.5 TWh	↓ 11.5%
2035	17.7 TWh	↓ 61.3%	17.7 TWh	↓ 61.3%
2040	4.4 TWh	↓ 90.3%	3.8 TWh	↓ 91.6%

The fuel-mix of electricity generation in 2021, 2025, 2030, 2035, and 2040 are presented in Table A2, Appendix A.

In 2021, under the EOM scenario, electricity production in hard coal-fired units is 81.2 TWh (2.4% lower when compared to 2018). Under the CM scenario, production in these units amounts to 88.0 TWh (an increase of 5.9% when compared to 2018). The difference between the scenarios is a consequence of maintaining the coal-fired units under the CM scenario, which signed contracts of the capacity obligation, and the commissioning of new natural gas units under the EOM scenario. Natural gas units have lower generation costs than obsolete coal units these years. Therefore, the demand is covered by production from these units in priority.

In 2025, the total volume of electricity is 183.6 TWh, an increase of 6.1% compared to 2021. The results show that hard coal remains the dominant fuel. Electricity production in lignite units is the same under both scenarios and amounts to 43.7 TWh, which is a decrease of 7.9% compared to 2018. It is a consequence of withdrawing lignite-fired units from the system due to their technical condition. In 2025, under the EOM scenario, production in hard coal-fired units is 72.2 TWh and is 11.1% lower compared to 2021. Under the CM scenario, production in these units is 76.6 TWh, which is a decrease compared to 2018 by 13.0%. Hard coal consumption decreases under both scenarios due to the cheaper electricity produced in natural gas units. The total electricity production in natural gas units is 33.2 TWh under the EOM scenario and is 50.5% higher compared to 2021. Under the CM scenario, the volume of electricity is 28.9 TWh, which is an increase of 79.8% when compared to 2021.

In 2030, the total volume of electricity is 197.8 TWh, which is an increase of 7.7% when compared to 2021. Most electricity under both scenarios is produced in natural gas units. It is a consequence of the increase of new natural gas units added to the system in order to cover the power demand. Considering the increasing prices of CO2 European Emission Allowances, these units are characterised by a lower cost of electricity generation than most units using solid fossil fuels. The volume of electricity produced in lignite-fired units is the same under both scenarios in 2030 and amounts to 40.5 TWh, which decreases by

7.3% compared to 2025. The progressive increase in prices of carbon certificates means that lignite-fired units produce electricity at a higher production cost than new natural gas units. In 2030, under the EOM scenario, production in hard coal-fired generation units is 43.7 TWh and is 39.5% lower compared to 2025. Under the CM scenario, production in these units is 48.4 TWh, which is 36.8% less when compared to 2018.

In 2035, the total volume of electricity produced this year is 213.1 TWh, 7.7% higher when compared to 2030. The dominant units in the electricity production fuel-mix are natural gas-fired units. Electricity production in natural gas units under the EOM scenario is 89.7 TWh, which is an increase of 37.9% when compared to 2030. Under the CM scenario, the production volume is 89.9 TWh and is higher by 48.9% when compared to 2030. The decline in the growth rate of electricity production from natural gas-fired units is a consequence of the commissioning of two nuclear units to the power system. These units are characterised by lower production costs than other conventional units, so the electricity produced in them meets the demand in prior. Electricity production in nuclear units is the same under both analysed scenarios and amounts to 21.6 TWh.

In 2040, the total volume of electricity produced is 229.6 TWh, 7.7% higher when compared to 2035. Natural gas is also the dominant fuel. Electricity production in natural gas-fired units is 106.4 TWh under the EOM scenario, 18.7% more than in 2035. Under the CM scenario, the production volume is 108.2 TWh and is higher by 20.3% compared to 2030. Production in nuclear units is the same under both scenarios and amounts to 32.2 TWh, which is an increase of 50.0% compared to 2035.

3.3. Coal Consumption for Electricity Generation

Fuel consumption is directly dependent on the structure of electricity generation. Therefore, coal consumption depends on generation by coal-fired capacity in the power system and the availability of generation units. In order to convert demand for coal consumption from energy units to mass units, the calorific value is adopted in line with data published by the Energy Market Agency (e.g., 21,075 MJ/Mg in hard coal-fired power plants, 21,952 MJ/Mg in hard coal-fired CHP, and 8,019 MJ/Mg in lignite-fired power plants) [37].

3.3.1. Hard Coal Consumption

Hard coal consumption over the period 2021–2040 under both scenarios is shown in Figure 15, and the differences between the scenario results are presented in Figure 16. Hard coal consumption for electricity generation decreases in both the EOM and CM scenarios, but the characteristics of these changes are different. Table 8 provides detailed information about these differences over the period analysed and the scenarios examined. The changes over the periods are greater than changes in electricity generation in hard coal-fired units which stems from the increase in net electrical efficiency in existing and new hard coal-fired power generation units. % start a new page without indent 4.6cm

Table 8. Hard coal consumption for electricity generation.

	Energy Only Market (EOM)		**Capacity Market (CM)**	
2018	**37.1 Million Mg**			
	Hard coal consumption	Changes compared to 2018	Hard coal consumption	Changes compared to 2018
2021	33.8 million Mg	↓ 9.0%	37.2 million Mg	↑ 0.2%
2025	29.1 million Mg	↓ 21.5%	31.4 million Mg	↓ 15.4%
2030	15.7 million Mg	↓ 57.7%	17.9 million Mg	↓ 51.9%
2035	8.9 million Mg	↓ 75.9%	8.9 million Mg	↓ 76.1%
2040	4.9 million Mg	↓ 86.9%	4.5 million Mg	↓ 87.9%

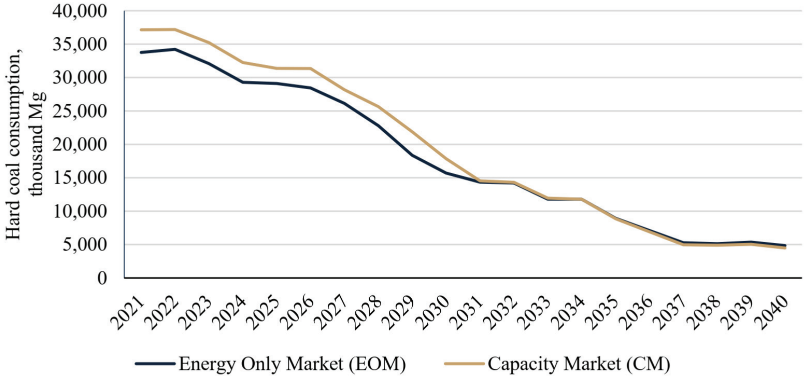

Figure 15. Hard coal consumption for electricity generation under the EOM and CM scenarios in 2021–2040.

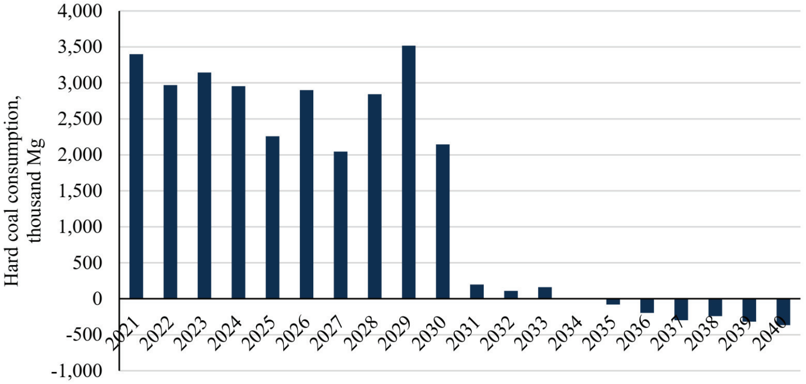

Figure 16. Differences in hard coal consumption between the CM and EOM scenarios in 2021–2040.

In 2021–2024, hard coal consumption decreases from 37.2 million Mg to 32.3 million Mg under the CM scenario. In this period, the consumption under the EOM scenario is lower on average by 9.7%. The difference is mainly due to the lower generation capacity in hard coal-fired power plants and CHP plants. Consequently, there is a lower volume of electricity generated in these units under the EOM scenario. In the CM scenario, some units with negative financial results from the energy market receive financial support from the capacity market and are still in the power system.

In 2025–2026, hard coal consumption still decreases in both scenarios. Additionally, some units are decommissioned from the power system due to their technical condition. As a result, the consumption in the CM scenario is higher by 7.8% in 2025 and 10.2% in 2026 when compared to the EOM scenario.

In 2027–2029, hard coal consumption decreases to 21.9 million Mg in the CM scenario. However, the difference between the two scenarios increases compared to the previous years and reaches 19.2% (3.5 million Mg) in 2029. The maintenance of hard coal-fired power generation units in the power system through the support mechanism results in the commissioning of a smaller volume of new generation capacity. Thus, the operation of the capacity market contributes to maintaining the existing generation units that meet the peak power demand. There are no requirements to commission many new units in the CM scenario.

In 2030, hard coal consumption in the CM scenario decreases to 19.9 million Mg. The difference between the scenarios decreases to 2.1 million Mg due to the fact that there are also smaller differences between hard coal generation capacity in the system in both scenarios in 2030. It should also be noted that due to the increasing prices of the CO_2 European Emission Allowances, hard coal-fired units are becoming less and less competitive when compared to other technologies. In the following years, the differences between the hard coal consumption in the scenarios are much smaller, and in 2034 hard coal consumption is almost the same in both scenarios.

In 2035–2040, hard coal consumption in the CM scenario reaches 4.2 million Mg (7.6% lower than the EOM scenario). The change of the trend is caused by the greater volume of gas-fired capacity generation in the CM scenario. Natural gas-fired power units are characterised by much lower generation costs than hard coal-fired units due to further increases in the prices of the CO_2 European Emission Allowances.

3.3.2. Lignite Consumption

Lignite consumption over the period 2021–2040 under both of the scenarios examined is shown in Figure 17. As is the case with hard coal consumption, the decrease is observed throughout the entire period of analysis and under the two scenarios. Similarly, periods with characteristic differences are observed (Figure 18). Table 9 provides detailed information about these differences over the period analysed and the scenarios examined.

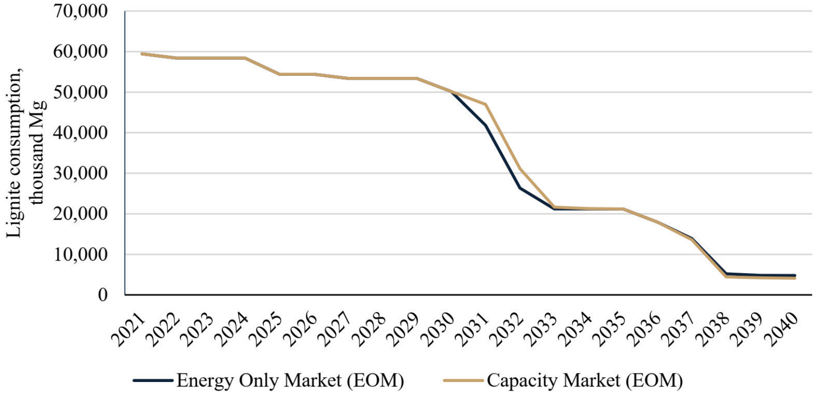

Figure 17. Lignite consumption for electricity generation under the EOM and CM scenarios in 2021–2040.

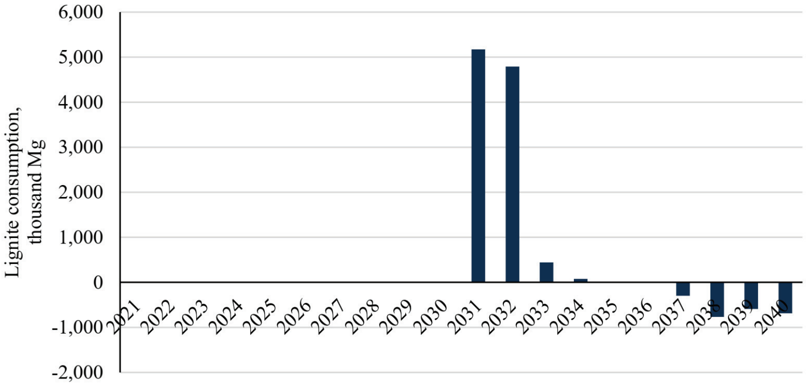

Figure 18. Differences in lignite consumption between the CM and EOM scenarios in 2021–2040.

Table 9. Lignite consumption for electricity generation.

	Energy Only Market (EOM)		Capacity Market (CM)	
2018	**58.4 Million Mg**			
	Lignite consumption	Changes compared to 2018	Lignite consumption	Changes compared to 2018
2021	59.4	↑ 1.8%	59.4	↑ 1.8%
2025	54.4	↓ 6.8%	54.4	↓ 6.8%
2030	50.2	↓ 14.1%	50.2	↓ 14.1%
2035	21.2	↓ 63.7%	21.2	↓ 63.7%
2040	4.8	↓ 91.8%	4.1	↓ 93.0%

In 2021–2030, lignite consumption decreases from 59.4 million Mg to 50.2 million Mg. The reduction stems from the fact that some lignite-fired power generation units are decommissioned. However, as previously mentioned, the causes of the decommissioning are technical, not financial. The results indicate that lignite-fired units meet the condition of economic efficiency, and they work as base-load units in these years.

The difference between the scenarios is the greatest in 2031–2032. During this period, lignite-fired power units generate a smaller amount of electricity in the EOM scenario because other units have priority due to lower generation costs (e.g., renewable, gas-fired). Increasing prices of the CO_2 European Emission Allowances result in increasing costs of electricity generation in lignite-fired power generation units when compared to other technologies. In the following years, lignite consumption is similar under the scenarios examined (2033–2034) or even the same (2035).

In 2037–2040, the lignite consumption is greater in the EOM scenario (4.9 million Mg compared to 4.5 million Mg in the CM scenario). The change of the trend stems from the fact that there is a lower gas-fired generation capacity in the EOM scenario (with a lower cost of power generation). This level is higher in the CM scenario due to reserve margin requirements in the power system at 30.91%.

3.4. Electricity Prices

The electricity prices in both scenarios are shown in Figure 19. The prices are higher under the EOM scenario regardless of the year of analysis. They range from EUR 62.2/MWh to EUR 84.4/MWh, while in the CM scenario, electricity prices range from EUR 47.7/MWh to EUR 78.8/MWh. This is because electricity prices reflect not only the generation cost but also the reserve margin in the power system. Since the assumption of a reserve margin at 30.91% was adopted in the capacity market (based on past auctions), this is sufficient to maintain lower prices. In the EOM scenario, the reserve margin is always lower, resulting in greater electricity prices.

Table 10. Average annual electricity prices.

	Energy Only Market (EOM)		Capacity Market (CM)	
2018	**EUR 52.4/MWh**			
	Electricity price	Changes compared to 2018	Electricity price	Changes compared to 2018
2021	EUR 62.2	↑ 18.8%	EUR 47.7	↓ 9.0%
2025	EUR 74.5	↑ 42.2%	EUR 61.5	↑ 17.5%
2030	EUR 71.9	↑ 37.2%	EUR 66.5	↑ 26.9%
2035	EUR 68.8	↑ 31.4%	EUR 62.9	↑ 20.0%
2040	EUR 84.4	↑ 61.1%	EUR 75.8	↑ 44.7%

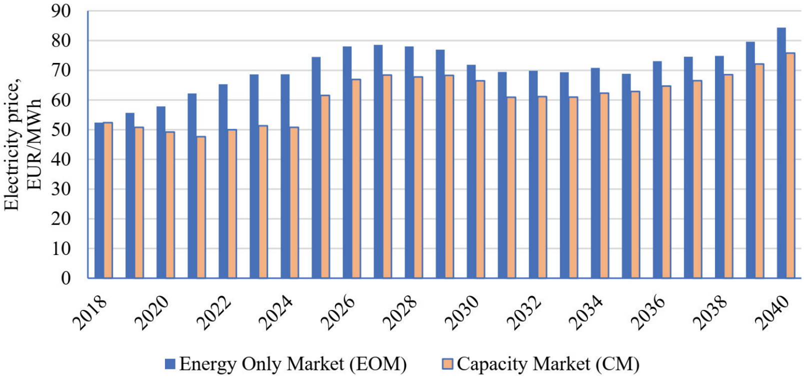

Figure 19. Electricity prices under the EOM and CM scenarios in 2021–2040.

Table 10 provides more detailed information about changes in the electricity prices over the period analysed and the scenarios examined.

4. Conclusions

The research carried out in this paper forms the first study on the quantitative assessment of the long-term impact of the introduction of a capacity market on decarbonisation in power systems with a high penetration of fossil fuels. Since the capacity market has been introduced in Poland relatively recently, the results of the analyses and the conclusions drawn on their basis constitute a significant contribution to the discussion on the legitimacy and consequences of its implementation.

The impact of the introduction of a capacity market on the decarbonisation of the Polish power system was assessed based on the (i) coal-fired generation capacity in the power system, (ii) electricity generation from coal-fired units, and (iii) quantity of coal consumption for electricity generation. Additionally, the forecasts for electricity prices in 2021–40 were also calculated.

The findings show that the introduction of the capacity market results in the slowing down of the decarbonisation process in Poland. This instrument mainly provides support for thermal power plants that consume fossil fuels. The consequences of lengthy capacity agreements (for as long as 15 years) are observed in the long-run. As a result, coal-fired power units are maintained far longer than without the capacity remuneration mechanism.

The results indicate that the decarbonisation of the Polish power system is inevitable by 2040 regardless of the scenario analysed. Hard coal consumption decreases by 86.9% and 87.9%, respectively, in the EOM and CM scenarios. Lignite consumption is reduced by 91.8% and by 93.0%, respectively. Research findings point out, however, that the introduction of a capacity market results in a delay in the process of decarbonisation of the Polish power system. A slowing down of the process of withdrawing hard coal-fired power generation units is observed in 2021–2030, and in the case of lignite-fired units in 2031–2032. The greatest difference between hard coal consumption for power generation under EOM and CM scenarios is as much as 19.2% per year. Whereas, in the case of lignite, the greatest difference is 18.2%.

Coal consumption for electricity generation also decreases regardless of the research scenario. Differences are observed between the two scenarios, especially in the case of hard coal consumption. The capacity market supported these units in the first years of its operation. The results indicate that numerous hard coal-fired power units would have to be decommissioned from the power system without the support from the capacity mechanism because maintaining them in the system would be unprofitable. The introduction of the capacity market does not significantly impact lignite consumption. In the first ten years of the analysis, the volume of generation capacity in the system is the same for both scenarios. Lignite consumption decreases regardless of the scenario considered (due to the technical condition of the plants, not because of economic inefficiency). These units generate electricity at a sufficiently low price to operate as the base-load of the power system. The differences between the scenarios occur when the increase in the price of the CO_2 European Emission Allowances is large enough to push them out of the system by units with lower generation costs.

In the last year of analysis, the hard coal and lignite consumption is greater in the scenario without a capacity remuneration mechanism. This stems from the fact that coal-fired units have a greater share in the EOM scenario. Consequently, more coal-fired units generate electricity in peak demand than is the case in the CM scenario.

The decarbonisation of the Polish power system through the phasing-out of coal-fired units is inevitable by 2040 regardless of the scenario analysed. The capacity market does not stop the transformation, although it delays the process significantly, particularly in the upcoming years. As a result, the capacity market has a negative impact on carbon neutrality in the short- and mid-term.

However, the operation of the capacity market ensures an adequate reserve margin in the power system. As a consequence, energy security is improved. In addition, the implementation of the capacity remuneration mechanism ensures the stability of energy supplies during the first phase of the decarbonisation process of the Polish power system. The support mechanism also extends the time for the preparation of new regulations and support schemes for other technologies (e.g., renewables, energy storage, demand-side response) and the climate and energy policies required for further phases of the energy transition and decarbonisation of the Polish power system.

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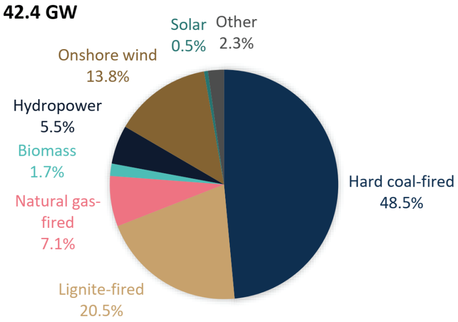
Abbreviations

CHP	Combined Heat and Power
CM	Capacity Market
CRM	Capacity Remuneration Mechanism
DSR	Demand-Side Response
EESs	Energy Storage Systems
EDP	Economic Dispatch Problem
EOM	Energy Only Market
GHG	Greenhouse Gas
LP	Linear Programming
PHS	Pumped Hydro Storage
TSO	Transmission System Operator
VoLL	Value of Lost Load
VOM	Variable Operations and Maintenance

Appendix A

Table A1. Structure of generation capacity under the EOM and CM scenarios.

<table>
<tr><td>2018</td><td colspan="2">

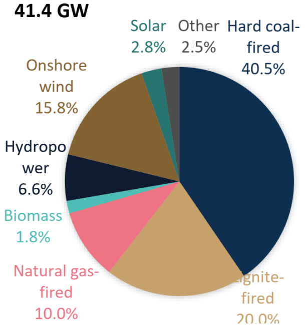
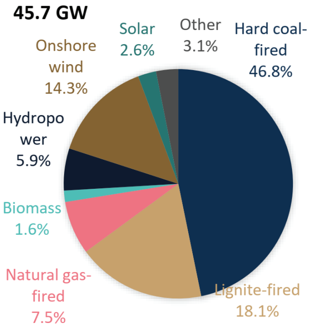
Source: [20,35]</td></tr>
<tr><td></td><td>Energy Only Market (EOM)</td><td>Capacity Market (CM)</td></tr>
<tr><td>2021</td><td>
</td><td>
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Table A1. *Cont.*

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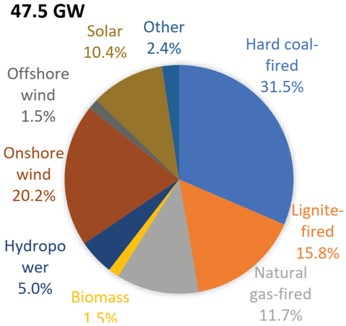
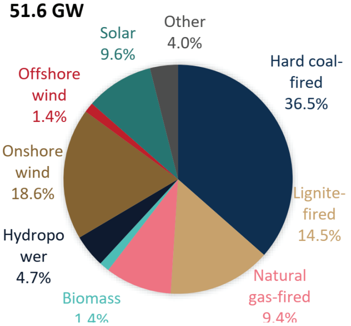
<tr><td>2025</td><td>
</td><td>
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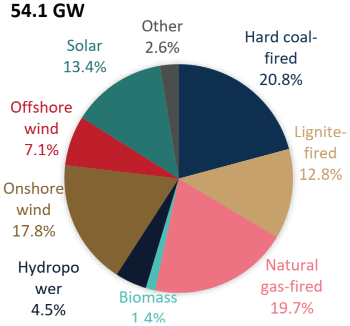
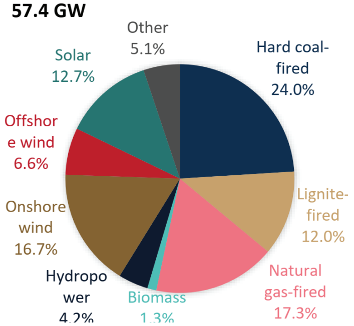
<tr><td>2030</td><td>
</td><td>
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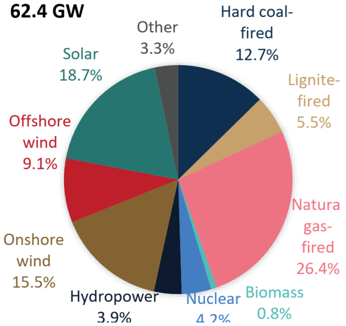
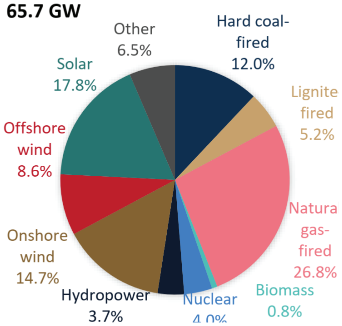
<tr><td>2035</td><td>
</td><td>
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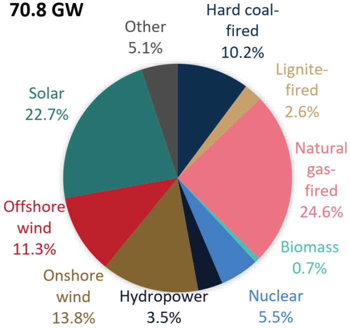
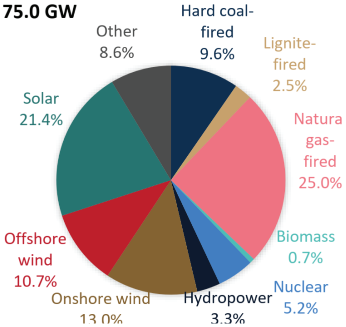
<tr><td>2040</td><td>
</td><td>
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Table A2. Fuel-mix of electricity generation under the EOM and CM scenarios.

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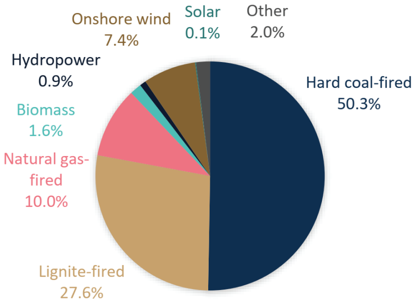
165.5 TWh</td><td colspan="2">
Source: [20,26]</td></tr>
<tr><td></td><td>Energy Only Market (EOM)</td><td>Capacity Market (CM)</td></tr>
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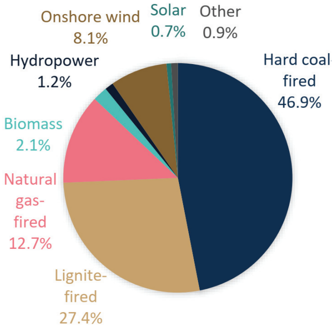
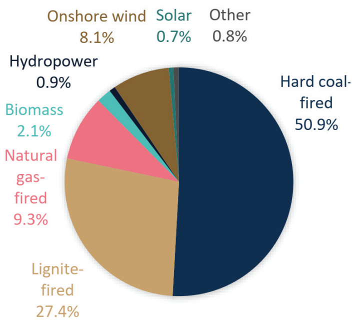
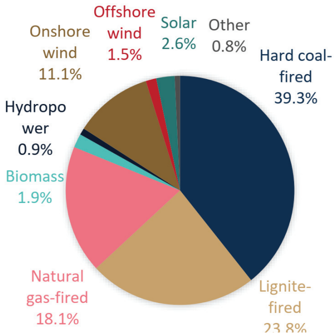
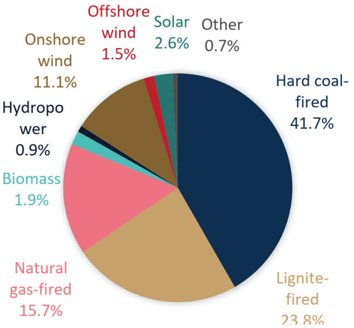
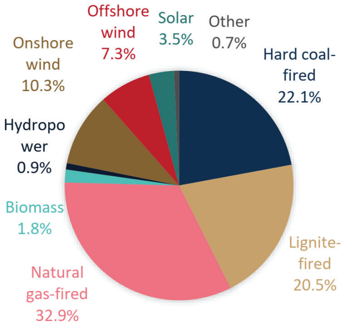
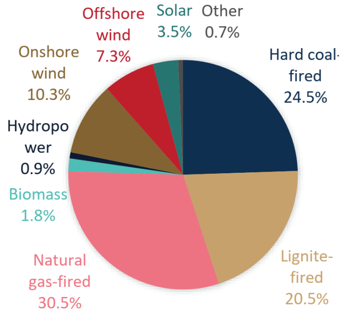
173.0 TWh</td><td> </td><td> </td></tr>
<tr><td>2025
183.6 TWh</td><td> </td><td> </td></tr>
<tr><td>2030
197.8 TWh</td><td> </td><td> </td></tr>
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Table A2. *Cont.*

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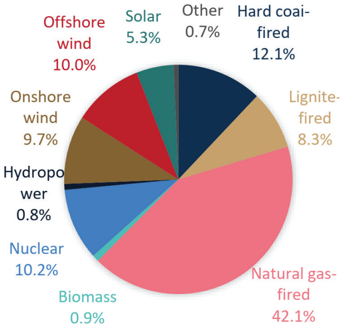
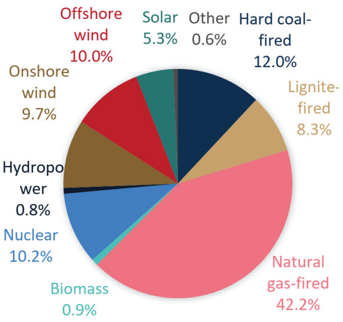
213.1 TWh</td><td>
</td><td>
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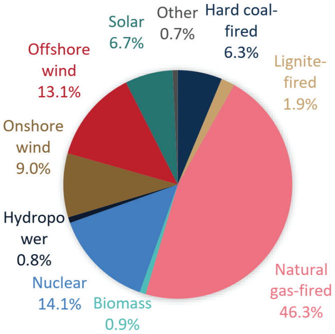
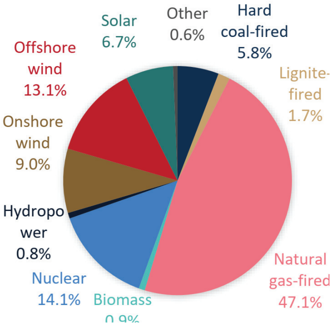
229.6 TWh</td><td>
</td><td>
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References

1. Kueppers, M.; Pineda, S.N.P.; Metzger, M.; Huber, M.; Paulus, S.; Heger, H.J.; Niessen, S. Decarbonization pathways of worldwide energy systems—Definition and modeling of archetypes. *Appl. Energy* **2021**, *285*, 116438. [CrossRef]
2. Goldthau, A.; Sovacool, B.K. The uniqueness of the energy security, justice, and governance problem. *Energy Policy* **2012**, *41*, 232–240. [CrossRef]
3. Zhang, X.; Löschel, A.; Lewis, J.; Zhang, D.; Yan, J. Emissions trading systems for global low carbon energy and economic transformation. *Appl. Energy* **2020**, *279*, 115858. [CrossRef]
4. Pietzcker, R.C.; Osorio, S.; Rodrigues, R. Tightening EU ETS targets in line with the European Green Deal: Impacts on the decarbonization of the EU power sector. *Appl. Energy* **2021**, *293*, 116914. [CrossRef]
5. Audoly, R.; Vogt-Schilb, A.; Guivarch, C.; Pfeiffer, A. Pathways toward zero-carbon electricity required for climate stabilization. *Appl. Energy* **2018**, *225*, 884–901. [CrossRef]
6. Kamiński, J. The impact of liberalisation of the electricity market on the hard coal mining sector in Poland. *Energy Policy* **2009**, *37*, 925–939. [CrossRef]
7. Bowring, J. Capacity Markets in PJM. *Econ. Energy Environ. Policy* **2013**, *2*, 47–65. [CrossRef]
8. Kirschen, D.; Strbac, G. *Fundamentals of Power System Economics*, 2nd ed.; John Wiley & Sons Ltd.: Hoboken, NJ, USA, 2004.
9. Bastos, J.P.; Cunha, G.; Barroso, L.A.; Aquino, T. Reliability mechanism design: An economic approach to enhance adequate remuneration and enable efficient expansion. *Energy* **2018**, *158*, 1150–1159. [CrossRef]
10. Cramton, P.; Ockenfels, A.; Stoft, S. Capacity Market Fundamentals. *Econ. Energy Environ. Policy* **2013**, *2*, 27–46. [CrossRef]
11. Komorowska, A. Capacity remuneration mechanisms: Classification and experiences. *Polityka Energetyczna Energy Policy J.* **2021**, *24*, 101–114. [CrossRef]
12. ACER. Capacity Remuneration Mechanisms and the Internal Market for Electricity. 2013. Available online: https://documents.acer.europa.eu/Official_documents/Acts_of_the_Agency/Publication/CRMs%20and%20the%20IEM%20Report%20130730.pdf (accessed on 20 August 2021).
13. Bhagwat, P. Security of Supply During the Energy Transition. The Role of Capacity Mechanisms. Ph.D. Thesis, Delft University of Technology, Delft, The Netherlands, 2016.
14. Spees, K.; Newell, S.A.; Pfeifenberger, J.P. Capacity Markets—Lessons Learned from the First Decade. *Econ. Energy Environ. Policy* **2013**, *2*, 3–26. [CrossRef]
15. Briggs, R.; Kleit, A.N. Resource adequacy reliability and the impacts of capacity subsidies in competitive electricity markets. *Energy Econ.* **2013**, *40*, 297–305. [CrossRef]

16. Mays, J.; Morton, D.P.; O'Neill, R.P. Decarbonizing electricity requires re-evaluating capacity mechanisms. *Nat. Energy* **2019**, *4*, 912–913. [CrossRef]
17. Lin, J.; Vatani, B. Impact of capacity market design on power system decarbonization. In Proceedings of the 2017 14th International Conference on the European Energy Market (EEM), Dresden, Germany, 6–9 June 2017; IEEE: Piscataway, NJ, USA, 2017; pp. 1–6.
18. Polzin, F.; Egli, F.; Steffen, B.; Schmidt, T. How do policies mobilize private finance for renewable energy?—A systematic review with an investor perspective. *Appl. Energy* **2019**, *236*, 1249–1268. [CrossRef]
19. Fang, X.; Hodge, B.-M.; Li, F. Capacity Market Model Considering Flexible Resource Requirements. In Proceedings of the 2018 IEEE Power & Energy Society General Meeting (PESGM), Portland, OR, USA, 5–10 August 2018; IEEE: Piscataway, NJ, USA, 2018; pp. 1–5.
20. Komorowska, A.; Benalcazar, P.; Kaszyński, P.; Kamiński, J. Economic consequences of a capacity market implementation: The case of Poland. *Energy Policy* **2020**, *144*, 111683. [CrossRef]
21. PSE. Summary of Quantitative Data on the Functioning of the National Power System in 2019. 2020. Available online: https://www.pse.pl/dane-systemowe/funkcjonowanie-kse/raporty-roczne-z-funkcjonowania-kse-za-rok/raporty-za-rok-2019. (accessed on 5 June 2020).
22. Papadis, E.; Tsatsaronis, G. Challenges in the decarbonization of the energy sector. *Energy* **2020**, *205*, 118025. [CrossRef]
23. Olczak, P.; Kryzia, D.; Matuszewska, D.; Kuta, M. "My Electricity" Program Effectiveness Supporting the Development of PV Installation in Poland. *Energies* **2021**, *14*, 231. [CrossRef]
24. European Commission. The European Green Deal. 2019. Available online: https://ec.europa.eu/clima/policies/eu-climate-action_en (accessed on 20 August 2021).
25. Magazzino, C. Is per capita energy use stationary? Time series evidence for the EMU countries. *Energy Explor. Exploit.* **2016**, *35*, 24–32. [CrossRef]
26. Magazzino, C.; Porrini, D.; Fusco, G.; Schneider, N. Investigating the link among ICT, electricity consumption, air pollution, and economic growth in EU countries. *Energy Sour. Part B Econ. Plann. Policy* **2021**, 1–23. [CrossRef]
27. Farzaneh, H. *Energy Systems Modeling—Principles and Applications*; Springer: Berlin/Heidelberg, Germany, 2019.
28. Ministry of Energy. Project of the Polish Energy Policy. 2019. Available online: https://www.gov.pl/attachment/cff9e33d-426a-4673-a92b-eb4fb0bf4a04 (accessed on 5 June 2020).
29. Komorowska, A.; Kamiński, J. A review of the 2018 Polish capacity market auctions. *Polityka Energet. Energy Policy J.* **2019**, *22*, 75–88. [CrossRef]
30. European Parliament and Council. *Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal Market for Electricity*; European Parliament and Council: Strasbourg, France, 2019.
31. PSE SA. Summary of Quantitative Data on Polish Power System in 2018. 2019. Available online: https://www.pse.pl/dane-systemowe/funkcjonowanie-kse/raporty-roczne-z-funkcjonowania-kse-za-rok/raporty-za-rok-2018 (accessed on 17 August 2019).
32. Komorowska, A. Cross-border exchange of electricity between Poland and the neighboring countries. *Polityka Energet. Energy Policy J.* **2019**, *22*, 37–52. [CrossRef]
33. PSE SA. Electricity Generation. Available online: https://www.pse.pl/dane-systemowe/funkcjonowanie-kse/raporty-dobowe-z-pracy-kse/generacja-mocy-jednostek-wytworczych (accessed on 13 April 2019).
34. ENTSO-E. Actual Generation per Production Type. 2019. Available online: https://transparency.entsoe.eu/generation/r2/actualGenerationPerProductionType/show (accessed on 14 August 2019).
35. IEA. World Energy Outlook 2018. 2019. Available online: https://iea.blob.core.windows.net/assets/77ecf96c-5f4b-4d0d-9d93-d81b938217cb/World_Energy_Outlook_2018.pdf (accessed on 5 April 2020).
36. Kryzia, D.; Gawlik, L. Forecasting the price of uranium based on the costs of uranium deposits exploitation. *Gospod. Surowcami Miner.* **2016**, *32*, 93–110. [CrossRef]
37. Energy Market Agency. *Statistical Information on Electricity 2018*; Energy Market Agency: Warszawa, Poland, 2019.
38. Energy Market Agency. *Technical and Economic Situation in the Power Sector 2018*; Energy Market Agency: Warszawa, Poland, 2019.
39. CIRE. CO2 European Emission Allowance in 2003–2019. 2019. Available online: https://handel-emisjami-co2.cire.pl (accessed on 4 October 2019).
40. Ministry of Energy. *The Act of 8 December 2017 on capacity market (Dz.U. 2018 poz. 9)*; Ministry of Energy: Warszawa, Poland, 2018.
41. Brinsmead, T.S.; Graham, P.; Hayward, J.; Ratnam, E.L.; Reedman, L. *Future Energy Storage Trends. An assessment of the Economic Viability, Potential Uptake and Impacts of Electrical Energy Storage on the NEM 2015–2035*; CSIRO Energy: Newcastle, Australia, 2015.
42. PIME. *Electricity Storage Market in Poland—Technologies, Implementations, Regulations*; PIME: Warszawa, Poland, 2019.
43. Gawel, E.; Strunz, S.; Lehmann, P.; Purkus, A. *The European Dimension of Germany's Energy Transition*; Springer: Berlin/Heidelberg, Germany, 2019.
44. Ministry of Infrastructure and Development. *Guidelines on Issues Related to the Preparation of Investment Projects, Including Income-Generating and Hybrid Projects for 2014–2020*; Ministry of Infrastructure and Development: Warszawa, Poland, 2019.
45. Widera, M.; Kasztelewicz, Z.; Ptak, M. Lignite mining and electricity generation in Poland: The current state and future prospects. *Energy Policy* **2016**, *92*, 151–157. [CrossRef]

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Limestone Sorbents Market for Flue Gas Desulphurisation in Coal-Fired Power Plants in the Context of the Transformation of the Power Industry—A Case of Poland

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Abstract: Since the beginning of the 1990s, due to international regulations on air quality, a large number of flue gas desulphurisation (FGD) installations have been constructed in the Polish coal-fired power industry. Thanks to that, SO_2 capture in this industry increased to ca. 90%. Since wet lime or fluidized bed boilers were mostly used for FGD purposes, a significant increase in the domestic demand for lime sorbents has been reported. Between 1994 and 2019, it has increased from virtually zero before 1994 to about 3.3–3.4 million tpy (tonnes per year) today. On the basis of official governmental data and completed surveys of the Polish power companies, the paper analyses the process of the implementation of FGD in Poland along with limestone sorbents consumption and FGD gypsum production in the Polish coal-fired power plants. It also presents the current and potential limestone resource base for production of limestone sorbents applied in FGD. Electric energy mix in Poland is expected to be changed radically in the coming 30 years. Share of coal-based electricity is still very high—ca. 80%—and it will remain dominant for at least next decade. With the next coming FGD installations, further moderate increase of limestone sorbents consumption is expected, up to 3.7 million tpy in 2030. After 2030, a significant, quick decrease of share of coal-fired electricity is expected in Poland, down to max. 30% just before 2050. This will result in a gradual decrease in limestone sorbent demand, to max. 1.3 million tpy before 2050 and virtually zero after 2050, which will be followed by collapse of FGD gypsum production.

Keywords: limestone sorbents; flue gas desulphurisation; FGD gypsum; coal-fired power plants; energy transition; climate policy

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1. Introduction

Global climate warming and pollution-related effects on human health have placed air pollution at the heart of EU policy decision-making [1]. Although from a global perspective, coal will remain one of the main sources of energy for a long time [2], the European Union have implemented strict regulations to improve air quality, including—or even especially—in the Eastern European countries admitted to the EU in 2004 and 2007. First air quality directives at European level were introduced in 1970, 1980 and 1985 [3]. However, a significant step was made in 1996, when the EU adopted a series of actions to decrease pollutant emissions throughout Europe, also implementing harmonised structure for monitoring, reporting and managing air quality across the EU through 1996 Air Quality Framework Directive [4] and its daughter directives, e.g., setting limit values and alert thresholds for major pollutants. The first such daughter directive [5] established limit values for sulphur dioxide, nitrogen oxides, lead and particulates. In 2005, according to 2005 Thematic Strategy on Air Pollution [6], the European Commission proposed to consolidate the Framework Directive and the first three daughter directives into a single Ambient Air Quality Directive, what was finally adopted as [7], providing the current framework for the control of ambient concentrations of air pollution in the EU. As a consequence of these actions, further more detailed actions have been carried out by the European Commission for individual types of activities related to the emission of pollutants into the air. For large combustion plants these have been: the European Union's Directive 2001/80/EC [8], Directive 2010/75/EU [9] or BAT reference documents [10]. As a result, also intensive Flue Gas Desulphurisation investments have been conducted in recent decades in coal-based power industries of numerous countries, not only in those belonging to the EU [11–13].

In recent years, energy and climate started to be one of the cornerstones of EU policy [14]. This process was initiated by establishing a scheme for greenhouse gas emission allowance trading in 2003 [15], improved and extended in 2009 [16]. Recently, the EU energy and climate goals have been incorporated into the Europe 2020 Strategy for smart, sustainable and inclusive growth. The EU has set overarching targets of greenhouse gas (GHG) emissions reduction known as so-called 20/20/20 targets, namely, reduction of GHG emissions by 20%, increase of Renewable Energy Sources (RES) share to 20% and increase of energy efficiency by 20%, until 2020 [17,18]. In 2019, the EC adopted "Clean Energy for Europe Package" which upheld the right of the EU member states to continue their own energy mix, but with an increased share of renewables in it (on average, 32% in 2030 in the EU), with appropriate measures to accommodate such rising share of renewable energy [19]. As a result, decarbonisation of electricity systems together with substantial increase in renewable energy sources is one of the main policy priorities to foster EU energy transition. Thus, energy mixes are at the moment coal-free in 6 EU and 3 EEA countries and are planned to be coal-free until 2030 in the next 12 EU countries, but this is still not the case for numerous Eastern EU countries, including Poland [20].

The above-mentioned EU actions have been followed by detailed actions at the level of individual EU countries [21]. In Poland, the most important of them are at the moment: the "National Air Protection Program by 2020" adopted in 2015 [22], a 2021 Energy Policy of Poland until 2040 adopted in February 2021 [23], and National energy and climate plan for 2021–2030 adopted in December 2019 [24].

In Poland, coal has been a key driver of energy security for decades. Hard coal and lignite are traditionally the most important fuels used in Poland due to their abundant resources available in the country. Despite all transition trends resulting in its declining role, it still accounts for majority of the Polish electricity mix [25,26]. Without doubt, the Polish power industry stands at a crossroads, facing pathways with various ambitions of emission reductions, being strongly affected by environmental and decarbonisation regulations. According to the latest Energy Policy of Poland until 2040, the share of coal in the Polish electricity mix will decrease to a maximum of 56% in 2030, while share of RES will rise to 32%. In the next decade, pace of further decrease of coal in electricity mix will heavily depend on EU ETS allowances prices, achieving 37% in 2040 [24]. Various electricity mix scenarios in perspective of 2050 are still possible. In the strong decarbonisation (high EU ETS allowances prices) scenario, it is assumed that in 2050 coal will be used in Poland at most in CHP (Central Heating Plants) generating electricity together with hot water for district heating networks, with coal-based electricity generation decreasing from ca. 130 TWh in 2015 down to 30–50 TWh in 2050, constituting ca. 15% of the electricity mix. A complete phase-out of coal-based power industry by 2050 also cannot be excluded [26,27].

As the Polish power industry has traditionally relied on the combustion of coal (hard coal and lignite), it has generated significant amounts of SO_2 and other gases. Commercial power generation emitted about 1.6 million tonnes SO_2 in 1990, about 0.8 million tonnes SO_2 in 2000, and only about 0.25 million tonnes SO_2 in 2018. The total amount of SO_2 generated from combustion processes (mainly coal combustion) was much higher, but there has been a fundamental change in the extent of active flue gas desulphurisation (FGD) systems at domestic power plants and combined heat and power plants over the last 30 years. As a result, the amount of SO_2 retained at these FGD plants increased from ca. 0.33 million tonnes SO_2 in 1990 to ca. 0.60 million tonnes SO_2 in 2000 and ca. 1.9 million tonnes SO_2 in 2018 [28–30], meaning that these FGD plants were already retaining nearly 90% of the SO_2 generated.

Due to the above-mentioned factors, an intensive modernisation process in the Polish power industry started in the early 1990s, concerning in particular the construction of FGD plants, or in the case of general modernisation of power units, sometimes introduction of fluidized bed boilers, where the desulphurisation process takes place in the boiler immediately after the combustion of fuel (mainly coal) [29]. The technological solutions applied to capture the SO_2 generated during combustion vary; nevertheless, two approaches have gained the greatest importance in Poland: construction of FGD using the wet limestone method, and semi-dry method, at the existing, modernized or newly built power units burning hard coal or lignite, or the aforementioned introduction of fluidized bed boilers. In both cases, limestone of suitable quality is used as sorbent, with limestone flour, of finer granulation, in the wet limestone method and limestone sand, of slightly coarser granulation, in fluidized bed boilers. In the semi-dry method of flue gas desulphurisation, the main type of sorbent is a quicklime [31,32].

The progressing process of implementation of FGD methods in the Polish power industry (as well as in industrial power sector and partly in the heat industry) contributed to the development of domestic demand for limestone sorbents from practically zero level at the beginning of 1990s to about 3.5 million tpy (tonnes per year) at present. As a result, the power industry has become one of the most important customers of the Polish lime industry, which, on the other hand, have experienced a significant reduction in demand for traditional lime products, in particular for various types of lime [33].

By considering all of the factors mentioned above, this article aims to analyse sources of limestone sorbents in Poland, as well as their use in the Polish power industry for FGD purposes. It has been done not only to recognize current situation, but also with an attempt to forecast in this respect in the perspective of 2050, taking into account the most important economic, technological, environmental and policy factors, both at the EU and at the national level.

2. Materials and Methods

Extensive analyses of the limestone resource base and of limestone use in Poland were performed. For these purposes, the most important sources of information were: annual publications on mineral resource base in Poland [34–36], publications reviewing this resources base [37,38], older analyses of industrial limestone market in Poland [39], and official data of the Statistics Poland (GUS) [28,40]. Other official reports on the domestic power generation industry were also used [41,42].

For obtaining reliable information on limestone flour consumption by the Polish power generation industry, the authors surveyed relevant power companies in the field of applied FGD methods, type, amounts and sources of limestone sorbent applied, as well as amount of FGD gypsum (and other FGD products) obtained. In total, 18 power companies were surveyed, of which 14 responded (including all seven major ones). Quantity of limestone consumption and FGD-gypsum production for power industry companies, which did not respond to the survey, were deduced from their actual energy production and known parameters of their FGD installations, as well as their prior available data on sorbent consumption.

3. Results

3.1. Methods of Desulphurisation Used in the Polish Power Plants and Central Heating Plants and the Main Sorbents Applied

The aim of flue gas desulphurisation processes is removing sulphur (mainly in the form of SO_2, less frequently other sulphur compounds) from flue gases generated in various industrial processes. The main sources of emissions of sulphur compounds are processes of combustion of fossil fuels (in Poland: especially hard coal and lignite), which in numerous countries still remain the main source for generation of electricity and heat. The amount of sulphur oxides produced in these processes depends on the type of fuel, the content of sulphur compounds in the fuel, as well as the combustion conditions in different types of furnaces [10].

Many methods are known for the removal of sulphur oxides from the flue gases of production processes. All of them involve the introduction of a sorbent into the system, which reacts with the gaseous SO_2 contained in the flue gas, binding it into solid compounds, with the removal of the reaction products from the system. Desulphurisation can be carried out on both dust-free gases and those carrying considerable quantities of dust. Moreover, desulphurisation processes can be carried out before, during and after fuel combustion. Sorbents most commonly used in desulphurisation processes are ground limestone (limestone flour), hydrated lime and ground quicklime. Much less commonly used are ground dolomite, calcined magnesite, sodium carbonate, and some industrial wastes (e.g., carbide lime) [10,43,44].

With respect to the ways of introducing the sorbent into the desulphurisation system and receiving the desulphurisation products, the following methods are distinguished: dry, semi-dry and wet. Dry methods are characterised by the fact that SO_2 chemical fixation processes take place in the dry state, i.e., in a gas–solid system, and desulphurisation products are obtained in the dry state. They are based on adsorption on solid sorbents with simultaneous drying of desulphurisation products. The most common dry FGD system of dust-free flue gases is spray dry FGD system with use of hydrated lime [45], while, e.g., furnace sorbent injection or duct sorbent injection have minor importance. Circulating Fluid Bed dry scrubbing in fluidized bed boilers is another important method, but in this case limestone or lime sorbent is introduced into the boiler before the combustion process [32,43]. In semi-dry and wet methods SO_2 sorbent is introduced to the desulphurisation plant in the form of suspension in liquid, while the desulphurisation products are received in dry state (semi-dry method) or in the form of suspension (wet method). According to the criteria given above, dry desulphurisation methods include also desulphurisation carried out during combustion in furnaces of fluidized bed boilers. The products of desulphurisation by dry and semi-dry methods are so-called desulphurisation ashes (sulfate-rich ashes). They are a mixture of ashes, desulphurisation products and unreacted sorbents. For the wet lime method, the main product is synthetic gypsum with a small amount of unreacted sorbent [10,46–48].

Limestone sorbents (lime flour or sand), in some cases also burnt or hydrated lime constitute the most numerous group of reagents used in flue gas desulphurisation systems. It is also the case of Poland, where they are applied mainly in the wet lime method and in fluidized bed boilers, to a lesser extent in semi-dry and dry methods (Table 1). In the Polish power industry, they are used in almost all existing flue gas desulphurisation plants. This is due to their widespread availability, low purchase cost and, in the case of the wet limestone method, the ease of disposal of the resulting synthetic gypsum. In general, calcium desulphurisation sorbents include: in dry desulphurisation methods—ground quicklime and limestone, in semi-dry desulphurisation methods—hydrated lime and ground quicklime, and in wet desulphurisation methods—ground quicklime, ground limestone and chalk [49,50].

3.2. Sources and Production of Limestone Sorbents in Poland

Limestones are sedimentary rocks whose main component is calcite $CaCO_3$, isomorphic with magnesite $MgCO_3$, siderite $FeCO_3$ and other anhydrous carbonates, as a result of which admixtures of MgO, FeO, etc., are present. Depending on the admixtures of other minerals, a number of varieties of transition rocks can be distinguished: with increasing amounts of clay minerals, these are marl limestones, marls and clayey marls, with admixture of silica—gaizes, and with quartz—sandy limestones and calcareous sandstones. The admixture of the dolomite mineral $CaMg[CO_3]_2$ is particularly common in rocks of mixed nature—dolomitic limestones and calcareous dolomites. A particular variety of limestone rocks, both in terms of genesis and properties and use, is the chalk [37,51].

Poland has numerous deposits of limestone rocks with the exception of the most noble varieties of sculptural and architectural marbles. The limestone resource base is divided into limestone and related minerals documented for various purposes: limestone for the lime industry, limestone and related rocks for the cement industry (both collectively known as industrial limestone), limestone for the production of crushed aggregates, as well as chalk and lake chalk. In practice, this division has a conventional meaning, as, e.g., cement and lime combinations operate on individual deposits, using the purer parts for lime products, and the remaining parts for cement or crushed aggregate production [37,52].

Limestone deposits for the lime industry are known mainly in the Świętokrzyskie province (60% of total resources, mainly Devonian and Jurassic limestone) as well as in the Łódzkie, Opolskie and Śląskie provinces. The total resources of 120 deposits amounted to 5.4 billion tonnes at the end of 2019 [35]. Deposits of limestone and related rocks for the cement industry are found in the following provinces: Lubelskie (26%, predominantly Cretaceous marls and chalk), Świętokrzyskie (17%, Devonian and Jurassic limestone), Łódzkie (15%, Jurassic limestone), Mazowieckie (12%, Jurassic limestone), smaller ones in Kujawsko-Pomorskie, Opolskie and Śląskie. Total resources of 69 deposits amounted to 12.7 billion tonnes at the end of 2019. Limestone deposits mostly for crushed aggregates production are found mainly in the Świętokrzyskie region (about 90% of resources, Devonian and Jurassic limestone). Many deposits were also documented in the Cracow-Częstochowa Upland and single ones in the Carpathians, Sudety Mountains, Lublin Upland and others. The total resources of 142 deposits of limestone and limestone-related rocks for crushed aggregates production amounted to 2.0 billion tonnes at the end of 2019 [35].

By age of limestone formations, the most significant are Jurassic limestones (over 59% of resources), followed by Cretaceous limestones and related rocks (over 21%), Devonian limestones (about 8%), Triassic limestones (about 8%), Tertiary limestones (about 3%), and marginally—Carboniferous, Cambrian and Precambrian limestones [34,35].

In 2019, limestone was mined in Poland in 86 open pits, of which there were 19 limestone and marl mines delivering the batch to the cement industry, 22 limestone mines—for the lime industry, 36 mines extracting limestone deposits documented for crushed aggregates production, as well as 9 chalk mines [35].

Limestone rocks are used in Poland to produce several groups of products: cement, lime, unburned lime products, crushed limestone aggregates and fertilizers. Burnt and hydrated lime, as well as unburned limestone products, with a diverse range, are manufactured by more than a dozen plants. Some lime plants produce also significant quantities of limestone rock for sale, used as a blast furnace flux or in sugar factories for the production of quicklime necessary for beet juice purification (Table 1). Limestone crushed aggregates for construction are obtained mostly from limestone crushed aggregates deposits, as well as in some industrial limestone mines. Fine waste fractions from limestone crushed aggregates production are often destined for calcium carbonate fertilizers manufacture [39].

At present, fine-grained limestone sorbents, often called limestone flour, with grain size under 100/120 µm are used in the Polish power industry as a sorbent for flue gas desulphurisation in the wet limestone method, while coarse-grained sorbents (so-called limestone sand), with grain size above 100/120 µm, are used mainly for desulphurisation during combustion in fluidized bed boilers.

Table 1. Mining production of limestone in major mines, delivering industrial limestones as the main or additional products (kt) [1] [34].

Mine (Deposit)	Province	Applications	2015	2016	2017	2018	2019
Barcin-Piechcin-Pakość	Kujawsko-Pomorskie	c,l,a,f,p	6252	6485	6606	7855	7423
Ostrówka	Świętokrzyskie	a,s,p	6417	5825	5817	5878	5980
Trzuskawica	Świętokrzyskie	l,p,a,s,f	3775	3401	3777	4002	4519
Górażdże	Opolskie	c,l,s,f	3508	3486	3761	4535	4239
Morawica III-1	Świętokrzyskie	a,s,f,d	2762	2248	2809	3237	3124
Jaźwica	Świętokrzyskie	a,s,f	1000	986	1678	2081	2425
Bukowa	Świętokrzyskie	l,s,p,f	2184	2430	2468	2585	2350
Czatkowice	Małopolskie	s,p,a	1892	1759	1487	1673	1752
Celiny I	Świętokrzyskie	a,s	936	1273	1175	1308	1481
Szymiszów	Opolskie	a,s,f	–	–	402	1018	1375
Tarnów Opolski	Opolskie	s,l,p,f	640	598	573	645	1089
Wierzbica	Świętokrzyskie	p,a,s	614	807	617	738	634
Połom	Dolnośląskie	a,s,p,f,l	462	531	540	703	578
Raciszyn	Łódzkie	p,f,d,s	100	2	281	324	484
Raciszyn II	Łódzkie	p,f,s	549	521	529	578	427
Sławno	Łódzkie	p,f	274	291	320	291	301
Chęciny-Wolica	Świętokrzyskie	p	–	38	107	256	260
Płaza	Małopolskie	f,a,p	231	33	123	26	34
Izbicko II	Opolskie	s,f,l	966	726	764	843	–

[1] Mines delivering limestone or similar rock only for cement production are excluded, mines delivering a different type of limestone flour are marked **in bold**. Applications: a—crushed aggregates, c—cement production, d—dimension limestone, f—limestone fertilizers, l—lime, p—limestone flour (powder), s—limestone rock for sale.

The majority of the Polish limestone milling plants which produce limestone flour for diverse purposes are located in the direct vicinity of extracted limestone deposits, which minimizes the cost of limestone transportation from the mine to the processing plant. This is why the largest limestone milling plants are located in the Świętokrzyskie province, as well as in the neighbouring provinces: Łódzkie and Małopolskie.

The most important domestic suppliers of limestone sorbents include: Lhoist Polska Sp. z o.o. (Bukowa, Tarnów Opolski, Górażdże, Wojcieszów/Połom plants), KW Czatkowice Sp. z o.o. (Czatkowice plant), ZPW Trzuskawica S.A. (Trzuskawica/Sitkówka and Bielawy plants), Nordkalk sp. z o.o. (Ostrówka, Chęciny-Wolica, Sławno plants), Labtar Sp. z o.o. (Tarnów Opolski plant), EGM Sp. z o.o. (Wierzbica plant) and WKG Sp. z o.o. (Raciszyn plant) (Tables 1 and 2). One of the basic parameters determining the effects of flue gas desulphurisation is the chemical purity of limestone. This usually means that for such desulphurisation limestone flour should exhibit $CaCO_3$ content of min. 94%, Fe_2O_3 content usually under 0.4%, and MgO usually <1%, with variable content of SiO_2 [49].

The largest limestone flour supplier in Poland is Lhoist Polska, where the production of limestone fine sorbents for FGD wet limestone method (at ca. 700,000 tpy) is carried out in two plants: Bukowa—using Jurassic limestone of Bukowa deposit, and Tarnów Opolski—using Triassic limestone of Tarnów Opolski deposit. Sorbents from the Bukowa plant have a high content of $CaCO_3$ (97–98%), while limestone from the Tarnów Opolski plant is slightly inferior in quality (94.7–96.5% $CaCO_3$). Based on Tarnów Opolski limestone, production of small quantities of fine-grained sorbents is also operated by Labtar Sp. z o.o. (Table 2).

The Czatkowice Limestone Mine (part of the Tauron Polska Energia power company) in Krzeszowice near Krakow is a significant supplier of high-quality limestone sorbents (over 450,000 tpy). It exploits the Czatkowice Carboniferous limestone deposit. It offers limestone sorbents in the form of limestone flour or limestone sand, characterised by high content of $CaCO_3$ (over 96%) and excellent sorption properties [52] (Table 2).

Table 2. Basic quality parameters of major limestone sorbents produced in Poland and utilised in wet limestone FGD process (surveyed producers' data).

Producer/Sorbent.	Sorbent Source	Chemical Composition					Grain Size Characteristics
		$CaCO_3$	SiO_2 + Insolubles	$MgCO_3$	Fe_2O_3	Al_2O_3	
ZPW Trzuskawica S.A., Trzuskawica plant/Limestone sorbent for FGD	Trzuskawica Devonian limestone	>98.0%	<1.0%	<2.0%	<0.06%	<0.25%	85–95% < 0.063 mm
ZPW Trzuskawica S.A., Bielawa plant/ Limestone flour	Barcin-Piechcin-Pakość Jurassic limestone	>93.0%	<3.0%	<1.5%	<0.4%	NA	min. 80% < 0.075 mm
KW Czatkowice Sp. z o.o./Limestone flour	Czatkowice Carboniferous limestone	96.0%	1.5%	1.5%	0.15%	0.09%	98.7% < 0.2 mm 89.4% < 0.09 mm
ZW Lhoist S.A./ Limestone sorbent for FGD	Tarnów Opolski Triassic limestone	97.5%	1.1%	0.9%	0.3%	0.1%	min. 90% < 0.09 mm
Labtar Sp. z o.o./ Fine-grained sorbent	Tarnów Opolski Triassic limestone	>94.0%	<2.5%	<2.0%	<0.7%	<0.7%	92.3% < 0063 mm 98.9% < 0.09 mm
Nordkalk Sp. z o.o./ Electra 90 (WO) sorbent	Wolica Jurassic limestone	97.0%	1.25%	0.70%	0.12%	0.12%	Various sizes: from 0–0.09 mm to 0.8–1.4 mm
EGM Sp. z o.o./ Limestone flour	Wierzbica Jurassic limestone	>97.3%	<0.5%	<1.2%	<0.15%	<0.4%	<0.1 mm
WKG Sp. z o.o./ Limestone flour	Raciszyn Jurassic limestone	>96.0%	<1.5%	<0.8%	<0.5%	<0.5%	<0.1 mm

Significant amounts of sorbents (over 200,000 tpy) are obtained on the basis of Jurassic Chęciny-Wolica limestone deposit in the Wolica plant near Kielce owned by Nordkalk Sp. z o.o. Moreover, less than 100,000 tpy of medium-grained sorbents with grain size < 0.15 mm are supplied by ZPW Trzuskawica (belonging to the Irish concern CRH) on the basis of Devonian highest-purity limestone from the Trzuskawica deposit. Smaller manufacturers of fine-grained limestone sorbents of high purity are EGM Sp. z o.o. (Wierzbica Jurassic limestone mine) and WKG Sp. z o.o. (Raciszyn Jurassic limestone deposit) (Tables 1 and 2).

In the future, it may be possible to commence the production of limestone flour sorbents on the basis of other limestone deposits characterised by the appropriate degree of purity (over 94% $CaCO_3$). It is worth mentioning that the largest domestic Bełchatów Power Plant have recently started to produce limestone sorbents in its own limestone milling plant for the needs of its own 12 power units. Limestone for such purposes is purchased mostly from the Raciszyn, Morawica and Bukowa mines, while the newest Bełchatów power unit uses limestone flour produced among others by Nordkalk, Trzuskawica, WKG Raciszyn and Czatkowice. Moreover, production of limestone flour for the needs of their own desulphurisation plants is carried out in Turów and Połaniec Power Plants.

The total production potential of the Polish plants delivering limestone flour for a variety of applications, is at the moment estimated at approximately 6.0 million tpy, with an increase of approximately 1.5 million tpy over the past decade due to the expansion of a number of existing milling plants (Bełchatów, Sławno, Wolica, Turów, Raciszyn, Wierzbica, Turów and Połaniec). In the coming years it should increase primarily as a result of the expansion of the milling plant located at the Bełchatów Power Plant by approximately 0.4 million tpy. Development of limestone flour production capacity could potentially take place, e.g., at the EGM plant in Wierzbica and at the ZPW Trzuskawica plant in Sitkówka [52].

3.3. Use of Limestone Sorbents in the Polish Power Industry with Obtaining FGD Gypsum and Other Desulphurisation Products

Among numerous desulphurisation methods used in large power plants and combined heat and power plants, with coal burning in conventional boilers, the non-regenerative wet limestone method of flue gas desulphurisation using fine limestone flour turned out to be the most effective, including in Poland. In this method, the dust-free flue gases are purified in the absorber by a limestone flour suspension flowing in counter-current. The sulphur dioxide (SO_2) present in the flue gas reacts with calcium carbonate ($CaCO_3$), the main component of limestone, resulting in intermediate calcium sulfite ($CaSO_3 \cdot {}^1/{}_2H_2O$) and then—after oxidation with air supplied from outside and after crystallization—gypsum ($CaSO_4 \cdot 2H_2O$). This desulphurisation product is received in the form of water suspension with subsequent water removal on appropriate belts or vacuum filters. Implementation of this method requires relatively high investment outlays, but is characterised by high desulphurisation efficiency (92–99%) and obtaining a fully economically useful product, i.e., synthetic gypsum [31,43,49].

The first wet limestone flue gas desulphurisation plants in Poland were put into operation at the Bełchatów Power Plant in 1994. It initiated in Poland the use of suitable limestone flour (limestone sorbent) for flue gas desulphurisation in power plants, together with the production of synthetic gypsum from flue gas desulphurisation. In the following several years, FGD plants using the wet limestone method were put into operation at 11 power plants (PPs) and 5 combined heat and power plants (CHPs) (Table 3). Currently, the maximum total demand of the Polish PPs and CHPs for the sorbent—limestone flour < 0.1 mm—is estimated at about 3.5 million tpy (which corresponds to synthetic gypsum production capacity of about 4.8 million tpy). The actual consumption of this flour in 2019 has been estimated at about 2.4 million tonnes, with synthetic gypsum production amounting to ca. 3.3 million tonnes.

Table 3. The main flue gas desulphurisation installations in the Polish power plants and central heating plants (as of 29 November 2019) [41,42], surveyed sorbent user data.

Power Plant (PP)/Central Heating Plant (CHP)	Achievable Power (MW)	Applied Flue Gas Desulphurisation Method	Type of Sorbent
Bełchatów PP	5102	Wet limestone	Limestone flour < 0.1 mm
Opole PP	3342	Wet limestone	Limestone flour < 0.1 mm
Kozienice PP	4016	Wet limestone	Limestone flour < 0.1 mm
Rybnik PP	1800	Wet limestone, semi-dry and dry	Limestone flour < 0.1 mm, Lime or hydrated lime
Połaniec PP	1657	Wet limestone	Limestone flour < 0.1 mm
Jaworzno III PP	1345	Wet limestone	Limestone flour < 0.1 mm
Łaziska PP	1155	Wet limestone, semi-dry	Limestone flour < 0.1 mm, Lime or hydrated lime
Pątnów I-II PP	1120	Wet limestone	Limestone flour < 0.1 mm
Dolna Odra PP	1350	Wet limestone	Limestone flour < 0.1 mm
CHPs: Kraków, Wrocław, Gdańsk, Gdynia	902 (in total)	Wet limestone	Limestone flour < 0.1 mm
Ostrołęka PP	690	Wet limestone	Limestone flour < 0.1 mm
Warsaw Siekierki CHP	523	Wet limestone, semi-dry	Limestone flour < 0.1 mm, Lime or hydrated lime
Konin PP	171	Wet limestone	Limestone flour < 0.1 mm
Skawina PP	389	Semi-dry	Lime or hydrated lime
Łódź 4, Poznań Karolin, Zabrze, Głogów, and Lublin-Megatem CHPs	838 (in total)	Semi-dry	Lime or hydrated lime
Miechowice, Lublin Wrotków, and Zgierz CHPs	303 (in total)	Dry	Lime or hydrated lime
Turów PP	1488	Fluidised bed boilers, Wet limestone	Limestone flour 0.1–1.2 mm, Limestone flour < 0.1 mm
Łagisza PP	700	Fluidised bed boilers, semi-dry	Limestone flour 0.1–1.2 mm, Lime or hydrated lime
Siersza PP	557	Fluidised bed boilers, semi-dry	Limestone flour 0.1–1.2 mm, Lime or hydrated lime
Warszawa Żerań CHP	375	Fluidised bed boilers	Limestone flour 0.1–1.2 mm
Chorzów CHP	156	Fluidised bed boilers, dry	Limestone flour 0.1–1.2 mm, Lime or hydrated lime
Jaworzno II PP	149	Fluidised bed boilers	Limestone flour 0.1–1.2 mm
Katowice CHP	125	Fluidised bed boilers	Limestone flour 0.1–1.2 mm
Bielsko-Biała CHP	103	Fluidised bed boilers, dry	Limestone flour 0.1–1.2 mm, Lime or hydrated lime

At present the most important users of limestone flour (sorbents) < 0.1 mm and synthetic gypsum producers in Poland are (Table 3):

- PGE Górnictwo i Energetyka Konwencjonalna S.A.—Bełchatów, Opole, Turów and Dolna Odra PPs;
- Tauron Wytwarzanie S.A.—Jaworzno III and Łaziska PPs;
- ZE Pątnów-Adamów-Konin S.A.—Konin and Pątnów I-II PPs;
- ENEA S.A.—Kozienice and Połaniec PPs;
- ENERGA S.A.—Ostrołęka PP;
- PGE Energia Ciepła S.A.—Rybnik PP, Gdańsk, Gdynia, Wrocław, and Kraków CHPs;
- PGNiG Termika S.A.—Warszawa Siekierki CHP.

The flue gas desulphurisation at the Bełchatów Power Plant has been in operation—as mentioned above—since 1994 and after gradual expansion it is currently the largest flue gas desulphurisation plant in Europe, operating on all active units. The maximum demand for limestone sorbent in this power plant reached 1.6 million tpy and the actual sorbent consumption in flue gas desulphurisation process in recent years has been approaching 1.5 million tpy (Table 3). Bełchatów Power Plant, as one of three in Poland, has its own limestone milling plant where the level of sorbent production reaches almost 1.3 million tpy, with limestone supplied from numerous mines. For flue gas desulphurisation in the newest power unit, there are used approximately 0.3 million tpy of sorbents supplied from the their main domestic suppliers.

Subsequent flue gas desulphurisation plants using the wet limestone method were commissioned successively at the following power plants and combined heat and power plants:

- Jaworzno III PP—since 1996, sorbent consumption 70,000–75,000 tpy;
- Opole PP—since 1997 with extension in 2019, sorbent consumption 60,000–90,000 tpy, with an expected increase even to 200,000–250,000 tpy;
- Konin PP—since 1997, sorbent consumption below 10,000 tpy;
- Połaniec PP—since 1999 with extension in 2008, sorbent consumption ca. 130,000 tpy, with own limestone milling plant of production capacity 200,000 tpy;
- Łaziska PP—since 2000, sorbent consumption 40,000 tpy;
- Dolna Odra PP—since 2000 with extension in 2003, sorbent consumption ca. 35,000 tpy;
- Kozienice PP—since 2001 with extension in 2007, 2010, 2015 and 2017, current sorbent consumption ca. 200,000 tpy and target consumption ca. 400,000 tpy;
- Ostrołęka PP—since 2008, sorbent consumption ca. 30,000 tpy;
- Rybnik PP—since 2008 (in 4 power units), consumption of limestone sorbent 70,000–75,000 tpy, additionally in the next 4 power units semi-dry or dry FGD with quicklime as sorbent;
- Pątnów I–II PP—since 2008, sorbent consumption up to 125,000 tpy;
- Siekierki CHP—since 2010, sorbent consumption up to 30,000 tpy;
- PGE Energia Ciepła S.A. CHPs in Kraków, Wrocław, Gdańsk and Gdynia—since 2015, total sorbent consumption ca. 50,000 tpy;
- Turów PP—since 2021, sorbent consumption 100,000–110,000 tpy, with own limestone milling plant producing limestone flour for wet limestone FGD and limestone sand for fluidised bed boilers.

Conducting the desulphurisation process during fuel combustion in fluidised bed boilers is the second most popular—after the wet limestone method—technological solution in Polish power plants and combined heat and power plants. It also began to be implemented in Poland in the 1990s. The choice of such solution resulted, among others, from the low temperature of the combustion process (850–950 °C), the possibility of reduction of both SO_2 and NOx emissions and the opportunity to use low-quality fuels [53]. Nowadays, fluidised bed boilers with a capacity of up to 500 MWe are in operation [54]. In fluidised bed boilers, ground fuel and sorbent (limestone sand) are fed into the combustion chamber where they form a so-called "bed" together with an inert material (e.g., sand). Continuous mixing of the bed particles with the air stream allows complete combustion of the fuel and capture of sulphur dioxide [55].

In Poland, for capture of sulphur dioxide emitted during fuel combustion in fluidised bed boilers, limestone sorbent (limestone sand) is primarily used, with the necessary stoichiometric excess of the sorbent. In the combustion process, a very important factor is the granulation of individual components forming the bed, which is usually within the range of 0.1–1.2 mm [31].

The first power units with fluidised bed boilers were commissioned in Poland between 1993 and 2004 in the Turów Power Plant (six boilers in total). At the same time, use of suitable limestone sand (coarse-grained sorbents) for flue gas desulphurisation in such boilers in Poland was initiated. In the following years, fluidised bed boilers were put into operation in the next three PPs and five CHPs. Currently, the maximal total demand of these PPs and CHPs for coarse-grained sorbent (limestone sand 0.1–1.2 mm) is estimated at about 1.5 million tpy, while the actual consumption is estimated at about 1.0 million tpy, including up to 0.5 million tpy at the Turów PP only.

At present, the most important users of coarse-grained sorbent (limestone sand 0.1–1.2 mm) used for desulphurisation in fluidised bed boilers in Poland are (Table 3):

- PGE Górnictwo i Energetyka Konwencjonalna S.A.—Turów PP;
- Tauron Wytwarzanie S.A.—Łagisza, Siersza and Jaworzno II PP;
- Tauron Ciepło Sp. z o.o.—Bielsko-Biała and Katowice CHPs;
- CEZ Chorzów S.A.—Chorzów CHP;
- PGNiG Termika S.A.—Warszawa Żerań CHP.

In the first phase of fast introduction of flue gas desulphurisation technologies in the Polish coal-based power plants in the years 1994–2000, the consumption of limestone flour showed a powerful upward trend. It was halted in the years 2001–2006 when domestic electricity generation was reduced (Figure 1). In order to meet the new gas emission standards introduced by Directive 2001/80/EC [8], Directive 2010/75/EU [9] and the obligations contained in the Accession Treaty following Poland's accession to the European Union [56], intensive activities were carried out in subsequent years, as a result of which FGD installations were built at numerous subsequent plants. The development of the use of the wet limestone method resulted in a parallel development of the production and consumption of the fine-grained limestone sorbent necessary for this method. A close correlation is observed between the development of limestone sorbent consumption and synthetic gypsum production coming from this process (Figure 1).

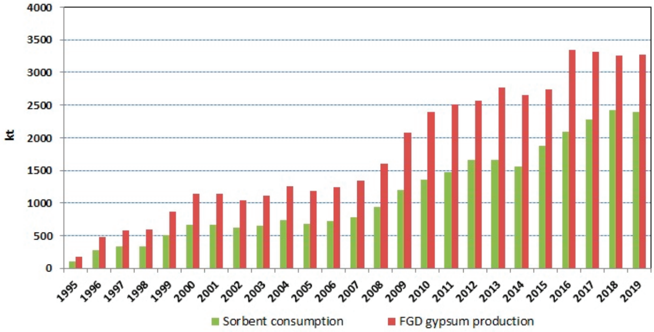

Figure 1. Comparison of the production volume of synthetic gypsum and consumption of limestone sorbents applied in flue gas desulphurisation in wet method (surveyed gypsum producers' and sorbent consumers' data).

As a result, during the last 25 years, the Polish demand for limestone sorbents (limestone flour) with granulation < 0.1 mm for flue gas desulphurisation by wet limestone method has gradually increased, reaching about 2.4 million tpy (Figure 1). At the same time, the consumption of coarse-grained sorbents (i.e., limestone sand with granulation of 0.1–1.2 mm) used as sorbents in fluidised bed boilers increased in Poland to about 1.0 million tpy. The overall consumption of ground limestone for use as a SO_2 sorbent in the domestic power industry in recent years has reached about 3.3–3.4 million tpy, and production of synthetic gypsum has stabilized at the level of approx. 3.3 million tonnes (Figure 1).

4. Discussion

Attempts to forecast the amount of limestone sorbent consumption in flue gas desulphurisation in Poland in the years to come have highly uncertain results, although there is no doubt that this amount will not be significantly reduced in a few years' perspective, and even, on the contrary, it should increase noticeably. The main factors influencing this will be, among others, the structure of electricity production (the so-called energy mix), current and expected share of hard coal and lignite burning in electricity production, the expected sulphur content in coals to be burnt, the range and scope of planned upgrading of existing power units or their replacement with new ones (taking into account the type of fuel used), and finally—the expected share of electricity generated from renewable sources [57,58].

Leaving aside the issues of the development of the energy mix and the growing share of renewable energy sources in total electricity production, there is no doubt that due to many years of backwardness of the Polish power industry, so far dominated by coal-fired power plants, significant investments are necessary to launch new electricity production capacities and transmission networks. Currently in Poland, 48% of active boilers and 44% of turbine sets are over 30 years old, and about 30% of boilers and about 32% of turbine sets are between 20 and 30 years old [25]. According to the actual Polish Energy Policy until 2040 [23], Poland will try to cover its power demand from its own resources. Polish coal resources will remain an important element of the country's energy security, but an increase in demand for energy will be met from sources other than coal-fired units. It is assumed that the share of coal in the energy consumption structure will be below 56% in 2030, and with the likely increase in EU ETS allowance prices it may reach the level of approximately 38%. In addition, renewable energy sources will play an increasingly important role, and their share in the structure of net domestic energy consumption will reach no less than 32% in 2030 [23]. This will be achieved primarily through the development of photovoltaics and offshore wind farms, which due to their characteristics of economic and technical conditions have the greatest potential for development. In addition, it is necessary to develop transmission infrastructure, energy storage technologies, as well as to expand the use of gas units as regulating capacity. It is assumed that from 2033, nuclear power will be implemented (a total of six nuclear power units with a total capacity of between six and nine GW are planned to be built), which will ensure the stability of the energy system and clearly reduce emissions from the sector. In subsequent years, low-efficiency generation units will be gradually phased out and replaced with higher-efficiency units (including cogeneration). Ultimately, a completely new energy system based on low- and zero-emission sources will be created by 2040 [23]. The implementation of the assumptions of this plan will significantly change the structure of the domestic energy sector in the future and will directly affect the demand for mineral sorbents for flue gas desulphurisation and for the production of synthetic gypsum.

Since 2016, the production of FGD synthetic gypsum in Poland remained at a similar level of about 3.3–3.4 million tpy, while the demand for limestone flour for the wet FGD method—at the level of 2.4–2.5 million tpy, and demand for limestone sand for fluidised bed boilers—ca. 1.0 million tpy. However, between 2018 and 2020, new flue gas desulphurisation plants were commissioned at four new coal-fired power units at Kozienice PP, Opole PP and Jaworzno III PP. Moreover, it is planned to complete the construction of the last new coal-fired power unit at the Turów PP with a capacity of 490 MW in 2021, also equipped with a flue gas desulphurisation plant using the wet limestone method. The construction of these new, conventional, power units allowed to replace a number of worn-out, oldest units. After 2021, new hard coal-fired or lignite-fired power units will not be built in Poland. So, eventually, starting from 2022, with perspective towards at least 2030, the total demand for limestone flour and limestone sand as FGD sorbents in Poland may achieve the record level of ca. 3.5–3.6 million tpy, including about 2.6 million tpy of fine-grained flour for flue gas desulphurisation in wet limestone method, and about 1.0 million tpy of coarse-grained flour (limestone sand) for desulphurisation in fluidised bed boilers and, subordinately, using dry or semi-dry methods. At the same time, the total production capacity of FGD synthetic gypsum in all Polish power plants can increase to about 5.7 million tpy, while its real production volume—to at least 4.6 million tpy. In the next few years, further new power units will undoubtedly be built in Poland, but they will not be based on hard coal or lignite burning, being mostly gas units and sometimes biomass units [23,57].

Forecasting the role of coal-fired power generation in Poland after 2030, and consequently the demand for limestone sorbents for desulphurisation in this sector, is extremely difficult and burdened with enormous uncertainty. The forecast error may even exceed 50%. The final shape of the Polish power industry is a matter of considerable uncertainty, especially in relation to economy decarbonisation processes pushed by the EU, with possible rapid reduction of the coal share in the energy mix in favour of increasing the RES share. After 2030, there will be another phase of phasing out the oldest power units, e.g., in Kozienice, Dolna Odra, Bełchatów and many other power plants. They are to be replaced mainly by gas units, nuclear units and renewable energy sources such as wind turbines and photovoltaic [23]. In such a scenario, total demand for limestone sorbents for desulphurisation will systematically fall and in 2050 may reach maximum level of about 1.3 million tpy, of which ca. 1.0 million tpy for wet limestone FGD method (Figure 2) and about 0.3 million tpy for flue gas desulphurisation in fluidised bed boilers. As a result, the production of synthetic gypsum in 2050 may decrease to only max. 1.5 million tpy. At that time, only those power units that were built between 2017 and 2021, and maybe also a few older coal-fired units that were upgraded in recent years, are likely to remain in operation. However, we cannot rule out that in 2050 the share of coal in the Polish energy mix may decrease even to zero, with closure of the last coal-fired PPs and CHPs. As a result, the consumption of sorbents for desulphurisation of flue gas coming from coal combustion will also practically disappear at this moment.

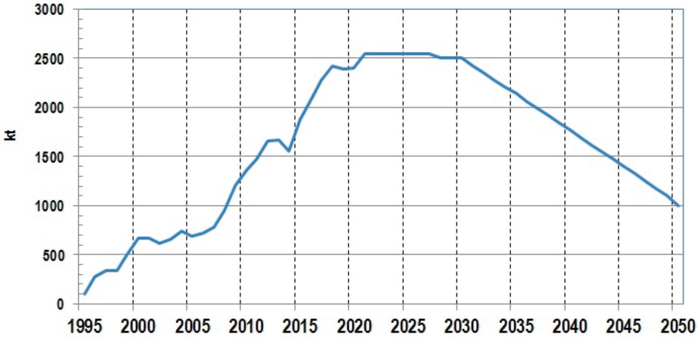

Figure 2. Forecast of limestone sorbents consumption for flue gas desulphurisation by wet limestone method in the years 2020–2050 (maximum expected forecasted quantities).

5. Conclusions

Measures taken since the beginning of 1990s to reduce SO_2 emissions in the Polish power industry (being mainly based on coal burning) resulted in the construction of numerous flue gas desulphurisation plants in the last 30 years. In Poland, they are mainly using the wet limestone method of dust-free flue gases, or use of fluidised bed boilers where the desulphurisation process takes place in the boiler immediately after coal combustion. In both main desulphurisation methods used in Poland, ground limestone of appropriate granulation is used for desulphurisation. This resulted in quick increase in demand for limestone sorbents: from zero in the early 1990s to about 3.4–3.5 million tpy at present. For the production of such limestone sorbent (limestone flour for wet limestone FGD method and limestone sand for fluidised bed boilers) different varieties of limestone are used in a few regions of the country, and they must meet basic requirements regarding, among others, chemical composition and granulation. At present, mostly Jurassic limestone, but also Devonian, Carboniferous and Triassic limestone varieties have the greatest significance in limestone sorbents production in Poland.

In 2022, after the completion of the last new investment project in the Polish coal-fired power industry in 2021—the new power unit in Turów Power Plant, the total demand for limestone FGD sorbents in domestic power plants will reach the maximum level of about 3.7 million tpy. Such a demand should be maintained until 2028–2030, after which it will systematically decrease in the following years, as a result of the gradual closure of subsequent coal-fired power units, while new production capacities based on hard coal or lignite are not expected to be built anymore. As a result of gradual decommissioning of coal-fired units in the 2050 perspective, the total consumption of sorbents in the domestic power sector should be reduced to a maximum of 1.3 million tpy, of which about 1.0 million tpy will be used for limestone flour consumption in wet limestone FGD installations and about 0.3 million tpy for limestone sand consumption in fluidised bed boilers. After 2050, it will probably be reduced practically to zero. As indirect consequence, the production of desulphurisation products, including in particular synthetic gypsum from the wet limestone method, will also decrease. Production of the latter could fall from about 3.6 million tpy in the coming years to only max. 1.5 million tpy just before 2050 and practically to zero after 2050.

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References

1. Bagayev, I.; Lochard, J. EU air pollution regulation: A breath of fresh air for Eastern European polluting industries? *J. Environ. Econ. Manag.* **2017**, *83*, 145–163. [CrossRef]
2. Cristobal, J.; Guillen-Gosalbez, G.; Jimenez, L.; Irabien, A. Optimization of global and local pollution control in electricity production from coal burning. *Appl. Energy* **2012**, *92*, 369–378. [CrossRef]
3. Crippa, M.; Janssens-Maenhout, G.; Dentener, F.; Guizzardi, D.; Sindelarova, K.; Muntean, M.; Van Dingenen, R.; Granier, C. Forty years of improvements in European air quality: Regional policy-industry interactions. *Atmos. Chem. Phys.* **2016**, *16*, 3825–3841. [CrossRef]
4. Council Directive 96/62/EC of 27 September 1996 on Ambient Air Quality Assessment and Management. 1996. Available online: https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX%3A31996L0062 (accessed on 29 January 2021).
5. Council Directive 1999/30/EC of 22 April 1999 Relating to Limit Values for Sulphur Dioxide, Nitrogen Dioxide and Oxides of Nitrogen, Particulate Matter and Lead in Ambient Air. 1999. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A31999L0030 (accessed on 29 January 2021).
6. Communication from the Commission to the Council and the European Parliament. In Proceedings of the Thematic Strategy on Air Pollution, COM(2005) 0446 Final, Brussels, Belgium, 21 September 2005; Available online: https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2005:0446:FIN:EN:PDF (accessed on 29 January 2021).
7. Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on Ambient Air Quality and Cleaner Air for Europe. 2008. Available online: https://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX%3A32008L0050 (accessed on 29 January 2021).
8. Directive 2001/80/EC of the European Parliament and of the Council of 23 October 2001 on the Limitation of Emissions of Certain Pollutants into the Air from Large Combustion Plants. 2001. Available online: https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX:32001L0080 (accessed on 29 January 2021).
9. Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on Industrial Emissions (Integrated Pollution Prevention and Control). 2010. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32010L0075 (accessed on 29 January 2021).
10. Lecomte, T.; de la Fuente, J.F.F.; Neuwahl, F.; Canova, M.; Pinasseau, A.; Jankov, I.; Brinkmann, T.; Roudier, S.; Sancho, L.D. *Best Available Techniques (BAT) Reference Document for Large Combustion Plants*; EC JRC Institute for Prospective Technological Studies: Seville, Spain, 2017.
11. Pouklikas, A. Review of design, operating, and financial considerations in flue gas desulfurizations systems. *Energy Technol. Policy* **2015**, *2*, 92–103. [CrossRef]
12. Kilic, O.; Acarkan, B.; Ay, S. FGD investments as part of energy policy: A case study for Turkey. *Energy Policy* **2013**, *62*, 1461–1469. [CrossRef]
13. Graus, W.; Worrel, E. Effects of SO_2 and NOx control on energy-efficiency power generation. *Energy Policy* **2007**, *35*, 3898–3908. [CrossRef]

14. Fernandez Gonzalez, P.; Landajo, M.; Presno, M.J. The driving forces behind changes in GHG emission levels in EU-27. Differences between member states. *Environ. Sci. Policy* **2014**, *38*, 11–16. [CrossRef]
15. Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 Establishing a Scheme for Greenhouse Gas Emission Allowance Trading within the Community and Amending Council Directive 96/61/EC (Text with EEA Relevance). 2003. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32003L0087 (accessed on 29 January 2021).
16. Directive 2009/29/EC of the European Parliament and of the Council of 23 April 2009 Amending Directive 2003/87/EC so as to Improve and Extend the Greenhouse Gas Emission Allowance Trading Scheme of the Community. 2009. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32009L0029 (accessed on 29 January 2021).
17. Liobikiene, G.; Butkus, M. The European Union possibilities to achieve targets of Europe 2020 and Paris agreement climate policy. *Ren. Energy* **2017**, *106*, 298–309. [CrossRef]
18. EC 2011—COM. A Resource-Efficient Europe—Flagship Initiative under the Europe 2020 Strategy. 2011. Available online: https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0021:FIN:EN:PDF (accessed on 29 January 2021).
19. Carlini, E.; Schroeder, R.; Birkebek, J.; Massaro, F. EU transition in power sector. How RES affects the design and operations of transmission power systems. *Electr. Power Syst. Res.* **2019**, *169*, 74–91. [CrossRef]
20. Tagliapietra, S.; Zachmann, G.; Edenhofer, O.; Glachant, J.M.; Linares, P.; Loeschel, A. The European union energy transition: Key priorities for the next five years. *Energy Policy* **2019**, *132*, 950–954. [CrossRef]
21. Heidrich, O.; Reckien, D.; Olazabal, M.; Foley, A.; Salvia, M.; de Gregorio Hurtado, S.; Orru, H.; Flacke, J.; Geneletti, D.; Pietrapertosa, F.; et al. National climate policies across Europe and their impacts on cities strategies. *J. Environ. Manag.* **2016**, *168*, 36–45. [CrossRef]
22. *National Air Protection Program until 2020 (with a Perspective until 2030)*; Ministry of Environment: Warsaw, Poland, 2015; Available online: File:///C:/Users/73RY74J/AppData/Local/Temp/Krajowy%20Program%20Ochrony%20Powietrza%20do%202020%20z%20perspektyw%C4%85%20do%202030.pdf (accessed on 29 January 2021). (In Polish)
23. Poland's Energy Policy until 2040—Announcement of the Minister of Climate and Environment of 2 March 2021 on the State's Energy Policy until 2040. *Polish Monitor*. 10 March 2021, p. 264. Available online: https://www.dziennikustaw.gov.pl/MP/2021/264 (accessed on 10 March 2021). (In Polish).
24. National Energy and Climate Plan for the Years 2021–2030; Ministry of State Assets: Warsaw, Poland. Available online: https://www.gov.pl/web/aktywa-panstwowe/krajowy-plan-na-rzecz-energii-i-klimatu-na-lata-2021-2030-przekazany-do-ke (accessed on 30 April 2021). (In Polish)
25. Gawlik, L. The Polish power industry in energy transformation process. *Miner. Econ.* **2018**, *31*, 229–237. [CrossRef]
26. Kaszyński, P.; Kamiński, J. Coal Demand and Environmental Regulations: A Case study of the Polish Power Sector. *Energies* **2020**, *13*, 1521. [CrossRef]
27. Antosiewicz, M.; Nikas, A.; Szpor, A.; Witajewski-Baltvilks, J.; Doukas, H. Pathways for the transition of the Polish power sector and associated risks. *Environ. Innov. Soc. Transit.* **2020**, *35*, 271–291. [CrossRef]
28. The Statistics Poland (GUS). *Environment 2020*; GUS: Warszawa, Poland, 2020; ISSN 0867–3217. Available online: https://stat.gov.pl/obszary-tematyczne/srodowisko-energia/srodowisko/ochrona-srodowiska-2020,1,21.html (accessed on 29 January 2021). (In Polish)
29. Galos, K.; Smakowski, T.; Szlugaj, J. Flue-gas desulphurisation products from Polish coal-fired power plants. *Appl. Energy* **2003**, *75*, 257–265. [CrossRef]
30. Galos, K.; Szlugaj, J.; Burkowicz, A. Sources of limestone sorbents for flue gas desulphurization in Poland in the context of the needs of domestic power industry. *Polityka Energetyczna Energy Policy J.* **2016**, *19*, 149–170.
31. Gawlicki, M.; Galos, K.; Szlugaj, J. Waste mineral raw materials from power plants, combined heat and power plants and heating plants. In *Mineral Raw Materials of Poland. Waste Mineral Raw Materials*; Galos, K., Ed.; IGSMiE PAN: Kraków, Poland, 2009; pp. 139–211. (In Polish)
32. Hlincik, T.; Buryan, P. Evaluation of limestones for the purposes of desulphurization during the fluid combustion of brown coal. *Fuel* **2013**, *104*, 208–215. [CrossRef]
33. Burkowicz, A.; Galos, K. Limestone and lime. In *Minerals Yearbook of Poland 2013*; Smakowski, T., Galos, K., Lewicka, E., Eds.; PIG-PIB: Warszawa, Poland, 2014; pp. 313–323. (In Polish)
34. Szuflicki, M.; Malon, A.; Tymiński, M. (Eds.) *The Balance of Mineral Resources Deposits in Poland as of 31 XII 2015–2019*; PIG-PIB: Warszawa, Poland, 2019. (In Polish)
35. Brzeziński, D. Limestone and marl for the cement and limestone industries. In *The Balance of Mineral Resources Deposits in Poland as of 31 XII 2019*; Szuflicki, M., Malon, A., Tymiński, M., Eds.; PIG-PIB: Warszawa, Poland, 2020; pp. 468–476. (In Polish)
36. Brzeziński, D.; Miśkiewicz, W. Crushed and dimension stone. In *The Balance of Mineral Resources Deposits in Poland as of 31 XII 2019*; Szuflicki, M., Malon, A., Tymiński, M., Eds.; PIG-PIB: Warszawa, Poland, 2020; pp. 105–127. (In Polish)
37. Wyszomirski, P.; Galos, K. *Mineral and Chemical Raw Materials of the Ceramics Industry*; UWND AGH: Kraków, Poland, 2007; pp. 133–140. (In Polish)
38. Nieć, M.; Tchórzewska, D. Limestone and other calcium minerals deposits. In *Minerals of Poland. Rock Minerals: Carbonate Minerals*; Ney, R., Ed.; IGSMiE PAN: Kraków, Poland, 2000; pp. 122–125. (In Polish)
39. Burkowicz, A.; Galos, K. Limestone, lime. In *The Balance of Mineral Raw Materials Management in Poland and in the World 2013*; Smakowski, T., Galos, K., Lewicka, E., Eds.; PIG-PIB: Warszawa, Poland, 2015; pp. 1013–1034. (In Polish)

40. The Statistics Poland (GUS). *Production of Industrial Products in 2019 (and Unpublished Data)*; GUS: Warszawa, Poland, 2019. Available online: https://stat.gov.pl/obszary-tematyczne/przemysl-budownictwo-srodki-trwale/przemysl/produkcja-wyrobow-przemyslowych-w-2019-roku (accessed on 29 January 2021).
41. Emitor 2014. *Emission of Environment Pollutants from Power Plants and Central Heating Plants—Report of the Agency of Energy Market*; Agencja Rynku Energii: Warszawa, Poland, 2015. (In Polish)
42. PSE—Polish Power Grids—Information on the PPS Generation Resources (as of 29 November 2019). Available online: https://www.pse.pl/documents/20182/f6bcb852-387b-4158-be1c-8ef58d25adb0?safeargs=646f776e6c6f61643d74727565 (accessed on 29 January 2021). (In Polish)
43. Córdoba, P. Status of Flue Gas Desulphurisation (FGD) systems from coal-fired power plants: Overview of the physic-chemical control processes of wet limestone FGDs. *Fuel* **2015**, *144*, 274–286. [CrossRef]
44. Hycnar, E.; Ratajczak, T.; Sęk, M. Dolomites as SO_2 Sorbents in Fluid Combustion Technology. *Resources* **2020**, *9*, 121. [CrossRef]
45. Zheng, Y.; Kill, S.; Johnsson, J.E.; Zhong, Q. Use of spray dry absorption product in wet flue gas desulphurization plants: Pilot-scale experiments. *Fuel* **2002**, *81*, 1899–1905. [CrossRef]
46. Roszczynialski, W.; Gawlicki, M. Management directions for flue gas desulphurisation products. In Proceedings of the 7th Conference on "Current Issues and Prospects of Mineral Resources Management", Polanica Zdrój, Poland, 19–21 November 1997. (In Polish)
47. Bis, Z. Lime sorbents in power industry. In *Processing and Use of Rock Raw Materials*; Galos, K., Ed.; IGSMiE PAN: Kraków, Poland, 2002. (In Polish)
48. Knura, P. Semi-dry flue gas desulphurization method using a pneumatic reactor integrated with a fabric filter (PR + FF method)—Directions of technology development, potential and possibilities. In Proceedings of the 2nd Conference of Electricity Generators, Skawina, Poland, 28–30 September 2011. (In Polish)
49. Szmigielska, E.; Głomba, M. Physico-chemical analysis of limestone utilized in desulfurization methods of flue gas from the power energy. In Proceedings of the Conference POL-EMIS: Atmospheric Air Protection, Sienna-Czarna Góra, Poland, 13–16 June 2012. (In Polish)
50. Gutierrez Ortiz, F.J. A simple realistic modeling of full-scale wet limestone FGD units. *Chem. Eng. J.* **2010**, *165*, 426–439. [CrossRef]
51. Tegethoff, F.W. (Ed.) *Calcium Carbonate. From the Cretaceous Period into the 21st Century*; Birkhäuser Verlag: Basel, Switzerland, 2001.
52. Lewicka, E.; Szlugaj, J.; Burkowicz, A.; Galos, K. Sources and markets of limestone flour in Poland. *Resources* **2020**, *9*, 118. [CrossRef]
53. Niesler, J. Development of fluidised bed furnaces in the power industry. *Piece Przemysłowe Kotły* **2011**, *4*, 33–36. (In Polish)
54. Hycnar, J. Fluidized beds—An example of rational solution of wastes problems. *Polityka Energetyczna Energy Policy J.* **2006**, *9*, 365–376. (In Polish)
55. Trybuś, T. Fluidized-Bed Combustion (FBC) as a method of abating sulphur dioxide and nitrogen oxides emission. *Environ. Pollut. Control. J. Pol. Sanit. Eng. Assoc.* **1995**, *2*, 15–18. (In Polish)
56. European Parliament Legislative Resolution on the Application by the Republic of Poland to Become a Member of the European Union (AA-AFNS 1-6—C5-0122/2003—2003/0901G(AVC)). Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52003AP0176&from=ES (accessed on 29 January 2021).
57. Szlugaj, J.; Naworyta, W. Analysis of the changes in the Polish gypsum resources in the context of flue gas desulfurization in conventional power plants. *Gospod. Surowcami Miner. Miner. Resour. Manag.* **2015**, *31*, 93–108. (In Polish)
58. Gawlik, L.; Grudziński, Z.; Kamiński, J.; Kaszyński, P.; Kryzia, D.; Lorenz, U.; Mirowski, T.; Mokrzycki, E.; Olkuski, T.; Ozga-Blaschke, U. *Węgiel dla Polskiej Energetyki w Perspektywie 2050 Roku—Analizy Scenariuszowe*; Górnicza Izba Przemysłowo-Handlowa: Katowice, Poland, 2013. (In Polish)

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The Economic Aspect of Using Different Plug-In Hybrid Driving Techniques in Urban Conditions

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Abstract: Plug-in hybrids (PHEV) have become popular due to zero-emission driving, e.g., in urban areas, and using an internal combustion engine on longer distances. Energy consumption by the PHEV depends on many factors which can be either dependent or independent of the driver. The article examines how the driver can use the vehicle's capabilities to influence its wear. Determining the optimal driving technique, due to the adopted nature of the timetable, is the basic variable that determines the profitability of using a given drive system. Four driving techniques have been selected to determine which one can offer the largest advantages. A vehicle-dedicated application has recorded the drivetrain performance on a predetermined route through an urban area. The analysis of results has demonstrated which of the driving techniques provides measurable effects in terms of reduced energy consumption and the shortest travelling time. The study shows longitudinal acceleration and torque generated by the electric drive. The information included in the study can help any PHEV user reduce the operating cost by applying an appropriate driving technique. The proposed research introduces the possibilities of assessing the influence of the driving style on energy consumption. The innovative side of this research is the observation of stochastic phenomena that are difficult to detect when using approximation modelling.

Keywords: electric car; electromobility; PHEV; data analysis; driving technique; energy consumption

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1. Introduction

A large number of vehicles on our roads have a negative impact on the environment. This impact is already generated at the stage of manufacturing and operation. Manufacturers make every effort to make the construction of vehicles as light as possible [1,2]. Hence, internal combustion engines can use less fuel and produce small volumes of toxic compounds emitted to the atmosphere [3–5]. Alternative fuel technologies [6–8] and hybrid vehicle propulsion systems [9–11] have been extensively developed.

When analyzing the above technologies, it can be noted that hybrid vehicles are considered to be the most sensible solutions to reduce fuel consumption and toxic emissions without compromising the vehicle's drivability [9–13]. PHEVs use energy management systems to reduce fuel and energy consumption originating from several energy sources [14–16]. Among hybrid vehicles, the largest attention of researchers has been drawn to the electric plug-in hybrid vehicles (PHEV) due to their batteries and an advanced propulsion system [17–21]. These are universal vehicles designed to produce zero-emission while driving in urban areas, and travel long distances while using the combustion engine. The complex propulsion system helps reduce carbon dioxide emission, in particular in urban areas [22,23].

PHEVs are cheaper than electric vehicles and, at the same time, still have advantages over internal combustion engine vehicles (ICEV) [24]. The analysis of distances covered by owners of conventional vehicles shows that most of them travel less than 32 km per day and, in the case of PHEV users, it is less than 11 km per day [25]. The plug-in hybrid (PHEV) is used to describe a conventional hybrid vehicle with a battery rechargeable from a conventional power socket, recuperated energy from braking or by a combustion engine-driven generator [26,27]. The PHEV uses an electric motor of 60–70 kW [28]. The optimal battery capacity compared to the BEV enables to maintain the range in the urban driving mode and a partial reduction of the combustion engine use over the distance [29,30]. When the battery is discharged, the internal combustion engine starts to drive the vehicle and the generator operated until the battery is recharged. The combustion engine also operates at the start-up when the outside temperature is low. This is referred to as a cold start and occurs after a continuous 12-h shut-down [31]. This is the cause of fuel consumption when driving on short distances with fully charged batteries.

The combination of an internal combustion engine and an electric engine makes the vehicle independent from access to the electric charger. However, if one travels on short distances in a zero-emission mode, the vehicle uses electricity. To reduce the energy used during a journey, one should plan the route well and take into account the traffic. Although the approach is presented by authors of numerous publications [32,33], the final energy needed to cover the route depends on yet another factor that has not been addressed by scientific research. It is the driving technique that, in addition to the factors mentioned above, such as the construction and capability of a vehicle and conditions and road infrastructure, has untapped potential in terms of energy saving. The driver is able to use systems installed in the vehicle and his assessment of the road traffic to use less energy on a previously planned route [34–36]. In the opinion of the authors, it is worth determining the extent and benefits of a few simple driving techniques in combination with systems made available by the vehicle manufacturer. The subject of electromobility of exhaust emissions and trends in discharged systems in Poland was discussed in the works [37–42].

This paper expands the current electromobility and PHEV studies by demonstrating which driving technique produces measurable results in terms of reduced energy consumption and the shortest travelling time. The goal is to determine optimum operating conditions for the electrical power management system in serial and parallel modes in an SUV 4 × 4 class PHEV. The combination of studies and real-time reading of operational parameters enables to examine the performance of the system and optimize parameters of the kinetic energy recuperation system and the systems monitoring the battery charging process. Such studies are based on the monitoring of the parameters and the performance of the electric drive and batteries in real driving conditions, in urban traffic, with a high traffic intensity and frequent energy recovery from braking. In addition, the study uses data pertaining to the speed profile in a given area and the operation of inbuilt systems. Data were derived from the GPS vehicle location reading and mobile applications. These procedures also provide data on vehicle movement in time, braking and acceleration frequencies, average traffic speed and mileage per traffic sections. Once we collated these data and detailed information from experimental studies of a test vehicle, it was possible to determine the nature of traffic and the expected electricity demand. Therefore, it is possible to set an appropriate energy management strategy to maximize the lifetime of the main batteries.

Drawbacks of electrochemical cells used in electric vehicles include their low power density which determines high current values and the loss of capacity, high mass, and a relatively small number of charge and discharge cycles. Despite the application of increasingly sophisticated energy storage technologies using rare elements, the operation of batteries needs to be continuously monitored. Therefore, a precise electricity management, depending on the area, vehicle class, and the number of driven axles, is essential to maintain the cost-efficiency of batteries. The power management system can therefore be enhanced with speed limit solutions, torque reduction and rated power depending on the temperature and the actual status of the batteries. The development of such systems is in progress, but most authors focus on real traffic vehicle testing over short distances to collect more reliable data. This study, however, combines user data and experimental data. Based on this data and a large population of vehicles, strategic conditions can be established to optimize the durability of electrochemical cells in the PHEV power supply system.

The main issue related to PHEVs is the range and life-cycle. These are determined by the capacity of the power source (main and secondary energy sources and capacitors), whose energy accumulation capacity is limited and the charging time unsatisfactory.

The battery management system (BMS) measures the current from the power unit, the voltage at individual cells, and the instantaneous temperature (temperature of cells inside the housing and safety unit). The measurement of these parameters enables to determine the state of charge (SOC) and the state of health (SOH) of the power unit and the rated capacity of cells. The BMS should intervene in case of overload, i.e., exceeded SOC limit or control system overheating. It should disconnect or request the electrochemical cell assembly to be disconnected from the electrical system. The BMS determines the instantaneous status of the cell pack and sends data (output signals) over the controller area network (CAN) to supervisory systems. These values include charge and discharge currents and critical power. The purpose of the system that monitors charging and operation is to keep the SOC within the acceptable range and to maintain the power range in the BMS control system. In the case the cell assembly is in continuous operation (discharge) during the urban mode driving (electricity consumption by an electric motor), the system needs to disconnect the power unit from the vehicle's electrical system. The energy required to support safety or monitoring systems may be taken from the secondary source responsible for the start-up of the internal combustion engine, because of the negligible current and voltage if compared to the secondary (main) energy source. In some applications, the BMS controller determines the power range, and the circuit shutdown in the cell assembly is determined by a master controller. In this system, the BMS affects the cooling of the cell assembly and the SOC status.

To maintain the long life cycle of electrochemical cells during cyclic load changes, the temperature must be maintained between 5 °C and 25 °C depending on the base material of electrodes and electrolyte. The life cycle of batteries is reversely proportional to the average operating temperature.

In traction PHEVs, the secondary energy source is charged at regular charging and discharge intervals. The optimum cyclical changes affect the efficiency of the electric drive and the kinetic energy recuperation from braking or idle driving. The cycle frequency management strategy (loading-unloading) should take into account parameters describing the operation of electrochemical cells and the gravimetric capacity. The combination of these parameters enables to reduce the weight of the unit while maintaining the required service life. The strategy for the managing of energy transmission to the generator-combustion engine unit and from cells to the electric motor should be based on experimental tests. Tests should integrate the speed profile and input values defining the vehicle, durability of its energy unit, recuperation and absorption of kinetic energy by a set of capacitors, and efficiency of the combustion engine and power generator under predefined operating conditions, i.e., forced nominal power demand.

The battery management system should also provide the user with the possibility to exercise supervision and control over basic operating parameters of the vehicle, e.g., comfort and safety equipment, or to monitor their status automatically. The introduction of a passive power control algorithm would certainly allow increasing the range until battery discharge. If necessary, the electric power control unit stored in an automatic mode in the secondary energy source would switch off individual comfort devices in the agreed priority order, e.g., radio, interior lighting, air conditioning and ventilator, etc. This would certainly contribute to a more efficient use of energy and to maintain a long life cycle of batteries.

If the cell bank's low state of charge is exceeded, the discharge process must be reduced and the heat engine started, especially in the warm-up mode. When the charging of the cell pack drops below its lower limit, it is recommended to start intensive charging by increasing the charging current and controlling the operation of the combustion engine. The discharge power reaches zero when the lower charging limit is significantly exceeded. During the operation of the system, the lower charging limit should never be reached to maintain the vehicle's acceleration capacity. At the design stage, when energy balance is calculated, the rated power of the combustion engine and the generator should be adapted to the gravimetric capacity of the electrochemical cell unit and the electric motor to prevent reduced vehicle's acceleration capability. The determination of the lower charging limit affects the vehicle's acceleration capacity and the life cycle of the battery pack. For the battery pack adopted, based on performance parameters, the lower charging limit is 20%. The introduction of an additional control system (additional controller) will ensure that the designated control algorithms are integrated and durability and charging capacity maintained at the limit level. The strategy to maintain the preset charging level of the secondary energy source in traction vehicles requires the adjustment of the combustion engine operation frequency and its operating point to ensure the overall cost efficiency of the PHEV. The determination of the appropriate operating conditions for these systems based on precise charging and energy supply parameters based on tests is a valuable source of information about the behavior of the system and the maximum battery pack lifetime and the SUV class vehicles operated in the urban mode. It can also help other authors in similar studies.

The article focuses mainly on experimental research. The shortcomings of ICEV systems are discussed in the works [43–45]. The parameters of the timetable are intentionally very similar. There are quite a few studies that underpin the cost-effectiveness of introducing hybrid vehicles to the automotive market. In particular, data on the impact of aperiodic faults on the profitability of using individual types of drive systems are included in the authors' works [46,47]. It is worth mentioning, however, that there are applied works on verifying the nature of driving for the battery consumption process. In these studies, careful attention was paid to the parameters of the battery, environmental conditions and the conditions for changing the operating parameters of batteries in SUVs often used in urban mode. These studies supplement the existing data set with new operational information.

Design trends in lithium-ion batteries show that an increase in energy density and safety can be expected over the next decade. Base material costs account for the bulk of the cost of a battery pack (66%). By using silicone batteries, costs can be reduced by 30% per kWh. Accordingly, the limit of $100/kWh will be reached in 2020–2025 for silicon batteries and in 2025–2030 for NMC batteries. This low price will have a significant impact on the overall price of the PHEV and BEV. This will translate into profitability of the mass use of these drive system solutions [48].

The article structure is as follows: Section 2 provides an overview of the study. Section 3 includes an analysis of test results. Section 4 presents final conclusions from the study while indicating its limitations, practical application and the focus of future research in the area.

The main scientific objective of the article is to present the energy consumption of various driving techniques used by the driver for a given type of urban route for PHEV vehicles with four-wheel drive. The article fills the scientific gap in the field of experimental research on the demand for electricity in SUVs depending on the driving techniques used. As part of the experimental research, it was assumed that the length of the route does not change, the external conditions are stable and the only variable is the driving style of the driver. The nature of the route, such as: the number of crossings, hills, traffic volume, stopping time, number of traffic lights and road traffic restrictions are constant. Five driving modes have been adopted: "normal"—driving without paying attention to consumption while maintaining traffic continuity and road regulations, "pedal gas"—

braking and acceleration mode in order to maximize kinetic energy recuperation, “eco”—the mode in which the vehicle undergoes within the specified manufacturer parameters, for example, limiting speed, electric motor power and acceleration values, “rules”—traffic mode according to the road regulations with a speed limit of 50 km/h, “summer”—driving mode with maximum energy saving at 21 °C (air conditioning system and combustion engine are off). The “summer” mode was to be a reference to the most economical mode of driving the route during the research. Research in this area was not undertaken by researchers, they are limited to simulation calculations and the introduction of different timetables. In this study, the possibilities of reducing the energy consumption by the driver were analyzed using specific driving techniques implemented by the driver, and not the energy consumption monitoring systems. These studies provide a valuable complement to information on the energy consumption trends of 4WD SUVs and other PHEVs.

2. Materials and Methods

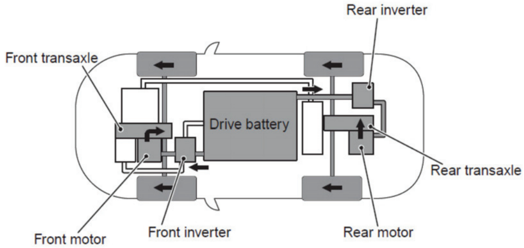
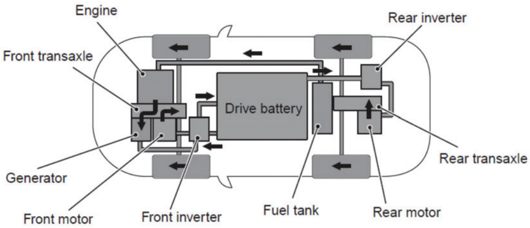
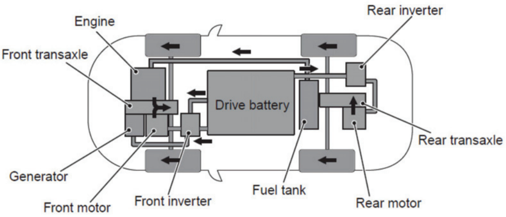
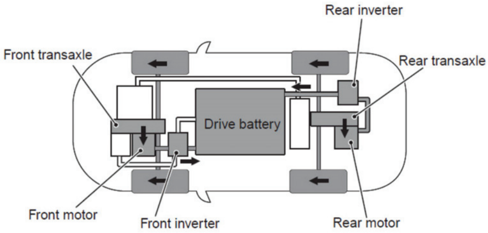
2.1. Characteristics of the PHEV Propulsion Used

The purpose of the study is to indicate optimum driving techniques supporting the reduction of energy consumption in the plug-in hybrid vehicle. A good example of such a vehicle already in-service is the SUV class Mitsubishi Outlander PHEV manufactured in 2014.

The study focuses on the SUV class which typically has an increased energy consumption compared to other vehicle classes, in particular, those of smaller dimensions and curb weight. Another advantage is the ability to incorporate a series and parallel drive, which provides additional research and knowledge aspects regarding trends in optimizing energy consumption in the urban driving mode. Results of the study will be used to estimate the electricity consumption in a wide range of vehicles and to optimize the energy management system in 4 × 4 SUVs. Based on information obtained and user data from GPS analysis of SUV vehicles, a simulation can be performed to introduce relevant energy forecasting algorithms based on accurate real-time traffic studies. They are very effective in the case of large urban agglomerations where the energy recuperation system is frequently operated comparing to the extra-urban mode. According to the authors, accurate experimental studies in combination with statistical data on braking and acceleration frequency, and the average speed in a given high traffic area with a high number of intersections and stopping points are used to better assess the range of SUV PHEVs. The main problem to be solved, which still limits the development of 4 × 4 PHEV electric motors fitted with energy recuperation systems, is the storage of energy required to drive the traction vehicle while maintaining its desired range and driving dynamics. To ensure that the optimization forecasts for the energy management system are correct, it is also necessary to provide information on the operating status and disturbances of the power supply system, as well as intermediate data, e.g., DC/DC converter. The latter data provide information on the power supply to stabilized voltage passive components (counteracting output voltage fluctuations), which causes changes in the DC voltage needed to correlate the high voltage system with the LDV vehicle’s 12 V voltage system.

At first, for further study, it is worth explaining the drive solution. It is a hybrid electric/petrol vehicle that can operate in parallel and series. Energy is transmitted to the wheels by two electric motors, one for the front and the other for the rear axle. These are two 60 kW engines of various torques: 137 Nm [front] and 197 Nm [rear]. The 2.0 L combustion engine cooperates with the front electric motor and has the power of 89 kW and a torque of 190 Nm [37]. It can have the front wheel propulsion through the gear in a parallel hybrid mode and the generator in a series mode. The series hybrid driving mode is used for heavy acceleration or driving in mountainous areas. When moving at high speeds, the combustion engine drives the front wheels and the generator operates as a parallel hybrid. The control unit is responsible for switching between the different driving modes. The vehicle can be driven in the electric mode using electric motors only, but then the combustion engine is switched off. The range in this driving mode is limited by the capacity of the battery, which is 50 km according to the manufacturer's information. The electric motors are powered by a 300 V 12 kW Li-ion battery with 80 air-cooled cells. The battery is located in the middle section of the vehicle under the floor to improve the directional stability of the vehicle. Since two types of charging connectors and an external charger are provided, the vehicle can be charged using the AC240V (Type 1) connector from the home electrical socket and a DC charging station via the CHAdeMO connector. The individual modes of engine operation are presented in Table 1.

Table 1. Mitsubishi Outlander PHEV powertrain operation modes [37].

EV Mode	Series Mode
	
Paralel Mode	**Regeneration Mode**
	

The two electric motors in the drivetrain of the vehicle are used to generate power for the 4 × 4 drive. They are also used as power generators to produce braking force and to recover energy from braking. This solution allows controlling the driving power and braking force without removing the foot from the accelerator pedal. The depth at which the pedal is depressed corresponds to the driving power, and the release of the pedal activates recuperative braking.

The recuperative braking force can be controlled within five levels by levers on the steering column and within two levels via the drive mode selector. Levers at the steering wheel can be adjusted to a braking position of 5 to 0, where 5 is the largest force and 0 corresponds to the absence of recuperative braking. The drive mode selector, once moved to position B, sets braking at 5, and when it is moved to position B again, braking is set to position 5. This functionality has been used in one of the tests. In Table 2. the technical data of the vehicle used in the tests is included.

The functions introduced in this vehicle allow the introduction of driving techniques independent of the supervisory systems. A very identical distribution of the route has been intentionally selected in order to assess the possibilities of reducing energy through interference by the driver himself. This makes it possible to determine the optimal driving technique in urban territory, especially for highly energy-consuming SUVs with 4 × 4 drive. In addition, a comparative drive at a temperature of about 21 °C was introduced to the four selected driving techniques, which excludes the maximum operation of the internal combustion engine and the air conditioning system. This allows one to realistically assess the energy benefits for different driving techniques and different weather conditions. This research provides a significant indication for future drivers of PHEV SUVs.

Table 2. Technical parameters of the vehicle intended for experimental research.

Parameter	Value
Own weight	1871 kg
Mass during tests	2000 kg
Maximum load on the front axle	1160 kg
Maximum load on the rear axle	1255 kg
Internal combustion engine capacity	1998 cm^3
Internal combustion engine power	89 kW
Driving torque IC	190 Nm
The power of the electric motor that drives the front axle	60 kW
Drive torque of the electric motor driving the front axle	137 Nm
The power of the electric motor driving the rear axle	60 kW
The driving torque of the electric motor driving the rear axle	197 Nm
Traction battery capacity	40 Ah
Traction battery voltage	300 V
Tires	215/70 R16

2.2. A Map with a Route and Speed Profile

Road tests were carried out in Poznań, Poland, and its surroundings in late November and early December 2020. For comparative purposes, an additional drive of the vehicle was made on the same route using the most effective driving technique at a temperature of 21 °C. This drive was performed in May 2021. This allows for a comparative analysis of this driving technique excluding additional disturbances. This applies to the operation of the air conditioning system and the internal combustion engine. The city of Poznań is a typical large Polish metropolis, which justifies its choice for vehicle testing. Additional GPS data from 10 users of PHEVs were obtained from the area of Poznań and similar urban agglomerations with a similar distribution of junctions and traffic flow. The proposed short period of the real traffic experimental studies (detailed studies) resulted from the need to ensure a relatively stable ambient temperature during all test runs. Due to the long battery charging time, ambient conditions and fluctuating traffic, it was possible to have only one trip per day. The situation was similar in the case of statistical data, which indicated a very similar character of trips according to information from PHEV users. During all tests, the car was driven mostly in the electric mode, and in the serial hybrid mode only when the coolant was heated to the temperature that would allow the passenger compartment to warm up.

The route started at a private property where the vehicle was charged from an electrical socket overnight. The route went from the suburbs of Poznań through its center to a destination located in the area of the Poznań University of Technology. The distance between the vehicle stopover location and the destination was 13.9 km. There were 28 intersections along the route with traffic lights and pedestrian crossings. The speed limits applied to the entire route and ranged from 30 km/h in the center to 50 km/h in most built-up areas and 70 km/h in the section of the main access road. Trips were made between 9:30 and 10:00 in the morning. The average travelling time for the entire route was 34 min. The test runs ensured similar measurement conditions for all tests. The test run for the temperature of 21 °C was made for the same route at the same hours, with the same traffic volume and distribution of encountered road obstacles.

2.3. Performance of Tests

Before each test, the vehicle was parked in a garage and, at the start of the test, the outside temperature and the temperature of the car interior was 14 °C. After entering the vehicle, the driver turned on the start button and activated the mobile application. Then, the application was used to record parameters and the test started. While driving, changes of temperature in the passenger compartment and the ambient temperature were noted. The vehicle's interior temperature was set in the air-conditioning system at 21 °C. The ambient temperature was measured using a factory-mounted sensor in the car and the interior temperature was measures by the electronic service thermometer WT-2. The measuring range of the latter is -50 °C to +300 °C and the accuracy is ± 1 °C.

Before the test, the vehicle's battery was fully charged at 100% SOC (State of Charge). Measurements ended at a parking lot at the same location and logged in to a mobile application when the vehicle was stopped.

When driving at an ambient temperature of 21 °C, the interior of the vehicle had a similar temperature of about 22 °C, which excluded interference with the air conditioning system during tests. It also reduced the use of the internal combustion engine to a minimum.

2.4. Test Programs

The test programs used to compare energy consumption were selected in such a way that they do not absorb too much driver's attention and make the most of the car's capabilities. This enables any user of the vehicle to repeat the trip with similar energy consumption. The following four test programs were used:

- Regular driving in the "normal" driving mode—enables the vehicle to stay behind other vehicles without obstructing the traffic. All vehicle systems were set to "normal". This is the standard driving mode most often used by drivers.
- Regular driving in the "eco" driving mode—enables the vehicle to stay behind other vehicles without obstructing the traffic. All vehicle systems were set to the "eco" mode by pressing the "eco" button on the center panel. According to the manufacturer's information, this function changes the accelerator pedal's operating characteristics, resulting in a slow response from the drive to the pedal. It also changes the functioning of the air-conditioning system.
- Driving with "gas pedal" in the "normal" mode—enables regeneration braking. This driving mode is activated at the fifth level of recovery using levers at the steering wheel or by shifting the drive mode selector twice to position B. This and the prediction of the traffic enables driving virtually without touching the brake pedal.
- The "rules" mode—driving in line with regulations means that the driver follows all vertical and horizontal signs and speed limits throughout the test. The vehicle's speed limiter system was used to meet the requirement. After setting the speed limit, a message appeared on the dashboard and the vehicle did not allow the speed to be exceeded. Unfortunately, this type of driving requires continuous modification of speed limit settings depending on the required speed limit.
- The "summer" mode—driving in the most economical mode of the previous tests at an ambient temperature of around 21 °C. This allowed to reduce the maximum use of electricity from all systems determining the temperature of the interior of the vehicle. It also allows to reduce the share of the internal combustion engine to zero. According to the conducted analysis, this is the most effective mode of driving for SUVs with 4 × 4 drive.

2.5. Equipment and Software Used to Record Parameters

The tests used the communication with the vehicle via the standardized OBDII diagnostic interface. Information is picked up by the ELM 375 interface and transmitted via Bluetooth to the "PHEV Watchdog" application installed on the mobile device.

It is a free application that allows one to view real-time information from the Mitsubishi Outlander controllers. It enables to record 51 parameters and save their values in CSV files and provides 63 conversion parameters as maximum and average values. The information sampling frequency from the controllers during the tests was every 1.3 s. Such sampling is sufficient to compare energy consumption by the vehicle during tests. The number of parameters used for further analysis was limited to the most important ones from the point of view of energy consumption. Further analyses were based on the following values:

- Travelling time;
- Vehicle speed;
- Time of acceleration;
- Battery capacity used;
- Capacity recovered during the test;
- Power consumption by the EV during a test and its average value;
- Consumption of petrol by the combustion engine;
- Average regenerative braking power;
- Torque generated by the front and rear motors.

Additionally, the following values have been calculated based on the actual mileage:

- Longitudinal acceleration;
- Braking delays;
- Total traction torque of electric motors;
- Total braking torque of electric motors.

Parameters registered by the application have been converted to enable their processing in Microsoft Excel.

3. Results and Discussion

Three test runs were made for each of the four test programs. Weather conditions and computer indications related to the expected range were recorded. A summary of the results related to the characteristics of the vehicle's route is shown in Table 3. Colors are used to mark maximum (green) and minimum (yellow) values. For each average value obtained from the measurements and given in Table 3, the accuracy of its measurement is given in square brackets. To assess this accuracy, the standard deviation method (σ) was used, which describes the dispersion of the measurement results around the average value. During road tests, the average ambient temperature was between −0.7 °C and 2 °C. The longest average travelling time was recorded for driving with the use of the acceleration pedal, and the shortest with the "eco" mode. However, the longest and shortest values attributed to the same driving techniques decreased slightly after the standstill time was subtracted.

Table 3. Average test results. Green and yellow are used to mark maximum and minimum values, respectively.

No	Parameter	Unit	Normal [σ]	Gas Pedal [σ]	Eco [σ]	Rules [σ]	Summer [σ]
1	Ambient temperature	°C	−0.7 [2.3]	2.0 [1]	1.7 [3.8]	1.7 [1.2]	21 [0]
2	Distance covered	km	13.9 [0.1]	13.9 [0.1]	13,9 [0]	13.9 [0]	13.9 [0]
3	Travelling time	min:sec	34:20 [01:23]	35:18 [02:21]	32:23 [02:18]	34:42 [02:03]	38:34 [01:01]
4	Stationary	%	30.92 [1.4]	28.6 [4.6]	26.1 [5.6]	24.6 [1.6]	31.4 [3]

The ambient temperature in the "summer" mode was 21 °C.

Other parameters, interesting from the point of view of the vehicle's energy consumption, are listed in Table 4. Green indicates the highest values and yellow the lowest ones. The data from the "summer" mode have been shown in gray for comparison. The analysis of data from this driving mode allows to assess to what extent the air conditioning system and the lack of interference of the internal combustion engine with the power supply of the drive system affect the energy consumption of PHEV 4 × 4 SUV vehicles. The fuel consumption for the internal combustion engine in the "summer" mode is marked in red. When analyzing trip parameters, it can be noted that the average speed was between 24.3 km/h and 26.5 km/h and that the maximum value of 78 km/h was reached while driving in the "normal" mode. The lowest speed value of 66 km/h was recorded for a run with "rules". Speed profiles for both cases are shown as test runs in Figures 1 and 2. The speed fluctuations during the "normal" and "rules" driving modes can be seen in the speed profile diagrams provided. They show the sections of the route where speed limits to 30, 50 and 70 km/h have been made. Both figures also show three lines corresponding to the individual limit values. In the "eco" and "summer" modes, the distribution of the driving speed profiles was very similar to the "normal" and "rules" modes. It is caused by driving on the same route with the same restrictions, e.g., traffic volume, number of lights, number of additional territorial obstacles.

Table 4. Mean values from the test runs, green is used to mark maximum values and yellow to mark minimum values. Data for the road test. These values are calculated as approximate and predicted—based on the road tests carried out.

Data for the Road Test Mitsubishi Outlander PHEV							
No.	**Parameter**	**Unit**	**Normal [σ]**	**Gas Pedal [σ]**	**Eco [σ]**	**Rules [σ]**	**Summer [σ]**
1	Average speed	km/h	25.0 [0.3]	24.4 [1.2]	26.5 [1.5]	24.3 [1.5]	21.9 [0.1]
2	Top speed	km/h	78 [2]	74.3 [6.7]	74 [3.5]	66 [0]	66 [0]
3	Glide time	%	2.5 [0.5]	2.9 [0.5]	2.1 [0.4]	2.4 [0.4]	2.8 [0.4]
4	Average acceleration value	m/s^2	0.75 [0.03]	0.72 [0]	0.65 [0.02]	0.69 [0.04]	0.70 [0.02]
5	Average deceleration on breaking	m/s^2	−0.83 [0.03]	−0.75 [0.09]	−0.72 [0.03]	−0.74 [0.03]	−0.73 [0.05]
6	Loss of range according to computer indications	km	21.3 [1.2]	20.7 [0.6]	19.7 [0.6]	18.7 [0.6]	12.5 [0.7]
7	Used battery capacity	Ah	12.9 [0.3]	12.0 [0.1]	11.6 [0.8]	10.8 [0.7]	7.9 [0.5]
8	Capacity recovered during the test	Ah	1.8 [0.5]	2.2 [0.3]	1.5 [0.4]	1.2 [0.3]	1.5 [0.1]
9	Average EV energy consumption in test	kWh/100 km	28.0 [0.9]	26.3 [0.4]	25.4 [1.8]	24.0 [1.5]	18.0 [1]
10	Petrol consumption by the internal combustion engine	L/100 km	1.4 [0]	1.4 [0]	0.9 [0.7]	0.7 [0.8]	0 [0]
11	Average recovery braking power	kW	8.5 [0.7]	8.0 [1.2]	7.2 [0.5]	6.3 [0.3]	6.2 [0.5]
12	Average drive torque	Nm	51.9 [2.9]	50.2 [2.3]	41.4 [1.5]	42.7 [1.5]	41.79 [1.26]
13	Average braking torque of EV engines	Nm	−35.3 [1.2]	−40.4 [0.4]	−31.8 [1.4]	−34.9 [0.3]	−34.87 [2.11]

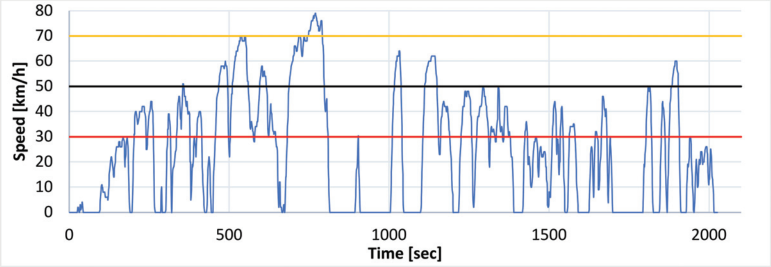


Figure 1. Speed profile for the test run in traffic and the "Normal" mode.

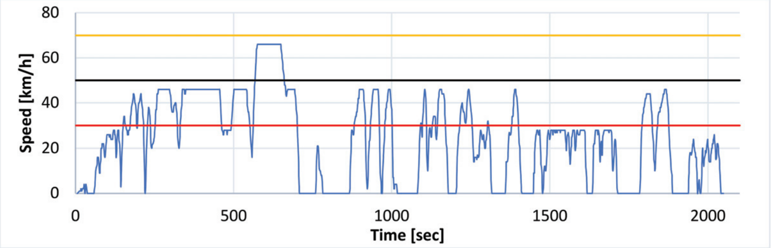


Figure 2. Speed profile for the test run "Rules".

Acceleration values over the measured section were between 0.65 and 0.75 m/s^2. Braking during the test was between -0.72 and -0.83 m/s^2, the most frequently encountered in urban traffic [34]. Speed and acceleration values are consistent with those obtained by other researchers when analyzing vehicle behavior in urban traffic [35,36]. An example of acceleration values recorded during one of the tests is shown in Figure 3.

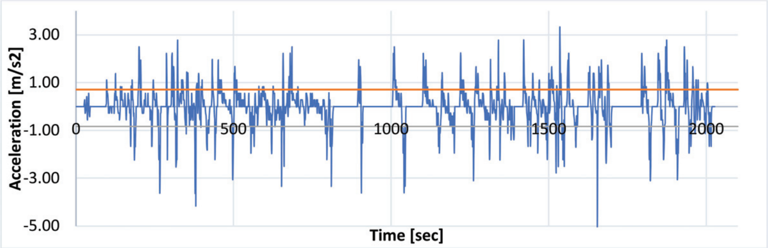


Figure 3. Acceleration values in the "eco" mode with highlighted average values for braking and acceleration.

It is interesting that the vehicle also moved with an idle acceleration since the values obtained are related to the instantaneous traffic and according to traffic lights. These values are between 2.1% and 2.6% of the total travelling time. When driving, the driver can use the on-board computer readouts to determine the range of the vehicle. Such information is approximate and, therefore, the results should be considered indicative only. During the tests, the loss of range after the test run was between 18.7 km and 21.3 km. The lowest value of the loss of range according to the indications of the measuring equipment is recorded for the "summer" mode. This means that the adoption of a specific driving technique significantly translates into the theoretical range of the vehicle. The "eco" and "rules" modes are the best. The parameters of the speed limit and acceleration values are largely decisive here. The mode of using additional devices also plays an important role here. As can be seen in the "summer" mode, the loss of the theoretical range is the smallest, which is largely due to the lack of air conditioning system operation. As it can be easily observed, it has a huge impact on the theoretical range of vehicles. The influence of comfort systems is of great importance on the energy consumption of the entire vehicle, it also allows one to plan the range of the vehicle and increase it during the journey in emergency situations, e.g., access to the charging station by switching off the air conditioning system.

While examining the range of electric vehicles, an important parameter is the loss of the battery's capacity after travelling over a certain distance. In the tests, the loss was between 10.8 Ah and 12.9 Ah. The decrease in battery capacity is shown in the example of Figure 4. During the runs, a part of the capacity was also recovered, and depending on the driving technique applied, it was between 1.2 Ah and 2.2 Ah. The lowest value of the consumed battery capacity was obtained for the "summer" mode. It was 7.9 Ah. In this mode, the recovery of electricity was similar to the "eco" mode and amounted to 1.5 Ah. Based on the road tests carried out, it can be concluded that the most effective energy recovery is represented by the "pedal gas" mode. Nevertheless, it did not guarantee the best results in terms of battery capacity loss, intensity of the braking process and fuel consumption by the internal combustion engine. Fuel consumption is the highest for the "normal" and "pedal gas" modes. Based on the obtained data, zero chemical energy consumption from fuel was obtained in the "summer" mode. For this mode, the lowest value of the average energy consumption during the test is also recorded. The value of this parameter is 18.0 kWh/100 km. Positive results were also obtained for the drive in the "summer" mode and the "rules" mode. The average value of energy consumption over time for this mode does not exceed 24.0 kWh/100 km. The above parameters show the ability to generate reusable energy. The average power recovered during regenerative braking was between 6.3 kW for driving in accordance with the regulations and 8.5 kW for the "normal" driving technique. The most appealing parameter and, at the same time, a measurable indicator for the use of a particular driving technique is the average energy consumption per 100 km. During the tests, the consumption varied from 24 kW/100 km to 28 kW/100 km. Based on the road tests carried out, it can be concluded that the average recuperative braking power is the highest for the "normal" mode. It amounts to 8.5 kW. For "rules" and "summer" modes, the average recuperative braking power ranged from 6.2 to 6.3 kW. The other modes are within the accepted range of maximum and minimum values. In connection with the adopted data, it can be concluded that the average power of regenerative braking does not always indicate energy gains and an increase in range. This is due to the fact that the greatest range was obtained for the "summer" and "rules" modes, despite the lowest braking energy recovery value.

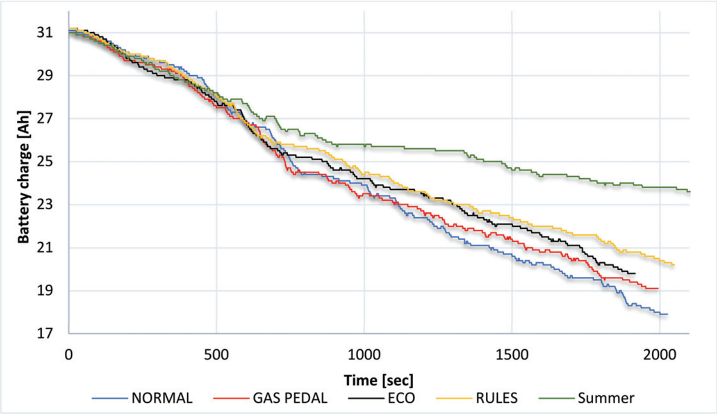


Figure 4. Battery capacity changes in "eco" mode.

The observation of the powertrain during the test runs shows differences between the different driving techniques. The differences reach 20% between the extreme torque values generated by both engines in "normal" and "eco" drive modes, respectively, 51.9 Nm and 41.4 Nm. When braking with electric motors, braking torques were from −31.8 Nm ("Eco") to 40.4 Nm ("pedal gas"). Examples of characteristics are shown in Figures 5 and 6. For the "summer" mode, the results of the average driving torque were similar to the "rules" and "eco" modes.

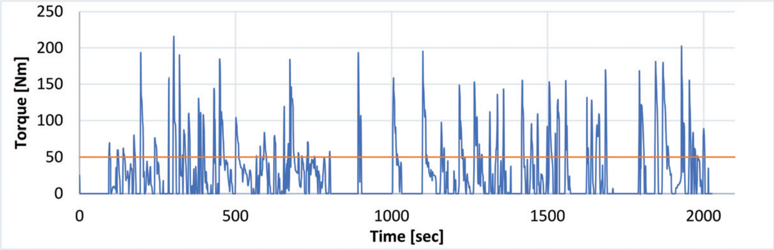


Figure 5. Changes in the total driving torque with the average value marked for "eco" driving.

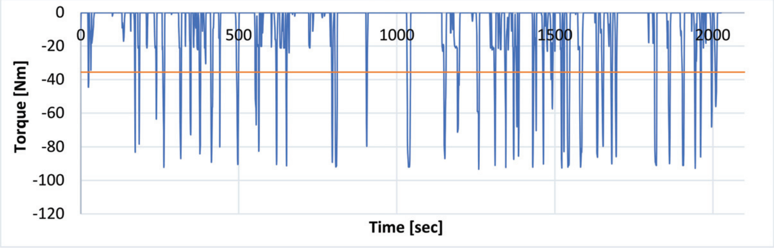


Figure 6. Variation in the total braking torque generated by electric motors with the average value marked for "eco" driving.

When analyzing the energy consumption of the Mitsubishi Outlander Hybrid, the fuel consumption by the combustion engine must not be forgotten. Although due to a low ambient temperature, the combustion engine started to heat the coolant to a certain temperature, it used petrol as well. According to the manufacturer, when the ambient temperature falls below 5 °C, the control unit starts the engine in order to heat the coolant to 60 °C [37]. This is less energy-consuming than the use of an electric heater. Thus, fuel used during the tests varied from 0.7 L/100 km to 1.4 L/100 km, and it directly depended on the ambient temperature. During the tests, the combustion engine started to heat the liquid only. It is demonstrated by the recorded generator power values, which during all tests were equal to 0 kW. To highlight the differences and indicate energy savings from a driving technique, the values of the three parameters are collated in the table below. These parameters are the average values for all tests, i.e., the gain in the range as indicated by the on-board computer in km, remaining battery capacity in Ah after the test, and the difference in the vehicle power consumption in kW/100 km. In the "summer" mode, the failure to switch on the electric motor is registered. This is an interesting reference to the other driving modes. Assuming the above data, it can be concluded that the use of SUVs with a 4 × 4 drive in the summer period allows one to reduce fuel consumption to zero and significantly increase the range of the vehicle. This is mainly due to the lack of need to heat the liquid for heating the interior of the vehicle. The "summer" mode allows to present the realistically achievable maximum range for this type of vehicle. It is significantly larger than the other modes. By using the "rules" or "eco" driving technique in the "summer" mode, it will allow one to achieve significant effects in the form of energy benefits.

Valuable scientific information is the fact that resignation from the vehicle heating systems increases its range by 41.3%, and the energy consumption per 100 km decreases by 35.7%. This is especially true for the "summer" mode.

Table 5 shows the difference between the normal and the other driving techniques analyzed.

Table 5. Average values of the test run parameters in relation to the normal driving mode.

No.	Parameter	Unit	Gas Pedal	Eco	Rules	Summer
1	Gain as indicated by the on-board computer	km	0.6 (2.8%)	1.6 (7.5%)	2.6 (12.2%)	8.8 (41.3%)
2	Remaining battery capacity	Ah	0.9 (7%)	1.5 (11.6%)	2.1 (16.3%)	5.0 (38.8%)
3	Reduction of average energy consumption	kW/100 km	1.7 (6.1%)	2.6 (9.3%)	4.0 (14.3%)	10.0 (35.7%)

4. Conclusions

Plans for the development of electromobility in Poland have provided incentives to expand knowledge about low-carbon vehicles offered on the Polish market [38]. So far, research in this area has focused on technological issues (description of PHEV technology) or environmental aspects (comparison of CO_2 emission levels) [39–44]. This study is a new economic approach on the use of PHEVs in urban traffic. It indicates which driving techniques and which vehicle systems the driver can use to reduce the vehicle's energy consumption and therefore its operating costs. Data are based on a developed experimental system and information from users of class SUV PHEVs operated in the urban mode. The method used for measurement data conversion may be also used in other studies. The results show how systems fitted to the vehicle can be used to reduce the energy consumption. Approximate data from both types of tests indicate how the energy management system can be optimized and which limitations need to be introduced to achieve the maximum durability and efficiency of the main batteries [44–47]. The hypothesis of the work confirmed that the driving style is the main factor influencing the strategy of using the vehicle in the economic aspect. This criterion does not only depend on the environment in which the vehicle is moving. The driving style has energy for the essential functional aspects which determine the energy consumption of the accumulator and recuperative unit. This parameter is mainly decided by the user. In particular, it concerns the acceleration value and the time of the impact of aerodynamic drag. It is also reflected in the braking frequency and the efficiency of the energy recuperation system. In addition, the driving style affects the frequency of periodic and aperiodic faults, and this significantly reduces the profitability of using hybrid vehicles. Therefore, it can be assumed that taking into account these conditions and programming certain habits among users may contribute to a significant reduction in energy consumption.

On the basis of the conducted experimental studies, the following conclusions can be presented:

- The "eco" and "rules" driving modes are characterized by the lowest electricity consumption at low ambient temperatures with switched-on air conditioning systems.
- According to the data on electric energy feedback from braking, it is stated that not always a large share of this process translates into a significant increase in range, which can be seen on the basis of data from the "eco" and "rules" modes.
- Using the "rules" driving mode, one can achieve a reduction in energy consumption of 14.3% and an increase in the battery capacity for a given schedule by 16.3%. This allows one to increase the effective range in relation to the "normal" mode by 12.2%.
- Driving in the "pedal gas" mode is not a promising driving technique where energy savings are recommended, indirect but not very dynamic driving mode is the "eco" system, which allows for a 9.3% reduction in energy consumption compared to the "normal" mode. This mode allows one to keep driving dynamics more like in the "rules" mode.

- The “summer” mode turns out to be the most advantageous driving mode. It allows one to increase the range by over 41% and reduce the energy consumption by over 35% compared to the “normal” mode. The “summer” mode in combination with the “rules” mode allows one to achieve very good results in terms of increased energy consumption and loss of battery capacity for the same road journeys. Based on the data from the “summer” mode, it can be assumed that the ambient temperature, which was 21 °C, plays an important role in saving energy. In this operating temperature range, air conditioning systems are turned off and the combustion engine is not turned on. This allows one to maximize the range of the vehicle in electric mode and reduce the consumption of conventional fuel to zero.
- On the basis of the tests carried out, it can be said that the energy consumption of the vehicle is not largely influenced by the nature of the route, but by the style of driving the vehicle through the driver. This means that the effects of energy consumption are mainly influenced by the driver and the systems used by the manufacturer are only systems supporting the driver. It is the driver who decides how to increase the range of the vehicle using a given driving technique.

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References

1. Bubna, P.; Wiseman, M. Impact of light-weight design on manufacturing cost—A review of BMW i3 and Toyota Corolla Body Components; Technical Report; SAE Technical Paper. In Proceedings of the SAE World Congress and Exhibition, Detroit, MI, USA, 12–14 April 2016.
2. Seyfried, P.; Taiss, E.J.M.; Calijorne, A.C.; Li, F.P.; Song, Q.F. Light weighting opportunities and material choice for commercial vehicle frame structures from a design point of view. *Adv. Manuf.* **2015**, *3*, 19–26. [CrossRef]
3. Agarwal, A.K.; Srivastava, D.K.; Dhar, A.; Maurya, R.K.; Shukla, P.C.; Singh, A.P. Effect of fuel injection timing and pressure on combustion, emissions and performance characteristics of a single cylinder diesel engine. *Fuel* **2013**, *111*, 374–383. [CrossRef]
4. Sajjad, H.; Masjuki, H.; Varman, M.; Kalam, M.; Arbab, M.; Imtenan, S.; Rahman, S.A. Engine combustion, performance and emission char-acteristics of gas to liquid (GTL) fuels and its blends with diesel and bio-diesel. *Renew. Sustain. Energy Rev.* **2014**, *30*, 961–986. [CrossRef]
5. Kong, S.C.; Marriott, C.D.; Reitz, R.D.; Christensen, M. Modeling and experiments of hcci engine combustion using detailed chemical kinetics with multidimensional cfd; Technical Report; SAE Technical Paper. In Proceedings of the SAEWorld Congress, Detroit, MI, USA, 5–8 March 2001.
6. Chen, L.; Zhang, J.; Li, Y.; Ye, Y. Mechanism analysis and evaluation methodology of regenerative braking contribution to energy efficiency improvement of electrified vehicles. *Energy Convers. Manag.* **2015**, *92*, 469–482.
7. Koetse, M.J.; Hoen, A. Preferences for alternative fuel vehicles of company car drivers. *Resour. Energy Econ.* **2014**, *37*, 279–301. [CrossRef]
8. Lee, S.; Speight, J.G.; Loyalka, S.K. *Handbook of Alternative Fuel Technologies*; CRC Press: Boca Raton, FL, USA, 2014.
9. Hu, X.; Murgovski, N.; Johannesson, L.M.; Egardt, B. Comparison of three electrochemical energy buffers applied to a hybrid bus powertrain with simultaneous optimal sizing and energy management. *IEEE Trans. Intell. Transp. Syst.* **2014**, *15*, 1193–1205. [CrossRef]
10. Lv, C.; Zhang, J.; Li, Y.; Yuan, Y. Directional-stability-aware brake blending control synthesis for over-actuated electric vehicles during straight-line deceleration. *Mechatronics* **2016**, *38*, 121–131. [CrossRef]
11. Sockeel, N.; Shi, J.; Shahverdi, M.; Mazzola, M. Sensitivity analysis of the battery model for model predictive control implemented into a plug-in hybrid electric vehicle. In Proceedings of the 2017 IEEE Transportation Electrification Conference and Expo, Chicago, IL, USA, 22–24 June 2017; pp. 493–500.

12. Zhang, J.; Lv, C.; Gou, J.; Kong, D. Cooperative control of regenerative braking and hydraulic braking of an electrified passenger car. *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.* **2012**, *226*, 1289–1302. [CrossRef]
13. Heutel, G.; Muehlegger, E. Consumer learning and hybrid vehicle adoption. *Environ. Resour. Econ.* **2015**, *62*, 125–161. [CrossRef]
14. Shabbir, W.; Evangelou, S.A. Real-time control strategy to maximize hybrid electric vehicle powertrain efficiency. *Appl. Energy* **2014**, *135*, 512–522. [CrossRef]
15. Škugor, B.; Deur, J.; Cipek, M.; Pavkovic, D. Design of a power-split hybrid electric vehicle control system utilizing a rule-based controller and an equivalent consumption minimization strategy. *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.* **2014**, *228*, 631–648. [CrossRef]
16. Zou, Y.; Hou, S.; Li, D.; Gao, W.; Hu, X.S. Optimal energy control strategy design for a hybrid electric vehicle. *Discret. Dyn. Nat. Soc.* **2013**, *2013*, 132064. [CrossRef]
17. Li, Y.; Lu, X.; Kar, N.C. Rule-based control strategy with novel parameters optimization using NSGA-II for power-split PHEV operation cost minimization. *IEEE Trans. Veh. Technol.* **2014**, *63*, 3051–3061. [CrossRef]
18. Sim, K.; Jeong, H.; Kim, D.R.; Lee, T.K.; Han, K.; Hwang, S.H. Control strategy with the slope of SOC trajectory for plug-in diesel hybrid electric vehicle with dual clutch transmission. In Proceedings of the 25th International Electric Vehicle Symposium and Exhibition (EVS28), Koyang, Korea, 3–6 May 2015.
19. Lian, J.; Liu, S.; Li, L.; Liu, X.; Zhou, Y.; Yang, F.; Yuan, L. A mixed logical dynamical-model predictive control (MLD-MPC) energy management control strategy for plug-in hybrid electric vehicles (PHEVs). *Energies* **2017**, *10*, 74. [CrossRef]
20. Berthold, F.; Ravey, A.; Blunier, B.; Bouquain, D.; Williamson, S.; Miraoui, A. Design and development of a smart control strategy for plug-in hybrid vehicles including vehicle-to-home functionality. *IEEE Trans. Transp. Electr.* **2015**, *1*, 168–177. [CrossRef]
21. Tribioli, L.; Barbieri, M.; Capata, R.; Sciubba, E.; Jannelli, E.; Bella, G. A real time energy management strategy for plug-in hybrid electric vehicles based on optimal control theory. *Energy Procedia* **2014**, *45*, 949–958. [CrossRef]
22. Millo, F.; Rolando, L.; Fuso, R. Real world operation of a complex plug-in hybrid electric vehicle: Analysis of its CO_2 emissions and operating costs. *Energies* **2014**, *7*, 4554–4570. [CrossRef]
23. Chen, Y.; Hu, K.; Zhao, J.; Li, G.; Johnson, J.; Zietsman, J. In-use energy and CO_2 emissions impact of a plug-in hybrid and battery electric vehicle based on real-world driving. *Int. J. Environ. Sci. Technol.* **2018**, *15*, 1001–1008. [CrossRef]
24. Lane, B.W.; Dumortier, J.; Carley, S.; Siddiki, S.; Clark-Sutton, K.; Graham, J.D. All plug-in electric vehicles are not the same: Predictors of preference for a plug-in hybrid versus a battery-electric vehicle. *Transp. Res. Part D* **2018**, *65*, 1–13. [CrossRef]
25. Williams, B.; Martin, E.; Lipman, T.; Dammen, D. Plug-in-hybrid vehicle use, energy consumption, and greenhouse emissions: An analysis of household vehicle placements in Northern California. *Energies* **2011**, *4*, 435–457. [CrossRef]
26. Karbowski, D.; Rousseau, A.; Pagerit, S.; Sharer, P. Plug-in vehicle control strategy: From global optimization to real time application. In Proceedings of the 22nd Electric Vehicle Symposium, Japan Automobile Research Institute, EVS22, Yokohama, Japan, 22–28 October 2006.
27. Jefferson, C.M.; Barnard, R.H. *Hybrid Vehicle Propulsion*; WIT Press: Billerica, MA, USA, 2002.
28. Kupiec, J.; Kupiec, A. Automotive Monthly for vehicle repairers and testers. *Badanie Hybryd w SKP* **2013**, *9*, 20–23.
29. Fan, H.; Peng, J.; He, H. Rule-based plug-in hybrid school bus energy management control strategy simulation. In Proceedings of the 10th Asian Control Conference (ASCC), Kota Kinabalu, Malaysia, 31 May–3 June 2015; pp. 1–6.
30. Shen, X.; Zhang, J.; Shen, T. Real-time scenario-based stochastic optimal energy management strategy for HEVs. In Proceedings of the 2016 European Control Conference (ECC), Ålborg, Denmark, 29 June–1 July 2016; pp. 631–636.
31. Markey, J. *Federal Test Procedure Review Project: Preliminary Technical Report*; EPA 420-R-93–007; USA Environmental Protection Agency: Ann Arbor, MI, USA, 1993.
32. Bast, H.; Delling, D.; Goldberg, A.; Muller-Hannemann, M.; Pajor, T.; Sanders, P.; Wagner, D.; Werneck, R.F. Route planning in transportation networks. In *Algorithm Engineering*; Springer: Berlin/Heidelberg, Germany, 2016; pp. 19–80.
33. Letchner, J.M.; Krumm, J.C.; Horvitz, E.J. Collaborative Route Planning for Generating Personalized and Context-Sensitive Routing Recommendations. U.S. Patent 8,718,925, 6 May 2014.
34. Kupiec, J.; Ślaski, G.; Pikosz, H. Parametry pracy układu hamulców samochodu osobowego w badaniach eksperymentalnych, czasopismo Autobusy. *Tech. Eksploat. Syst. Transp.* **2018**, *12*, 500–507.
35. Ohde, B.; Ślaski, G.; Maciejewski, M. Statistical analysis of real-world urban driving cycles for modeling Energy consumption of electric vehicles. *J. Mech. Transp. Eng.* **2016**, *68*, 25–39. [CrossRef]
36. Ślaski, G.; Ohde, B.; Pikosz, H. Modelowanie energochłonności eksploatacji samo-chodu elektrycznego w warunkach ruchu miejskiego dla potrzeb symulacji zużycia energii przez flotę taksówek. *Logistyka* **2014**, *4*, 2517–2526.
37. Mitsubishi Outlander PHEV MY 2014, Owner's Manual, Mitsubishi Motors Coroporation 2013. Available online: http://mmc-manuals.ru/manuals/outlander_iii/online/Service_Manual_2013/2014 (accessed on 12 December 2020).
38. Drożdż, W.; Radziński, M.; Mathews, A. The role of DSOs in the development of reaching points for electric vechicles. In *Electromobility as a Megatrend of Contemporary Economy*, 1st ed.; Drożdż, W., Ed.; Polish Scientific Publishers PWN: Warsaw, Poland, 2021; pp. 27–33.
39. Palkowski, K. Electric car and atmosphere protection. *Ann. Set Environ. Prot.* **2016**, *18*, 628–639.
40. Kopczyński, A.; Krawczyk, P.; Lasocki, J. Parameters selection of extended-range electric vehicle supplied with alternative fuel. *E3S Web Conf.* **2018**, *44*, 00073. [CrossRef]

41. Tucki, K.; Orynycz, O.; Swić, A.; Mitoraj-Wojtanek, M. The development of electromobility in Poland and EU states as a tool for management of CO2 emissions. *Energies* **2019**, *12*, 2942. [CrossRef]
42. Tucki, K.; Orynycz, O.; Mitoraj-Wojtanek, M. Perspectives for mitigation of CO2 Emission due to development of electromobility in several countries. *Energies* **2020**, *13*, 4127. [CrossRef]
43. Wróblewski, P.; Iskra, A. Problems of Reducing Friction Losses of a Piston-Ring-Cylinder Configuration in a Combustion Piston Engine with an Increased Isochoric Pressure Gain; SAE Technical Paper 2020-01-2227; SAE International USA. In Proceedings of the SAE Powertrains, Fuels & Lubricants Meeting, Krakow, Poland, 22–24 September 2020. [CrossRef]
44. Wróblewski, P. The effect of the distribution of variable characteristics determining the asymmetry of the sealing rings sliding surfaces on the values of friction loss coefficients and other selected parameters of oil film, VII International Congress on Combustion Engines. *Combust. Engines* **2017**, *171*, 107–116. [CrossRef]
45. Wróblewski, P. Technology for Obtaining Asymmetries of Stereometric Shapes of the Sealing Rings Sliding Surfaces for Selected Anti-Wear Coatings; SAE Technical Paper 2020-01-2229; SAE International USA. In Proceedings of the SAE Powertrains, Fuels & Lubricants Meeting, Krakow, Poland, 22–24 September 2020. [CrossRef]
46. Wróblewski, P.; Drożdż, W.; Lewicki, W.; Dowejko, J. Total cost of ownership and its potential consequences for the development of the hydrogen fuel cell powered vehicle market in Poland. *Energies* **2021**, *14*, 2131. [CrossRef]
47. Wróblewski, P.; Drożdż, W.; Lewicki, W.; Miązek, P. Methodology for assessing the impact of aperiodic phenomena on the energy balance of propulsion engines in vehicle electromobility systems for given areas. *Energies* **2021**, *14*, 2314. [CrossRef]
48. Berckmans, G.; Messagie, M.; Smekens, J.; Omar, N.; Vanhaverbeke, L.; Van Mierlo, J. Cost projection of state of the art lithium-ion batteries for electric vehicles up to 2030. *Energies* **2017**, *10*, 1314. [CrossRef]

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Article

Hydrogen Technology on the Polish Electromobility Market. Legal, Economic, and Social Aspects

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Abstract: The aim of this study was to evaluate the motorization market of electric vehicles powered by hydrogen cells in Poland. European conditions of such technology were indicated, as well as original proposals on amendments to the law to increase the development pace of electromobility based on hydrogen cells. There were also presented economic aspects of this economic phenomenon. Moreover, survey research was conducted to examine the preferences of hydrogen and electric vehicle users in 5 primary Polish cities. In this way, the level of social acceptance for the technological revolution based on hydrogen cells and taking place in the motorization sector was determined.

Keywords: electromobility; hydrogen cells; energy law; customer preferences

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1. Introduction

Electromobility as part of the alternative fuel market, also embracing hydrogen technologies, can currently be called a megatrend on the global and European scale both on the motorization market and on the electric energy market. On the one hand, the development of the alternative fuel market is a market trend whereas, on the other hand, this trend mainly arose from the promotion of the development of this market by the energy policy and climate change policy of the European Union (EU), which is not only reflected in the strategic and program documents of the European Union [1] but, first of all, in the form of legal acts.

The primary objectives of the climate and energy policy of the EU are to reduce the emission of greenhouse gases, to increase the percentage of renewable energy sources in the final consumption of energy gross leading to the decarbonization of the power industry, and to increase the energy efficiency, which in consequence shall result in climatic neutrality, which is the purpose of the energy and climate policy of the European Union, expressed in a Communication of the European Commission—European Green Deal [2]. The said primary objectives shall also be achieved in the transportation sector with the aim to use zero-emission and low-emission technologies and fuels. The legal framework for the development of alternative fuels in the EU law was constituted, in the current legal state, by the directive of the European Parliament and of the Council 2014/94/EU of 22 October 2014 on the development of alternative fuel infrastructure (Directive 2014/94) [3].

Electrical energy and hydrogen are alternative fuels that are now the object of high interest on the market of transport. It must be noted that electric vehicles and vehicles driven by hydrogen cause a smaller emission of CO2, specks of dust, and gases harmful to the health and the environment. It must be taken into consideration that reduced emission of contaminants depends on the sources which generate the electric energy used for charging the electric vehicles—a considerable percentage of renewable sources increased the ecological value of electric and hydrogen drives.

The term electromobility, including hydrogen technologies, may be understood as a combination of two segments of this market: the charging or refueling stations (component of infrastructure) as well as the electric and hydrogen vehicles (component of infrastructure and vehicle users).

Consequently, in the market of electromobility, as a new market of electric energy, one can separate a segment of vehicles and a segment of infrastructure, which are inseparable and cannot function independently of each other. With the increase in the number of charging or refueling stations, the number of electric vehicles and vehicles driven by hydrogen will be on the rise, which will lead to significant growth of the market of alternative fuels sensu largo. As indicated in a justification to the Act of 11 January 2018 on electromobility and alternative fuels—alternative fuels require a unique infrastructure used for refueling and charging motor vehicles driven by these fuels. Without creating appropriate infrastructures, consumers would not be interested in changing motor vehicles driven by conventional fuels (e.g., petroleum, diesel oil) into vehicles using alternative fuels as a drive. In turn, entrepreneurs would not be interested in carrying out economic activities related to alternative fuels since there are no customers [4].

On 8 July 2020, communication between the European Commission and the European Parliament, Council, European Economic and Social Committee, and Committee of the Regions was published—a strategy within the scope of hydrogen for the benefit of a neutral Europe for the climate (hydrogen strategy) [5] that must be deemed a derivative of provisions of the European Green Deal, and a starting point for an analysis contained herein. Hydrogen, including, particularly, the one obtained from renewable sources—so-called green hydrogen—was mentioned as one of the vital energy media which may contribute to the achievement of the assumptions of the European Green Deal. The primary objective of the published strategy was to stimulate and enlarge the renewable sector with green hydrogen so that it would be an entirely zero-emission, generally available source of energy in the EU until 2050. The hydrogen strategy also indicated that investments in hydrogen would contribute to sustainable economic growth and to the creation of jobs, which will be of vital importance in the context of coming out of the crisis connected with COVID-19. The hydrogen strategy also emphasized the reconstruction plan [6] presented by the European Commission, in which the necessity of unblocking the investments in pure technologies and the value chains of vital significance was highlighted. The plan underlined that clean hydrogen is one of the significant areas which must be dealt with in the context of the energy transition and indicated many possibilities and ways of supporting this process [7].

The hydrogen strategy also described hydrogen production methods (types of hydrogen), possible exploitation of hydrogen in the industry and transport, and a plan of support of this fuel by the EU.

The primary types of hydrogen in the hydrogen strategy were as follows:

- Electrolytic hydrogen—hydrogen generated within the electrolysis of water (in an electrolyzer powered by energy) regardless of the source of electric energy. The emissions of greenhouse gases of the whole life cycle related to the production of electrolytic hydrogen depending on the method of production of electric energy.
- Renewable hydrogen (pure hydrogen)—hydrogen generated within the electrolysis of water (in an electrolyzer powered by electric energy) with the reservation that electric energy comes from renewable sources. The emissions of greenhouse gases of the whole life cycle related to the production of renewable hydrogen are close to zero.
- Hydrogen of fossil fuels—hydrogen generated within various processes in which fossil fuels are used as raw materials (natural gas reforming or coal gasification). It accounts for a more significant part of hydrogen produced now. The emissions of greenhouse gases of the life cycle related to the production of hydrogen from fossil fuels are high.
- Hydrogen of fossil fuels with carbon capture—a subtype of hydrogen of fossil fuels with the reservation that the greenhouse gases emitted in the production process of this hydrogen are captured. The emissions of greenhouse gases connected to the production of hydrogen of fossil fuels with carbon capture or with the use of pyrolysis

are lower than in the case of hydrogen of fossil fuels, but the changeable effectiveness of greenhouse gas capture must be taken into consideration (maximum 90%).

- Synthetic hydrogen derivatives—various gas and liquid fuels based on hydrogen and coal. A hydrogen fraction of the synthesized gas should be renewable so that synthetic fuels can be considered renewable. For example, renewable fuels include synthetic naphtha in aviation, synthetic diesel oil for cars, and different molecules used for the production of chemicals and fertilizers. With regard to air pollution, the combustion of synthetic fuels generates similar levels of emission of contaminants as fossil fuels [8].

As indicated in the hydrogen strategy, now-renewable hydrogen, electrolytic hydrogen, and hydrogen of fossil fuels with carbon capture are not competitive in terms of costs compared to the hydrogen of fossil fuels (the current estimated price of hydrogen of fossil fuels is approximately EUR 1.50/kg. To a large extent, the price depends on the prices for natural gas and does not include CO_2 costs. The estimated price of hydrogen from fossil fuels with carbon capture and storage is around EUR 2.00/kg, whereas the price of renewable hydrogen is between EUR 2.50 and EUR 5.50/kg–Hydrogen strategy, page 5 of the report of the International Energy Agency, the Future of Hydrogen pertaining to hydrogen for 2019, page 42: https://www.iea.org/reports/the-future-of-hydrogen# [accessed on 4 March 2021]. The calculations were based on the assumed natural gas prices for the EU of the amount of EUR 22.00 per MWh, the electric energy prices between EUR 35.00 and 87.00/MWh, and the costs of the production capacity coming to EUR 600.00/kW) [9]. However, in the long run (years 2030–2050), the priority of the EU is the development of the production of renewable hydrogen with the use of wind and solar energy mainly. The renewable hydrogen is most consistent with the long-run objective of the EU within the scope of the climatic neutrality and with the aim to achieve zero-emission of contaminants, and most coherent with the integrated energy system.

It was indicated in the hydrogen strategy that increased production of hydrogen is combined with the creation of new pioneer markets; two primary pioneer markets of which include industrial uses and mobility, which can be gradually developed to exploit the potential of hydrogen reasonably in terms of costs for the benefit of the economy neutral for the climate. Hydrogen may be applied in the transportation sectors in which electrification procures difficulties. In the initial period of implementing hydrogen technology solutions, hydrogen may be used in local city buses, in commercial fleets (e.g., taxis), or components of railway networks, in the cases in which electrification is unfeasible or unprofitable. At the subsequent stages of implementing hydrogen as a fuel in transport, it is necessary to propagate using hydrogen fuel cells in heavy road vehicles—coaches, special purpose vehicles, and vehicles for long-distance road transport—due to a high emission level of CO2 thereof. Hydrogen may also become an alternative low-emission fuel in the case of inland shipping, short sea shipping and may contribute to decarbonization of the aviation and maritime sectors (hydrogen strategy, pages 12–13. In the case of aviation and sea transport, hydrogen may help to decrease the emission of greenhouse gases and air pollutants thanks to the production of synthetic liquid naphtha or other synthetic fuels. The long-term potential option for aviation may also be hydrogen fuel cells which require the adaptation of the construction of an aircraft or jet engines propelled by hydrogen) [10].

Adoption of the hydrogen strategy by the European Commission must be treated as another argument for assuming that hydrogen technologies and hydrogen as a chemical component have become the object of interest not only in Europe but also all over the world, because they may be used as raw material, fuel or as an energy medium and energy storage facility, including on the market of electromobility transport.

As indicated in the literature, it is needed to develop a cheap, fast, and efficient method of production of hydrogen so that it can replace the current energy media. At present, approximately 48% of the produced hydrogen is formed due to methane reforming with the use of water vapor, 30% crude oil (mainly in refineries), 18% of coal, and the remaining 4% comes from the electrolysis of water. The best-known methods of obtainment of hydrogen include:

- natural gas reforming,
- coal or coke gasification,
- plasma technology,
- electrolysis of water,
- photo-electrolysis,
- biological methods [11].

It is also worth noting that, already now, Poland—with the production at the level of approximately 1 million tons per annum (globally approximately 74 million tons)—is an essential player on the market of so-called grey hydrogen manufactured from fossil fuels. It is mainly used as a raw material in chemical production processes (e.g., from ammonia) and refinery processes [12].

Data obtained at the end of 2018, classified Poland as one of the primary producers of hydrogen in the EU, generating 1.3 million tons of hydrogen per annum in total. The most significant Polish producers are Grupa Azoty S.A. (approximately 420 thousand tons), PKN Orlen S.A., Grupa Lotos S.A. and, JSW S.A. [13]. However, this hydrogen is not currently used as a fuel for vehicles in transport.

It must be noted that the objectives of the energy and climate policy of the EU may be achieved, first of all, by the so-called pure hydrogen—renewable hydrogen produced from renewable energy sources. Now, it accounts for approximately 5% of the total global production of this raw material—generation of green hydrogen is still more expensive than other forms of production thereof. The progress of this market's segment is, for the time being, in the initial phase of evolving but, to stimulate innovations and reduce emissions, Poland should also commence research, adopt the strategies, implement legal regulations and incentives, and conduct programs of support to increase the use of hydrogen in transport and to be able to compete with other countries.

Hydrogen is perceived as a fuel of the future for the transport and power industry. The current sources of hydrogen are mainly based on fossil fuel processing technologies (natural gas, crude oil, coal). The prosperity of the technologies for the obtainment of hydrogen, with the use of renewable sources, is very intense, and it is forecast that in 2050 approximately 25% of hydrogen will be reached through electrolysis or directly through the gasification of biomass. In a more extended perspective, the blossom of electric transport, particularly long-distance transport, will be based on hydrogen drives with the use of fuel cells. The spread of high-power fuel cells is a barrier in energy uses on a considerable scale. The fact that, as already said above, one of the significant sources of hydrogen in Poland is the excessive coke oven gas, which contains more than 55% of hydrogen, is essential information too [14].

The subject matter of the analysis in this publication was hydrogen technology and hydrogen as one of the types of alternative fuels being part of the electromobility market in line with the classification adopted both in strategic documents and in the European Union law, and in Polish national law. Using the hydrogen technologies term in the definition of electromobility was also justified for the second reason. Hydrogen as a transportation fuel may be used in two ways:

(1) as a fuel which was combusted in an engine bay and
(2) with the use of fuel cells, generating energy driving an electric motor.

Due to many advantages (lightness, easy and fast filling of tanks) and specific problems with the use in a combustion engine (e.g., pre-ignition, hydrogen storage energy consumption in a liquid aggregate state), particularly the technology which uses hydrogen for the generation of electric energy through fuel cells is being developed now [15]. Therefore, hydrogen-driven vehicles and hydrogen-fueling infrastructure may be considered a part of the electromobility term, in which alternative fuel is not electric energy but hydrogen.

2. Methodology

In order to fulfill the purpose of the article, a comprehensive analysis of the legal acts of the polish and European legislation was carried out in the context of their impact on hydrogen technology in electromobility. In order to investigate the economic and social aspects, a questionnaire was created. To determine the preferences of potential users of electric vehicles based on hydrogen cells, survey research was conducted amongst users of hybrid and electric vehicles of 4 motorization companies (2 German and 1 French, and 1 Japanese). The group of respondents was selected not accidentally, since, based on results from earlier original research of November 2019, it was found that by far the largest interest in the hydrogen technology in motorization was demonstrated by the current users of vehicles with an electric drive or a combustion-electric drive (more than 77%), whereas the coefficient of interest in the hydrogen technology in motorization amongst users of traditional combustion vehicles came to only 35%. The research was carried out in 5 primary cities of Poland: Gdansk, Kraków, Szczecin, Warsaw, and Wroclaw, where the percentage of electric vehicles in the overall number of registered vehicles and pro-ecological awareness was the highest. In total, 171 users of hybrid and electric vehicles responded to 10 survey questions. A starting point for an analysis of the matters related to the hydrogen technology and maturing thereof should be the strategic documents adopted at the EU level and reflected in the legal acts of the EU, which would be either binding directly in the Member States of the EU (laws) or would have to be transposed into domestic law orders (directives), under Article 288 of the Treaty on the Functioning of the European Union (TFEU) [16].

In the European Green Deal it was indicated that the "achievement of climatic neutrality also requires a smart infrastructure. Closer cross-border and regional cooperation will help to benefit from transformation into pure energy at moderate prices. It will be necessary to review the frameworks regulating the energy infrastructure to ensure cohesion with the climatic neutrality objective. The said frameworks should be conducive to the use of innovative technologies and infrastructures, such as smart networks, hydrogen networks, and carbon capture, storage and utilization, storage of energy and should also enable integration of the sector" [17].

The consequence of implementing the European Green Deal was the adoption of the Hydrogen Strategy of the most significant assumptions presented in Chapter 1 of the publication.

The energy and climate policy of the EU and the legal acts entered into force at the level of the EU law should be reflected in policies and domestic law orders of the EU Member States. It is worth reminding that under Article 288 of the TFEU, a directive is binding in every Member State to which it is addressed regarding the result that shall be achieved. However, it leaves the freedom of choosing the form and means, and measures of domestic bodies. Therefore, the manners of implementing the Directive 2014/94 in the individual EU Member States may differ.

So far, Poland has implemented the Electromobility Development Program within the framework of the Strategy for Responsible Development until 2020 (with an outlook to 2030) [18]. Achievement of its objectives was the basis for the implementation of a regulatory package, which incorporated the matter of electromobility into the Polish policy and domestic law order, and, in principle, the problem related to the alternative fuel market, of which electromobility is a part. The Electromobility Development Program consists of the following strategic documents:

- the Development Plan of Electromobility in Poland Energy for the Future adopted by the Council of Ministers on 16 March 2017 [19]:
- the National frameworks of the policy for the growth of alternative fuel infrastructures, which have to be developed under the Directive 2014/94, adopted by the Council of Ministers on 29 March 2017 (national frameworks of the policy for development of alternative fuel infrastructure) [20].

In principle, the previous documents did not refer to hydrogen technology and hydrogen as an alternative fuel, mainly focusing on electric energy and gas fuels.

The draft document of the Energy Policy of Poland until 2040 along with updates (PEP 2040) [21] and the national plan for the benefit of energy and climate for 2021–2030, enlarged of which until the end of 2019 arose from the obligation imposed on the EU Members States by way of the Regulation of the European Parliament and of the Council (EU) 2018/1999 of 11 December 2018 on the management of the Energy Union, and activities in the area of climate [22] indicating the guarantee of functioning conditions and instrumentation of support of the alternative fuel market, particularly electromobility, as the strategic project. It was emphasized in the national plan for the benefit of energy and climate for the years 2021–2030 that the potential of using hydrogen should not be searched for only in the car transport but also in the railway, air, and sea intended use [23].

The PEP2040 project indicated that, due to the vast possibilities of using and the considerable interest in the technology, special attention should be paid to the production and use of hydrogen in transport and in other sectors. At present, hydrogen is applicable in the refinery industry, metallurgy, and during the production of fertilizers; however, the demand for this gas will be increased if it is possible to introduce it to the gas networks and to use it in fuel cells for the production of electric energy. Thanks to it, apart from the existing uses, it will be able to be successfully used in the transportation sector (cars, trucks, public transport, shipping, aviation), heat, and electrical power sectors (in fuel cells and gas turbines).

In PEP 2040, attention was paid to the fact that, due to the hitherto prevailing unprofitability of using hydrogen for energetic purposes, this technology was at a low level of development. However, because of the physical properties of hydrogen (it is light, reactive, it can be stored, it has high energy content per unit of mass), the ecological character (its combustion product is water vapor only), the problem of using hydrogen for energetic purposes became a point of the increasingly common interest. It would be a desirable situation, if the production of hydrogen in the future was carried out with the use of renewable energy sources, also as a way of managing energy production surpluses. In PEP 2040, it was also indicated that research projects and exchange of the hitherto prevailing experiences of interested entities and creation of a regulatory zone regarding the use of hydrogen in the transportation sector and power industry would serve the purpose of stimulating this market. The legal frameworks to use hydrogen shall be drawn up until 2021 so that the market can be developed entirely in the perspective of 2030 [24].

As it results from the above, the progressing of the energy markets including electromobility, which also comprised hydrogen technology and hydrogen as an alternative fuel, was one of the strategic projects of draft PEP 2040, which indicated that hydrogen technology should be at the center of interest of bodies competent to implement the energy policy. Ipso facto, the strategic projects should be transformed into legal regulations that would include standards assigning rights and obligations of particular entities to support the development of the electromobility market. Here, it must be reserved that it was necessary to specify that the planned policy within the scope of supporting the hydrogen technologies—which may take place, e.g., in the published hydrogen strategy, which, as it arose from communications of the Ministry of Climate and the Environment, the ministry is currently working on—shall be presented in a broader scope below.

However, it must be noted that the PEP 2040 project was adopted and announced under the provisions of the Act of 10 April 1997—Energy Law (Energy Law Act) [25]. According to Article 15a (1) and (2) of the Energy Law Act, the Council of Ministers—upon request of the minister in charge of energy affairs—adopted the energy policy of the country, and the minister in charge of energy affairs announced the energy policy of the country under an announcement in the Official Journal of the Republic of Poland Monitor Polski. Therefore, it must be considered now that PEP 2040 was not a binding document but only a draft document of the country's energy policy. Notwithstanding the above, one could put forward a thesis that hydrogen technology was part of the strategic documents and policies of the European Union and the PEP project until 2040 and the National Plan for the benefit of energy and climate. The development of the electromobility and alternative fuel markets could be considered a priority objective of the Polish energy and climate strategy.

At present, works on creating the Polish hydrogen strategy, which is to be adopted under a resolution of the Council of Ministers, are pending in the Polish Ministry of Climate and the Environment. A starting point to the works on the hydrogen strategy was the fact of signing a letter of intent by representatives of the Ministry of Climate and the Environment, and the most significant and strategic companies of the energy and transportation sectors, on the establishment of partnership for the benefit of building the hydrogen economy and entering into a sectoral hydrogen agreement.

In line with the published heralds, the primary objectives of the hydrogen strategy were based on:

1. creating a value chain for low-emission hydrogen technologies;
2. strengthening the role of hydrogen in building Polish energy safety and security;
3. implementing hydrogen as a transportation fuel;
4. preparation of new laws for the hydrogen market [26].

Going on to the analysis of binding legal provisions concerning hydrogen technology and hydrogen both at the level of the EU law and at the domestic level, Directive 2014/94 must be taken as a starting point.

According to Article 2 point 1 of Directive 2014/94, alternative fuels were fuels or sources of energy, which were used at least partially as a substitute for the sources of energy coming from raw crude oil in transport and which may potentially contribute to the decarbonization of transport and improvement of the greenness of the transportation sector. They included, among other things, electric energy, hydrogen, bio-fuels defined in Article 2 (i) of the Directive 2009/28/EC of 23 April 2009 on the promotion of using energy from renewable sources [27], synthetic and paraffin fuels, natural gas including bio-methane in the form of gas (compressed natural gas—CNG) and in the liquid form (liquefied natural gas—LNG), and liquefied petroleum gas (LPG). Thus, hydrogen was deemed an alternative fuel.

Motor vehicles driven by hydrogen, including vehicles of category L (motor vehicles having two or three wheels, some motor vehicles having four wheels and mopeds—Appendix No 2 of the Act of 20 June 1997; Road Traffic Law (consolidated text: (Journal of Laws) OJ of 2020, item 110) [28]—driven by hydrogen, as indicated in point 37 of the introduction to Directive 2014/94, are currently characterized by a very low market penetration coefficient. Therefore, an extension of a sufficient hydrogen-refueling infrastructure was an indispensable condition making it possible for motor vehicles driven by hydrogen to be spread on a considerable scale.

Point 38 of the introduction to Directive 2014/94 indicates that the Member States, which decide to cover hydrogen-refueling points with national frameworks of the policy, should ensure that publicly available hydrogen supply infrastructure for motor vehicles shall be created, ensuring that motor vehicles driven by hydrogen would move within the networks specified by the Member States. In the relevant cases, it was necessary to take into consideration cross-border connections, which would allow motor vehicles driven by hydrogen to move around the whole Union. According to Article 3 of Directive 2014/94, Member States were obliged to adopt the national frameworks of the policy concerning the development of the market regarding alternative fuels in the transportation sector and to the development of proper infrastructure. The national frameworks of the policy should have been adopted by 18 November 2016. The introduction to Directive 2014/94 and Article 3 showed that taking into consideration hydrogen-refueling points in the national policies and provisions was optional and depended on the decision of the given Member State, whereas Directive 2014/94 requireed taking into account publicly accessible electric vehicle charging points in the national frameworks of the policy and legal regulations (Article 3 (8) and Article 4), and publicly accessible gas-fuel-refueling points—LNG and CNG for motor vehicles (Article 3 (8) and Article 6).

A reference to hydrogen was also made in Article 5 of Directive 2014/94 in accordance with which the Member States, which would decide to include publicly accessible hydrogen-refueling points in their national frameworks of policies, shall ensure the accessibility of an appropriate number of such points until 31 December 2025 to guarantee that motor vehicles driven by hydrogen, including vehicles driven by fuel cells, shall move within the limits of the networks specified by the said Member States including, in relevant cases, cross-border connections.

According to Article 11 (1), Directive 2014/94 should have been implemented by 18 November 2016. Poland adopted provisions of the Directive 2014/94 with more than one -year delay and, as indicated above, the adopted national frameworks of the policy and provisions did not take into consideration the creation of the publicly accessible hydrogen supply infrastructure for motor vehicles, which proved that, at the date of implementing the EU law provisions concerning electromobility and alternative fuels, hydrogen was not a priority objective for the Polish legislator. At that time, much more significant pressure was put on the infrastructure for charging electric vehicles, among other things, due to the fact that the obligation to take into consideration electric vehicle charging points and stations in the national frameworks of the policy arose out of provisions of the Directive 2014/94.

Apart from the Directive 2014/94, it was also necessary to invoke the Regulation of the European Parliament and of the Council (EC) No 79/2009 of 14 January 2009 on the type-approval of motor vehicles driven by hydrogen and amending Directive 2007/46/EC (regulation on type-approval) [29] which had a technical nature. The regulation on the type-approval established requirements for the type-approval of motor vehicles regarding the hydrogen driven and type-approval of hydrogen components and installations. The laws also established requirements for the assembly of such components and installations. Significant provisions of the regulation on the type-approval included the indication of obligations of hydrogen vehicle manufacturers and general and detailed requirements for hydrogen components and installations. The said legal act indicated that vehicles driven by hydrogen had already been an object of interest of the EU legislator over 10 years ago. A broader analysis of the regulation on the type-approval, which had an overly technical nature, went beyond the frameworks and subject matter hereof (beyond the scope of this publication was also an analysis of Directive 2009/31/WE of 23 April 2009 on the geological storage of carbon dioxide, and amending the Council Directive 85/337/EEC, Euratom, Directives of the European Parliament and of the Council 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC, and Regulation (EC) No 1013/2006 (OJ of EU of 5.6.2009 L 140/114) concerning CCS (carbon capture and storage) technology, i.e., CO2 sequestration. The CCS technology was the process of preventing the emission of carbon dioxide (CO_2) being released into the atmosphere from power stations and heavy industry factories. Directive 2009/31/EC was implemented to the Energy Law Act and the Act of 9 June 2011—Geological and Mining Law (consolidated text: OJ of 2020, item 1064) [30].

Going on to the national law, it must be indicated that within the framework of transposition of the Directive 2014/94, primarily two statutory regulations, along with implementing acts, were implemented, i.e.:

- the act of 11 January 2018 on electromobility and alternative fuels, which came into force on 22 February 2018 (Electromobility Act) [31];
- acts establishing the Low-Emission Transport Fund (FNT), i.e., the Act of 6 June 2018 on the amendment to the Act on bio components and liquid biofuels, and some other acts, which came into force on 28 July 2018 [32].

The Act on electromobility left both the hydrogen-refueling infrastructure and hydrogen vehicles on the margin of laws compared to the electric vehicle charging infrastructure and gas-fuel-refueling infrastructure; therefore, the provisions referred to hydrogen only in several places. This mainly arose from provisions of the Directive 2014/94, which provided the Member States with the right not to take into consideration the hydrogen-refueling infrastructure in national policies and provisions, differently than in the case of the electric vehicle charging infrastructure and gas-fuel-refueling infrastructure—LNG and CNG.

An analogous description of alternative fuels (identical in terms of scope) to the description included in the Directive 2014/94 was stipulated in Article 2 point 11 of the Act on electromobility, where alternative fuels were considered fuels or electric energy used for driving engines of motor vehicles or vessels, constituting a substitute for fuels derived from crude oil. Thus, hydrogen was deemed one of the types of alternative fuel.

Moreover, hydrogen as an alternative fuel was part of several statutory definitions:

(1) a zero-emission bus was also considered a bus using electric energy as a drive generated from hydrogen in fuel cells installed in it (Article 2 point 1 of the Act on electromobility);
(2) the scope of the road-public-transport-charging infrastructure, including hydrogen charging or refueling points along with the accompanying infrastructure necessary for them to function, intended for charging or refueling, particularly zero-emission buses used in public transport (Article 2 point 3 of the Act on electromobility).

The said laws indicated that the legislator treated hydrogen equally to electric energy considering them as emission-free alternative fuels.

The definition of vehicles driven by hydrogen was vital for the hydrogen technology, i.e., the motor vehicle within the meaning of Article 2 point 33 of the Act of 20 June 1997—Road Traffic Law—using electric energy as a drive, generated from hydrogen in fuel cells installed in it. A significant provision indicating that the legislator included hydrogen technology in the market of alternative fuels was Article 32 (6) of the Act on electromobility. According to this regulation, the General Director of National Roads and Motorways (GDDKiA) may include the location of hydrogen-refueling points in the location plan of generally accessible charging stations and natural gas stations along roads of the Trans-European transport network (TEN-T), base network remaining under their management, i.e., a set of devices used for supplying hydrogen to vehicles driven by hydrogen to drive engines of these vehicles if the location of such points was justified by the needs for the development of the alternative fuel market. The plan was developed for a period of not less than 5 years.

A provision of Article 39 (1) point 2 of the Act on electromobility also indicated that limitations on the entry into clean transport zones in city centers having more than 100 thousand residents should not be binding on vehicles driven by hydrogen.

As a result of an analysis of the aforementioned regulations of the Act on electromobility, one can put forward the thesis that the regulation of hydrogen technology in transport-refueling infrastructure and hydrogen vehicles was residual compared with the laws implemented within the scope of electric energy and gas fuels. Such a legal state should be changed if the legislator intends to promote using hydrogen in transport. Here, it was necessary to go on to an analysis of legal regulations within the scope of the electromobility support system, including hydrogen technologies.

In consequence of establishing the FNT, based on a delegation for issuance of the laws contained in the Act of 25 August 2006 on bio components and liquid biofuels (Act on biofuels [33]), the following implementing acts were issued:

- the regulation of the Minister of Energy of 5 November 2019 on the detailed conditions for providing support for the purchase of new vehicles from FNT resources to natural persons not carrying out economic activities and conditions for settlement of the said support [34];
- the regulation of the Minister of State Assets of 23 December 2019 on the detailed criteria for the selection of projects to provide support from FNT resources [35];
- the regulation of the Minister of State Assets of 23 December 2019 on the detailed conditions for the provision of and method of settlement of support given from FNT resources [36].

By way of a provision of Article 10 of the Act of 14 August 2020 on the amendment to the Act on bio components and liquid biofuels and some other acts (Amending Act [37]), the FNT was liquidated, thereby changing the model of support and co-financing of electromobility and alternative fuels resigning from a separate fund, i.e., the FNT, which was managed by the National Fund for Environmental Protection and Water Management (NFOŚiGW; Pursuant to Articles 400 and 400b of the Act of 27 April 2001—Environmental Protection Law (consolidated text: OJ of 2020, item 1219), the NFOŚiGW is a state legal entity responsible and liable for financing environmental protection and water management within the scope stipulated in this act) [38] and handing over the competencies with regard to supporting the co-financing of electromobility and alternative fuels directly to the NFOŚiGW.

The forms of supporting electromobility and alternative fuels, and funds for financing the support were slightly modified. Repealed provisions of the Act on biofuels were transferred to the Environmental Protection Law Act dated 27 April 2001 (EPL Act) [39].

For this analysis, it was significant that the Amending Act incorporated a new form of support, i.e., the support in the form of co-financing the purchase of new M1 category vehicles (M category vehicles are motor vehicles designed and constructed mainly for the transport of people and baggage thereof. The M1 category includes vehicles having not more than eight seats apart from the driver's seat) [40] referred to in appendix No 2 of the Act of 20 June 1997—Road Traffic Law [41]—using electric energy as a drive, generated from hydrogen in fuel cells or using only electric energy as a drive (Article 401c (9c) point 12 of the EPL Act). Adding this form of support emphasized the fact that the legislator wanted to support vehicles driven by electric energy generated from hydrogen or only driven by electric energy, i.e., the broadly understood electromobility in a special way. The currently binding provisions which regulate the forms of supporting electromobility and hydrogen technologies, i.e., Article 401c (9c) points 1–13 of the EPL Act, also maintained the support in the form of co-financing construction or extension of the infrastructure for the distribution or the sale of hydrogen, and co-financing for manufacturers of means of transport using hydrogen as a drive including enterprises carrying out activities within the scope of production of components for means of transport driven by hydrogen. Such a range of support in the statutory provisions, which maintained and which, in the case of hydrogen technology, even extended the scope of support, and which allowed the NFOŚiGW to commence the construction and implementation of support programs could be considered satisfactory.

According to Article 28ze (1) of the Act on biofuels (currently Article 401c (9c) of the EPL Act) repealed on 1 October 2020, resources of the FNT (at present resources of the NFOŚiGW) could be allocated, among other things, for:

- supporting the construction or extension of the infrastructure for distribution or sale of compressed natural gas (CNG) or liquefied natural gas (LNG) including gas derived from biomethane or hydrogen, or construction or extension of the infrastructure for charging vehicles with electric energy, used in transportation;
- supporting the manufacturers of means of transport using electric energy, CNG or LNG as a drive including gas derived from biomethane or hydrogen and entrepreneurs within the meaning of provisions of the Act of 6 March 2018—Law on entrepreneurs—carrying out activities within the scope of production of components for the said means of transport;
- supporting the public-collective transport functioning particularly in urban agglomerations, health resorts, on areas where nature protection forms were established under the environmental protection provisions;
- supporting the research connected with the development of new types of bio components, liquid biofuels, other renewable fuels, or with the use of CNG or LNG, including gas derived from biomethane or hydrogen, or electric energy, used in transportation or the new construction solutions related to this and the support of exploitation implementations of research results;

- supporting the educational programs;
- supporting the purchase of new vehicles and vessels;
- supporting the activities related to analysis and survey of the market of bio components.

According to Article 28ze (3) of the Act on biofuels, the support for the aforementioned projects given from FNT resources, including the purposeful grant, could have the following form:

(1) grants;
(2) loans, including those given to territorial self-government units and other returnable financial support;
(3) taking up or acquiring by the FNT disposer, i.e., the minister in charge of energy affairs, for the benefit of the state treasury:
    a. stocks or shares of companies;
    b. bonds issued by entities other than the State Treasury or territorial self-government units, which carry out activities within the scope covered by the support.

In the current legal state, the ways of financing electromobility and alternative fuels, taking into consideration the previous forms of support, were specified in Article 411 of the EPL Act. A provision of Article 28zd (1) of the Act on biofuels also ensured financing the FNT. The revenues of the FNT were:

(1) purposeful grants from the state budget of up to 1.5% of proceeds from the excise duty on motor fuels planned in the previous fiscal year; the amount of the purposeful grant was specified by the Budgetary Act in the budgetary part of the disposer, of which was the minister in charge of energy affairs;
(2) interest on the free resources of the FNT handed over for the management under the provisions on public finance;
(3) resources handed over by the power transmission system operator of 0.1% of the justified return on capital involved in the conducted economic activity within the scope of the transmission of electric energy, referred to in Article 16b (3) of the Energy Law Act;
(4) proceeds from the substitution fee referred to in Article 23 (1a) of the Act on biofuels;
(5) proceeds from the emission fee referred to in Article 321a of the EPL Act, in part falling on the FNT;
(6) other revenues.

In the current legal state, revenues of the NFOŚiGW, including the previous categories of resources, were specified in Article 401 of the EPL Act. As the aforementioned analysis showed, the forms of supporting alternative fuels including the hydrogen technologies and revenues of the NFOŚiGW, which are allocated for granting this support, were transferred in principle in whole to the EPL Act. The change above, i.e., liquidation of the FNT, was difficult to be assessed now because provisions of the Act on biofuels regulating the support from the FNT and provisions of the EPL Act determining the support given directly from the NFOŚiGW were not binding in a more extended period. Indeed, this change must be assessed negatively in part due to the fact that no change for the NFT to the function was given, and afterward, no assessment of the support system operation was carried out. Not earlier than after the entry into the force of the statutory provisions, along with implementing acts and conducting at least several competitions for the obtainment of a particular type of support, one could think about making a correction of the provisions in force. Furthermore, there were statutory provisions regulating the rules on the functioning of the FNT, revenues of the fund, and supported activities. There were also issued extensive implementing acts, which allowed to conduct competitions for the support of individual activities, which, de facto, were not applied in practice owing to the liquidation of the FNT. Indeed, such activity had no positive influence on taking up actions, including investments aimed at developing the infrastructure of alternative fuels and vehicles driven by these fuels, including the commencement of investments in hydrogen technologies. The competitions for the support due to an amendment of the provisions were not announced and carried out. Not earlier than after the amendment of the provisions, the NFOŚiGW could commence work on the announcement of calls within the scope of supporting electromobility and alternative fuels, which considerably delayed the start of the works on implementing the hydrogen technologies on the Polish transportation market.

On the other hand, the implementation of the provisions, which incorporated the basis for granting support by the NFOŚiGW based on provisions of the EPL Act and the calls within the framework of the announced programs, ensured the cohesion of the law system in this respect because the NFOŚiGW provided support for the development of electromobility and alternative fuels in the same way as for other environmental protection projects—we did not have to do with a fund functioning on the basis of a separate act, which may make the management of the support by the NFOŚiGW easier. Similarly, the determination of the rules on calls for individual types of support within the framework of the programs announced by the NFOŚiGW directly based on the provisions of the act may be more flexible than in the case of the regulation of the principles on calls in the form of laws to the act. Incorporating the modifications in the rules of support, e.g., favorable to beneficiaries, would require changing the regulation or laws, which would indeed last longer than the change of the rules on calls within the framework of the program implemented by the NFOŚiGW.

The currently binding statutory provisions, along with the programs of support implemented by the NFOŚiGW, should be assessed after implementing at least several co-financing programs and granting support for given projects.

It was necessary to pay attention to the fact that, at present, there were pending works on implementing the priority program New Energy within the performance of the provisions of the PEP 2040, the objective of which would be to support projects aimed at developing emission-free hydrogen technologies and production, and the technologies for transmission and the use of hydrogen, including, among other things, the following technologies:

- adaptation of the infrastructure to transportation of hydrogen;
- storage of hydrogen;
- use of hydrogen in the road, railway, or water transport;
- using synergic effects between the linking of sectors.

As indicated in a communication of the NFOŚiGW and in the available presentation, the budget of the New Energy amounts to PLN 2.5 billion—PLN 2.3 billion for loans and PLN 200 million for grants. The program included:

- a possibility of obtaining an innovative bonus up to 20% of the amount of the loan; however, not more than PLN 10 million for the achievement of the tangible effect of a given project;
- a potential grace period in repayment of the loan (18 months from the project completion date);
- a potential grace period in repayment of interest (for projects which last shorter than 2 years);
- a possibility of canceling up to 25% of the loan amount decreased by the amount of an innovative bonus provided that the amount of cancellation was allocated for the next project concerning the implementation of the same technology [42].

Moreover, the programs financing electric vehicles, activated by the NFOŚiGW, may be a model for implementing the system of support for hydrogen technologies:

- eVAN—co-financing of the purchase of an electric delivery van (N1);
- green car—co-financing of the purchase of an electric passenger car (M1);
- Koliber—a taxi good for the climate pilot project;
- green public transport [43].

3. Proposals of Amendments to the Legal State and Programs of Support of the Legislation in the Context of Optimization of the Development Process Electromobility Based on Hydrogen Cells in Poland

As the analysis conducted above showed, the EU and, first of all, the Polish legal regulations included residual provisions on hydrogen technology and hydrogen as a fuel compared to alternative fuels, such as electric energy, gas fuels (CNG, LNG, LPG), or biofuels.

It would be necessary to construct and implement legal regulations which, firstly, describe the rules of the creation and growth of the hydrogen technology infrastructure, including entities, which are to participate in the development of hydrogen technology.

A starting point should be the approval of the PEP2040 so that the draft would finally become a binding document. Afterward, it would be necessary to specify the policy on the support of electromobility and alternative fuels through the implementation of the hydrogen strategy by imitating the strategy adopted by the European Commission, which would be an addition to the draft PEP2040 and national plan for the benefit of energy and climate for the years 2020–2030, and which would be the basis for the implementation of the legal regulations and the incorporation of the systems for support of hydrogen technologies in transportation. Moreover, it would be required to update the national frameworks of the policy on the alternative fuel infrastructure to take into consideration the hydrogen-refueling infrastructure in the document.

In September 2020, a press release of the Vice-Minister of Climate Ireneusz Zysk, who heralded the creation of the draft hydrogen law act (W. Jakóbik; The Ministry of Climate was already drawing up the hydrogen law. It will be ready in the third quarter of 2021; https://biznesalert.pl/ustawa-prawo-wodorowe-prace-ministerstwo-klimatu-trzecikwartal-2021-energetyka-wodor-innowacje/, accessed on 12 January 2020), [44] appeared. The act's task was to implement the assumptions of the energy strategy within the scope of using hydrogen technologies. Based on this legal act, energy purposes until 2030 and until 2050 shall be determined. This project is to be ready already until the third quarter of 2021. As indicated in the Second Chapter of the publication, there were pending works on implementing the Polish hydrogen strategy. Thus, the heralds showed that the Polish Ministry of Climate and the Environment intended to implement the hydrogen strategy and draw up the draft hydrogen law act. The announcement of the adoption of a separate act pertaining only to hydrogen shall be treated as another argument for the thesis that the Polish legislator planned to implement the hydrogen technology into the transportation market and intended to activate the programs of the support for hydrogen. Both of these intentions, in terms of direction, must be assessed positively. At present, we do not know the details of the said activities; thus, we cannot analyze and assess them.

Going on to the postulates of the authors hereof, first, it was necessary to indicate that a very significant aspect would be to create a legal environment for the functioning of the hydrogen technology infrastructure—including hydrogen-refueling stations in imitation of the provisions on charging stations, and CNG- and LNG-refueling stations in the Act on electromobility, without which it would be difficult to commence the investments and commence the implementation of the support programs by the NFOŚiGW and other institutions. One may take into consideration the implementation of the new Act on hydrogen technology (Act on hydrogen) or the amendment of the Act on electromobility and alternative fuels by adding solutions concerning the hydrogen-refueling infrastructure. Because of the cohesion of the law system—arising, among other things, from Polish legislative technique principles [45]—where it was indicated in § 2, among other things, that the act should exhaustively regulate a given field of matters, not leaving beyond the scope of its regulation of significant fragments of the said field; it would be necessary to declare an amendment of the Act on electromobility and alternative fuels so that the provisions on all alternative fuels would be in one legal act.

Therefore, it would be necessary to postulate the introduction of the laws within the scope of the hydrogen infrastructure, which were at least analogous as in the case of the charging stations and gas-fuel-refueling stations, for example:

(1) introduction of the definition of a generally accessible hydrogen-refueling station and hydrogen charging points;
(2) introduction of the definition of an operator of a generally accessible hydrogen-refueling station and an indication of what entity may be or will be an operator of a hydrogen-refueling station;
(3) adding provisions specifying the rights and obligations of an operator of a generally accessible hydrogen-refueling station;
(4) introduction of provisions specifying the obligation to draw up a construction plan and schedule for generally accessible hydrogen-refueling stations along with the indication of an entity obliged to draw it up for a given area (e.g., territorial self-government unit body—in the case of the municipality: commune head, mayor, president of the city);
(5) potential indication of an entity obliged to construct generally accessible hydrogen-refueling stations if the number of stations built on a given area is not achieved within the indicated deadline and indication of sources of financing these investments;
(6) introduction of provisions along with implementing acts determining an obligation and scope of technical tests of hydrogen-refueling stations and an entity entitled to conduct the said tests (e.g., the Office of Technical Inspection (UDT) or the Transport Technical Supervision (TDT));
(7) taking into consideration generally accessible hydrogen-refueling stations, apart from charging stations and CNG- and LNG-refueling stations, in the Alternative Fuel Infrastructure records [46].

It would also be essential to indicate the role of public institutions in the implementation of hydrogen technology. Similarly, as in the case of electric vehicles, one might take into consideration the incorporation of an obligation to have a particular share of hydrogen vehicles in the company car fleets used in central offices of public administration bodies and bodies of territorial self-government units.

It would also be significant to take into account the role of public collective transport in the increased use of alternative fuels and to introduce an obligation in collective transport fleets concerning a particular share of zero-emission buses driven by hydrogen.

It would be essential to promote hydrogen vehicles by introducing incentives into the tax law. It would be necessary to preserve an exemption from the excise duty on passenger cars being hydrogen vehicles (Article 109a (1) of the Act of 6 December 2008 (consolidated text OJ of 2020, item 722)) [47]. Additionally, there should be introduced, in analogy to the case of electric vehicles, increased amortization and depreciation allowances on the wear of hydrogen vehicles in the acts regulating income taxes (amendments in the Act of 26 July 1991 on personal income tax (consolidated text: OJ of 2020, item 1426) and Act of 15 February 1992 on corporate income tax (consolidated text: OJ of 2020, item 1406)) [48].

Facilities in the building law would be another measure that might facilitate and accelerate the investments into the hydrogen-refueling infrastructure. One of the favorable solutions, like in the case of electric vehicle charging stations was the introduction of an exemption from the obligation to obtain a decision on the permit for building hydrogen-refueling stations, in Article 29 of the Act of 7 July 1994—Building Law (consolidated text OJ of 2020, item 1333.) [49].

It would also be necessary to postulate maintaining the provisions in force, or extending the scope thereof, which introduce the incentives for acquiring and moving vehicles driven by hydrogen, like in the case of the privileges incorporated for electric vehicles, for example: free of charge parking in city centers, the right to enter low-emission transport zones, the right to move along traffic lanes intended for urban communication and taxies (bus passes), and distinguishing hydrogen vehicles through different registration plates (green registration plates).

Within the scope of the provisions on support of electromobility and alternative fuels, including hydrogen, as it arose from the previous analysis, in the current legal state there are provisions in the EPL Act which formed the basis, among other things, for supporting activities related to an analysis and study of the hydrogen market and implementation of this fuel in transportation, providing grants and loans both for the construction of the hydrogen-refueling infrastructure and for the purchase of vehicles driven by hydrogen, supporting manufacturers of vehicles driven by hydrogen and co-financing of public collective transport to acquire vehicles driven by hydrogen. Maintenance of said laws in force, despite the liquidation of the FNT, must be assessed positively. The presented laws must remain in force and, on their basis, the NFOŚiGW should commence calls for the programs of support in individual scopes for the hydrogen technologies. By this time, as indicated above, it would be necessary to extend the laws pertaining at least to the functioning scope of the hydrogen-refueling infrastructure.

As it arose from the entire analysis carried out above, the implementation of hydrogen technology in transportation by the time when it could compete with conventional fuels—i.e., the price of hydrogen and the investments in the infrastructure would be comparable to solutions of the currently existing technologies—it seems necessary to implement adequate systems of support, which would allow for the gradual implementation of hydrogen as a fuel not only into the transportation market—electromobility market—but also into the entire economy.

4. Economic Aspects of Motorization Based on Hydrogen Cells

A modern energy system should take into consideration the possibilities of obtaining energy from renewable sources to the maximum possible extent. Those obviously include solar energy, wind energy, water (i.e., rivers, sea forces), but also nuclear energy, biomass, biogases, and bioliquids, geothermal energy, aerothermal energy, hydrothermal energy, and biomass combustion processes. In numerous aspects, hydrogen is also an excellent fuel. It is an overly efficient fuel, does not emit waste gases (in a combustion process), and is not a greenhouse gas itself. Thus, it is not toxic, and, apart from the common neutral occurrence, it can be generated without limit from renewable energy sources. As the European Commission claims, hydrogen will help to decarbonize the industry and transport; to generate energy in the whole of Europe; and the entire strategy will be based on the investment potential, regulation, and the new market based on innovations and research of the research and development (R+D) sector. Hydrogen can be a source of energy in sectors that, so far, have not been fitted for electrification and which can enable the storage of energy to balance the flows of energy from renewable sources. The achievement of this result requires the coordination of actions between the public sector and private sector at the EU level, and a special priority is the production of the so-called clean hydrogen, mainly from wind and solar energy. As mentioned before, the energy reformation process does not take place at once; thus, it requires a process-based attitude, and the EU policy classifies it in the following manner:

- in the years 2020–2024, the support for the installation of hydrogen electrolyzers powered by energy from renewable sources, with the power of at least 6 gigawatts, producing up to one million tons of renewable hydrogen;
- in the years 2025–2030, hydrogen must become an integral part of a modern energy system, with electrolyzers characterized by the power of at least 40 gigawatts and the production of up to 10 million tons of renewable hydrogen in the EU;
- in the years 2030–2050, the technologies for the production of renewable hydrogen should achieve maturity and be implemented on a considerable scale in all sectors that are difficult to be decarbonized.

The initiated European Clean Hydrogen Alliance, which united representatives on the social side, and leaders of the industry, national ministries, and the European Investment Bank (EBI), created a specific kind of institution for the support of investments, aimed at developing the production of the so-called green hydrogen and at stimulating the demand for implementation of hydrogen in countries of the EU community. According to reports of the European Commission, every week, new projects appeared for the benefit of developing hydrogen energy (frequently already even with the power of 1 gigawatt), and from November 2019 to March 2020, the list of planned global investments was increased from 3.2 GW to 8.2 GW of electrolyzers with the realization period until 2030 (57% of which were located in countries of the EU). Analysts of the European Commission also noted down a considerable increase in the number of entities acceding to the International Hydrogen Council, i.e., from 13 units (2017) to 81 as of today. Thus, in accordance with forecasts, more and more entities discerned the energy potential of hydrogen as an energy medium, possible to be applied on a vast scale. In its strategic vision of an energetically neutral Europe, in November 2018, the European Parliament published information on a planned change of the community's energy mix in which the percentage of hydrogen, from the level of 2-4%, shall account for 13–14% until 2050.

The energy revolution also pertained to other sectors. They included, e.g., the motorization sector in which an electromobility development trend is currently noticeable. It seemed that the electromobility term itself had already had a different influence for some time on social awareness, and this idea was positively received. First, people had to get acquainted with bases of such a progressive direction, accept it, and afterward, popularize such a trend in the motorization sector, and become users of vehicles with a non-conventional drive of their own. Advantages of an electric car were already commonly known, but still, there are many types of barriers having an influence on customers' preferences. First of all, the cost of the purchase influenced the popularity of these types of vehicles. Furthermore, these vehicles have a smaller range than models with a combustion drive and a relatively long charging time. Still, the most significant manufacturers from the sector cope with technical exploitation aspects. This data was reflected in the number of vehicles moving today on European including Polish roads.

A report of the International Council on Clean Transportation—the European Electric Vehicle Factbook (2019/2020)—presented, in detail, the 16 most significant domestic markets in the European Union and European Free Trade Association (EFTA). In every country, there were identified metropolitan regions and areas where electric vehicles were most popular, including battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV), and the market dynamics were described in terms of the best models of electric vehicles and manufacturers. In 2019, in the whole of the EU, more than 560 thousand electric vehicles were registered, which was reflected in the final cumulative result at the level of 1.8 million registered vehicles at the end of 2019 and the second place in terms of sales in the world. In contrast, it was still China that was a power in this sector, with general sales at the level of 3.5 million since the beginning of the existence of the electromobility sector. Whereas, in the third place of the podium, United States were classified with the number of 1.4 million vehicles. According to the authors of the report, sales of electric vehicles had still been on the rise since 2010 (with an average annual increase of 50% over the last five years). A share of vehicles in the European motorization market was dispersed, and other countries with the highest percentage in 2019 were Norway (56%), the Netherlands (15%), and Sweden (11%). Unfortunately, the percentage of other representatives of the EU community still remained at the level of 1–2%.

However, the technology is still being perfected, and the most significant motorization groups are searching for newer and newer solutions concerning drives. Additionally, the increasingly strict EU provisions on the emission of CO_2 increased the orientation of production towards vehicles with an alternative hydrogen drive. However, it was worth emphasizing already at the start that the so-called hydrogen vehicles were also electric cars, but they did not store energy in a battery but in a specially adapted tank with compressed hydrogen. From the said tank, hydrogen was sent to the cells, where it generated energy with an admixture of oxygen. Regardless of the model, it was necessary to pay attention to the fact that the costs of the exploitation of the vehicles would be lower than in the case of a car with a combustion engine. It involved a much smaller number of construction components and such, which required necessary replacements after a particular number of kilometers, were covered; thus, servicing costs would considerably decline. Additionally, the cost of obtaining the fuel itself was lower compared with fuels intended for conventional vehicles. Another aspect was also the potentially lower failure frequency of such a vehicle (it had fewer components exposed to damage). However, in a social aspect, there was still the fear of small or untrue distance (faster loss of the reach caused, e.g., by weather conditions), which could be covered by the vehicle with an alternative drive. Additionally, the energy efficiency aspect must be mentioned. In the case of electric vehicles, 8% of the loss was generated by the transmission moment of the energy to the battery itself. Next, as much as 18% was lost by the vehicle during the conversion of power necessary for the generation of the drive. That means that, while using a new, entirely operational car, already at the start, we could only use 70–80% of its efficiency (depending on the model). As a rule this vehicles are definitely exceptionally technologically advanced, various advantages and dis advantages are included in Table 1. However it cannot be clearly indicated that cars powered by renewable sources will be vastly popular, because there are a number of factors, including personal ones, that might determine it.

Table 1. Disadvantages and advantages of using the hydrogen drive.

Disadvantages	Advantages
Smaller efficiency in relation to the electric drive	Zero-emission of exhausted gases (formation of water steam)
Lack of available charging infrastructure	Resource of which the availability is unlimited
High flammability	Relatively fast vehicle charging process
High costs of maintenance and purchase of vehicle	Considerable range
Requires using even more specialized technical solutions than the standard electric vehicle charging points	Lack of noise when the engine works

Source: own study.

5. Results and Discussion

As a result of the research on the research sample, the following results were obtained in response to individual questions from the survey.

To the question: Are you interested in novelties in the area of electromobility based on hydrogen cells?—see Figure 1: almost 2/3 of the respondents answered rather yes. Next, 17% gave a definite confirming answer, which, in total, accounts for 82% of the researched sample group interested in novelties in this respect. Further, 15% of the interviewees indicated rather a lack of interest; and a definite lack of interest was expressed by only 2% of the researched sample group. The number of those who were indecisive was minimal, with 1% of the overall number of respondents. Such a distribution of answers confirmed the earlier original research stating that the group of drivers using hybrid and electric vehicles was a group with well visible preferences, as far as interest in another electromobility technology based on hydrogen cells was concerned.

With regard to the opinion of the respondents about electric vehicles based on hydrogen cells, over 2/3 of the interviewees stated that they would be, or would rather be, the future of motorization. Less than 1/5 of the respondents had a different standpoint, and 13% did not mind this respect—see Figure 2. Here, you could see an explicit correlation between the interest in novelties concerning hydrogen cells in motorization and the conviction of their indispensable domination in the future.

An indispensable topic discussed, while talking about development of electromobility based on hydrogen cells, was the matter related to the safe use of such vehicles—see Figure 2.

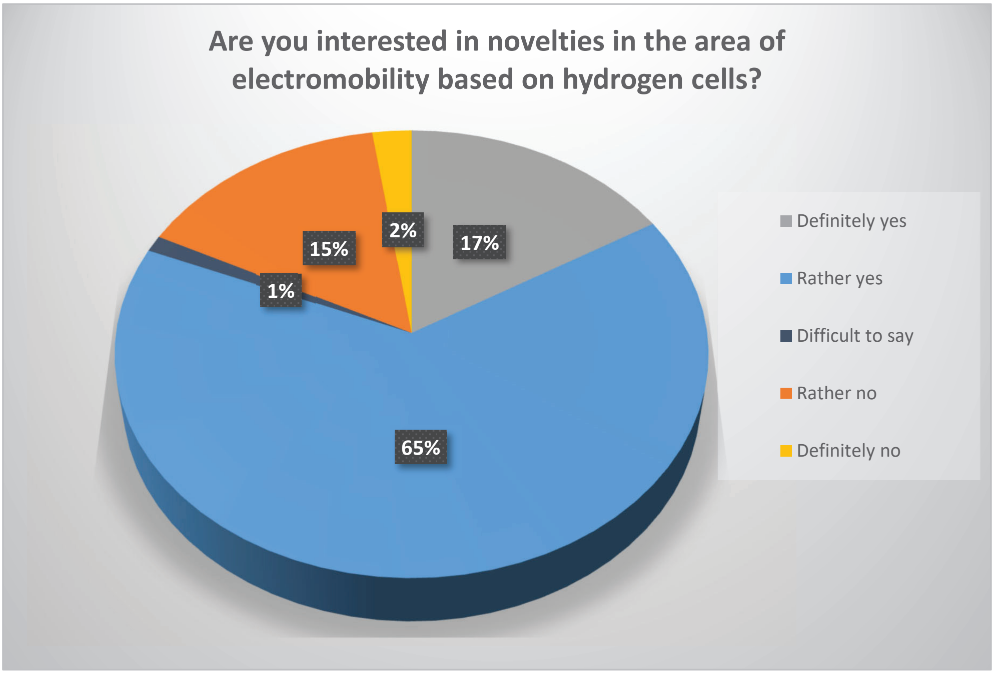

Figure 1. Survey question number 1. Source: own study.

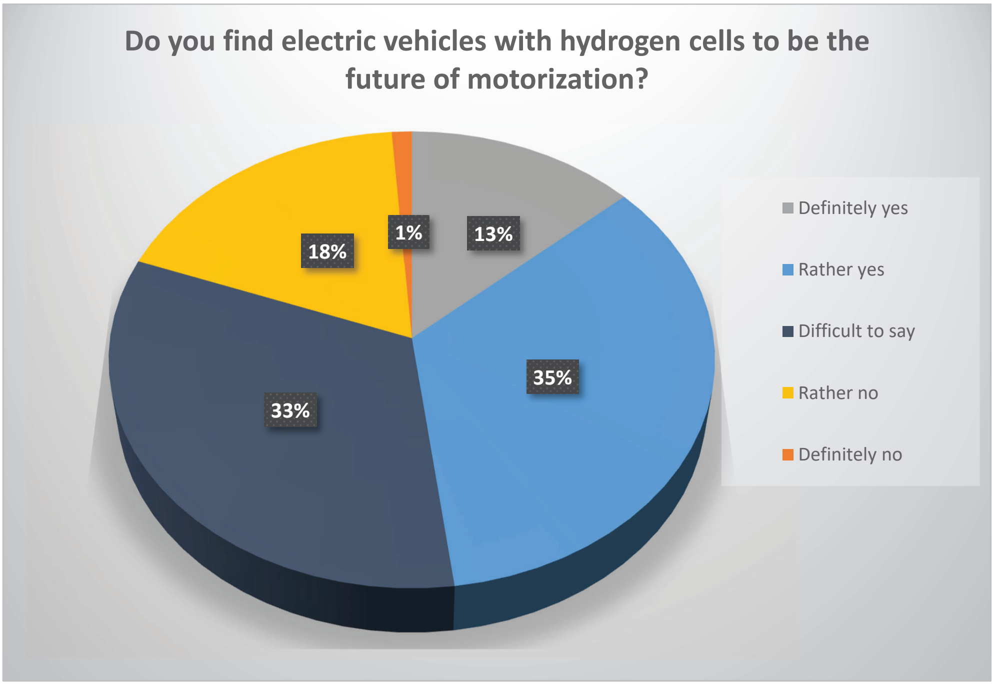

Figure 2. Survey question number 2. Source: own study.

Only 12% of the respondents definitely found them to be safe for users, whereas nearly 40% of the interviewees did not mind this respect. A comparable number of respondents—42%—indicated that such vehicles are rather safe. Such a high percentage of respondents who did not mind and those who found vehicles with hydrogen cells to be rather safe showed that there is a need to carry out a more effective information campaign about this technology and a necessity to indicate assets thereof in the area of safety. It must be remembered that the group of respondents was, anyway, the most positively oriented group of car users towards novelties in motorization.

Apart from the safety of use, an increasingly significant role in the choices concerning mobility was played by the problem related to the protection of the natural environment. In this respect, in total, 82% of the interviewees indicated that electric vehicles based on hydrogen cells were definitely or rather friendly to the environment. In total, 11% of the respondents had an opposite standpoint—see Figure 3. One can assume that such a high percentage of the respondents convinced of the friendly impact of the hydrogen technology in motorization arose from the shared knowledge of modernity of the said technology and, in consequence, of its greenness.

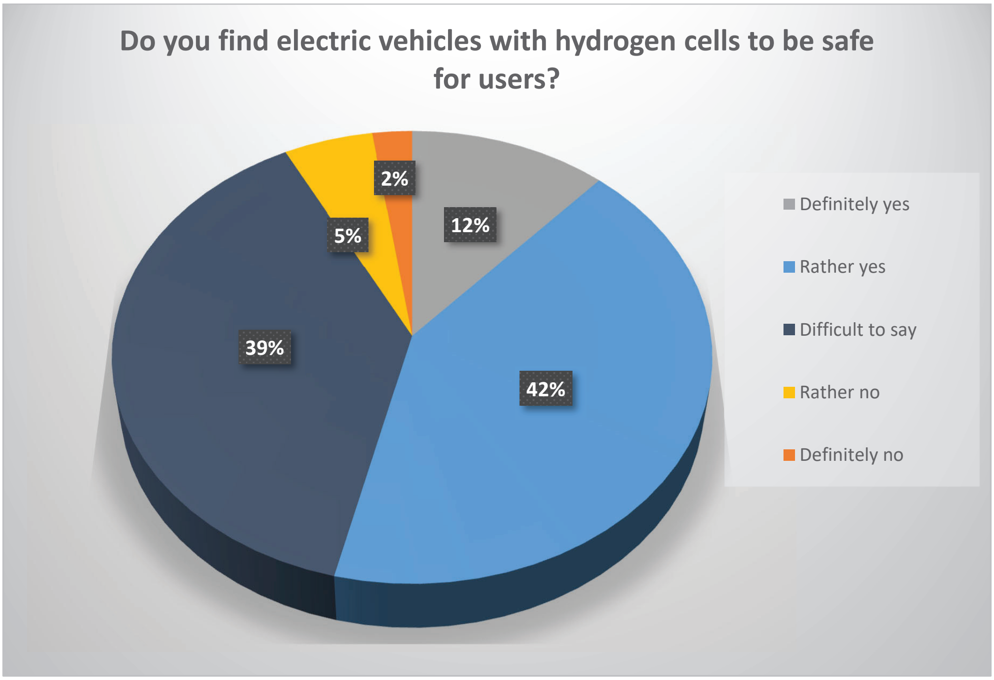

Figure 3. Survey question number 3. Source: own study.

Amongst users of hybrid and electric vehicles, in Poland, there was very high uncertainty in regard to the purchase of an electric vehicle with the technology of hydrogen cells. Nearly 60% of the respondents could not express their standpoint in this respect. Only 4% of the interviewees were decided to purchase such a vehicle, and $\frac{1}{4}$ of the respondents took such a possibility into consideration. Further, 12% of the respondents did rather not take into consideration or were definitely not interested in such a purchase—see Figure 4. This distribution of answers may indicate that the hydrogen technology in motorization is still a matter that is too distant for car users, and its real commonness in the upcoming years is still small.

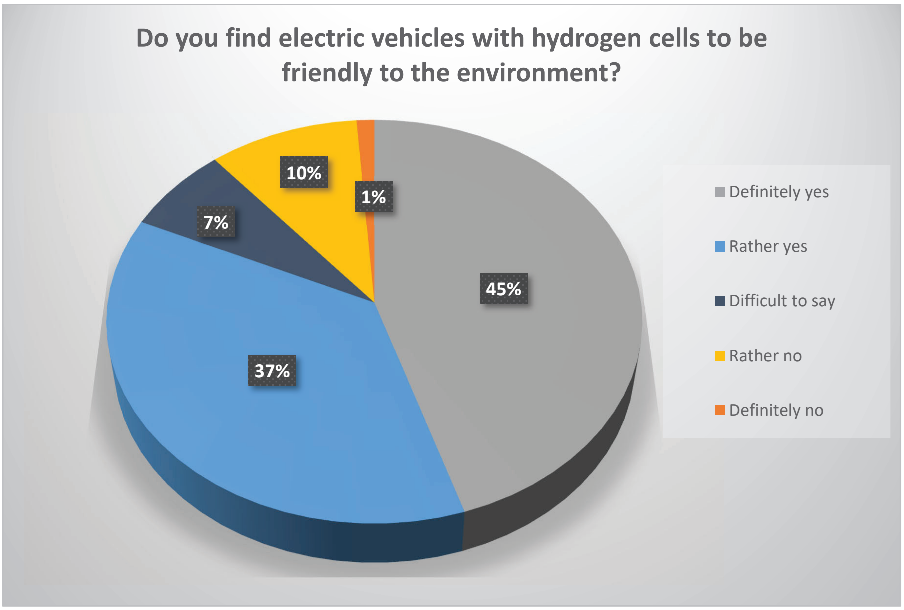

Figure 4. Survey question number 4. Source: own study.

While purchasing goods characterized by long-term use, such as cars, a very significant factor determining the purchase was the price. According to the vast majority of respondents—78%—the price for electric vehicles based on hydrogen cells was by far too high. Only 4% of the interviewees found the current prices for such vehicles to be appropriate, and nobody indicated that they were too low—see Figure 5.

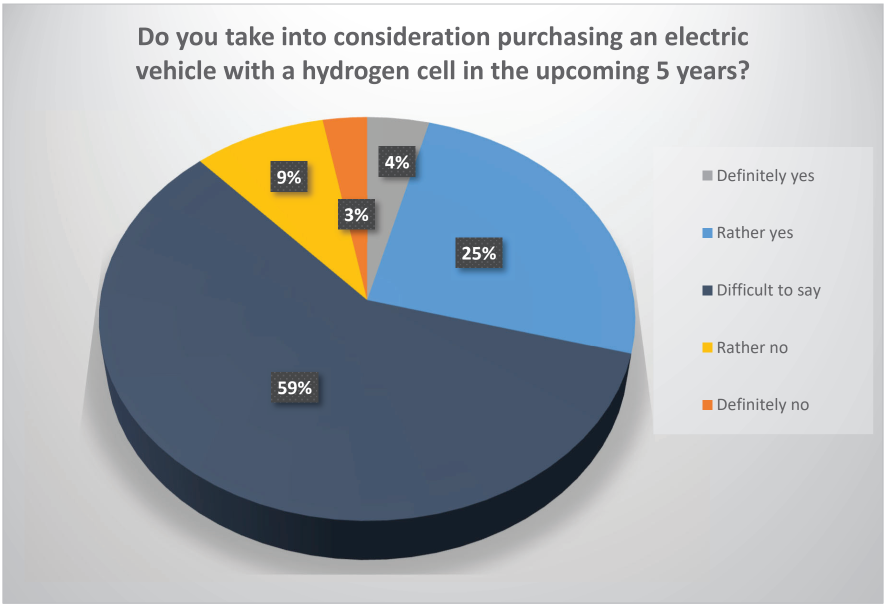

Figure 5. Survey question number 5. Source: own study.

The answers unequivocally indicated that, according to common belief, the price for purchasing a car in hydrogen technology is too high, especially that this was unequivocally indicated by users of vehicles who have already decided now to purchase relatively more expensive vehicles than the standard combustion cars.

A total of 72% of the respondents thought that the State should determine co-financing the development of electromobility for cars in the hydrogen technology, in relation to other electric cars, a priority. In total, 13% of the respondents had an opposite standpoint—see Figure 6. It must be remembered that the respondents were current users of hybrid and electric vehicles, who, despite this fact, indicated the need to establish a priority in co-financing electric vehicles based on hydrogen cells.

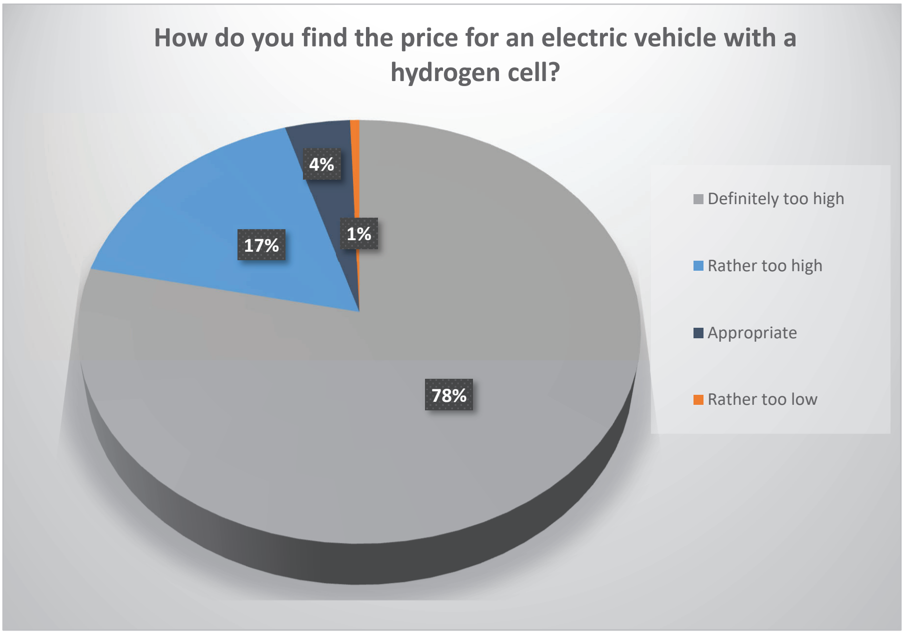

Figure 6. Survey question number 6. Source: own study.

Amongst the barriers to the development of motorization in the hydrogen technology, the interviewees mainly indicated an insufficient number of hydrogen-refueling points—nearly 90% of the answers; and, again too high price of this technology—85% of the answers. More than 1/3 of the respondents paid attention to the danger for users related to the properties of hydrogen. Inaccessibility of hydrogen fuel, as well as the mentality and habits of users, were considered by the interviewees to be much less significant—see Figure 7. The answers clearly showed that to decrease the barriers to the development of electromobility based on hydrogen cells, it is necessary to ensure an appropriate infrastructure for refueling hydrogen fuel and to reduce costs of the hydrogen technology in motorization.

Amongst the factors, which may have a positive impact on the development of electromobility based on hydrogen cells, the respondents in more than 90% indicated financial and fiscal incentives during the purchase of cars in this technology and the extension of the networks of hydrogen charging points in 89% of the answers. By far, the broader choice of car models in this technology and an increase in zero-emission zones in the cities were also mentioned by the interviewees as essential. Respectively, 68% and 45% of the answers—see Figure 8. Again, the price and infrastructural factors turned out to be the most significant.

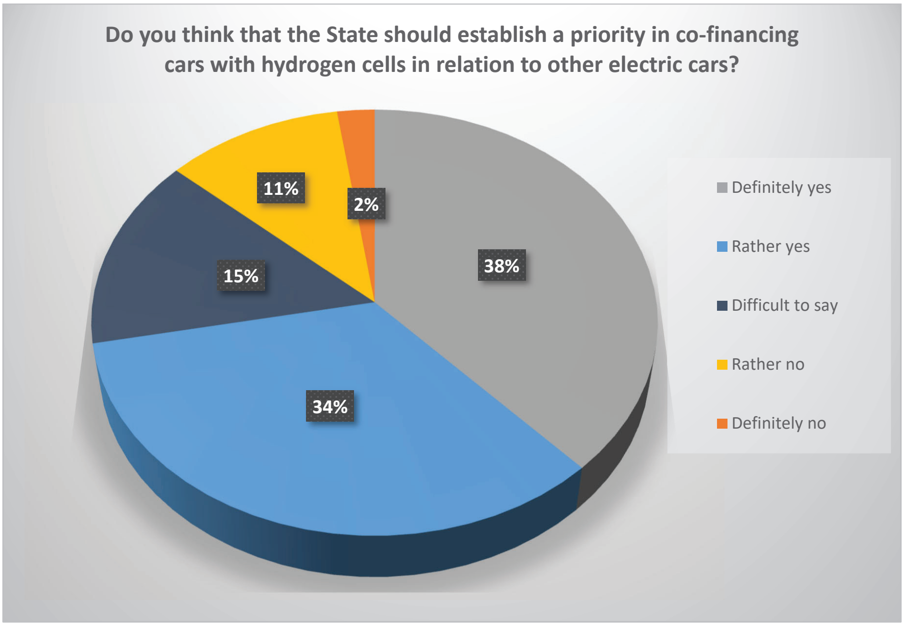

Figure 7. Survey question number 7. Source: own study.

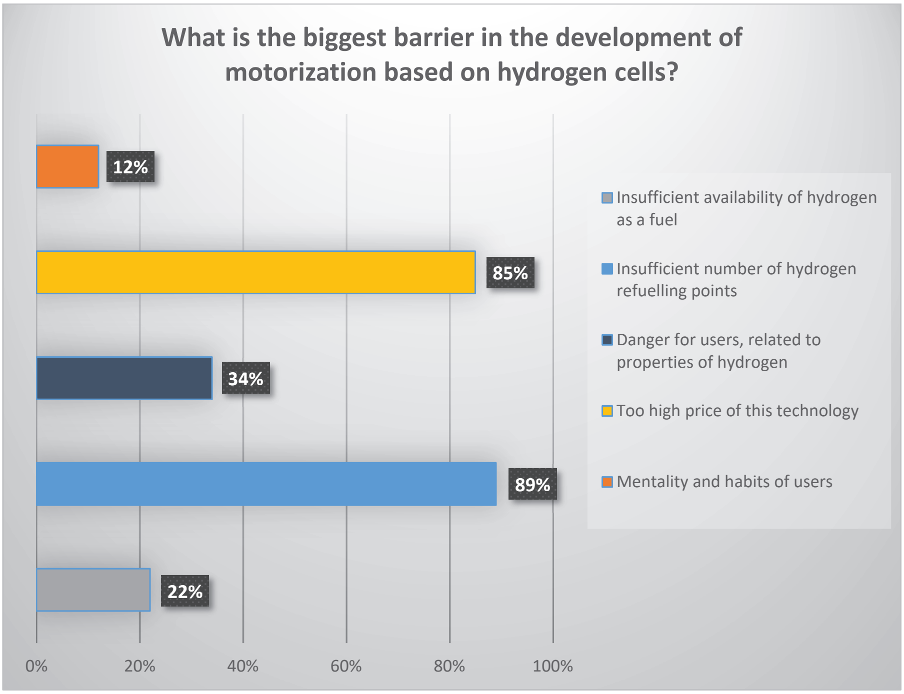

Figure 8. Survey question number 8. Source: own study.

The hydrogen technology in electromobility is a novelty amongst vehicle users, which does not mean that they do not have expectations towards further thrive thereof. Among the most essential areas requiring further development within the framework of this technology, the respondents indicated towards an increased safety of users—82% of the answers; and economy of exploitation of electric vehicles based on hydrogen cells—77% of the answers. The comfort of traveling, the autonomy of the vehicles, and the durability thereof turned out to be much less significant to the interviewees—see Figure 9.

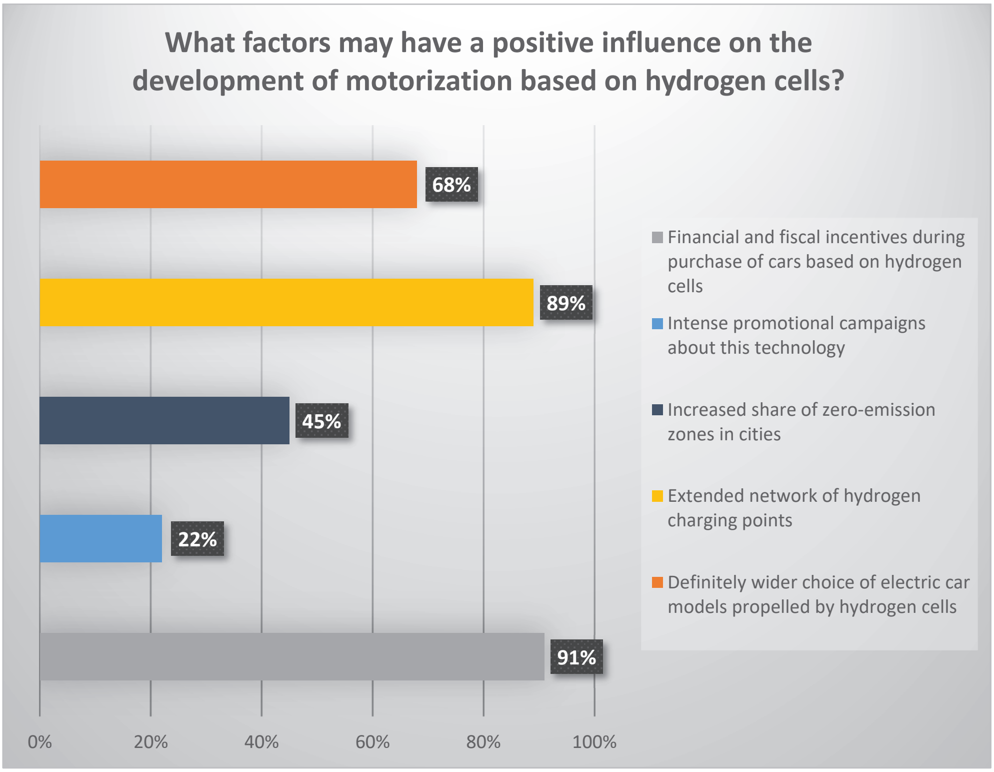

Figure 9. Survey question number 9. Source: own study.

In the final issue—see Figure 10, the respondents indicated the most sensitive areas related to the development of electromobility for vehicles powered by hydrogen energy. Two areas stands out: the costs related to the operation of the vehicle and the safty of use. The least important feature was selected by the respondents as the intense promotional campaigns about the durability of the battery itself (28 % of the respodents). However, vehicle battery life can be a significant issue. Travel comfort (45% of respodents) and vehicle autonomy (38%) are classified at similar levels.

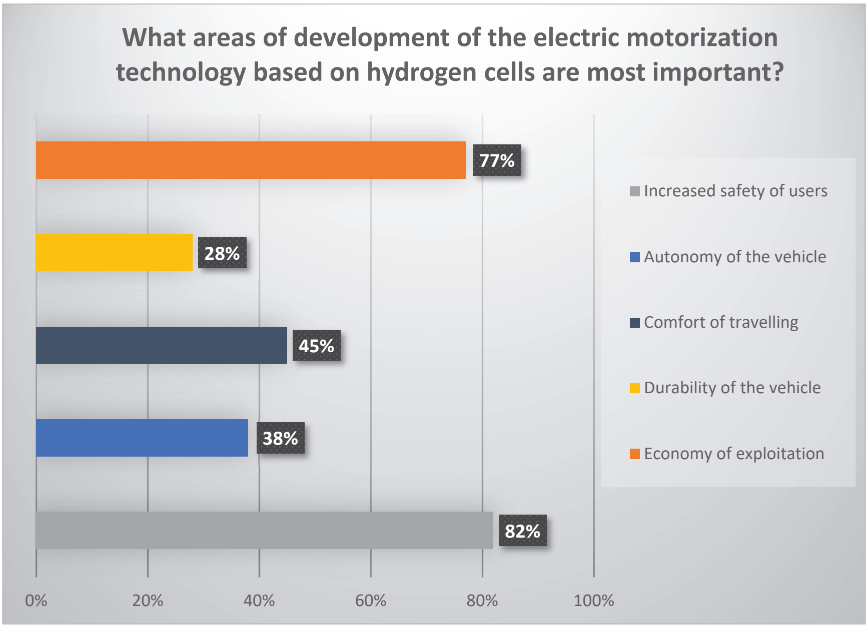

Figure 10. Survey question number 10. Source: own study.

6. Summary and Conclusions

It was an attempt to present a topic related to hydrogen-powered electromobility, based on a legal analysis, economic and social conditions. Although the research was conducted in Poland, based on a research group composed of electric vehicle users and on the basis of the Polish legal system, outwardly, the results of these studies can be applied to other European Union countries. Of course, this requires further research in other EU countries. This will enable a better understanding of the hydrogen cell challenges in the automotive industry.

Summing up, it must be stated that for the development of electromobility based on hydrogen cells in Poland, an overly significant matter was the construction and implementation of the law order based on the European and national legal acts because the current ones include residual provisions on the hydrogen technology only. Equally important to the development of this technology was an increase in its economic effectiveness and competitiveness in relation to other technologies used in motorization and an increase in the level of social trust for electric vehicles based on hydrogen cells. The research constituted an attempt to fill the gap in the relevant literature indicating the possible directions of development of the legal system and primary preferences of current Polish users of electric and hybrid vehicles in relation to vehicles in the hydrogen technology.

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References

1. 2020 Climate & Energy Package. Available online: https://ec.europa.eu/clima/policies/strategies/2020_en#tab-0-1 (accessed on 1 March 2020).
2. Biała Księga Komisji Europejskiej z 28 Marca 2011 r. Plan Utworzenia jednolitego Europejskiego Obszaru Transportu. Available online: https://ec.europa.eu/transport/sites/transport/files/themes/strategies/doc/2011_white_paper/white-paper-illustrated-brochure_pl.pdf (accessed on 1 March 2020).
3. Ramy Polityki w Zakresie Klimatu i Energii do Roku 2030 (Aktualizacja Pakietu Klimatyczno-Energetycznego). Available online: https://ec.europa.eu/clima/policies/strategies/2030_pl#tab-0-1 (accessed on 2 March 2020).
4. Czysta Energia dla Transportu: Europejska Strategia w Zakresie Paliw Alternatywnych. Available online: https://eur-lex.europa.eu/legal-content/pl/TXT/?uri=CELEX%3A52013PC0017 (accessed on 2 March 2020).
5. Europejska Strategia na Rzecz Mobilności Niskoemisyjnej. Available online: https://eur-lex.europa.eu/legal-content/pl/TXT/?uri=CELEX%3A52016DC0501 (accessed on 2 March 2020).
6. Clean Mobility Package z 2017 r. Available online: https://ec.europa.eu/transport/modes/road/news/2017-11-08-driving-clean-mobility_en (accessed on 5 March 2020).
7. Europejski Zielony Ład —The European Green Deal. Available online: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en (accessed on 5 March 2020).
8. Journal of Law UE from 28.10.2014, L 307/1. Available online: https://eur-lex.europa.eu/legal-content/PL/TXT/?uri=OJ%3AL%3A2014%3A307%3ATOC (accessed on 5 March 2020).
9. Rządowy Projekt Ustawy o Elektromobilności i Paliwach Alternatywnych. Available online: https://www.sejm.gov.pl/Sejm8.nsf/druk.xsp?nr=2147 (accessed on 17 December 2019).
10. EUR-Lex. Available online: https://eur-lex.europa.eu/legal-content/PL/TXT/?uri=CELEX:52020DC0301 (accessed on 18 December 2019).
11. Komunikat Komisji. Available online: https://eur-lex.europa.eu/legal-content/PL/TXT/PDF/?uri=CELEX:52020DC0456&from= (accessed on 29 March 2020).
12. Polska Strategia Wodorowa do Roku 2030. Available online: https://www.teraz-srodowisko.pl/media/pdf/aktualnosci/9801-Projekt-Polskiej-Strategii-Wodorowej-do-roku-2030-z-perspektywa-do-2040-r.pdf (accessed on 29 March 2020).
13. International Energy Agency, The Future of Hydrogen Dotyczące Wodoru za 2019 rok, Strona 42. Available online: https://www.iea.org/reports/the-future-of-hydrogen# (accessed on 18 March 2020).
14. Wiącek, D. Wodór jako paliwo przyszłości, Autobusy—Technika, Eksploatacja, Systemy Transportowe, nr 10/201. Available online: https://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-article-BWAW-0016-0061?q=d0898281-8b3d-46d9-98ee-c1494c638b19$2&qt=IN_PAGE (accessed on 18 March 2020).
15. Trwają Prace nad Strategią Wodorową Dla Polski. Potrzeba Innowacji i inwestycji. Available online: https://www.rynekinfrastruktury.pl/wiadomosci/drogi/trwaja-prace-nad-strategia-wodorowa-dla-polski-potrzeba-innowacji-i-inwestycji-74658.html (accessed on 21 May 2020).
16. Skłodowska, M.; Zasuń, R. Czy Polska ma Szanse Wyrosnąć na Wodorowego Potentata? Na Razie Sporo Nam Brakuje. Available online: https://wysokienapiecie.pl/31614-czy-polska-ma-szanse-wyrosnac-nawodorowego-potentata-na-razie-sporo-nam-brakuje/ (accessed on 12 January 2021).
17. Wodór -Paliwo Przyszłości. Available online: http://www.ichpw.pl/wp-content/uploads/2018/10/%C5%9Aci%C4%85%C5%BCko-Wodor-paliwo-przysz%C5%82o%C5%9Bci.pdf (accessed on 12 January 2021).
18. Czy Wodór ma Szansę Zostać Paliwem Przyszłości? Polska ma go pod Dostatkiem. Available online: https://moto.pl/MotoPL/7,88389,23160601,czy-wodor-ma-szanse-zostac-paliwem-przyszlosci-polska-ma-go.html (accessed on 19 March 2020).
19. Journal of Law 2004, no. 90 pos. 864/2 from 30 April 2004. Available online: http://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20040900864 (accessed on 19 March 2020).
20. Europejski Zielony Ład. Available online: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_pl (accessed on 22 March 2020).
21. Gov.pl. p 07.01.2021 r. Available online: https://www.gov.pl/web/fundusze-regiony/informacje-o-strategii-na-rzecz-odpowiedzialnego-rozwoju,dostę (accessed on 23 March 2020).
22. Elektromobilność w Polsce (Wersja Archiwalna). Available online: https://www.gov.pl/web/aktywa-panstwowe/elektromobilnosc-w-polsce (accessed on 11 December 2019).
23. Aktualizacja Projektu Polityki Energetycznej z 8 września 2020 r. Available online: https://www.gov.pl/web/klimat/projekt-polityki-energetycznej-polski-do-2040-r (accessed on 7 January 2020).
24. Krajowy Plan na Rzecz Energii i Klimatu na Lata 2021–2030 Przekazany do KE. Available online: https://www.gov.pl/web/aktywa-panstwowe/krajowy-plan-na-rzecz-energii-i-klimatu-na-lata-2021-2030-przekazany-do-ke (accessed on 23 March 2020).

25. Polityka energetyczna Polski do 2040 r. Available online: https://www.gov.pl/web/klimat/polityka-energetyczna-polski (accessed on 25 March 2020).
26. Journal of Law 2020 r. poz. 833. Available online: http://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20200000833 (accessed on 2 March 2020).
27. Podpisanie Listu Intencyjnego o Ustanowieniu Partnerstwa na Rzecz Budowy Gospodarki Wodorowej. Available online: https://www.gov.pl/web/klimat/podpisanie-listu-intencyjnego-o-ustanowieniu-partnerstwa-na-rzecz-budowy-gospodarki-wodorowej (accessed on 30 March 2020).
28. Journal of Law UE z 5.6.2009, L 140. Available online: https://eur-lex.europa.eu/legal-content/PL/TXT/PDF/?uri=OJ:L:2009:140:FULL&from=LT (accessed on 15 March 2020).
29. Journal of Law 2020 r., Item 110. Available online: https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20200000110 (accessed on 15 March 2020).
30. Journal of Law 25.7.2019 L 198/241. Available online: https://eur-lex.europa.eu/legal-content/PL/TXT/HTML/?uri=OJ:L:2019:198:FULL&from=EN (accessed on 14 March 2020).
31. Journal of Law 2019 r. Item 1124. Available online: https://www.dziennikustaw.gov.pl/D2012000112401.pdf (accessed on 14 March 2020).
32. Journal of Law 2018 r., Item 1356. Available online: https://dziennikustaw.gov.pl/D2020000135601.pdf (accessed on 15 March 2020).
33. Journal of Law 2006 nr 169 poz. 1199. Available online: http://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=wdu20061691199 (accessed on 18 March 2020).
34. Journal of Law 2019 r., Item 2189. Available online: https://dziennikustaw.gov.pl/D2020000218901.pdf (accessed on 18 March 2020).
35. Journal of Law 2019 r., Item 2526. Available online: http://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20180002526 (accessed on 21 March 2020).
36. Journal of Law 2019 r., Item 2538. Available online: http://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20180002538 (accessed on 21 March 2020).
37. Journal of Law 2020 Item 1565. Available online: https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20200001565 (accessed on 30 March 2020).
38. Journal of Law 2018 r. Item 799 and 1356. Available online: http://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20180001356/O/D20181356.pdf (accessed on 21 March 2020).
39. Journal of Law 2020 r. Item 110, 284, 568, 695, 1087 and 1517. Available online: http://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20200000110 (accessed on 18 March 2020).
40. NFOŚiGW Konsultuje Wsparcie dla Gospodarki Wodorowej. Available online: http://nfosigw.gov.pl/o-nfosigw/aktualnosci/art,1684,nfosigw-konsultuje-wsparcie-dla-gospodarki-wodorowej.html (accessed on 30 March 2020).
41. Nowa Energia. Available online: http://nfosigw.gov.pl/gfx/nfosigw/userfiles/files/prezentacja_nowa_energia_sielamowicz_wydzial_innowacji.pdf (accessed on 14 March 2020).
42. Programy 2015–2020. Available online: http://nfosigw.gov.pl/oferta-finansowania/srodki-krajowe/programy-priorytetowe/ (accessed on 3 March 2020).
43. Biznes Alert. Available online: https://biznesalert.pl/ustawa-prawo-wodorowe-prace-ministerstwo-klimatu-trzecikwartal-2021-energetyka-wodor-innowacje/ (accessed on 12 January 2020).
44. Journal of Law 2016, Item. 283. Available online: https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20200000283 (accessed on 18 March 2020).
45. Ewidencja Infrastruktury Paliw Alternatywnych. Available online: https://eipa.udt.gov.pl/ (accessed on 3 March 2020).
46. European Comission. Available online: https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy (accessed on 26 November 2020).
47. Tworzenie Gospodarki Neutralnej dla Klimatu: Komisja Przedstawia Plany Dotyczące Systemu Energetycznego Przyszłości i Czystego Wodoru. Available online: https://ec.europa.eu/commission/presscorner/detail/pl/ip_20_1259 (accessed on 19 November 2020).
48. Narodowy Fundusz. Available online: https://www.nfosigw.gov.pl (accessed on 2 April 2021).
49. Journal of Law of 2020, Item 1333. Available online: https://dziennikustaw.gov.pl/D2020000133301.pdf (accessed on 30 March 2020).

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Methodology for Assessing the Impact of Aperiodic Phenomena on the Energy Balance of Propulsion Engines in Vehicle Electromobility Systems for Given Areas

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Abstract: The article presents the methodology of isolating aperiodic phenomena constituting the basis of the energy balance of vehicles for the analysis of electromobility system indicators. The symptom observation matrix (SOM) and experimental input data are used to analyze periodic phenomena symptoms. The multidimensional nature of the engine efficiency shortage has been well defined and analyzed in terms of errors in the general model using neural networks, singular value decomposition, and principal component analysis. A more difficult task is the analysis of a multidimensional decision-making process. The research used a data fusion method and the concept of symptom reliability, which is applied to the generalized failure symptom obtained by applying the singular value decomposition (SVD). The model research has been based on the gray system theory (GST) and GM forecasting models (1,1). Input data were obtained from the assessment of driving cycles and analysis of the failure frequency for 1200 vehicles and mileage of 150,000 km. Based on this analysis, it can be concluded that with the current infrastructure and operating costs and the frequency of failure of PHEV and BEV drives, ICEV vehicles are unrivaled in terms of their operating costs.

Keywords: electric vehicle; electromobility; energy balance; sustainable development; efficiency engines; clustering; charging stations; data analysis

1. Introduction

Currently, to reduce the environmental impact of the transport sector, governments and institutions have been introducing increasingly stringent regulations and limits on pollutant emissions [1,2]. To meet such demanding emission standards and reduce fuel consumption while maintaining the required durability of the drive unit, car manufacturers must develop more and more advanced drive systems and energy conversion systems. This is followed by an increasing number of unforeseen aperiodic factors of a stochastic nature that affect the long-term cost of the solution used. Due to the high cost of batteries, electric vehicles are still not able to fully meet the requirements [3–5]. The current energy policy objectives result from a correlation between limitations due to the depletion of natural energy resources, the risk of environmental pollution, and the strategy of creating an infrastructure that allows for the efficient use of electromobility systems. Energy is an added value that has various forms; it is a function of the state and thermodynamic potential, which describes the interaction of physical objects, physical and chemical transformations, and processes occurring in nature. The prospect of the conventional energy reserves being exhausted and the restrictive environmental protection measures have boosted the interest in alternative energy sources used in internal combustion engine vehicles (ICEV).

The efficient use of alternative energy sources is hampered by technological, economic, political, and legal constraints. Today's petroleum fuels are used in ICEVs, e.g., gasoline and diesel (fossil fuels). The conversion of the chemical energy in petroleum-based fuels into thermal energy is associated with a harmful impact on the environment, and forecasts for this form of energy resources necessitate the development of alternative fuels that can be used in battery electric vehicles (BEV) and plug-in hybrids (PHEV). Energy is an indispensable factor that determines the chain of obtaining and processing power for specific technologies. Since petroleum-based fuels belong to a group of nonrenewable energy sources, this necessitates their limited use in vehicle propulsion. The extraction, processing, and transport of petroleum fuel for internal combustion engines have a massive impact on the natural environment. Previous research into the use of alternative fuels as the primary form of energy and an efficient replacement for conventional fuels have not produced conclusive results. This is determined by energy conditions and technology that converts a given state of life into the required mechanical work necessary to achieve the desired range and dynamics of passenger vehicles, trucks, and public transport vehicles.

The current studies do not promote the adoption of an unambiguous substitute for petroleum fuels for vehicle propulsion following design parameters, i.e., vehicle range and dynamics, the emission of harmful combustion substances, and the economic factors. Just like gasoline and diesel oil, the currently available alternative fuels, e.g., liquefied petroleum gas (LPG), despite their fairly common use, are a petroleum products. Another example is natural gas, the resources of which are also limited due to the irreversible course of the combustion process. Hydrogen obtained from water through electrolysis is used as an energy source for fuel cells used in electric motors. The introduction of hydrogen propulsion in traction vehicles brings advantages resulting from the overall efficiency of the fuel cell (more generous than in internal combustion engines), fuel energy efficiency (translating into range when compared to vehicles with tanks of equal volume), and environmentally neutral emission. From an economic point of view, alternative fuels from biological products, e.g., ethanol, biodiesel, are a good energy source, limited only by the cultivation capacity of the raw material. Due to the limitation of land available, the demand for biodiesel as a replacement for conventional fuel cannot be met. The use of alternative fuel vehicles (AFV) has been followed by the introduction of a primary terminological differentiation: dedicated—vehicles powered by one energy source, having low emissions to the optimization of the engine operating parameters; dual-fuel—vehicles that use conventional fuel and alternative fuel as energy sources; bifuel—a two-tank car running on traditional fuel (gasoline or diesel) and, depending on the type of fuel system (propane or natural gas), using a single or combined cycle switched by the driver or an automatic control unit based on an algorithm (emission optimization point and vehicle economy); flex-fuel—single-tank vehicles fueled by petrol, methanol or ethanol, which form a homogeneous mixture.

The demand for conventional energy has forced the development of innovative vehicle designs based on alternative sources that promote the correlation between the following parameters: fuel consumption, the emission of toxic exhaust gas components, and the comfort of the vehicle movement. Energy consumption depends mainly on the vehicle's energy demand, the efficiency of its drive system, and the energy source. In 2030, on the North American market, hybrid cars are expected to account for 10% of the total number of cars. Hybrid and electric motors will create significant competition for internal combustion engines on the European market. Sales of hybrid and electric engines in OECD countries, mainly Australia, New Zealand, and Japan, will secure the leading share of these countries in the automotive industry in the coming years. According to the 2030 forecast, the US market demand for fossil fuel (petroleum derivatives) will remain at a steady level. Internal combustion engine vehicles show a limited capacity to reduce fuel consumption, due to the Euro 6 emission standard for LDVs. Combustion taking place in the cylinder working space translates into the engine's efficiency and the emission of harmful combustion products. These are unavoidable processes that accompany energy conversion in internal combustion engines.

Fuel cell hybrid electric vehicles are fitted with fuel cells as a source of power. It enables manufacturers to switch from using a piston internal combustion engine and exclude fossil fuels (petroleum derivatives). The hydrogen energy contained in the fuel cells is sufficient for the electric motor to operate. An electric vehicle generates zero emissions of harmful combustion products. Alternative fuels, used as a source of energy to propel vehicles, enable the reduction of substances toxic to the environment to a predefined level. By analyzing driving and energy properties in electric cars, it is possible to determine the operating conditions to maintain a sufficient durability and economic aspects of vehicles equipped with a given drive unit.

The currently adopted energy indicators determine the nature of the experimental research. These include the vehicle range at selected constant speeds depending on the vehicle class or capacity consistent with a speed profile, including the required phases, e.g., acceleration, motion at a constant speed and constant load, deceleration during braking, and standstill (static condition). In electric vehicles, the energy stored in electrochemical batteries may cause well-known repercussions. Scheduled test conditions are determined in terms of the energy balance. The parameters specific to a vehicle model, such as the total weight, the front surface (aerodynamic model), the rolling resistance coefficients, the efficiency of the drive unit and the entire drive train, and other electronic systems of the vehicle, are used to determine the energy status of the car. Many models undergo energy analysis to assess the effective use of the energy source for propulsion. Much attention is also paid to the vehicle's range, the technical possibility of accumulating energy, and the efficiency of its recovery, e.g., the recovery of kinetic energy during braking. As it turns out, relatively little attention is paid to aperiodic factors of a stochastic nature, contributing to the reduction in the vehicle operating cost. In the case of electric and hybrid vehicles, these are the main factors related to the unforeseen energy capacity loss of the primary energy source, failures of the energy management system pieces, damage to the drive of smaller components, changes in the driving conditions when traveling long-distance in unknown territory. Then, the values recorded by the energy management system are unsuitable for determining the future range of the vehicle. Other factors include the limitations of the charging technology and the availability of spare parts in the event of minor driveline failures. It should be remembered that in cars with an internal combustion engine, unforeseen external losses of, for example, the drive system or other energy management system components can be quickly rectified due to the well-developed service station networks and the availability of spare parts. The same applies to the availability of power supply stations for a given energy system.

The basic limitation for BEVs is their energy source, which in most cases is a set of electrochemical cells, e.g., lithium-ion cells. Their durability over a longer period of operation is insufficient, the charging time is very long, and the purchase cost is very high in relation to the energy benefits [6–8]. Additionally, many design measures are required to ensure maximum durability for various drive system operating conditions, energy load resulting from energy consumption by electrical equipment, and the nature of driving over a given distance [9,10]. Apart from these fundamental disadvantages of BEVs, there are also difficulties related to the progress in the development of the fast charging infrastructure in rural areas and smaller towns [11–13]. Therefore, these difficulties make long distances traveling in nonurban areas with limited access to the charging infrastructure reduce the energy and economic viability of BEVs [14,15]. In this case, it is necessary to apply appropriate management strategies while introducing BEVs to the automotive market to ensure the maximum efficiency of the electromobility system [16,17]. To reduce certain limitations related to driving system solutions, the use of the PHEV, which combines BEV and ICEV systems, should be considered during the transition period [18–20]. The ability to improve the overall efficiency of ICEV's drive units is minimal. Therefore, it is not possible to achieve a significant reduction in fuel consumption, i.e., 20–30%, assuming the necessary power and torque of the engine [21–23]. The problem becomes more complicated in the case of large internal combustion engines designated for trucks and buses, since they require engines of significantly increasing and modified mechanical efficiency to reach the desired reliability and structural strength of the main kinetic unit. The combination of the two power sources in PHEV vehicles may contribute to the vehicle's range [24,25]. This will significantly extend the time needed for BEVs to adapt to the development of the charging infrastructure in nonurban areas. In real terms, this allows the vehicle range to be increased from about 70–100 km to 600 km [26–28], and maintain mobility in case batteries are completely discharged, and the electric drive unit is excluded [29–31]. To determine appropriate energy balances, many complex algorithms for forecasting the potential energy consumption are used. They take into account the route to be covered based on satellite navigation [32–34]. Such energy management models and strategies are used in various vehicle energy management concepts [35–37]. Due to the complexity of the system, the capabilities vary and allow different effects to be achieved depending on route planning and the availability of charging stations [38–40].

Modern PHEVs with an electrochemical energy source are still equipped with an internal combustion engine, electric motor, electric generator, and an electrochemical energy source. They can work in series and in parallel. In a series configuration, the total energy of the internal combustion engine with a generator is converted into electric energy, which determines the mechanical work of the drive unit. The piston internal combustion engine drives a direct current or alternating current generator (integrated with rectifier) [41,42]. An automatic transmission coupled with an electric motor drives the wheels. The system consists of primary and secondary energy sources. The power balance in a series configuration distinguishes between two operating states. An energy shortage in an electrochemical energy source is compensated by the internal combustion engine energy surplus resulting from the combustion engine's work schedule. Internal combustion engine stabilizers force its operation at constant useful power adjusted to the energy balance. This determines the optimal overall efficiency of the internal combustion engine [43–45].

Kinetic energy is recovered when braking enables the energy necessary to charge the secondary source with only the electric motor working as a generator. In a parallel hybrid system, electrical energy, transferred from mechanical work to the crankshaft of the internal combustion engine, is converted into energy supplying the secondary energy source and transmitted through the mechanical units to the driving wheels. The drive train clutch enables the separation of the electric and combustion engines. The automatic transmission in the power unit enables the connection in parallel of the electric and combustion engines. The torque measured on the motor output shafts is the sum of the unit torques. When the drive wheels are heavily loaded, the internal combustion engine is supported by an electric motor that uses energy from an electrochemical source. When the nominal useful power of the internal combustion engine exceeds the capacity of motion resistance and the braking mode is applied in a vehicle, the electric motor works as a generator. The main criterion determining the use of a given design solution in a PHEV with electric electrochemical energy accumulation is to fulfill conditions for optimal energy accumulation resulting from the excess useful power of the internal combustion engine and its healing, i.e., secondary recovery of the energy in vehicles with electric or hybrid drive by using an electric motor as a generator and the conversion of the kinetic energy into electricity supplying an electrochemical energy source. The use of secondary energy generation to drive the vehicle significantly increases its overall efficiency. The research carried out as part of the energy accumulation and recuperation project has helped to develop prototype solutions, which have been then implemented into serial production. The hybrid electrochemical drive system in PHEVs that uses a secondary mechanical or hydraulic energy source constitutes a separate group of energy accumulation systems cooperating with the electrochemical energy source.

In traction vehicles, the primary energy source is an internal combustion engine (ICE), from which the chemical energy from the combustion process is converted into mechanical work. The specific mass-energy of the fossil fuel (gasoline) is 9000 J/kg. The efficiency of its use depends on the overall traction efficiency of a piston internal combustion engine and the range of the crankshaft rotation speeds. The combustion engine used in conventional vehicles is characterized by the low overall efficiency of the primary energy source. In hybrid systems, the combustion engine does not require changes in the rotation speed of the crankshaft throughout the vehicle operation mode when generating a constant rated power. The combustion engines used in hybrid systems must have a low weight and increased durability, as well which as their rated power needs to exceed the power demand of a given vehicle. Based on the heat strength tests of the engine materials, it has been found that spark ignition engines, compression ignition engines, rotary engines with a rotating piston, Stirling engines, and gas turbine engines meet the requirements of an electromechanical hybrid drive in PHEVs.

The preliminary analytical studies of the thermal engine as a primary source of energy in LDVs with a hybrid drive have fully confirmed that the original internal combustion engine can fulfill all of the operating conditions. Due to the durability required (piston–rings–cylinder assemblies), a spark-ignition internal combustion engine cannot work continuously while transferring useful work to the crankshaft with loads equal to the rated power more significant than 50%. To rectify the above, it is necessary to improve the kinetic properties of the main engine mechanisms. The optimization of these parameters determines the improvement of the overall efficiency of the engine. The ignition internal combustion engines used in PHEVs need to have a regular output of their rated power at a constant load of 50% to 80% of the maximum capacity. Considerable resistance to wear and tear during the combined operation of the LDV and PHEV drives is characteristic of compression–ignition combustion engines due to their reduced rotation speed of the crankshaft and the combustion process. This comparison shows a specific limitation that depends on the weight of the compression–ignition internal combustion engine, curb weight, which is considerably larger than in spark-ignition internal combustion engines. Rotary combustion engines have the lowest curb weight but a significantly lower overall efficiency. Stirling engines and gas turbine engines require higher quality materials due to thermal loads and operating conditions. This excludes their service as the primary source of energy. The heat engine in traction LDVs with a series connection of a hybrid electromechanical PHEV drive is connected to a direct or alternating current generator. Mechanical work is transformed into electricity in an electric generator. The energy is transferred to the alternator, the second primary energy source in the internal combustion engine assembly.

Regarding the method of excitation, direct current generators can be divided into individually excited and self-excited (shunt, series, and shunt–series). In the first assembly, the excitation current is taken from the secondary energy source, and in the second, from the armature circuit. The demand for mechanical work is proportional to the electrical output power, which is determined by the generator’s efficiency. Losses of the electric energy output result from internal friction in the bearings, conditioned by the construction of the reception unit (electric energy) or the rings. There may also be winding losses, hysteresis losses (magnetization losses), and rectifier losses. The combination of the internal combustion engine with the PHEV hybrid drive of LDV traction vehicles and a variety of energy sources—diesel engines, ZI engines with a flywheel, gas turbines, batteries, and ultracapacitors—may contribute to the compliance with the exhaust gas toxicity standards for ULEV (Ultra Low Emission Vehicle) and SULEV (Super Ultra Low Emission Vehicle).

Most of the complex systems dealing with energy consumption and the development of the energy–mobility infrastructure of motor vehicles, which are considered for aperiodic reasons, e.g., unforeseen damage to drive systems contributing to the loss of vehicle range, are based on incomplete and uncertain information about their structure and behavior. The methods used for their analysis and evaluation (probability, fuzzy and coarse sets), can be extended with the gray system theory (GST). The advantage is that the method does not require many assumptions about the size and distribution of samples relevant for the abovementioned methods, and the minimum number of data that justifies the use of the GST ($n \geq 4$). By using the technique, one can predict the future behavior of the system, mainly the occurrence of unforeseen phenomena for a given power source, assess the interdependence of the observation vectors, and evaluate the effectiveness of reactions to possible situations and make optimal decisions, as well as group them and study them. This allows for a realistic comparison of the grounds for using specific systems depending on several side factors not directly related to the promised benefits of a given solution. It also enables the analysis of the stochastic parameters that affect the economic aspects of data application in terms of the territorial nature and available infrastructure supporting the operation and service of ICEV, PHEV, and BEVs.

To optimize energy consumption in hybrid PHEV and BEV electric powertrains, several complex control strategies have been developed. However, not all of these models consider aperiodic phenomena affecting the energy balance in propulsion engines in regional electromobility systems. In such a model, engine efficiency indicators should also be introduced, based on the energy balance regarding the quantity and efficiency of the resources required. The adopted method enables the evaluation of the scale of the compromise between the effective range with the primary batteries, which are fully charged, the payload and the required minimum amount of vehicle resources to create the necessary infrastructure. If the operational parameters of BEVs are similar to those of vehicles powered by internal combustion engines (ICEV), a complete analysis of the vehicle's energy balance is an effective solution. By adopting the economic compromise criterion, it is necessary to establish whether the increase in the capacity of the main corresponds to the expansion of the fast charging infrastructure in terms of the stochastic operation of the drive units. Intelligent systems analyzing the engine energy balance based on advanced algorithms can contribute to the effective use of electromobility systems not only in urban but also nonurban systems, where the vehicle range is more important.

2. Materials and Methods

2.1. Resistance to Motion in Classic ICEVs, PHEVs, and BEVs in Terms of Energy Consumption by Selected Operation Schedules—Gray System Theory (GST)

The LDV traction vehicle traffic within a metropolitan agglomeration and in the undeveloped area diversifies the actual speed profile. Operating conditions of the drive system determined by the period and frequency of starting and braking phases and standstill periods, are stochastic in terms of the vehicle's energy demand. This makes it difficult to determine resistance to motion data throughout the drive cycle for different drive units. Each drive system is characterized by various operating conditions. It is challenging to adjust them during one cycle due to energy consumption and the maximum total efficiency of the vehicle. Additionally, there are operational and utility factors of an aperiodic nature, the determination of which can only be performed using predictive methods. For this purpose, one can use a computational system based on the GST, divided into five phases: generation and smoothing of observation vectors, impact analysis, gray cluster analysis, forecasting, and analysis and decision making. The Gray System Theory (GST) was developed in China in 1982. It was created by Juo-Long Deng, a professor at Huazhong University, who presented the concept in a publication [46]. Complex systems encompass different types of notions, such as matter, energy, and information [47–49]. To a large extent, their organization is hierarchical, and often heterarchical, where each of the subassemblies are linked to one another and constitute a compatible chain of cause-and-effect relationships. Then, the positive synergy of the activity can be fully manifested. Therefore, we are talking about a wide class of systems, from complex systems in the entire cycle of service, operation, design, and reliability of a vehicle to socio-engineering systems with a several subsystems, e.g., impact of the nature of infrastructure in a given territory on user preferences as to the nature of the speed profile and the scale of traffic resistance [50–52].

2.2. Comparison of Drive System General Efficiency and the Character of a Speed Profile

In classic ICEVs, the internal combustion engine operates in a variable, indefinite range of changes at rated power, the rotational speed of the crankshaft, and general efficiency. The kinetic energy released during the deceleration of a vehicle (braking) determines the decrease in the overall efficiency of the classic drive system. The motion of a traction vehicle expressed in the EPA-Highway schedule occurs in constant operating conditions of the drive system. The operating conditions of the ICEV driveline with the LDV variable speed profile significantly reduce the efficiency of the system. This is similar to the use of combustion engines in PHEVs. The research on the balance of LDV traction traffic shows the benefits of an urban speed profile in most areas where motor vehicles are used for passenger transport. The situation is changing in the case of heavy vehicles operated in nonurban areas. There, operating conditions change dramatically. In this timeframe, ICEVs show certain overall advantages. It is worth mentioning that the operational capacity is largely primarily influenced by the support infrastructure in PHEVs and BEVs in the country or the region. Based on a speed profile adapted to the operating conditions of a the vehicle, it is possible to determine the value of the energy generated during the vehicle's motion that can be accumulated in a secondary energy source. Apart from losses due to air and motion resistance, ideal conditions for the recovery of braking energy determine the overall accumulation of power between the initial speed and the end of the decelerated motion. The urban driving schedule enables the collection of power by recuperating the kinetic energy of the vehicle in the deceleration of the car and taking over the excess of the instantaneous engine rated power over the required output power necessary for the movement of the driving wheels. Due to the way energy is accumulated in secondary sources in traction vehicles with PHEV drive, such vehicles require electrochemical, kinetic (mechanical), hydropneumatic accumulators, and batteries, and ultracapacitors. The efficiency of energy transmission and transformation systems that cooperate with batteries (secondary energy source) is not constant and depends on energy losses.

In LDV traction vehicles, moving at a low speed, the combustion engine is connected to the wheel drive via a generator and an electric (drive) motor. The increase in demand for power applied to driving wheels, which exceeds the rated capacity of the internal combustion engine, is supplemented by energy from the secondary energy source. The surplus energy generated by the internal combustion engine is used to increase energy in the secondary energy source. By introducing a stabilizer into the assembly of an internal combustion engine, it is possible to obtain a constant power output at a constant rotation speed of the crankshaft. Optimal operating conditions of a combustion engine enable a reduction in fuel consumption (i.e., more effective use of the chemical energy contained in the fuel by improving the overall efficiency of the machine). The hybrid drive in series with the PHEV series is more economical than in a parallel arrangement at an unfavorable power-to-weight ratio. The internal combustion engine in series with the PHEV hybrid drive operates in a narrow range of rotational speeds, which improves the stability of the rotational speed and load changes during the assembly operation. This reduces the emission of toxic combustion products. The traction range of the LDV in serial production is much more extensive, provided the dimensions of the interior combustion engine and the power generator are small. For BEVs, there is no internal combustion engine assembly, but only electric drive components such as propulsion motors, power converters, and an energy source. A significant disadvantage of this solution is its low energy efficiency and significant production and operation costs. In case of any failure of the auxiliary equipment used to control the process of charging and propulsion in PHEVs and BEVs, the cost-effectiveness of introducing the system as a replacement for ICEV vehicles is significantly reduced and in the case of traffic in extraurban mode becomes uneconomical.

The only advantage of this solution is the protection of the natural environment. The presented relationships make it difficult to determine the parameters that influence the assumed conditions, i.e., the range of a vehicle, economy, durability, and the optimal overall capacity. The operating needs and the requirements for LDV traction vehicles powered by an alternative energy source must also take into account driving comfort within a given schedule resulting from the intended use of the car. Regardless of its arrangement (parallel or series), a heat engine can operate at reduced consumption of chemical energy (fuel). The target parameter can be met only by the proper selection of the energy parameters, based on assessing the energy consumption and efficiency of the mechanical–electrical assembly. A critical parametric condition for the bodies of the presented hybrid PHEV systems with electric electrochemical energy accumulation provides the possibility of obtaining energy from excess power of the internal combustion engine and regenerative braking. This enables the effective use of the mechanical energy generated by the internal combustion engine based on inner energy transformation determined by general efficiency. The value of the average energy consumption of the vehicle determines its fuel consumption. This enables the optimization of the traveling profile (speed profile), while taking into account partial phases of movement, e.g., acceleration, training at a constant speed, and deceleration, depending on the nature of a given area. The determination of the exact value of the vehicle's energy consumption with a minor deviation (transient conditions) determines the effectiveness of forecasting and designing these systems. The fuel consumption of the car in real motion and its energy consumption, supported by the general adaptive characteristics of the engine, makes it possible to select the optimal operating conditions for the PHEV hybrid system. The increase in the overall efficiency of the electromechanical drive unit ensures a weight reduction of the secondary energy source (electrochemical batteries) and an increase in the vehicle range, while maintaining constant dynamics of the vehicle's movement. The main disadvantages of modern electromechanical hybrid drives are the low durability of the batteries depending on the technology, the method of energy resource control, and the frequency of charging. The increase in the overall efficiency and power of the combustion engine–power generator unit enables a weight reduction of the secondary energy source. The efficiency of the LDV traction vehicle, which uses an electrochemical battery to accumulate the energy necessary to increase the vehicle's range and increase the power with a temporary load increase over the electric motor power, strictly depends on the number of cells of the secondary energy source.

The electrochemical battery requires periodic replacement due to the side reactions (active wear) depending on the number of charging cycles and the value of the charging current delivered through the booster (internal combustion engine–power generator). Providing the optimal conditions for the accumulation and recovery of energy extends the life cycle of the secondary energy source by increasing its durability. These conditions and all other indirect factors influencing the economics of ICEV, PHEV, and BEV systems are aperiodic parameters. Their separation must be determined individually for a given group of vehicles, comfort class, range, and energy source technology. Thus, it is possible to assess the justification of using PHEVs and BEVs in a given area, taking into account all external factors, including technological possibilities of making a given vehicle and adapting it to the site concerned. In this case, the economic efficiency of the solutions is determined by the durability of the batteries, their operation based on forecast traveling profiles, and access to the charging infrastructure and service centers. It is mostly influenced by the frequency of the defects in a given group of vehicles and their potential repair costs.

2.3. General Mathematical Relations Concerning the Determination of Vehicle Energy Losses

ICEVs, PHEVs, and BEVs have common features that affect energy consumption in motion. It is mainly the resistance to motion, which consists of: air resistance, rolling resistance, hill resistance, and acceleration resistance. In general terms, this relation can be expressed by the equation:

$$P_{nICEV} = P_{nPHEV} = P_{nBEV} = \frac{\rho}{2} V_{\infty}^{2} C_T P_{pC} + f_R P_{cpN} + P sin\alpha + V P_{cPN}(1 + \varepsilon_1)\ [\mathrm{N}]. \quad (1)$$

The resulting inflow velocity V_∞ is the vector sum of the vehicle speed V_{Rmob} and the wind speed V_{win}. The airflow resistance depends on the air attack angle β and the vehicle motion parameters, which can be expressed by the average drag coefficient C_w^* at any angle of air attack: start a new page without indent 4.6cm

$$C_w^* = \frac{W^*}{\frac{\text{б}}{2} V_{Rmob}^2 P_{pC}} = \frac{1}{\pi} \int_0^\pi C_T(\beta) \left[\frac{V_\infty}{V_{Rmob}} (\text{б}) \right]^2 d\text{б} = \frac{1}{\pi} \int_0^\pi C_T(\beta) \left[1 + \left(\frac{V_{win}}{V_{Rmob}} \right)^2 + \frac{V_{win}}{V_{Rmob}} cos\text{б} \right] d\text{б}. \tag{2}$$

With the incoming air (supporting the movement) or the opposite inflow of air, the equation expressing the air resistance W_L can be derived from the above relations:

$$W_L = \frac{\rho}{2} (V_{Rmob} \pm V_{win})^2 C_w^* P_{pC} \text{ [N]}. \tag{3}$$

In the absence of air, which is an unusual case in reality, this relation can be written as follows:

$$W_L = \frac{\rho}{2} {V_{Rmob}}^2 C_w^* P_{pC} \text{ [N]}. \tag{4}$$

This enables us to determine the average dependence of the power demand of the drive unit needed to overcome the resistance to motion. This parameter is significantly influenced by components of the total efficiency of all ICEV, PHEV, and BEV systems.

$$P_{powerICEV} = \frac{P_{nICEV} V_{Rmob}}{\eta_{UNIC} \eta_{UK} \eta_{PNIC}} 10^{-3} \text{ [kW]}, \tag{5}$$

$$P_{powerPHEV} = \frac{P_{nPHEV} V_{Rmob}}{\eta_{UNIC} \eta_{PNIC} \eta_{UNEE} \eta_{PNEE} \eta_{UK}} 10^{-3} \text{ [kW]}, \tag{6}$$

$$P_{powerBEV} = \frac{P_{nBEV} V_{Rmob}}{\eta_{UNEE} \eta_{PNEE} \eta_{UK}} 10^{-3} \text{ [kW]}. \tag{7}$$

For PHEVs and BEVs, there are additional factors such as braking energy recovery efficiency η_{RE} and the charging efficiency of batteries and capacitors η_{CHB+C}:

$$\eta_{UNEE} = \frac{P_{OD}}{P_{EE} - P_{RE}}, \quad \eta_{CHB+C} = \frac{P_{EE}}{P_{CHB+C}}, \quad \eta_{RE} = \frac{P_{RE}}{P_{CH-EE}}. \tag{8}$$

Based on these considerations, assuming the same body shape for all drive system solutions, their energy consumption is determined by the efficiency of: drive systems, steering systems, drive transmission systems, systems supporting energy recovery from braking, other systems supporting the charging of batteries, and capacitors, all intermediate mechanisms accompanying the electric and internal combustion drive, and other components necessary to ensure the required comfort and safety of the vehicle. The overall efficiency depends mainly on energy losses resulting from the electrical and mechanical equipment. Therefore, PHEVs are characterized by the highest general energy consumption, followed by ICEVs and BEVs. This means that BEVs can achieve the highest overall efficiency compared to ICEVs and PHEVs. However, other features must also be taken into account, such as the durability and reliability of the BEV system and potential repairs at a low cost. In fact, all service activities for these vehicles are currently not very popular, and the network of private garages is insufficiently developed. This translates into a significant increase in the cost of repair and parts compared to ICEVs. In PHEVs, due to the dual-source of propulsion, the frequency of probable malfunctions of the drive system, drive train, and energy storage system is significantly higher than in other systems. Therefore, appropriate algorithms should be used to assess the economic aspects of using all propulsion sources due to aperiodic features, limiting the efficiency of the system due to the damage of components and unforeseen road situations.

Table 1 shows the characteristics of example vehicles from a given group. The intention was to compare cars with identical values of resistance to motion, total weight, and the power of an electric motor or an electric motor in combination with an internal combustion engine. Therefore, since the given parameters for the PHEV and BEV groups are identical, the effective range of the vehicle was mainly influenced by the energy consumption by individual components. These were included in calculations based on the above mathematical equations. The given algorithmic relations are only examples, and measures have been extended to a more significant number of factors determining the individual efficiency of a given drive system. By taking into account aperiodic phenomena in the general data analysis, it is possible to decide on the economic efficiency of a given group of vehicles. Such studies were carried out on long-distance routes and in urban mode over a more extended vehicle operation of approximately 150,000 km. These data are presented in Figures 1–4. Listed below are a few example speed profiles in the daily process. Their repeatability is high. Hence, the conditions of using a given drive system are very similar, which translates into high reliability of statistical data over a more extended period. The approximate operating conditions of individual drive systems, drive train, and energy management systems are necessary for the correct assessment of economic effects. Speed profiles were prepared for 24 vehicles, and average results were calculated in a given group (urban or extraurban). For this purpose, advanced GPS devices were used, with the possibility of recording driving techniques and locations. The analysis of aperiodic factors, such as unforeseen damage to the power and drive systems, which determine the economy of ICEVs, PHEVs, and BEVs, was carried out for a group of 1200 vehicles operating in two areas (urban and long-distance). Data were obtained from websites dealing with servicing selected groups of cars, with their breakdown by comfort class.

Table 1. Characteristics of PHEVs and BEVs.

Type PHEV	Small City Vehicle	Medium Limousine	Sport Utility Vehicle	Medium Multiperson Vehicle	Large Limousine	4x4 Vehicle
Weight (kg)	1000	1300	1600	1600	1800	2000
Front surface (m^2)	1.86	2.24	2.43	2.65	2.34	2.56
Power (kW)	90	100	100	100	100	100
Drag coefficient	0.3	0.31	0.33	0.36	0.33	0.34
Engine displacement (cm^3)	1400	2000	2000	2000	2000	2000
Fuel tank capacity (L)	45	50	60	60	60	60
Type BEV	Small city vehicle	Medium limousine	Sport utility vehicle	Medium multiperson vehicle	Large limousine	4x4 vehicle
Weight (kg)	1000	1300	1600	1600	1800	2000
Front surface (m^2)	1.86	2.24	2.43	2.65	2.34	2.56
Electric motor power (kW)	90	100	100	100	100	100
Drag coefficient	0.3	0.31	0.33	0.36	0.33	0.34

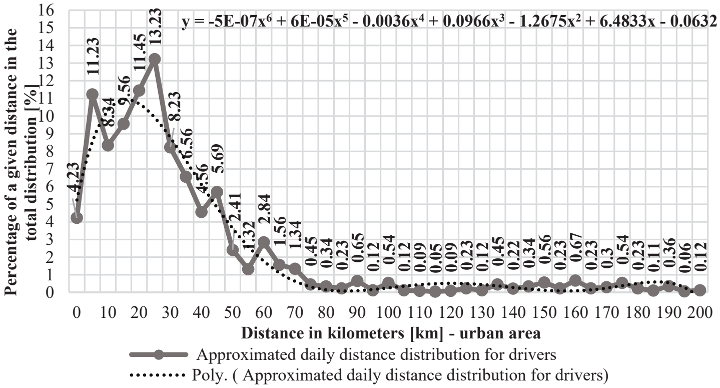

Figure 1. Daily distance distribution for ICEVs, PHEVs, and BEVs operating in urban mode—approximate value based on experimental studies.

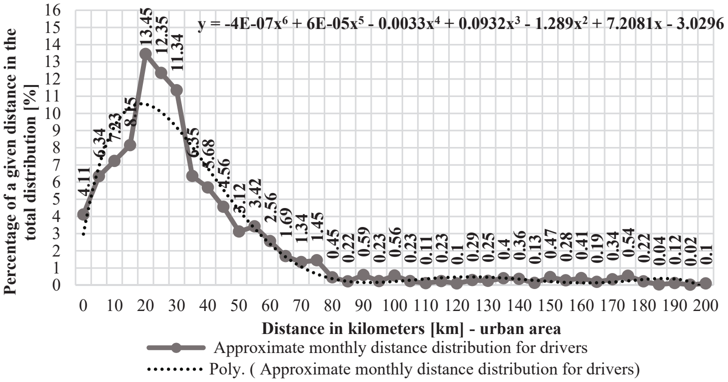

Figure 2. Monthly distance distribution for ICEVs, PHEVs, and BEVs operated in urban mode—approximate value based on experimental tests.

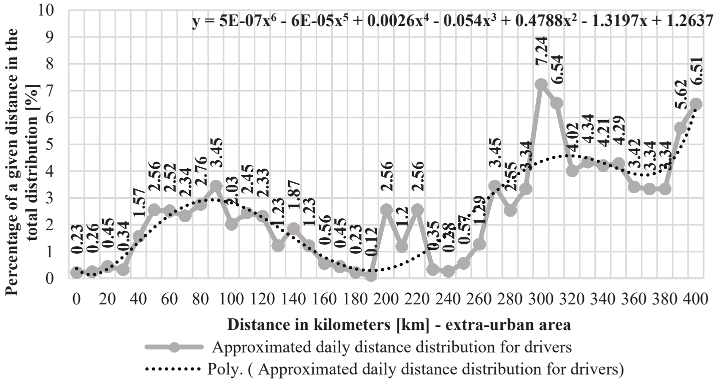

Figure 3. Daily distance distribution for ICEVs, PHEVs, and BEVs operated in extraurban mode—approximate value based on experimental tests.

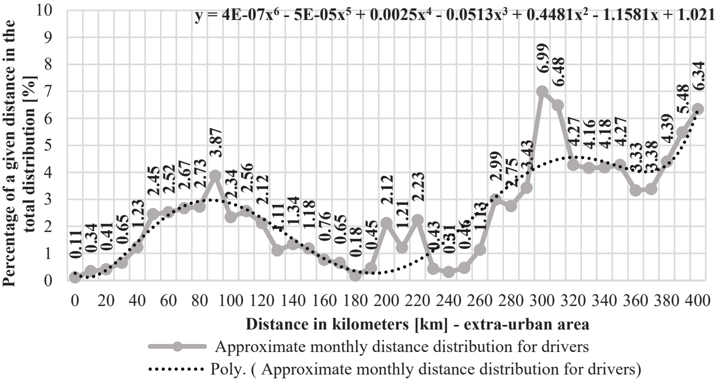

Figure 4. Monthly distance distribution for ICEVs, PHEVs, and BEVs operated in extraurban mode—approximate value based on experimental tests.

As shown in Figure 5, depending on the type of battery, the demand for power and weight is proportional to the resistance to motion. This means that vehicles with appropriately selected aerodynamics can generate significant energy benefits, especially in the case of BEVs. It is evident that 4x4 vehicles are characterized by the most considerable energy demand. This is related to the design of their drive system. In particular, a significant difference can be seen in the energy demand in BEVs and PHEVs, where PHEVs have a much higher demand for electricity from batteries and capacitors. This is related to additional energy losses associated with the double drive system. This causes a significant increase in the resistance to motion in moving mechanisms and a greater demand for electricity in additional actuating and measuring equipment. Comparing BEVs (small city vehicles) of an appropriate design, e.g., energy demand of about 50 kWh, with higher comfort vehicles (limousines), we can see that the battery weight doubles to ensure the same range. This means that for higher-class vehicles, the theoretical capacity of these vehicles with the permissible curb weight of the energy source must be reduced to maintain an appropriate energy consumption level. The use of larger batteries increases the weight and thus reduces the efficiency of the drive system in PHEVs and BEVs. This means that PHEVs and BEVs must have an appropriate body shape that reduces aerodynamic drag and a low battery weight, that does not exceed 300 kg. Further increase in the mass of the source of electrical energy deteriorates the overall energy efficiency of the vehicle resulting in low cost-efficiency of such solutions. Therefore, in larger vehicles, the ICEV driveline is much more efficient and does not significantly affect the overall efficiency of the drive system.

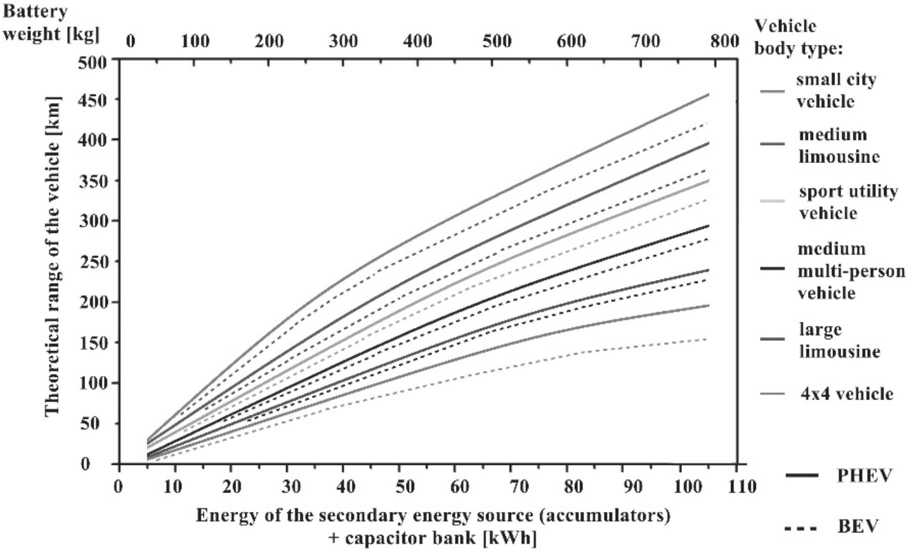

Figure 5. Energy demand depending on various vehicle body types, the weight of batteries, and a theoretical range of PHEVs and BEVs.

Despite these shortcomings of PHEVs, a growing number of stringent CO_2 emission regulations [53] along with rising fuel prices [54] have led to a significant change in the perception of specific vehicle design solutions, including PHEVs and BEVs. The growing demand for city-type vehicles indicates a positive attitude of vehicle users to this group of cars, despite the inconvenience of battery charging, low range, and low availability of charging stations and repair services. Despite the fact that the operating cost of these vehicles is very high in the event of even a minor failure, users often decide to buy such a car. This is probably related to the social pressure on ecology and low emissions.

For this purpose, we may use integrated systems of operational suitability indicators and intermediate systems based on the energy balance, which depends on the quantity and efficiency of the required resources. The complexity of the system is unlimited and involves the implementation of individual efficiencies for each component of the system. Additionally, we need to introduce a method for assessing the probability and predicting potential aperiodic phenomena affecting the total efficiency of the system in a given area.

2.4. Research Capacity of the Gray System Theory (GST) and Statistical Models While Considering Aperiodic Phenomena in the Energy Consumption Balance

The model studies are based on the GST and GM prognostic models (1,1). Various sizes of windows were adopted for the calculation of energy balance parameters and aperiodic features. Such models have several indirect features that are favorable due to the characteristics of data in the model, e.g., diagnostics and the frequency of failures [55–57]. When using a moving window, the GM (1,1) models are especially adaptable. Adopting the wrong window size can amplify the measurement error and lead to wrong conclusions. These models have been developed in several studies. They are mainly used to assess machine reliability and social engineering issues [58–60]. If we observe a selected number of damage symptoms to a given component, e.g., a PHEV, we can obtain specific damage information using the so-called Symptomatic Observation Matrix (SOM) [61]. One method of further extracting this Diagnostic information is to use the Specific Value Distribution (SVD) to the SOM [62–64].

The multidimensional nature of the inefficiency space in machine operation monitoring is now well defined and analyzed in terms of existing model errors through the use of neural networks [65], singular value decomposition [66], or principal component analysis [67]. A more difficult task is the multidimensional decision-making process, where we have a data fusion method [68] and the concept of symptom reliability applied to a general failure obtained by using singular value decomposition (SVD) [69]. Based on the model presented in the above publications, a generalization of the SVD method was used. It considers other SOMs of similar objects with the same number of symptoms (columns); however, the number of rows (observations) may differ [70,71]. The intelligent model learning has been applied [72–74]. The GSVD concept based on a prior SVD application has been used until initial results can be seen as possible use of the GSVD in machine condition monitoring, especially when looking for similar symptoms and wear based on aperiodic damage in the entire energy system in ICEVs, PHEVs, and BEVs [75–77]. An example of the use of the model has been shown in Figure 6, which shows the results of using the model for a diesel engine.

The paper uses a predictive method for the comparative verification of GST models with statistical data about the frequency of aperiodic failures. Six vehicle classes (Figure 5) and three types of ICEV, PHEV, and BEV drivelines were taken into account in a group of 1200 vehicles. It was assumed that speed profiles for individual groups in urban and long-distance modes are very similar for the total population of 1200 vehicles analyzed against aperiodic phenomena during their operation over a distance of 150,000 km.

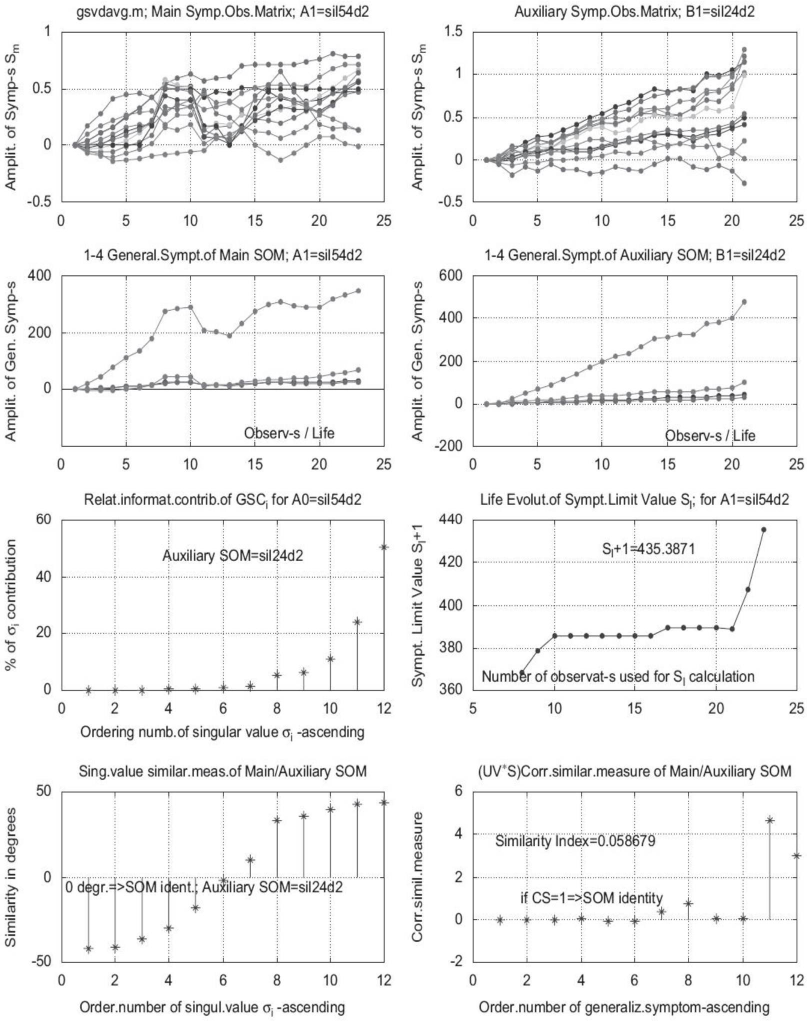

Figure 6. GSVD comparison of two different examples of the same diesel engines [78]. Reprinted with permission from ref. [78]. Copyright 2021 Elsevier.

3. Results

3.1. Costs of Aperiodic Failures in the Entire Balance of Vehicle Operating Costs Resulting from Periodic Inspections and the Replacement of Components Recommended by the Manufacturer

The average values were calculated for individual types of vehicles, their drive systems and speed profiles. The frequency of aperiodic phenomena for particular groups of cars are shown in Figures 7–12. The impact on the change in energy consumption regarding phenomena for two extreme groups of cars has been shown in Figures 13 and 14. Based on the data, simple analytical methods have been used to determine coefficients that are decisive regarding the impact of aperiodic phenomena on the reduction of vehicle economics with reliability criteria and the costs of repairing defects.

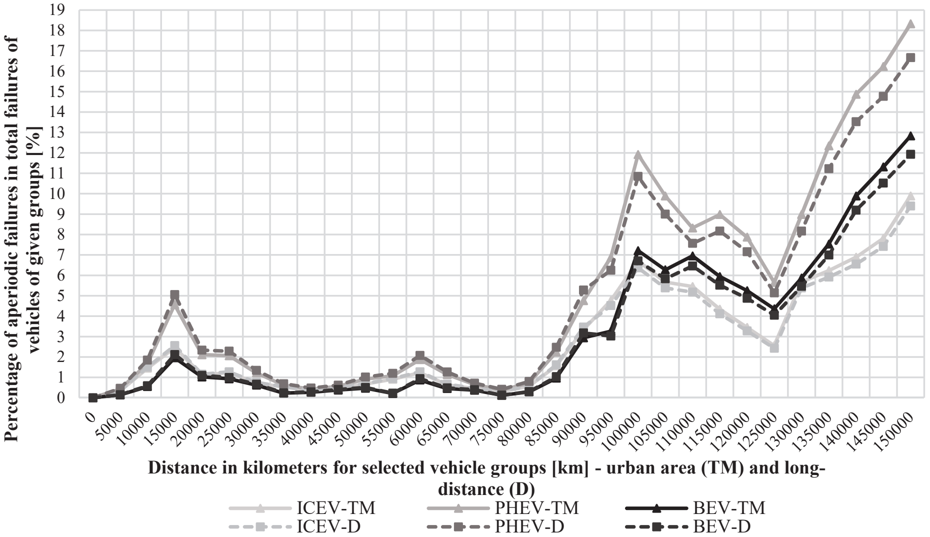

Figure 7. Distribution of aperiodic failures for a small city vehicle with ICEV, PHEV, and BEV propulsion for urban and long-distance speed profiles over a distance of 150,000 km.

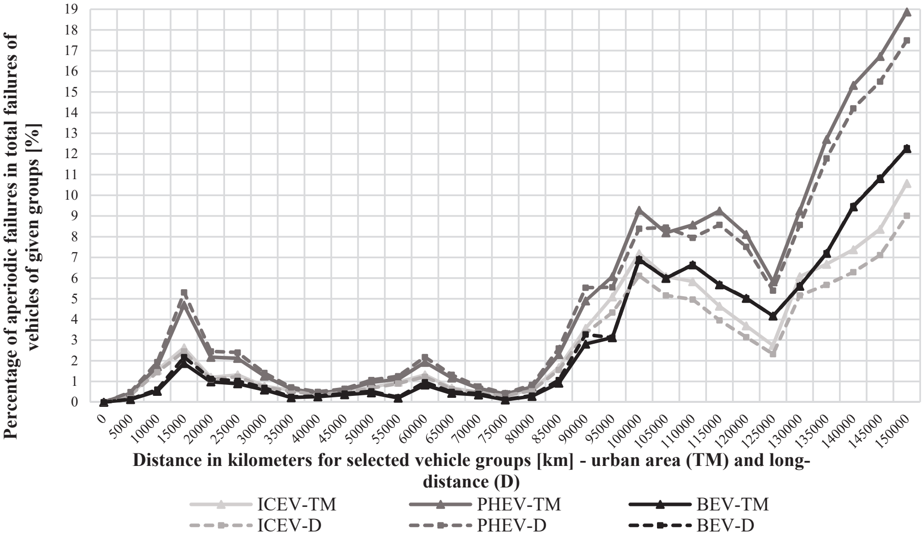

Figure 8. Distribution of aperiodic failures for a medium limousine with ICEV, PHEV, and BEV propulsion for urban and long-distance speed profiles over a distance of 150,000 km.

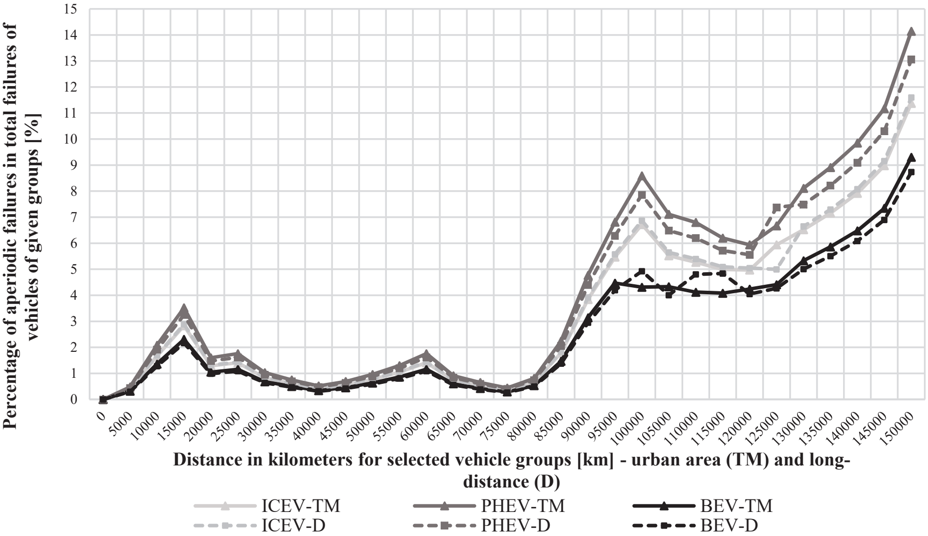

Figure 9. Distribution of aperiodic failures for a sport utility vehicle with ICEV, PHEV, and BEV propulsion for urban and long-distance speed profiles over a distance of 150,000 km.

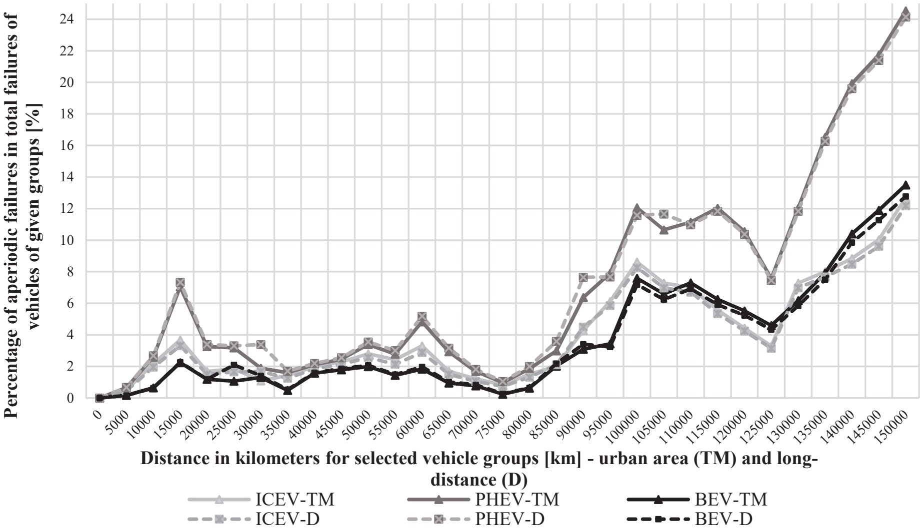

Figure 10. Distribution of aperiodic failures for a medium multiperson vehicle with ICEV, PHEV, and BEV propulsion for urban and long-distance speed profiles over a distance of 150,000 km.

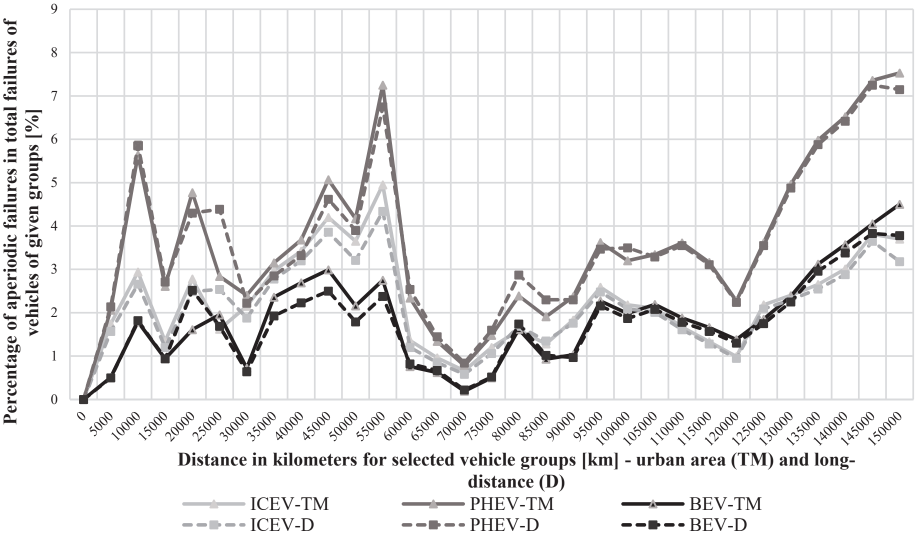

Figure 11. Distribution of aperiodic failures for a large limousine with ICEV, PHEV, and BEV propulsion for urban and long-distance speed profiles over a distance of 150,000 km.

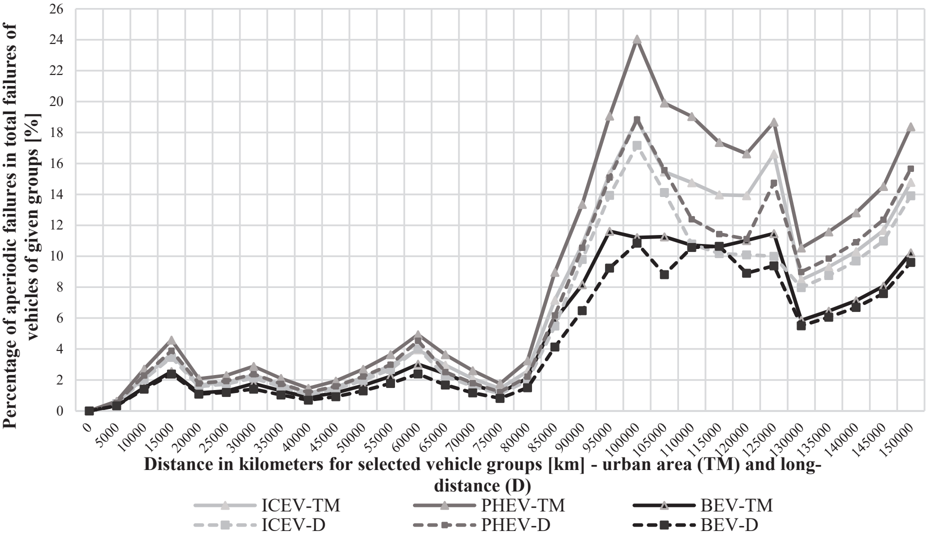

Figure 12. Distribution of aperiodic failures for a 4x4 vehicle with ICEV, PHEV, and BEV propulsion for urban and long-distance speed profiles over a distance of 150,000 km.

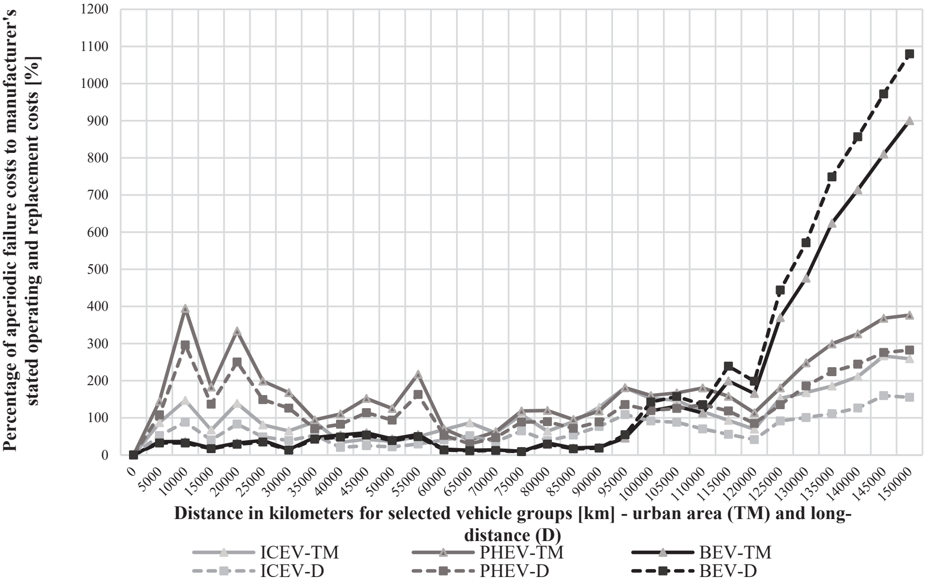

Figure 13. Percentage of aperiodic failures cost in the entire balance of vehicle operating costs resulting from periodic inspections and replacement of components recommended by the manufacturer—a high-class limousine.

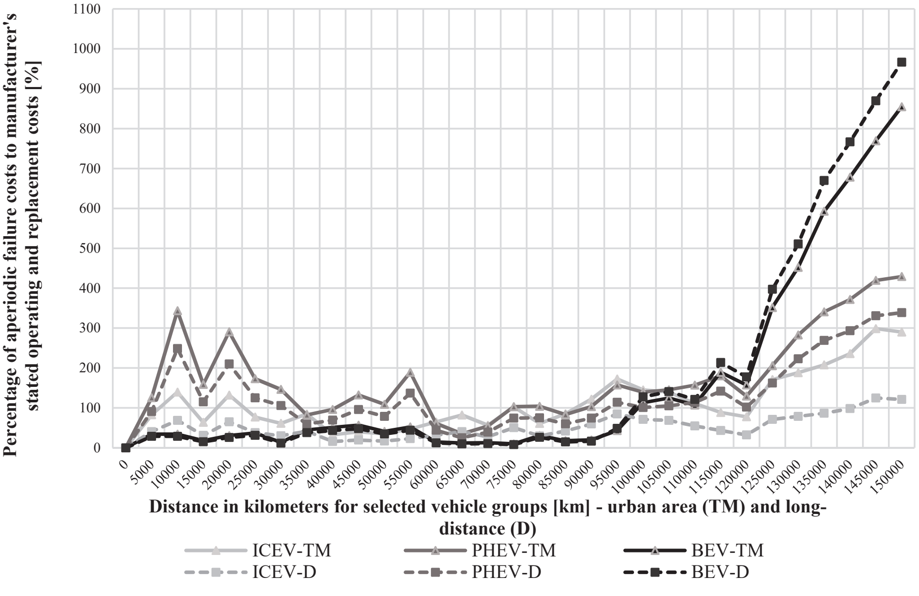

Figure 14. Percentage of aperiodic failures cost in the entire balance of vehicle operating costs resulting from periodic inspections and replacement of components recommended by the manufacturer—4x4 vehicle.

Based on Figures 7–12, it can be concluded that the occurrence of aperiodic failures after covering certain distances depends on the vehicle body type. In all cases, the BEV drive showed the lowest percentage of aperiodic shortcomings in the overall failure balance. The PHEV drive was the worst. ICEVs showed a high frequency of aperiodic failures after a distance of 100,000 km. Therefore, it can be concluded that the PHEV drive is the worst with regard to this evaluation criterion. The frequency of aperiodic failures, in this case, is the result of the dual-drive, which consists of an electric motor and an internal combustion engine, as well as many of the additional components in the energy management system. All this contributes to a large number of failures in the initial period of vehicle operation and after the distance of 80,000 km. It should be mentioned that even a high percentage of these failures in the overall balance does not have to translate into a reduced range and deterioration of the overall efficiency of a given drive system. This directly influences the economy of a given drive system. The relation is verified in Figures 13 and 14. The study covered two extreme body systems for high-class limousines and a 4x4 vehicle. Higher class limousines (Figure 11) are characterized by a low percentage of aperiodic failures throughout their life cycle compared to other types of vehicle bodies—regardless of the drive system used (ICEV, PHEV, BEV). For this type of body, many failures occur in the initial period of operation, and such failures are mainly associated with the comfort and safety systems. This does not translate into the loss of the drive unit efficiency.

Unfortunately, the cost of removing such failures is also high, although it is still much less than for other body types. In 4x4 vehicles, the frequency of aperiodic failures after a distance of around 80,000 km is at an average level, i.e., 1% to 5%. Their percentage significantly increases beyond this mileage, even over 24% from 90 to 110,000 km. After this distance, the rate of failures decreases, but it is still very high. In this system, the losses are most often associated with the drivetrain or the drivetrain in combination with the four-wheel drive, which significantly worsens the economy of these vehicles, especially with the PHEV drive.

In most cases, the failure frequency is the highest for cars moving in city traffic. It is related to the high frequency of braking and accelerating and the poor condition of the road surface. All this translates into a greater frequency of aperiodic failures in the suspension and steering systems.

3.2. Proportion of Aperiodic Failure Costs in the Entire Vehicle Balance by Body Type and Speed Profile

Based on Figures 13 and 14, it can be concluded that indicators of aperiodic operation incidents are high due to the number of failures. After taking their costs into account, it is possible to assess their impact on the vehicle's economy. As shown in Figures 13 and 14, the prices of aperiodic failures attributable to PHEVs and ICEVs are much higher than for BEVs in the initial period of operation up to about 50,000 km. Nevertheless, these costs are relatively acceptable to users. They occur mainly due to construction errors and minor glitches in the electronic equipment.

During further operation above 50,000 km, in terms of operating costs, the share of this type of failure as part of the total number of operational and maintenance failures decreases. The cost of aperiodic losses is much higher after driving a distance of about 100,000 km. It increases several times compared to the cost of essential operation provided by the manufacturer for all drive types. It can be seen that the costs of aperiodic failures in BEVs after 120,000 km increase dramatically. They are larger than those for PHEVs, despite a much smaller number of random failures. This is mainly related to the maintenance of the primary and auxiliary batteries and the cost of their replacement. On this basis, it can be said that despite an insignificant number of failures in BEVs after driving a distance of 120,000 km, their repair cost is strongly related to their nature. The difference between the price of aperiodic losses in PHEVs and BEVs is related to the higher-rated capacities of the primary batteries in BEVs. After the batteries lose their full power, their purchase or regeneration cost is very high.

In the case of both body types of ICEVs (4x4 drive and high-class limousine), the cost of replacing components as compared to PHEV and BEV drive systems is the lowest despite a much larger number of aperiodic failures of the ICEV drive. The nature of failures is also closely related to the speed profile and the area of operation. In the case of BEVs, the vehicle's long-distance operation contributes to a faster loss of the efficiency of the primary batteries as a result of their deep discharge. In a city mode, failures related to the power unit and the driveline are much more frequent and depend on operating conditions. Based on the analysis, considering the current infrastructure and operating costs and the frequency of aperiodic failures in PHEV and BEV drives, ICEVs are unrivaled in their operating costs. BEVs are promising, but so far, the cost of battery replacement is too high and determines the overall economy of the vehicle. Since their range is limited, PHEVs perform well in cities, but their dual drivetrain worsens their operating costs compared to ICEVs.

4. Discussion and Conclusions

The adopted method of examining the engine energy balance allows assessing the measurable benefits generated by the massive use of electric vehicles (EV) in comparison to conventional combustion engines and other alternative vehicle propulsion instruments. The presented model, based on the gray system theory (GST) to assess the impact of drive unit energy balance regarding economic and environmental parameters, and the adjustment of infrastructure to specific drive units in use, can be applied in complex multiple-parameter stochastic analyses. The model can be used to verify decisions on selecting electric vehicles (BEVs), plug-in hybrids (PHEVs), and combustion engine vehicles (ICEVs). As shown by the extensive experimental mobility study for ICEVs, PHEVs, and BEVs, the impact of aperiodic failures of the economic operation of a given drive system is huge. It is closely related to the nature of the speed profile, and it mainly affects drive system operating conditions and energy consumption, regardless of the solution used.

The introduction of a given electromobility system depends on economic factors. This indicates that the currently developed infrastructure and well-established production technology adversely influence the development of mass electromobility despite the findings of ICEVs operation and the energy balance analysis of the individual drive units. The results suggest that all vehicle technologies will play an essential role in transforming a sustainable mobility system.

Using discrete selection behavioral mix models and taking into account hidden variables, mainly the energy balance of the engine, it is also possible to determine the impact of various alternatives on potential vehicle demand (EV). It can be concluded that the engine power does not have much influence on the market for electric vehicles, since primary factors include their range and the availability of charging infrastructure, and the operating cost in comparison with ICEVs. The research conducted based on the adopted models has shown a large role of the drive system energy balance for electric vehicles (BEV), plug-in hybrids (PHEV), and internal combustion vehicles (ICEV) on the implementation of specific concepts in a given area.

Aperiodic phenomena during the operation of selected drive systems in motor vehicles, and environmental and infrastructural factors, determine the application of a given electromobility concept during the transition period. The impact of aperiodic phenomena on the suitability of a given drive system is significant. The high frequency of such phenomena worsens the economic justification for electric vehicles in comparison to conventional solutions. It is estimated that this impact may exceed 10% of the total energy balance for PHEVs and more than 7% for BEVs due to additional failures in the drivetrain and energy supply mechanisms. To a large extent, awareness of the potential benefits of using a given power system can be a decisive factor that adds to the demand.

The abovementioned models predict that the impact of aperiodic failures on the development of electromobility systems in a given area may contribute to an increase in demand for electric vehicles and improvement of infrastructure during the adaptation period.

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Abbreviations

$P_{powerICEV}$	the power of the internal combustion engine to overcome the resistance to motion of the ICEV vehicle:
$P_{powerPHEV}$	the power of the combustion engine and electric engine to overcome resistance to motion for PHEV vehicles,
$P_{powerBEV}$	electric power necessary to overcome resistance to motion for BEVs,
P_{nICEV}	total force on the driving wheels of the ICEV [N],
P_{nPHEV}	total force on the drive wheels of the PHEV [N],
P_{nBEV}	total force on the driving wheels of the BEV [N],
C_w^*	average drag coefficient considering the lateral airflow,
C_T	tangential resistance coefficient,
ρ	air density [kg/m^3],
V_∞	the resultant velocity of inflow [m/s],
V_{Rmob}	vehicle speed [m/s],
V_{win}	the speed of air inflow [m/s],
W_L	air resistance [N],
P_{pC}	frontal (roundabout) surface [m^2],
η_{UNIC}	total efficiency of the drive system components with the internal combustion engine,
η_{PNIC}	total efficiency of components of the drive train with an internal combustion engine,
η_{UNEE}	total efficiency of the drive system components with an electric motor,
η_{PNEE}	total efficiency of components of the drive train with an electric motor,
η_{CHB+C}	total efficiency of charging batteries and capacitors,
η_{RE}	total efficiency of braking energy recovery,
η_{UK}	total efficiency of the steering system components,
P_{OD}	driving resistance power [W],
P_{EE}	the power of the electric vehicle drive [W],
P_{RE}	the power to recover energy from decelerated (braking) motion [W],
P_{CH-EE}	electric machine braking power [W]

References

1. Drozdz, W. The development of electromobility in Poland. *Virtual Econ.* **2019**, *2*, 61–69. [CrossRef]
2. Rabe, M.; Streimikiene, D.; Drożdż, W.; Bilan, Y.; Kasperowicz, R. Sustainable regional energy planning: The case of hydro. *Sustain. Dev.* **2020**, *28*, 1652–1662. [CrossRef]
3. Pilecki, B. *Infrastruktura Społeczna i Jej Znaczenie w Rozwoju Regionalnym*; Wydawnictwo Naukowe Uniwersytetu Szczecińskiego: Szczecin, Poland, 2019; pp. 79–85.
4. Lewicki, W. The case study of the impact of the costs of operational repairs of cars on the development of electromobility in Poland. *Arch. Automot. Eng.* **2017**, *78*, 107–116.
5. Drożdż, W.; Dowejko, J. *Electromobility in Selected National Economies Electromobility as a Megatrend of Contemporary Economy*; PWN: Warszawa, Poland, 2021; pp. 44–46.
6. Barkenbus, J. Our electric automotive future: CO$_2$ savings through a disruptive technology. *Policy Soc.* **2009**, *27*, 399–410. [CrossRef]
7. Devloo, T.; Leemput, N.; Member, G.S.; Roy Geth, F.; Driesen, J.; Member, S. Component Improvements in the Electrification of Passenger Vehicles Drivetrains. In Proceedings of the 2013 IEEE Transportation Electrification Conference and Expo (ITEC), Detroit, MI, USA, 16–19 June 2013.
8. Drożdż, W.; Miśkiewicz, R.; Pokrzywniak, J.; Elżanowski, F. *Urban Electromobility in the Context of Industry 4.0*; Adam Marszałek: Torun, Poland, 2019; pp. 48–56.

9. Chrenko, D.; Gan, S.; Gutenkunst, C.; Kriesten, R.; Moyne, L.L. Novel Classification of Control Strategies for Hybrid Electric Vehicles. In Proceedings of the 2015 IEEE Vehicle Power Propulsion Conference, Montreal, QC, Canada, 19–22 October 2015; pp. 1–6.
10. Liu, T.; Wang, B.; Yang, C. Online Markov Chain-based energy management for a hybrid tracked vehicle with speedy Q-learning. *Energy* **2018**, *160*, 544–555. [CrossRef]
11. Zhang, P.; Yan, F.; Du, C. A comprehensive analysis of energy management strategies for hybrid electric vehicles based on bibliometrics. *Renew. Sustain. Energy Rev.* **2015**, *48*, 88–104. [CrossRef]
12. Moura, S.J.; Fathy, H.K.; Callaway, D.S.; Stein, J.L. A Stochastic Optimal Control Approach for Power Management in Plug-In Hybrid Electric Vehicles. *IEEE Trans. Control Syst. Technol.* **2011**, *19*, 545–555. [CrossRef]
13. Wang, H.; Huang, Y.; Khajepour, A.; He, H.; Cao, D. A novel energy management for hybrid off-road vehicles without future driving cycles as a priori. *Energy* **2007**, *133*, 929–940. [CrossRef]
14. Katrašnik, T. Hybridization of powertrain and downsizing of IC engine—A way to reduce fuel consumption and pollutant emissions—Part 1. *Energy Convers. Manag.* **2007**, *48*, 1411–1423. [CrossRef]
15. Petris, C.D.; Giglio, V.; Police, G.; Police, G. Can Hybrid Vehicles Reduce the Pollutant Emission in Urban Environments? *SAE Tech. Paper* **1993**, 930046. [CrossRef]
16. Demirdöven, N.; Deutch, J. Hybrid cars now, fuel cell cars later. *Science* **2004**, *305*, 974–976. [CrossRef]
17. Wróblewski, P. Technology for Obtaining Asymmetries of Stereometric Shapes of the Sealing Rings Sliding Surfaces for Selected Anti-Wear Coatings. In Proceedings of the SAE Powertrains, Fuels & Lubricants Meeting, Krakow, Poland, 22–24 September 2020. [CrossRef]
18. Wróblewski, P.; Iskra, A. Problems of Reducing Friction Losses of a Piston-Ring-Cylinder Configuration in a Combustion Piston Engine with an Increased Isochoric Pressure Gain. In Proceedings of the SAE Powertrains, Fuels & Lubricants Meeting, Krakow, Poland, 22–24 September 2020. [CrossRef]
19. Wróblewski, P.; Iskra, A. Geometry of shape of profiles of the sliding surface of ring seals in the aspect of friction losses and oil film parameters. *Combust. Engines* **2016**, *167*, 24–38. [CrossRef]
20. Wróblewski, P. Effect of asymmetric elliptical shapes of the sealing ring sliding surface on the main parameters of the oil film. VII International Congress on Combustion Engines. *Combust. Engines* **2017**, *168*, 84–93. [CrossRef]
21. Wróblewski, P. The effect of the distribution of variable characteristics determining the asymmetry of the sealing rings sliding surfaces on the values of friction loss coefficients and other selected parameters of oil film. *Combus. Engines* **2017**, *171*, 107–116. [CrossRef]
22. Ericsson, E. Variability in urban driving patterns. *Transp. Res. Part D* **2000**, *5*, 337–354. [CrossRef]
23. Wirasingha, S.G.; Schofield, N.; Emadi, A. Plug-in hybrid electric vehicle developments in the US: Trends, barriers, and economic feasibility. In Proceedings of the 2008 IEEE Vehicle Power Propulsion Conference, Harbin, China, 3–5 September 2008; pp. 1–8.
24. Ericsson, E. Independent driving pattern factors and their influence on fuel-use and exhaust emission factors. *Transp. Res. Part D* **2001**, *6*, 325–345. [CrossRef]
25. Wirasingha, S.G.; Emadi, A. Classification and Review of Control Strategies for Plug-In Hybrid Electric Vehicles. *IEEE Trans. Veh. Technol.* **2011**, *60*, 111–122. [CrossRef]
26. Khan, M.; Kockelma, K.M. Predicting the market potential of plug-in electric vehicles using multiday GPS data. *Energy Policy* **2012**, *46*, 225–233. [CrossRef]
27. Gong, Q.; Li, Y.; Peng, Z.R. Trip Based Power Management of Plug-in Hybrid Electric Vehicle with Two-Scale Dynamic Programming. In Proceedings of the IEEE Vehicle Power and Propulsion Conference, Arlington, TX, USA, 9–12 September 2007; pp. 12–19.
28. Mehar, S.; Senouci, S.M.; Remy, G. EV-planning: Electric vehicle itinerary planning. In Proceedings of the Smart Communications in Network Technologies (SaCoNeT), 2013 International Conference, Paris, France, 17–19 June 2013; pp. 1–5.
29. Larsson, V.; Mårdh, L.J.; Egardt, B.; Karlsson, S. Commuter Route Optimized Energy Management of Hybrid Electric Vehicles. *IEEE Trans. Intell. Transp. Syst.* **2014**, *15*, 1145–1154. [CrossRef]
30. Karden, E.; Ploumen, S.; Fricke, B.; Miller, T.; Snyder, K. Energy storage devices for future hybrid electric vehicles. *J. Power Sources* **2007**, *168*, 2–11. [CrossRef]
31. Li, M.; Xu, H.; Li, W.; Liu, Y.; Li, F.; Hu, Y.; Liu, L. The structure and control method of hybrid power source for electric vehicle. *Energy* **2016**, *112*, 1273–1285. [CrossRef]
32. Lee, S.; Kim, J. Implementation methodology of powertrain for series-hybrid military vehicles applications equipped with hybrid energy storage. *Energy* **2017**, *120*, 229–240. [CrossRef]
33. Borhan, H.; Vahidi, A.; Phillips, A.M.; Kuang, M.L.; Kolmanovsky, I.V.; Cairano, S.D. MPC-Based Energy Management of a Power-Split Hybrid Electric Vehicle. *IEEE Trans. Control Syst. Technol.* **2012**, *20*, 593–603. [CrossRef]
34. Du, J.; Chen, J.; Song, Z.; Gao, M.; Ouyang, M. Design method of a power management strategy for variable battery capacities range-extended electric vehicles to improve energy efficiency and cost-effectiveness. *Energy* **2017**, *121*, 32–42. [CrossRef]
35. Shen, P.; Zhao, Z.; Zhan, X.; Li, J. Particle swarm optimization of driving torque demand decision based on fuel economy for plug-in hybrid electric vehicle. *Energy* **2017**, *123*, 89–107. [CrossRef]
36. Vinot, E.; Trigui, R. Optimal energy management of HEVs with hybrid storage system. *Energy Convers. Manag.* **2013**, *76*, 437–452. [CrossRef]

37. Shen, P.; Zhiguo, Z.; Xiaowen, Z.; Jingwei, L.; Iuyi, G. Optimal energy management strategy for a plug-in hybrid electric commercial vehicle based on velocity prediction. *Energy* **2018**, *155*, 838–852. [CrossRef]
38. Birrell, S.; Taylor, J.; McGordon, A.; Son, J.; Jennings, P. Analysis of three independent real-world driving studies: A data driven and expert analysis approach to determining parameters affecting fuel economy. *Transp. Res. Part D* **2014**, *33*, 74–86. [CrossRef]
39. Pasaoglu, G.; Fiorello, D.; Martino, A.; Scarcella, G.; Alemanno, A.; Zubaryeva, C.; Thiel, C. European Commission. Joint Research Centre. Institute for Energy and Transport. In *Driving and Parking Patterns of European Car Drivers: A Mobility Survey*; Publications Office of the European Union: Brussels, Belgium, 2012; ISBN 9789279277399.
40. Iglesias-Émbil, M.; Valero, A.; Ortego, A.; Villacampa, M.; Vilaró, J.; Villalba, G. Raw material use in a battery electric car—A thermodynamic rarity assessment. *Resour. Conserv. Recycl.* **2020**, *158*, 104820. [CrossRef]
41. Sanguinetti, A.; Kurani, K.; Davies, J. The many reasons your mileage may vary: Toward a unifying typology of eco-driving behaviors. *Transp. Res. Part D Transp. Environ.* **2017**, *52*, 73–84. [CrossRef]
42. Armoogum, J.; Bouffard-Savary, É.; Caenen, Y.; Couderc, C.; Courel, J.; Delisle, F.; Duprat, P.; Fouin, L.; François, D.; Gascon, M.-O. *La Mobilité des Français, Panorama Issu de l'Enquête Nationale Transports et Déplacements 2008*; Ministère de l'écologie: Paris, France, 2010.
43. Asus, Z.; Chrenko, D.; Aglzim, E.H.; Kéromnès, A.; Moyne, L.L. Simple method of estimating consumption of internal combustion engine for hybrid application. In Proceedings of the 2012 IEEE Transportation Electrification Conference and Expo, ITEC 2012, Dearborn, MI, USA, 18–20 June 2012; IEEE: New York, NY, USA, 2012; pp. 1–6, ISBN 978-1-4673-1408-4.
44. Chrenko, D.; Garcia Diez, I.; Moyne, L.L. Artificial Driving cycles for the evaluation of energetic needs for electric vehicles. In Proceedings of the iTEC, Dearborn, IL, USA, 17–20 June 2012; pp. 18–20.
45. Horrein, L.; Bouscayrol, A.; Cheng, Y.; Fassi, M.E. Dynamical and quasi-static multi-physical models of a diesel internal combustion engine using Energetic Macroscopic Representation. *Energy Convers. Manag.* **2015**, *91*, 280–291. [CrossRef]
46. Caposi, A.; Myers, M. *Systems for All*; Imperial College Press: London, UK, 2001; p. 375.
47. Li, G.-D.; Yamaguchi, D.; Nagai, M. A GM(1,1)–Markov chain combined model with an application to predict the number of Chinese international airlines. *Technol. Forecast. Soc. Chang.* **2007**, *74*, 1465–1481. [CrossRef]
48. Li, G.-D.; Yamaguchi, D.; Nagai, M. Prediction of relative dynamic elasticity modulus by extending grey system theory. *Meas. Sci. Technol.* **2007**, *18*, 827–834. [CrossRef]
49. Liu, J.; Qiao, J.-Z. A grey rough set model for evaluation and selection of software cost estimation methods. *Grey Syst. Theory Appl.* **2014**, *4*, 3–12. [CrossRef]
50. Liu, S.F.; Dang, Y.G.; Li, B.J.; Li, X.; Wang, L. Computational analysis on the periodic contribution of technological advances in Henan Province. *J. Henan Agric. Univ.* **1998**, *32*, 203–207.
51. Liu, S.F. Grey forecast of drought and inundation in Henan Province. *J. Grey Syst.* **1994**, *6*, 279–288.
52. Liu, S.F.; Lin, Y. *Grey System—Theory and Applications*; Springer: Berlin, Germany, 2010; p. 379.
53. Fontaras, G.; Dilara, P. The evolution of European passenger car characteristics 2000–2010 and its effects on real-world CO2 emissions and CO_2 reduction policy. *Energy Policy* **2012**, *49*, 719–730. [CrossRef]
54. Macharis, C.; van Hoeck, E.; Pekin, E.; van Lier, T. A decision analysis framework for intermodal transport: Comparing fuel price increases and the internal is ation of external costs. *Transport. Res. Part A Policy Practice* **2010**, *44*, 550–561. [CrossRef]
55. Kayacan, E.; Ulutas, B.; Kaynak, O. Grey system theory-based models in time series prediction. *Expert Syst. Appl.* **2010**, *37*, 1784–1789. [CrossRef]
56. Lin, Z.; Zhang, Q.; Liu, H. Parameters optimization of GM(1,1) model based on artificial fish swarm algorithm. *Grey Syst. Theory Appl.* **2012**, *2*, 166–177. [CrossRef]
57. Yao Albert, W.L.; Chi, S.C. Analysis and design of a Taguchi–Grey based electricity demand predictor for energy management systems. *Energy Convers. Manag.* **2004**, *45*, 1205–1217.
58. Trivedi, H.V.; Singh, K.J. Application of grey system theory in the development of a runoff prediction model. *Biosyst. Eng.* **2005**, *92*, 521–526. [CrossRef]
59. Deng, J.L. Control problems of grey systems. *Syst. Control Lett.* **1982**, *5*, 288–294.
60. Guo, R. Repairable system modelling via grey differential equations. *J. Grey Syst.* **2005**, *8*, 69–91.
61. Lin, C.T.; Yang, S.Y. Forecast of the output value of Taiwan's optoelectronics industry using the grey forecasting model. *Technol. Forecast. Soc. Chang.* **2003**, *70*, 177–186. [CrossRef]
62. Sijing, C.; Guangxu, T.; Hualin, G. Grey system theory applied to rock mechanics. *Geomech. Abstr.* **1993**, *30*, 473–478.
63. Lim, D.; Anthony, P.; Mun, H.C. Maximizing bidder's profit in online auctions using grey system theory's predictor agent. *Grey Syst. Theory Appl.* **2012**, *2*, 105–128. [CrossRef]
64. Dang, L.; Song, B. Analysis of the income elasticity of the consumer demand of Chinese rural residents and prediction of its trend. *Grey Syst. Theory Appl.* **2012**, *2*, 148–156.
65. Pantopian, N.H.; Larsen, J. Unsupervised condition detection in large diesel engines. In Proceedings of the IEEE Workshop on Neural Networks, Toulouse, France, 22–25 August 1999.
66. Cempel, C. Innovative developments in systems condition monitoring. *Key Eng. Mater.* **1999**, *167–168*, 172–188. [CrossRef]
67. Tumer, I.Y.; Huff, E.M. Principal component analysis of tri-axial vibration data from helicopter transmission. In Proceedings of the 56th Meeting of the Society of Machine Failure Prevention Technology, Virginia Beach, VI, USA, 15–19 April 2002.

68. Gui, L.; Wu, X. KPCA based multisensor data fusion for the machine fault diagnosis. In Proceedings of the ICME06, Chengdu, China, 15–18 October 2006; pp. 342–352.
69. Cempel, C.; Natke, H.G.; Yao, J.P.T. Symptom reliability and hazard for systems condition monitoring. *Mech. Syst. Signal Process.* **2000**, *14*, 495–505. [CrossRef]
70. Liu, C.; Gao, Y.; Liu, L. Toward safe rapid battery charging: Design optimal fast charging strategies thorough a physics-based model considering lithium plating. *Int. J. Energy Res.* **2021**, *45*, 2303–2320. [CrossRef]
71. Liu, L.; Zhu, M. Modeling of SEI Layer Growth and Electrochemical Impedance Spectroscopy Response using a Thermal-Electrochemical Model of Li-ion Batteries. *ECS Meet. Abstr.* **2014**, *61*, 43–58. [CrossRef]
72. Liu, C.; Liu, L. Optimizing Battery Design for Fast Charge through a Genetic Algorithm Based Multi-Objective Optimization Framework. *ECS Meet. Abstr.* **2017**, *77*, 257–270. [CrossRef]
73. Liu, L.; Guan, P. Phase-Field Modeling of Solid Electrolyte Interphase (SEI) Evolution: Considering Cracking and Dissolution during Battery Cycling. *ECS Meet. Abstr.* **2019**, *89*, 101–109. [CrossRef]
74. Jiang, K.; Liu, X.; Lou, G.; Wen, Z.; Liu, L. Parameter sensitivity analysis and cathode structure optimization of a non-aqueous Li-O_2 battery model. *J. Power Sources* **2020**, *451*, 227821. [CrossRef]
75. Liu, S.; Liu, X.; Dou, R.; Zhou, W.; Wen, Z.; Liu, L. Experimental and simulation study on thermal characteristics of 18,650 lithium-iron-phosphate battery with and without spot-welding tabs. *Appl. Therm. Eng.* **2020**, *166*, 114648. [CrossRef]
76. Mu, W.; Liu, X.; Wen, Z.; Liu, L. Numercial simulation of the factors affecting the growth of lithium dendrites. *J. Energy Storage* **2019**, *26*, 100921. [CrossRef]
77. O'Malley, R.; Liu, L.; Depcik, C. Comparative study of various cathodes for lithium ion batteries using an enhanced Peukert capacity model. *J. Power Sources* **2018**, *396*, 621–631. [CrossRef]
78. Cempel, C. Generalized singular value decomposition in multidimensional condition monitoring of machines-A proposal of comparative diagnostics. *Mech. Syst. Signal Process.* **2009**, *23*, 701–711. [CrossRef]

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Varying the Energy Mix in the EU-28 and in Poland as a Step towards Sustainable Development

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Abstract: The demand for clean energy is a key global issue requiring global ideas to be implemented through local action. This is particularly important in Poland's energy transition, since the country produces energy mainly from conventional sources, i.e., coal, gas, and crude oil. Adverse climate change caused by high emissions of the economy based on the combustion of hydrocarbons as well as the growing public awareness have made it necessary to look for new environmentally friendly energy sources. The aim of the paper is to demonstrate that the use of alternative energy sources, biomass in particular, is compatible with sustainable development policy. Eight indicators for the EU-28 and for Poland were analysed in order to verify the progress in modifying the energy mix between 2010 and 2018 in the context of implementing Sustainable Development Goals (SDGs). The analysis showed that both in the EU-28 and in Poland, the aggregated indicator taking into account the positive and negative change in the values of individual indicators improved between 2010 and 2018. In the EU-28, this indicator is higher (180.1) than in Poland (152.3). The lower value for Poland is mainly due to the fact that the main source of energy in Poland remains hard coal and lignite. However, the noticeable increase in recent years in the share of energy from renewable sources, biomass included, allows us to look with hope to a rapidly growing indicator measuring progress towards a sustainable development goal, and to improving environmental standards.

Keywords: sustainable development; climate and energy policy; indicators; renewable energy; biomass

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1. Introduction

Adverse climate change caused by carbon dioxide emissions and the burning of fossil fuels has been a major global economic, ecological, and social problem for several decades. Developing global economies need electricity and heat as well as the security of its supply while in parallel maintaining the principles of sustainable development [1]. This is the main goal of energy policy and environmental policy in European Union (EU) countries, including Poland. Sustainable energy management is undoubtedly associated with an increased share of renewable energy sources that ensure energy security, diversification of energy supply, and improve the quality of the environment and the life of local communities [2,3].

The European Union's consistent policy on limiting carbon dioxide emissions has forced the Member States to take various measures. This has resulted in the development of a low-carbon power sector. These low-carbon sources include wind power, solar power, geothermal power, tidal power, hydropower, and biomass power. The use of renewable energy sources brings many benefits, contributes to reducing the emission of harmful substances into the air, and enables the creation of new jobs. Furthermore, increasing the share of renewable energy sources in the energy mix contributes to increased energy security, reduces dependence on imported energy carriers, and saves fossil resources.

The issues related to modifying the structure of sources from which energy is produced, and the necessity to look for new and environmentally friendly energy sources in the context of sustainable development have been discussed in numerous publications.

This particularly applies to countries where energy is obtained mainly from conventional sources, e.g., China, Turkey, and EU countries, including Poland. A very interesting thing is the comparison of the state of sustainable development of the energy sector in the European Union countries and in China [4]. The analysis of the work shows that China lags behind the EU countries in terms of sustainability of the energy sector, but the country made very good progress in the analysed period 2005–2016. The research also investigated the relationship between renewable energy consumption and economic growth for the EU-28 between 1995 and 2015 over a longer time horizon [5]. The research shows that the use of renewable energy sources in the EU-28 is the only way to reduce environmental pollution. The European Union is the undisputed leader in introducing the idea of sustainable economy [1]. Practically all EU-28 countries pursue a policy of increasing electric power capacity from renewable sources [6]. Moreover, candidate countries for European Union membership, such as Turkey, have to attach increasing importance to sustainable development. The research for determining the renewable energy perspective in Turkey used the energy indicators for sustainable development, which were introduced by the International Atomic Energy Agency in 2005 [7]. Growing social awareness and increasingly restrictive climate strategies adopted by the EU make it necessary to change the structure of energy generation in Poland as well. The use of conventional energy sources should be limited and replaced by RES [3]. There is a clear process of gradual transformation from a coal-based economy to an economy using green, low-carbon technologies that meet social needs, ensure energy diversification, energy security not only on a local scale, but also on a regional scale and even in the long-term perspective [2].

During the preparation of the bibliography review, we did not find results of scientific research on estimating the dynamics of changes in the structure of energy production in the context of achieving sustainable development goals, and this paper makes such an attempt for the EU-28 countries and for Poland.

The actual implementation of the sustainable development strategy consists in harmonising economic, environmental, and social criteria and treating the natural environment as an entity that evolves and is subject to change (in most cases anthropogenic change) [8–10].

The World Commission on Environment and Development [8] defines sustainable development as: “Development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. From the very beginning, environmental considerations have been studied in conjunction with human activities, i.e., social, cultural, ethical, economic, and technological aspects [11,12]. Since then, our understanding of the concept of sustainable development has evolved significantly [13].

In 2015, the United Nations (UN) General Assembly formally adopted “The 2030 Agenda for Sustainable Development”, providing a shared blueprint for “peace and prosperity for people and the planet, now and into the future” [14]. As part of this agreement, all UN member states agreed on sustainable development goals that could be used to measure progress towards the main goal of sustainable development.

There are currently 17 Sustainable Development Goals (SDGs), including 169 targets, and as many as 232 sustainable development indicators [15]; the range of goals and indicators is constantly updated and redesigned.

Sustainable development indicators are an information and diagnostic tool that facilitates the assessment and management of the social, economic, and environmental spheres on a local, regional, and national scale. Many scholars emphasise the need for indicators, pointing to elements arising from the definition of sustainable development, namely long-term effects, recognition of the needs of future generations, and identification of relationships between economic, social, and environmental issues [8,11,13].

Different methods are used to assess progress towards the SDGs. Quantitative assessment of the 17 SDGs involves the formulation of appropriate targets and indicators to monitor final success, and the collection of comprehensive and reliable data [16,17]. At this stage, the selection and assessment of the relevance of indicators are crucial [1,18]. There is no single universally accepted data source representing each of the 17 SDGs. In the absence of such data, it is difficult to select an appropriate indicator or group of indicators for each goal and to access reliable data for that indicator or group of indicators [19]. Selecting any one indicator or combination of indicators from a range of available indicators reflecting the performance of single SDGs is problematic, and any analysis of the selected indicator will only reflect a particular aspect of the broader SDG.

A very important issue in the analyses of progress towards a selected SDG is a parallel consideration of interactions in the achievement of other SDGs. This aspect was highlighted by Barbier E.B and Burgess J. C. [13,20], who measured the change in well-being for no poverty improvement (SDG1) taking into account interactions with other sustainable development goals.

A growing number of studies have attempted to develop an analytical framework for the formal analysis of possible trade-offs and complementarities in achieving various sustainable development goals to support decision making. Multicriteria analysis methods are used to assess and priorities the SDGs [21] in the context of parameterizing low carbon energy sources [7].

To evaluate progress towards sustainable development, the Human Development Index (HDI) is also used [22]. In order to create a full sustainable HDI that reflects the state and process of achieving sustainable development while taking into account environmental aspects, the authors extended the basic three-dimensional HDI (health, education, standard of living) with a fourth component: Environmental.

The research objective of this paper is to answer the question of whether obtaining energy from low-carbon sources (biomass in particular) is an appropriate solution in the energy policy of the EU and of Poland, and whether it is consistent with sustainable development indicators. In order to achieve this goal, an analysis was carried out of the values of eight selected indicators for the years 2010–2018 for the EU countries and for Poland. A methodology was developed to estimate changes in the values of the indicators in achieving the six sustainable development goals.

The paper is structured as follows. In the Section 2, we describe the assumptions of the energy policy in the EU and in Poland and the changes that have taken place in the share of renewable energy in final energy consumption in the EU countries and in Poland since 2010. Section 3 provides a methodology for measuring progress towards sustainable development goals in the context of energy diversification. We describe representative indicators for individual pillars of sustainable development. Using these indicators, Section 4 provides a quantitative assessment of the current progress between 2010 and 2018 in achieving the Sustainable Development Goals for the EU-28 and for Poland. We conclude our paper by discussing the results of our research and their implications for the country's environmental and energy policies.

2. Assumptions of the Energy Policy

2.1. The Climate and Energy Policy of the European Union

The main goal of this policy is to counteract climate changes. The document "An Energy Policy for Europe" [23] specifies the EU objectives:

- reduction of greenhouse gases (GHG) emissions in developed countries by 30% until 2020 (compared to the 1990 level) and reduction of global emissions by 50% until 2050 (including the reduction of emissions in industrialized countries by 60–80%), to reduce global warming to 2 °C;
- domestic reduction of greenhouse gases emissions by at least 20% when compared to the 1990 levels;
- increase of the share of renewable energy in the total energy balance of the European Union, from the current level of less than 7% to 20% until 2020, and at least a 10% share of biofuels (the objectives after 2020 will be analysed in the light of technological progress, and the contribution of each Member State to achieving the EU goals must take into account the diverse conditions and different starting points in different countries);

- implementation of a strategic plan in the field of energy technologies which will lower the cost of clean energy (what is meant here are initially renewable energy sources, and in 2050 hydrogen energy, nuclear power, and fourth generation nuclear fusion power) coupled with increasing the energy efficiency of buildings, appliances, equipment, industrial processes, and systems of transport;
- development of an EU framework for nuclear energy, subject to the most stringent safety standards, including nuclear waste management and decommissioning of nuclear facilities;
- pursuing an active, common European Union foreign policy in the field of energy.
- nowadays, in terms of reduction of GHGs emissions, the action plan sets the goals:
- reduction of domestic GHGs emissions by 80% until 2050 when compared with emissions in 1990 (in all EU Member States);
- program of obligatory reduction of GHGs emissions in the subsequent years: 25% in 2020, 40% in 2030, 60% in 2040, 80% in 2050.

More widespread utilization of low-emission technologies is emphasized in particular. In terms of energy generation, using energy from renewable sources and other low-emission solutions will be promoted. Strong support for renewable energy sources is reflected in its enormous share in the gross final energy consumption: Approx. 75% in 2050, with a 97% share of renewable energy sources in electricity production.

Regarding the energy supply sector, member states are obliged to: (a) Adopt national plans to ensure high-efficiency local heating and cooling; (b) adopt licensing schemes to guarantee that the installations will be located in the vicinity of heat receiving points and that all new electricity generating installations (as well as existing installations undergoing substantial renovation) will be equipped with highly efficient cogeneration units.

2.2. Energy Policy of Poland

Poland is now faced with the task of developing a long-term energy policy for decades to come, a strategy capable of reconciling the security of power supplies as well as effective economic processes, ensuring adequate standards of environmental protection.

For decades, the Polish economy has relied heavily on utilizing abundant resources of hard and brown coal. The document adopted by the Council of Ministers on 10 November 2009: "Poland Energy Policy until 2030" stipulates that in order to ensure energy security for the state, coal shall remain in use as the main source of fuel for the power and heat industries [24]. However, the extraction and combustion of this raw material to utilize the energy stored within it poses a number of problems in terms of environmental protection.

Each passing year sees the establishment of more and more stringent EU standards and regulations—also resulting from international agreements. As an EU member state, Poland is obliged to take subsequent steps to bring the goal of achieving a sustainable, low-emission economy closer each year. It is also one of the conditions of the Accession Treaty [25], and the basis of the EU Climate and Energy Package that was adopted on 23 April 2009 [26]. The strong emphasis placed on cutting down CO_2 emissions resulting from EU climate and energy policy may lead to technological and economic deterioration in the Polish coal industry, as well as damaging the Polish economy in general. Poland will not be able to meet the objectives stipulated in the Kyoto Protocols without detriment to its national economy. The only thing that can be done is to work towards reducing the scope of economic losses, estimating them, and finding sources of their compensation.

However, in accordance with the Charter of the United Nations and the principles of international law, "the States have the sovereign right to exploit their own resources pursuant to their own environmental and developmental policies, and the responsibility to ensure that activities within their jurisdiction or control do not cause damage to the environment of other States or of areas beyond the limits of national jurisdiction" [27].

2.3. Energy from Renewable Sources

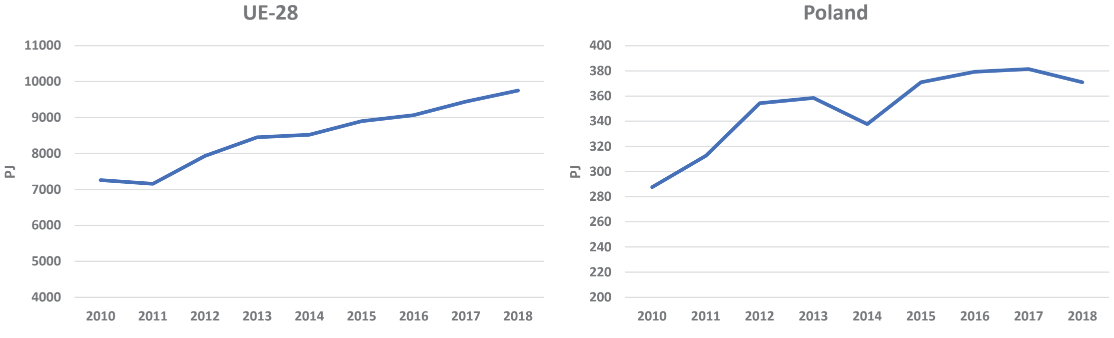
Energy from renewable sources means energy from natural processes, energy produced from non-fossil energy sources. The reserves from these sources complement each other in natural processes, which makes it possible to consider them as inexhaustible ones [28]. The European Green Deal [29], which provides guidance for a sustainable eco-friendly transformation, plans that by 2050 Europe will become the world's first climate-neutral continent.

With energy consumption forecast to continue to grow, the energy sector needs to be reoriented in such a way as to cover demand and minimize the adverse impact on the climate. The use of energy from renewable sources has a number of benefits, including the reduction of greenhouse gas emissions, diversification of energy supply, and independence from fossil fuel supply. The development of renewable energy sources ensures increased employment in the green technology sector [30].

Between 2010 and 2018, total primary energy generation in most EU-28, also in Poland, decreased by almost 11% from 35100 PJ to 31510 PJ, while in Poland by 8% from 2780 PJ to 2560 PJ [31] (Table 1, Figure 1).

Table 1. Total primary energy generation in EU-28 and in Poland [31].

Specification	2010	2018	2010	2018	2010	2018
	Total Primary Energy Generation				Share of Renewables in Total Primary Energy Generation (%)	
	Total (PJ)		Renewable Energy Sources (PJ)			
Poland	2784	2559	288	371	10.3	14.5
EU-28	35,103	31,510	7261	9749	20.7	30.9



(**a**) (**b**)

Figure 1. Total primary energy generation of renewables in EU-28 (a) and in Poland (b) (in PJ). Own study, based on [31].

Since the 1990s, Poland has been undergoing significant economic transformations and developing new, renewable energy sources. The generation of this form of energy has shown an upward trend in recent years: From 10.3% in 2010 to 14.5% in 2018. The structure of energy production from renewable sources for Poland results from the development of the existing resources.

In 2018, the amount of primary energy produced from renewable sources in Poland was 371 PJ. It comes from solid biofuels (69.3%), wind energy (12.4%), and liquid biofuels (10.2%) (Figure 2).

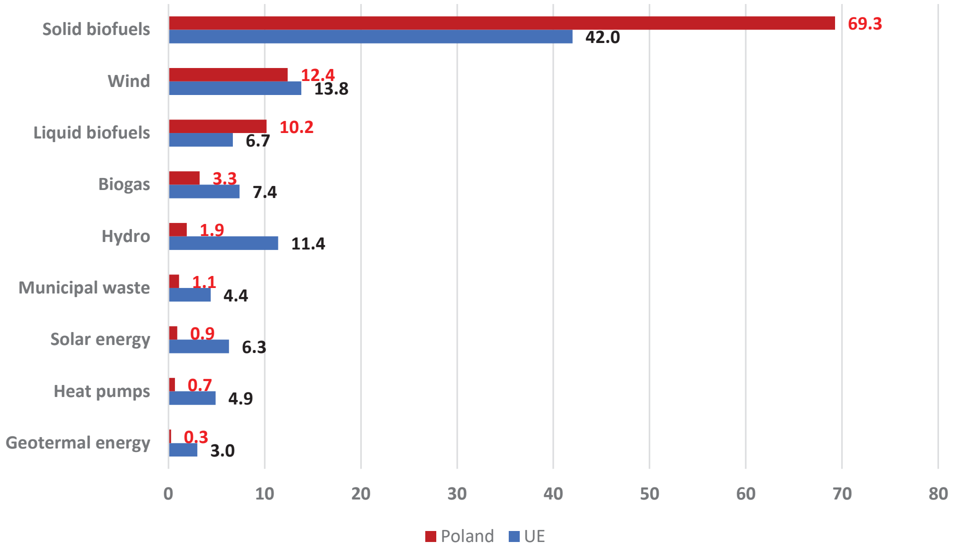


Figure 2. Kinds of energy obtained from renewable sources in Poland and in the EU by carriers in 2018 in relation to 100% primary energy production. Own study, based on [28].

Solid biofuels include organic non-fossil fuels used as a fuel for the production of heat or electricity. Solid biofuel includes firewood (wood chips, briquettes, pellets and forestry waste, shavings, sawdust), energy crops (fast-growing trees, dicotyledonous plants, perennial grasses, cereals grown for energy purposes), and organic residues from agriculture and horticulture (e.g., waste from horticulture, animal faeces, straw) [28].

3. Purpose and Research Methods

The following article has several objectives. First, we develop an analytical framework to describe changes in the value of indicators in achieving the six SDGs. We analyse the value of eight indicators between 2010 and 2018 for EU countries and Poland. We base this approach on standard methods for measuring the indicators, and then assess whether the analysed groups (EU, Poland) make progress in implementing SDGs. We used representative indicators for each goal we had selected. The selection of indicators was dictated by the following criteria:

- The indicator should show everyday life, not just an idea (regional social policy);
- achieving the indicator is possible in a moderately prosperous country (Poland);
- achieving the indicator shows how, in small steps, a great goal can be achieved (regional economic policy);
- achieving the indicator has a measurable impact on improving the condition of the environment (regional environmental policy).

We are aware of how problematic it is to choose any one indicator from a number of indicators reflecting the implementation of individual sustainable development goals. The analysis of a selected indicator reflects one specific aspect of a broader sustainable development goal. Nevertheless, we decided to choose these very indicators, which are achieved directly or indirectly in energy policy, particularly in renewable energy. Our criterion for selecting biomass was the fact that this alternative energy carrier is the most widely used in the world, EU, and Poland.

The research objective is to answer the question of whether the production of energy from biomass is compatible with the sustainable development indicators adopted by the UN Statistical Commission in 2016 [32]. Moreover, the purpose of the study is to show that when implementing the global idea of sustainable development, the right solutions are specific solutions included in the regional ecological, social, and economic policy. As emphasised by Udo and Pawłowski, "From a global public policy perspective, it is posited that sustainable development can be used as a goal for local and global governance." [11].

The research was conducted using the following methods: Examination of documents, examination of individual cases, analysis, and logical construction. The research technique consisted of observation and analysis of documents, and in the past, of sociometric techniques.

3.1. The Analysis of the Implementation of the Selected Indicators of the Social, Economic, and Environmental Pillars by the Biomass-Based Power Industry

3.1.1. Implementation of Social Pillar Indicators

Indicator: The exposure of urban population to the excessive effects of particulate matter PM10 (domain: Public health) is shown by the annual weighted average concentrations of PM10 at urban background stations located in agglomerations. Particulate matter is a mixture of very small solid and liquid particles, composed of organic and inorganic compounds. Despite actions taken to reduce PM10, exceeding the standards is one of the most important air quality issues in Poland. Out of 46 zones subject to air quality assessment in Poland in terms of average 24-h PM10 pollution, exceedances of the admissible level were found in 38 zones. In most zones the limit values for PM10 and PM2.5, and for benzo(a)pyrene are exceeded [33].

Biomass contains on average four times more oxygen compared to thermal coal and twice less carbon, but also less sulphur, nitrogen, and ash (on average 5 to 10 times less depending on the type of biomass). Moreover, it is characterised by a high volatile matter content (65–80%) and high reactivity that determine the need to use appropriate technical solutions guaranteeing its energy-efficient processing. The consequence is a higher proportion of emitted PM10 and PM2.5 particles, however, biomass fly ash contains significantly less metal atoms (Ti, Al, Fe) in the elemental composition than coal fly ash [24]. On the other hand, when burning biomass, much more charcoal is released into the atmosphere than when burning conventional fuel [34,35].

Indicator: The long-term unemployment rate (domain: Access to the labour market) is calculated as the share of the number of unemployed persons looking for a job for 12 months or more in the population of unemployed persons. Since Poland's accession to the EU, the share of the unemployed looking for a job for 12 months or more among the active population has been systematically decreasing [36]. In 2018, this share in Poland was lower than the average for EU countries (Table 2).

Table 2. Long-term unemployment in EU and Poland [31].

Long-Term Unemployment (%)			
EU-28		**Poland**	
2010	2018	2010	2018
42.9	44.7	37.2	26.9

Around 40% of Poland's population is made up of people living in rural areas. The most important real problems of the Polish countryside and agriculture are high unemployment, registered and hidden, low level of income limiting the demand for non-agricultural goods and services, and the employment of rural household members in the grey market [37]. The low level of activity of the rural community and the relatively low level of education exacerbated by the lack of vocational background complicate the situation on the labour market.

It is difficult to improve the financial situation of rural inhabitants by increasing agricultural production. An increase in the standard of living is possible if new sources of income are provided, in other words, new jobs are created in the non-agricultural sector. One of the proposals is to grow energy crops [38,39].

The well-being of the population is reflected in the availability of energy services. Energy supply is just as important for rural development as technical and social infrastructure. The production in rural areas of food and raw materials of agricultural origin requires an uninterrupted supply of energy. However, integrated and reliable power grids in Polish rural areas still await investment. The power industry in rural areas should develop towards diversification of energy sources and increased energy efficiency. Polish rural areas need access to modern renewable energy sources, which will increase security of supply.

Research on social and environmental factors of agricultural development was carried out several times in 2002–2004 in different regions of Poland, Ukraine, Belgium, and France. In 2005–2017, in the Małopolska region (Poland), empirical research was carried out on a plantation of fast-growing willow trees whose cultivation and energetic use influenced the economic activation of rural residents. The research confirmed that investments in RES, resulting from smart use of diversified sources for energy production, provide economic benefits for consumers [40–45].

Moreover, in 2016, a sociological survey was conducted among 177 inhabitants of rural areas of the Pomeranian region (Poland) [46]. The sustainable development of rural areas is associated with the possibility of using crop residues and livestock residues. The majority of respondents (70%) considered that energy from renewable sources has a significant impact on ensuring electricity supply (energy security). Energy from RES increases the thermal comfort of farmers' households, supports sources of lighting and water heating. More than three quarters of the respondents considered energy from RES to be a guarantee of social welfare. They claim that renewable energy has a positive impact on improving the economic situation of the inhabitants of the regions with a low level of development, since those are often rich in renewable energy sources.

In order to create new jobs, schemes are needed to facilitate the creation of companies employing more people. In addition to simple workshops, medium-sized companies, which are most susceptible to technical progress, should also be established. The Polish rural landscape is dominated by one-man operations or at most very small firms [39,42]. Increasing the production of biomass for energy needs is an important element of multifunctional rural development and has a positive impact on farmers' income.

The International Renewable Energy Agency (IRENA) has published statistics on global employment in the renewable energy sector. In 2017, the sector created more than 500,000 new jobs worldwide, and the total number of people employed in the sector exceeded 10 million. In 2012, the employment in the RES sector amounted to 7.14 million people, and in 2017 to 10 million [47]. An increase of 38% was recorded over 4 years. Poland was one of the European leaders of employment on the RES market (4th rank behind Germany, Great Britain, and France). More than 30,000 jobs have been created in biofuel-related sectors (8th rank in the world) and more than 10,000 jobs in wind energy (14th rank in the world).

Indicator: Household electricity consumption per capita (domain: Consumption patterns) represents the quantitative households consumption of electricity per capita. Household electricity consumption is the most important indicator for monitoring consumption. In Poland, a systematic increase in electricity consumption in households was observed in the years 2002–2018, resulting from, but not limited to, the widespread use of power equipment. Average electricity consumption in 2018 increased by 14% compared to 2002 and amounted to 2.9 GJ per capita [48]. In the structure of energy consumption in Polish households, solid fuels—mainly hard coal (which is the exception in the European Union) and firewood—are the most important. They were most often used for space heating (by 45% of households). These fuels were also used to heat water (25% of households).

Despite the fact that energy produced from biomass is able to meet the energy demand, the share of biomass consumption in the energy sector is decreasing. In the first quarter of

2017, the production of electricity from this source decreased by 30%. The reason for this was a reduction in the prices of green certificates, i.e., the basic support scheme.

3.1.2. Implementation of Economic Pillar Indicators

Indicator: Eco-innovation (domain: Innovation) is based on 16 indices from five areas: Three of them directly relate to eco-innovation. These are: Inputs, activities, and results. The other two groups of indices are the effects of introducing eco-innovation: Environmental and socio-economic effects. Innovation is strongly linked to sustainable development. Eco-innovation slows down the exploitation and use of natural resources and the release of harmful substances into the environment.

An example of an eco-innovation process is the use of biomass in energy production. By using biomass in the power industry, we prevent waste of food surpluses, manage production waste from the forestry and agricultural industries, and dispose of municipal waste [33]. However, Poland is one of the least eco-innovative countries in the European Union: In 2018, our country was ranked only 26th among 28 countries in the community [27].

Indicator: Percentage of the total utilised agricultural area of organic farms in the total utilised agricultural area (domain: Production patterns). An organic farm is certified by an authorised certification body or is in the process of converting to organic farming methods. Organic farming is a rapidly growing sector of conventional agriculture. It reduces the burden on the environment, contributing to the improvement of ecosystems. In organic farming, production and consumption take place in a closed loop. The requirement is to use at least 80% of the yield for processing, feeding the animals or transferring to other farms or sale [33]. According to the data of the Ministry of Agriculture, the years 2003–2013 saw a boom in organic farming in Poland, and the number of these farms increased 11 times (from 2300 to almost 27,000). In 2018, only just over 20,500 farms were operating in organic farming [49].

3.1.3. Implementation of Environmental Pillar Indicators

Indicator: Greenhouse gas emissions in CO_2 equivalent (domain: Climate change) determine total annual man-made greenhouse gas emissions in relation to base year 1988, in accordance with the Kyoto Protocol, excluding emissions from international aviation and maritime transport, land use change, and forestry. The Kyoto basket encompasses the following six greenhouse gases: Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and F-gases: Hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6). Greenhouse gas emissions are defined as the aggregated emission of the six greenhouse gases listed, weighted by global warming potentials on a 1988 basis equal to 100 [50]. Carbon dioxide equivalent shall be 1 Mg or an amount of another greenhouse gas equivalent to 1 Mg of carbon dioxide calculated using global warming potentials, e.g., one ton of methane corresponds to 25 tons of CO_2. The combustion of fossil fuels causes 70% of global CO_2 emissions [51]. Poland has a 10% share in CO_2 emissions in the European Community.

The year 1988 has been adopted for Poland as the base year for accounting for the fulfilment of the commitments of the United Nations Framework Convention on Climate Change (UNFCCC) and its Kyoto Protocol [33]. The Kyoto agreement is considered to be one of the first steps of the international community towards formalised action for effective environmental protection.

After the ratification of the Kyoto Agreement, Poland adopted several documents and implemented new regulations on energy development and climate protection, such as Polish Energy Policy until 2030 [24], the National Energy and Climate Plan 2021–2030 [52], Polish Energy Policy until 2040 [53], and Polish Energy Policy until 2050 [54].

The main objective of energy policy is to ensure the country's energy security, to increase the competitiveness of the economy and its energy efficiency, and to protect the environment from the effects of the power sector. The share of RES in the national energy balance is estimated at 15% (the target is 20%). It is also predicted that by 2050, dispersed photovoltaics and wind power plants will have become the leaders of RES.

Regulations that have been introduced relate both to industrial activities, including power industry, and to energy consumers (energy savings in individual farms, change of heating system, e.g., phasing out of solid fuel boilers and furnaces, connection to the district heating, gas boilers, low-emission solid fuel boilers, electric heating). With the implementation of the anti-smog resolution [55], 43,600 boilers and furnaces using solid fuels were phased out in the Małopolska region in 2013–2018, of which over 22,000 in Krakow. Renewable energy sources have been installed in more than 13,000 facilities (mostly solar collectors and photovoltaic panels). As a result of these activities, air pollution emission rates have significantly decreased in both large cities and small towns. In the last decade, dust emissions in the Małopolska Province were reduced by 70%. The improvement of air quality in the Małopolska region and Krakow is observed in the heating period from October to March. Average PM10 concentration between the winter season 2014–2015 and 2019–2020 dropped by 30% in the Małopolska region and by 45% in Krakow [56].

In order to increase the effectiveness of activities carried out as part of the implementation of the Air Protection Programme in Poland, financial mechanisms have been created to increase the effectiveness of the implementation of low emission reduction programmes, the inventory of low emission sources, and the functioning of local heat generation.

The commitment to reduce greenhouse gas emissions in the first period (2008–2012) was more than met by Poland (29% reduction) [57]. This has been achieved through the use of alternative energy sources, including biomass, which has a great advantage: When burned, CO_2 emissions are equivalent to the amount of CO_2 taken up during photosynthesis.

The source of pollutant emissions is also urban transport, which in large cities is responsible for up to 40% of pollutant emissions. The modernisation of the transport fleet is a great challenge for the city authorities. The focus was on low-emission and zero-emission transport. The Act of 11 January 2018 on e-mobility and alternative fuels [58] informs about the minimum share of electric vehicles in the fleets of official vehicles of state administration bodies and local government units: 10% from 1 January 2022; 20% from 1 January 2023. The document also mentions the share of zero-emission buses in the fleet of vehicles used: At least 5% from 1 January 2021; 10% from 1 January 2023; 20% from 1 January 2025.

As stated in the Act, it obliges local governments to have 10% of zero-emission vehicles from 2022, but the Krakow authorities took up this challenge much earlier. The Municipal Transport Company (MPK) in Krakow has purchased modern trams and buses: 364 of them meet the Euro 6 emission standard. The MPK fleet is equipped with 34 hybrid buses and 28 electric buses (a further 50 electric vehicles will be purchased in 2021). The share of zero-emission vehicles will be 14%. At the end of 2019, the city of Krakow had 39 electric vehicle charging stations.

Since the costs of technology for reducing traffic smog are very high, it is necessary to switch to alternative means of transport. The public bicycle has been included in the public transport system. Currently, the network of bicycle routes in Krakow is 235 km long. 65 km of contraflow bike lanes have been created on 270 one-way roads. Over the last seven years, 8000 bicycle racks and several dozen stands have been installed in Krakow. The inhabitants of Krakow have bicycle shelters and self-service bicycle repair points at their disposal.

Other pro-environmental solutions in large cities consist in implementing "green roofs" which have a large share, for example, in the filtration of air pollution, in reducing the discharge of rainwater, in mitigating the effect of "urban heat island". The modelling of the environmental impact of green roofs in the Opole agglomeration (southern Poland) is dealt with by Suszanowicz and Kolasa-Więcek [59,60]. They confirm the potential of green roofs in sequestering CO_2, NO_x, SO_2, and heavy metals in plants and soils. They emphasise that in Polish conditions, the use of green roofs in cities contributes to the protection of biodiversity threatened by urban trends. Nevertheless, the implementation of green roof systems involve high maintenance costs, significantly higher than in the case of conventional roofing.

A very important element of the pro-ecological regional policy of the city of Krakow is the information and education campaign under the slogan #EKOrEVOLUTION. The campaign consists of four spheres of the city's green activities related to the seasons: Winter–clean energy, autumn–traffic and transport, spring–greenery, summer–water. The campaign makes residents aware of how much everyone can do for the environment and what the city's pro-environmental actions are [61,62].

The need to diversify the electricity generation structure will contribute to reducing the role of coal in the energy balance. According to the proposal presented in the Polish Energy Policy until 2040 [53], the share of coal in electricity production by 2040 will be reduced to 28% in the case of a gradual (sustainable) increase in the prices of CO_2 emission allowances. In the case of the scenario of high prices of CO_2 emission allowances the projected share of coal may drop even to 11% (Figure 3). At the same time, it was announced that all mines using thermal coal would be closed by 2049. During the last summit of the European Council (December 2020), the heads of governments of the European Union member states adopted a new CO_2 reduction target for 2030. The Council decided that this target will be at least 55% compared to 1990. The EU's adoption of a new level of emission reduction may lead to a sudden increase in the price of emission allowances, even up to EUR 76 per ton of CO_2 [63], and consequently to a rapid dismantling of the Polish mining industry.

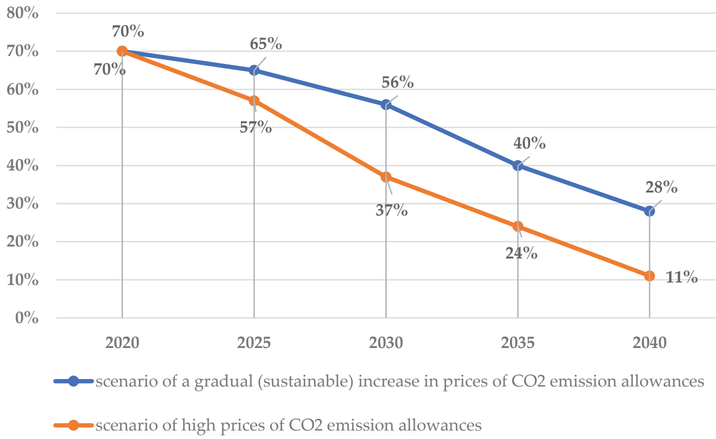


Figure 3. Forecast of the share of coal in electricity production until 2040 according to two scenarios [53].

Indicator: Share of energy from renewable sources in gross final consumption of energy from all sources (domain: Energy). Gross final energy consumption means the use of energy carriers for energy purposes (production of electricity, heat, and cooling) in industry, transport, households, public services, agriculture, forestry, and fisheries, together with losses of electricity and heat during transmission and distribution [64]. Poland as a country is systematically increasing the share of energy from renewable sources (Table 2) both in primary energy generation and in gross final energy consumption. The observed growth is also reflected in the increased diversification of these sources. The share of energy from renewable sources in gross final energy consumption in 2018 was 11.28% (Figure 4). According to the assumptions of the "Energy Policy of Poland until 2040", adopted by the Polish government on 2 February 2021 [65], the share of renewable energy in gross final energy consumption in 2030 will be at least 23%, not less than 32% in the electricity sector, 28% in heating, and 14% in transport.

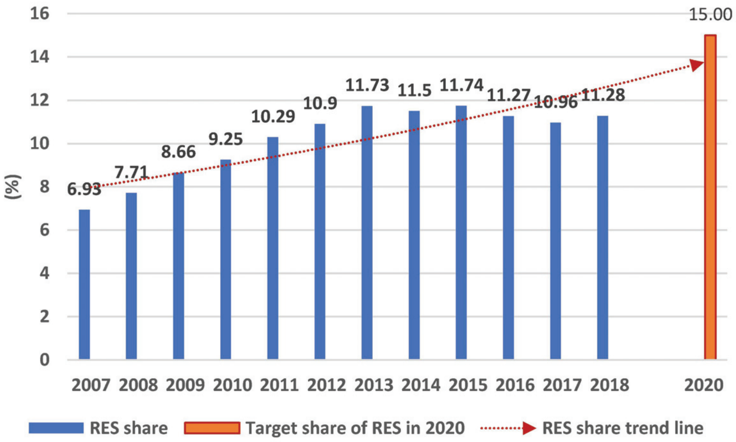


Figure 4. The share of energy from renewable sources in gross final energy consumption in 2018. Own study, based on [31].

The rationale for using this indicator results from the challenges facing Poland in reducing energy intensity of the economy. Solid biofuels occupy a dominant position in Poland in the acquisition and use of energy: In 2018, their share amounted to nearly 70% in the structure of renewable sources (Figure 3). They are mostly used in the heating and cooling sectors. There has been a decrease in the share of wind and water energy. Despite the fact that energy produced from biomass allows to meet the energy demand, the price reduction of green certificates, i.e., the basic support system in the power industry, has resulted in a decrease in the share of biomass consumption.

Indicator: The state of the air quality (domain: Air protection) allows monitoring the progress towards meeting EU air quality standards. Air quality has a significant impact on human living conditions, the condition of ecosystems, as well as processes relating to climate change. The effects of air pollution are particularly felt by the elderly, the sick, and children. Poland is divided into 46 zones where 12 air pollutants are monitored [66]. On the basis of the survey results, a ranking of the zones in terms of human health protection (classes: A, B, C) is prepared. Of all the zones, only one has been defined as class A (no exceedances were found). As many as 38 zones have been classified as class C (exceedance of the limit level plus margin of tolerance or target level).

Polish power plants are supported by alternative fuel coming from biomass, of which millions of tons are burnt each year. Unfortunately, a very large part of it has to be imported. According to the Renewable Energy Institute, by importing biomass the CO2 emission is increased instead of being reduced. Transportation of this raw material means that tons of conventional fuel are burnt by trucks and ships, tons of carbon dioxide are released into the atmosphere [67]. Nevertheless, energy obtained from biomass has a significant positive impact on the implementation of this indicator.

All selected and most important indicators that were used to assess the progress in varying the energy mix in the context of achieving the sustainable development goals are presented in Figure 5.

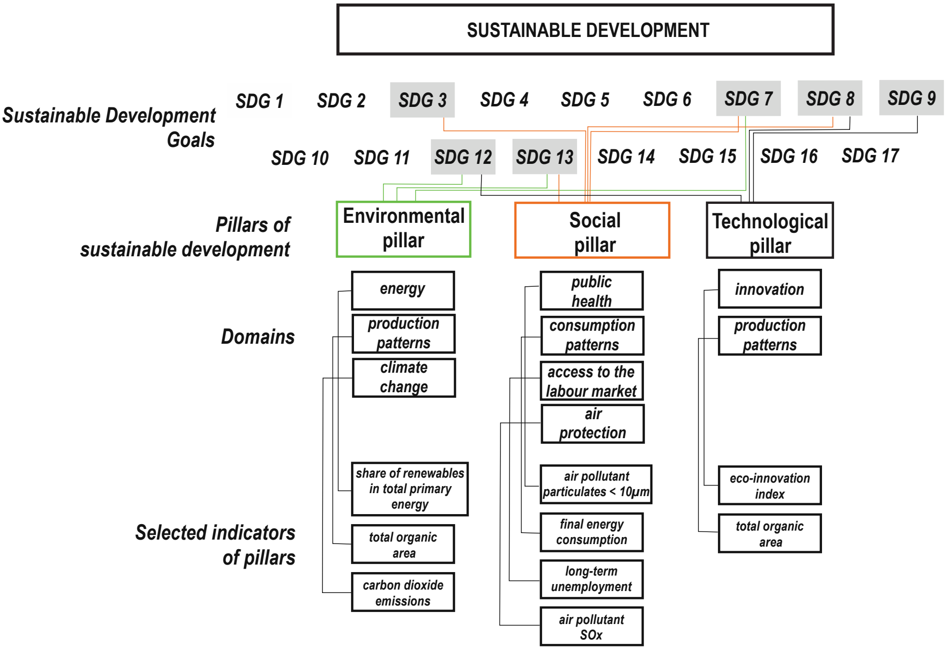


Figure 5. A flow chart showing the pursuit of sustainable development through the implementation of selected indicators in the context of diversification of energy sources. Own study, based on [10]. SDG 1: No poverty, SDG 2: Zero hunger, SDG 3: Good health and well-being, SDG 4: Quality education, SDG 5: Gender equality, SDG 6: Clean water and sanitation, SDG 7: Affordable and clean energy, SDG 8: Decent work and economic growth, SDG 9: Industry, innovation and infrastructure, SDG 10: Reduced inequalities, SDG 11: Sustainable cities and communities, SDG 12: Responsible consumption and production, SDG 13: Climate action, SDG 14: Life below water, SDG 15: Life on land, SDG 16: Peace, justice and strong institutions, SDG 17: Partnerships for the goals.

4. Analysis of Selected SDGs for EU-28 and Poland—Results and Discussion

In order to verify the progress in varying the energy mix in the context of achieving the sustainable development goals, an analysis was carried out of the indicators we had selected for the EU-28 and for Poland. In our analysis, we combine information about the absolute variation in the actual value of the indicators with the percentage change in these values compared to 2010. This allows us to assess whether the sustainable development goal improves or deteriorates while the result of the examined indicator is changed [13].

Table 3 shows the changes in the values of individual indicators in 2010 and 2018.

Figures 6 and 7 illustrate the percentage change in the levels of individual indicators between 2010 and 2018, from the highest increases to the highest decreases, for the EU-28 and Poland, respectively. As described in the research methodology, improving indicators have been given a positive rating and deteriorating indicators a negative rating. Both in the EU-28 and in Poland, the aggregate indicator taking into account positive and negative changes in the values of individual indicators improved between 2010 and 2018.

Table 3. Selected indicators of Sustainable Development Goals (SDG), EU-28 countries, and Poland in 2010–2018. Own study, based on [13,31].

Indicator	EU-28				Poland			
	2010	**2018**	**% Change**	**Outcome**	**2010**	**2018**	**% Change**	**Outcome**
The eco-innovation index	86.0	94.0	9.3	Improving	40.0	59.0	47.5	Improving
Total organic area (mln ha)	10.05	13.4	33.7	Improving	0.65	0.48	−26.1	Declining
Long-term unemployment (%)	42.9	44.7	4.2	Declining	37.2	26.9	−27.7	Improving
Carbon dioxide emissions (Mt)	3922.9	3466.5	−11.6	Improving	323.8	319.5	−1.3	Improving
Final energy consumption in households per capita (kgoe)	643.0	552.0	−14.2	Improving	578.0	508.0	−12.1	Improving
Air pollutant SOx (Mt)	4.1	2.04	−50.3	Improving	0.82	0.50	−38.5	Improving
Air pollutant-particulates < 10 µm (Mt)	2.4	1.99	−15.9	Improving	0.27	0.24	−11.3	Improving
Share of renewables in total primary energy (%)	20.7	30.9	49.3	Improving	10.3	14.5	39.9	Improving
Composite Index			180.1				152.3	

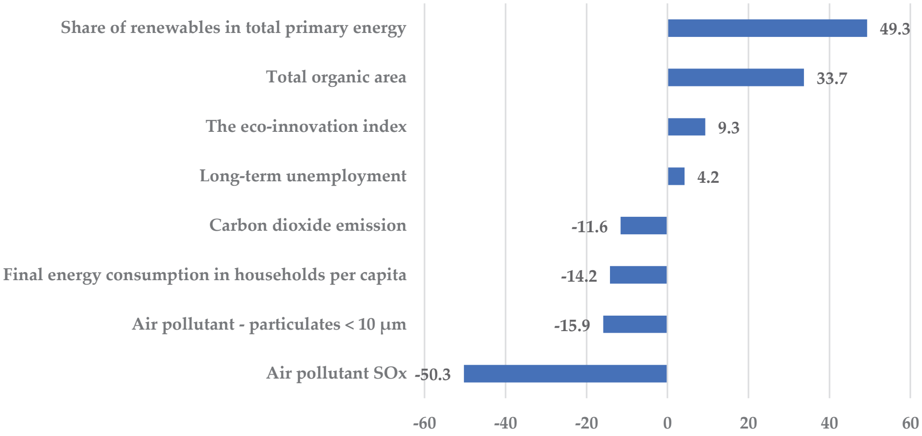


Figure 6. Net change (%) in SDG indicators, EU-28, 2010–2018. Own study, based on [31].

In the EU-28 this indicator is higher (180.1) than in Poland (152.3). This suggests that all the countries concerned are progressing in achieving their sustainable development goals.

In the case of the EU-28, the progress is significant, while in the case of Poland—despite the many positive actions which have been taken to protect the environment in recent years—progress towards the sustainable development goals concerned can be considered moderate. This is mainly due to the fact that the main source of energy in Poland remains hard coal and lignite. However, the noticeable increase in recent years in the share of energy from renewable sources, biomass included, allows us to look forward to a faster increase in the indicators measuring progress towards a sustainable development goal and to improvements in environmental standards.

In the EU-28, the greatest benefits between 2010 and 2018 were recorded in the indicators measuring progress in the environmental pillar, the SDG 7 "Affordable and Clean Energy" in particular. The final energy consumption in households per capita decreases (kgoe): −14.2%), while the share of renewables in total primary energy generation increases: 49.3%. Very good progress is also noted in the indicators for the SDG 13 "Climate Action" DG 3. The greatest improvement is observed in air protection: SOx emission: −50.3%, PM < 10 µm emission: −15.9, CO$_2$ emissions: −11.6%. Indicators on air purity also relate to progress in the social pillar (SDG 3 "Good Health and Well-being").

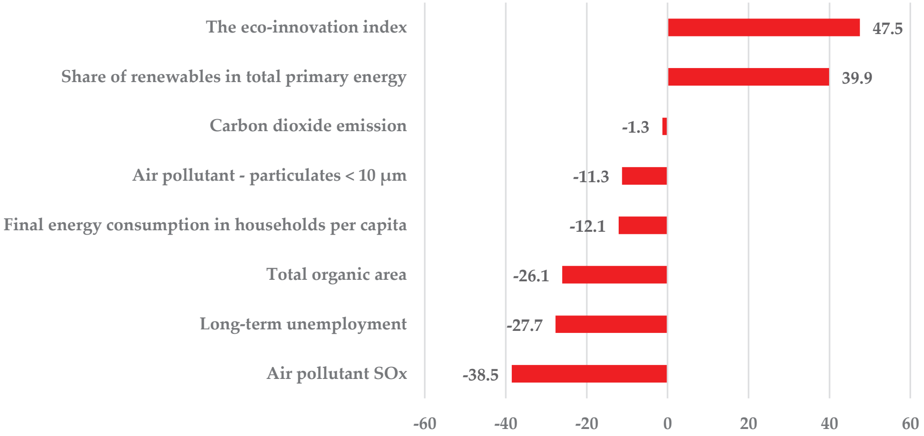


Figure 7. Net change (%) in SDG indicators, Poland, 2010–2018. Own study, based on [31].

It should be noted, however, that the social pillar has seen a significant increase in long-term unemployment in the EU-28: 4.2, the indicator which refers to the SDG 8 "Decent Work and Economic Growth".

In the assessment of the economic pillar, the greatest benefits over the period 2010–2018 were recorded in the indicator measuring the SDG 12 "Responsible Consumption and Production SDG" (total organic area: 33.7%).

A similar pattern of improvement and decrease in SDG indicators between 2010 and 2018 was observed in Poland. An exception is the very large decrease in the share of long-term unemployment (−27.7%) in the population of all the unemployed (social pillar). This is a very good change.

Unfortunately, in the case of SDG 13 "Climate Action", the Polish structure of energy production based on coal results in the analysed indicator "carbon dioxide emission" being decreased by only 1.3%. It is noteworthy that there has been a great deal of progress between 2010 and 2018 when it comes to SDG 9 "Industry, Innovation and Infrastructure". The analysis took into account the eco-innovation index, which shows the country's eco-innovation performance compared to the EU average, and includes 16 sub-indicators from five thematic areas: Eco-innovation inputs, eco-innovation activities, and eco-innovation outputs, as well as environmental outcomes and socio-economic outcomes. Compared to 2010, the value of this indicator has increased by 47.5%.

In the implementation of sustainable development goals in the context of diversification of energy sources, the quantitative assessment of changes in selected SD indicators in 2010–2018, shows a positive trend in both EU-28 and in Poland. The analysis shows that the goals can be achieved by means of various actions. Due to a large share of fossil fuels in energy generation, achieving the goals of the environmental pillar in our country is more difficult than in most of the EU-28 countries. However, the Polish economy is clearly changing positively towards reducing CO_2 emissions and slowing down global warming.

5. Conclusions

The article analyses selected indicators of social, economic, and environmental pillars in the context of biomass energy use. It has been shown that in a situation of a huge ecological crisis in the world, the use of biomass for energy production is in line with global trends in the development of global energy and climate protection. Biomass is the most frequently used unconventional energy source in the world, especially by the third world population, and this is where the chance to improve the environment should be seen.

Why should we go that way? What assumptions of the noble and laudable idea of sustainable development will be achieved? What reflection should accompany us in our daily, continuous use of energy in every area of life?

Sustainable development in the energy sector means finding a non-confrontational relationship between the social, economic, cultural, and natural aspects of energy production technology. Poland has one of the largest potential renewable energy resources in the EU. In order to be able to use it, it is necessary to increase financial outlays on research and technology development and to create a scheme of subsidies for projects. The actions should be modelled on the European Union that has been supporting the development of renewable energy sources for several years.

Attention is paid to the impact of the application of social governance assumptions on the health of society. It is necessary to ensure the conditions for the full combustion of the volatile products emitted from the decomposition of biomass.

The improvement of the economic situation of the inhabitants of rural areas can be sought in additional employment, which is the cultivation of energy crops. The household electricity consumption rate shows that the share of biomass consumption in the power industry is decreasing, which is due to unfavourable support schemes (reduced prices of green certificates). Among the indicators of the economic pillar, eco-innovativeness and production patterns are discussed. It is stressed that eco-innovations slow down the use of natural resources and thus reduce the emission of pollutants to the environment. The use of biomass in energy production is a good example of pro-environmental measures (carbon neutrality). The indicator "production patterns" is illustrated by organic farming where production and consumption take place in a closed loop. The presence of biomass determines the proper functioning of the farm.

To analyse the indicators of the environmental pillar, climate change, the share of renewable energy in final energy consumption, and air protection have been selected. Solid biofuels play an important role in the production and use of energy from renewable sources. The combustion of biomass has a net zero carbon footprint. In order to improve the quality of air, it is necessary to introduce clean combustion technologies that reduce pollutant emissions as well as to promote alternative energy sources such as biomass. The energetic use of biomass can significantly reduce the emission of greenhouse gases at several stages: The emission can be eliminated from the biological processing of biomass, from its storage, and can also be reduced at the transport stage. Through technical progress, this renewable energy source can be gradually integrated into the market.

Taking into account representative indicators, the progress towards the sustainable development goals in the context of diversification of energy sources was estimated. Using these indicators, a quantitative assessment of the current progress between 2010 and 2018 in the EU-28 and in Poland was carried out. Both in the EU-28 and in Poland, the summary indicator taking into account positive and negative changes in the values of individual indicators improves between 2010 and 2018. In the EU-28, this indicator is higher (180.1) than in the case of Poland (152.3). This suggests that all analysed countries are making progress in achieving sustainable development goals. The lower dynamics in the case of Poland results mainly from the fact that the basic source of power generation in Poland remains hard coal and lignite. However, the noticeable increase in recent years in the share of energy from renewable sources, including biomass, allows us to look with hope to a rapidly growing indicators measuring progress towards a Sustainable Development Goal, and to improving environmental standards.

Preserving the natural capital at the current or higher level is possible by putting in place an appropriate environmental and energy policy of the country. The strategy highlights that improved energy efficiency will reduce dependence on energy imports, reduce emissions, and drive jobs and growth, especially in a rural environment [68,69]. The implementation of sustainable development indicators must also be rooted in the social consciousness as environmental education is a factor of fundamental importance for environmental protection and preservation for future generations.

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References

1. Tutak, M.; Brodny, J.; Siwiec, D.; Ulewicz, R.; Bindzár, P. Studying the Level of Sustainable Energy Development of the European Union Countries and Their Similarity Based on the Economic and Demographic Potential. *Energies* **2020**, *13*, 6643. [CrossRef]
2. Pultowicz, A. Przesłanki rozwoju rynku odnawialnych źródeł energii w Polsce w świetle idei zrównoważonego rozwoju. *Probl. Sustain. Dev.* **2009**, *4*, 109–115.
3. Brodny, J.; Tutak, M.; Saki, S.A. Forecasting the Structure of Energy Production from Renewable Energy Sources and Biofuels in Poland. *Energies* **2020**, *13*, 2539. [CrossRef]
4. Su, W.; Zhang, D.; Zhang, C.; Streimikiene, D. Sustainability assessment of energy sector development in China and European Union. *Sustain. Dev.* **2020**, *28*, 1063–1076. [CrossRef]
5. Akadiria, S.; Ada, A.A.; Akadiria, C.; Alolab, U.V. Renewable energy consumption in EU-28 countries: Policy toward pollution mitigation and economic sustainability. *Energy Policy* **2019**, *132*, 803–810. [CrossRef]
6. Brożyna, J.; Mentel, G.; Ivanová, E.; Sorokin, G. Classification of Renewable Sources of Electricity in the Context of Sustainable Development of the New EU Member States. *Energies* **2019**, *12*, 2271. [CrossRef]
7. Pak, B.K.; Albayrak, E.; Erensal, Y.C. Renewable Energy Perspective for Turkey Using Sustainability Indicators. *Int. J. Comput. Intell. Syst.* **2015**, *8*, 187–197.
8. Barbier, E.B. The concept of sustainable economic development. *Environ. Conserv.* **1987**, *14*, 101–110. [CrossRef]
9. Holmberg, J.; Sandbrook, R. Sustainable development: What is to be done? In *Policies for a Small Planet: From the International Institute for Environment and Development (19–38)*; Holmberg, J., Ed.; Earthscan Publications: London, UK, 1992.
10. United Nations. The Sustainable Development Goals Report. 2020. Available online: https://unstats.un.org/sdgs/report/2020 (accessed on 20 October 2020).
11. Udo, V.; Pawlowski, A. Human Progress towards Equitable Sustainable Development, part II: Empirical Exploration. *Probl. Sustain. Dev.* **2011**, *6*, 33–62.
12. Ahmed, W.; Sarkar, B. Management of next-generation energy using a triple bottom line approach under a supply chain framework. *Resour. Conserv. Recycl.* **2019**, *150*, 4431. [CrossRef]
13. Barbier, E.B.; Burgess, J.C. The sustainable development goals and the systems approach to sustainability. Economics: The Open-Access. *Open-Assess. E J.* **2017**, *11*, 1–23. [CrossRef]
14. United Nations (UN). *Transforming our World: The 2030 Agenda for Sustainable Development*; United Nations: New York, NY, USA, 2015; Available online: https://sustainabledevelopment.un.org/post2015/transformingourworld/publication (accessed on 11 February 2021).
15. Sachs, J.D. From millennium development goals to sustainable development goals. *Lancet* **2012**, *379*, 2206–2211. [CrossRef]
16. Reyers, B.; Smith, S.M.; Erb, K.H.; Scholes, R.J.; Selomane, O. Essential Variables help to focus Sustainable Development Goals monitoring. *Curr. Opin. Environ. Sustain.* **2017**, *26*, 97–105. [CrossRef]
17. Lu, Y.; Nakicenovic, N.; Visback, M.; Stevance, A.S. Five priorities for the UN sustainable development goals. *Nature* **2015**, *520*, 432–433. [CrossRef] [PubMed]
18. Jacob, A. Mind the gap: Analyzing the impact of data gap in millennium development goals' (MDGs) indicators on the progress toward MDGs. *World Dev.* **2017**, *93*, 260–278. [CrossRef]
19. Hák, T.; Janoušková, S.; Moldan, B. Sustainable development goals: A need for relevant indicators. *Ecol. Indic.* **2016**, *60*, 565–573. [CrossRef]
20. Barbier, E.B.; Burgess, J.C. Sustainable development goal indicators: Analyzing trade-offs and complementarities. *World Devel.* **2019**, *122*, 295–305. [CrossRef]
21. Allen, C.; Metternicht, G.; Wiedmann, T. Prioritizing SDG targets: Assessing baselines, gaps and interlinkages. *Sustain. Sci.* **2019**, *14*, 421–438. [CrossRef]
22. Ivanov, A.; Peleah, M. *Sustainable Humand Development Index–A Pragmatic Proposal for Monitoring Sustainability within the Affordable Boundaries*; IARIW Bank of Korea: Seoul, Korea, 2017.
23. Commission of the European Communities. *Green Book. Market Instruments for Environmental and Related Policy*; Commission of the European Communities: Brussels, Belgium, 28 March 2007; Available online: https://ec.europa.eu/taxation_customs/consultations-get-involved/tax-consultations/green-paper-market-based-instruments-environment-related-policy-purposes_en (accessed on 19 October 2020).

24. The Council of Ministers. Poland's Energy Policy until 2030. 10 November 2009. Available online: https://www.google.com/search?client=firefox-b&q=Poland%27s+energy+policy+until+2030.+November+10%2C+2009.+The+Council+of+Ministers (accessed on 24 October 2020). (In Polish).
25. The Accession Treaty of Poland to the EU. 16 April 2003. Available online: https://eur-lex.europa.eu/collection/eu-law/treaties/treaties-accession.html?locale=pl#new-2-30 (accessed on 20 October 2020).
26. The 2020 Climate and Energy Package. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the Promotion of the Use of Energy from Renewable Sources, Amending and Subsequently Repealing Directives 2001/77/WE and 2003/30/WE. Available online: https://eur-lex.europa.eu/legal-content/PL/TXT/?uri=LEGISSUM:2001_8 (accessed on 24 October 2020).
27. United Nations Framework Convention on Climate Change. 9 May 1992. Available online: http://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=wdu19960530238 (accessed on 22 October 2020).
28. Energy from Renewable Sources in 2018. GUS Warszawa 2019. Available online: https://www.google.com/searchclient.firefox-b-d&q16.09Energy+from+renewable+sources+in+2018 (accessed on 21 July 2020).
29. The European Green Deal COM/2019/640. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/uriCOM3A20193A6403AFIN(COM(2019)640 (accessed on 21 June 2020).
30. Dychkovskyi, R.; Tabachenko, M.; Zhadiaieva, K.; Cabana, E. Some aspects of modern vision for geoenergy usage. *E3S Web Confer.* **2019**, *123*, 1010. [CrossRef]
31. Eurostat. 2020. Available online: https://ec.europa.eu/eurostat/data/database (accessed on 5 January 2021).
32. Report of the Inter-Agency and Expert Group on Sustainable Development Goal Indicators (E/CN.3/2016/2/Rev.1). The Report of the UN Statistical Commission. 2016. Available online: https://unstats.un.org/sdgs/iaeg-sdgs/report-iaeg-sdgs (accessed on 20 October 2020).
33. Urbaniec, M. Sustainable development indicators for Poland: Central Statistical Office and Statistical Office in Katowice. *Entrep. Bus. Econ. Rev.* **2015**, *3*, 119–134. (In Polish)
34. Czech, T.; Sobczyk, A.T.; Jaworek, A.; Krupa, A. Comparison of Physical Properties of Fly Ashes from Hard Coal, Lignite and Biomass Combustion. Conference Materials POL-EMIS. 2012, pp. 73–82. Available online: http://www.pzits.not.pl/docs/ksiazki/Pol_%202012/Czech%2073-82.pdf (accessed on 16 July 2020). (In Polish).
35. Zarzycki, G.; Wielgosinski, G. *Technologies and Processes of Air Protection*; Polish Scientific Publishers PWN: Poland, Warsaw, 2018. (In Polish)
36. Economic Activity of the Polish Population. Q4 2017. Information and Statistical Studies. GUS Warsaw 2018. Available online: www.stat.gov.pl (accessed on 22 July 2020). (In Polish)
37. Murawska, A. Factors Differing the Level of Unemployment in Rural Households in Poland. Association of Agricultural and Agribusiness Economists. *Sci. Ann.* **2015**, *17*, 283–289. (In Polish)
38. Wielewska, I. The development of renewable energy sources in rural areas and their impact on the natural environment, in the opinions of agricultural advisors. *Sci. Pap. Wars. Univ. Life Sci. Probl. World Agric.* **2014**, *14*, 186–195. (In Polish)
39. Sobczyk, W.; Kowalska, A. The techniques of producing energy from biomass. *TEKA Comm. Mot. Energetics Agric.* **2012**, *12*, 257–261.
40. Malada, A.; Sobczyk, W. Growing energy crops as a form of activation of rural environments. *Sci. J. Dep. Process Eng. University Opole* **2005**, *2*, 92–98. (In Polish)
41. Sobczyk, W. Yielding basket willow–In the light of research. *Polityka Energetyczna* **2007**, *10*, 547–556. (In Polish)
42. Sobczyk, W. Evaluation of harvest of energetic basket willow. *TEKA Comm. Mot. Energetics Agric.* **2011**, *11*, 343–352.
43. Sobczyk, W. Sustainable development of rural areas. *Probl. Sust. Dev.* **2014**, *9*, 119–126.
44. Sobczyk, W.; Sternik, K.; Sobczyk, E.J.; Noga, H. Yield evaluation of willow fertilized with sewage sludge. *Ann. Set Env. Prot.* **2015**, *17*, 1113–1124.
45. Sobczyk, W. The Use of Biomass for Energy Production. *Int. J. N. Technol. Sci. Eng.* **2016**, *3*, 35–40.
46. Wielewska, I.; Sobczyk, W.; Gliniak, M. Energy from Renewable Sources as Social Welfare in the Opinions of Polish Farmers. *Folia Pomer. Univ. Technol. Stetin. Oeconomica* **2017**, *333*, 91–100. (In Polish) [CrossRef]
47. International Renewable–International Renewable Energy Agency (IRENA). Available online: http://www.irena.org (accessed on 21 June 2020).
48. GUS. Energy Consumption in Households in 2018. 2019. Available online: https://stat.gov.pl/obszary-tematyczne/srodowisko-energia/energia/zuzycie-energii-w-gospodarstwach-domowych-w-2018,12,1.html.pl (accessed on 22 June 2020). (In Polish)
49. The Number of Organic Producers, as at 31 December 2018 in Poland, in the Structure of the Voivodeships and of the Categories of Activity. Available online: https://www.gov.pl/web/ijhars/dane-o-rolnictwie-ekologicznym (accessed on 1 July 2020). (In Polish)
50. Kyoto Protocol. Available online: https://pl.wikipedia.org/wiki/ProtokC3B3C582_Kioto.veaction (accessed on 1 July 2020).
51. Green Projects. Available online: https://www.green-projects.pl/najwieksi-emitenci-co2-niechlubny-ranking (accessed on 20 July 2020). (In Polish).
52. National Energy and Climate Plan for 2021–2030. *Assumptions and Goals as well as Policies and Activities*; Minister of State Assets: Warsaw, Poland, 30 December 2019.

53. Energy Policy for Poland by 2040. Development Strategy for the Fuel and Energy Sector (PEP2040). Ministry of State Assets. Available online: https://www.gov.pl/web/aktywa-panstwowe/zaktualizowany-projekt-polityki-energetycznej-polski-do-2040-r (accessed on 20 October 2020). (In Polish)
54. *Energy Policy for Poland by 2050*; ver. 0.6; The Ministry of Economy: Warsaw, Poland, 2015. (In Polish)
55. Resolution No. XVIII/243/16 of the Council of the Małopolska Province of 15 January 2016 on the introduction of restrictions in the operation of installations in which fuel combustion takes place in the area of the Municipality of Krakow. Available online: http://edziennik.malopolska.uw.gov.pl/ActDetails.aspx?year=2016&poz=812 (accessed on 1 December 2020). (In Polish)
56. Małopolska in a Healthy Atmosphere. Effects of Implementation. Available online: https://powietrze.malopolska.pl/program-ochrony-powietrza/efekty-realizacji (accessed on 20 October 2020). (In Polish).
57. Bezyk, Y.; Sowka, I. *Trends and Forecasts of Emissions of Selected Greenhouse Gases in Europe*; Kotowski, A., Piekarska, K., Kazmierczak, B., Eds.; Interdisciplinary Issues in Engineering and Environmental Protection: Washington, DC, USA, 2015; Volume 6, pp. 22–39. (In Polish)
58. Act of 11 January 2018 on Electromobility and Alternative Fuels. Available online: https://sip.lex.pl/akty-prawne/dzu-dziennik-ustaw/elektromobilnosc-i-paliwa-alternatywne-18683445 (accessed on 13 December 2020). (In Polish).
59. Więcek, K.A.; Suszanowicz, D. Air pollution in European countries and life expectancy–Modelling with the use of neural network. *Air Qual. Atmosph. Health* **2019**, *12*, 1335–1345. [CrossRef]
60. Suszanowicz, D.; Więcek, K.A. The impact of green roofs on the parameters of the environment in urban areas–Review. *Atmosphere* **2019**, *10*, 792. [CrossRef]
61. Walus, M. Proekologiczne Zmiany w Komunikacji Miejskiej. Nowoczesne Tramwaje i Autobusy, Przesiadka na Rowery. 11 December 2020. Available online: https://krakow.wyborcza.pl/krakow/7,44425,26593428,rower-na-trudne-czasy.html?disableRedirects=true (accessed on 12 December 2020). (In Polish).
62. Tonkha, O.; Mehbaliyeva, N.; Nagorniuk, O. Professional adaptation of the future agronomist as a psychological and pedagogical problem. *Educ. Technol. Comput. Sci.* **2019**, *4*, 247–254. [CrossRef]
63. Ceny Praw do Emisji CO2 Ponownie Zaskakują. 20 July 2020. Available online: https://wysokienapiecie.pl/30756-ceny-praw-emisji-co2-ponownie-zaskakuja (accessed on 15 December 2020). (In Polish).
64. Renewable Energy Association: GUS: Increase in the Share of Energy from Renewable Sources in Gross Final Energy Consumption in 2018. Available online: http://seo.org.pl/gus-wzrost-udzialu-energii-ze-zrodel-odnawialnych-w-koncowym-zuzyciu-energii-brutto-w-2018 (accessed on 22 July 2020). (In Polish).
65. Ministry of Climate and Environment. Poland's Energy Policy until 2040. 2 February 2021. Available online: https://www.gov.pl/web/klimat/polityka-energetyczna-polski (accessed on 20 February 2021).
66. Regulation of the Minister of the Environment of 2 August 2012 on Zones Where Air Quality Is Assessed. Available online: http://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp.id=WDU20120000914 (accessed on 23 July 2020). (In Polish)
67. Anteconomics and Anti-Ecology, That Is Energy from Imported Biomass. 23 December 2015. Available online: https://www.salon24.pl/u/energetyka (accessed on 3 July 2020). (In Polish).
68. Pradhan, P.; Costa, L.; Rybski, D.; Lucht, W.; Kropp, J.P. A systematic study of Sustainable Development Goal (SDG) interactions. *Earth's Future* **2017**, *5*, 1169–1179. [CrossRef]
69. Nagornyuk, O.M.; Palapa, N.V.; Temchenko, V.V. The value of material and technical support of organic production technologies for eco-safety of the agrosphere of Ukraine. *Agroecol. J.* **2019**, *4*, 42–49. Available online: http://journalagroeco.org.ua/issue/view/11465/showToc (accessed on 25 July 2020). [CrossRef]

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Determinants of Decarbonisation in the Transformation of the Energy Sector: The Case of Poland

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Abstract: This paper aims to identify the determinants of the decarbonisation processes in Poland within the scope of energy transformation. The purpose of the study is to identify how the public perceives decarbonisation determinants in order to develop a sustainable energy strategy for Poland. The transition of the energy market to low-carbon technology is a policy challenge. Governments must implement policies that are environmentally friendly, cost-effective, but, most of all, socially acceptable. Social acceptance risk plays a significant role in Poland, influencing the decarbonisation process. In Poland's case, the coal share is decreasing, but it is still the most important fuel for electricity production. This process of decarbonisation is a fundamental influence on the transformation of the energy sector in Poland. The social perception of solutions that can be applied was examined. The Polish natural environment is poisoned. Poles suffer from diseases related to the burning of coal for energy production. Societal awareness, how people perceive the government's actions, and what they expect in this regard is crucial.

Keywords: decarbonisation; energy transition; low-carbon technology; energy policy; climate change

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1. Introduction

Poland is not only using coal for much of its energy mix. Poland is also a significant producer of coal. The decarbonisation of the energy sector is therefore, closely linked to the linear reduction of the coal sector. This is also connected to the reduction of employment in the Polish coal mining industry. Our case study for Poland shows that in the past, about fifty per cent of all mining workers, who have left their job, have not moved to other industries and remained unemployed. This phenomenon should be explained, inter alia, by the fact that the level of education of miners is lower than the average on the labour market. This can also be explained by lower wages in sectors other than the mining sector.

Poland faces unique challenges in its energy transition due to the extreme dependence on coal. Nevertheless, many countries are already going through or will undertake the transition to a low-carbon economy [1] The traditional model for development and industrialisation is resource- and energy-intensive, with economic growth accompanied by increasing carbon dioxide (CO_2) emissions [2,3]. Keeping the average global temperature rise below 2 °C will require a drastic reduction in global net greenhouse gas emissions and, ultimately, zero emissions [4]. It is now considered possible to decarbonise economic growth and to achieve deep reductions in greenhouse gas emissions while increasing economic activity and prosperity [5]. Decarbonisation is based on better energy efficiency and the supply of zero-emission clean electricity instead of fossil fuel-derived electricity, where possible [6–8]. The necessary technologies already exist and are becoming increasingly available. There could also be considerable additional benefits, such as cleaner local environments and economic modernization [9–11]. However, making the transition to low-carbon technology is a policy challenge. Governments must implement environmentally friendly, cost-effective, and socially acceptable policies [12,13]. Social acceptance risk plays a significant role in Poland, influencing the decarbonisation process. Social acceptance is essential: we need to ask whether citizens' social acceptability is the same as economic viability, and if it is economically relevant [14–16].

Decarbonization without excluding energy security in the SEE region is a priority of EU foreign and environmental policy. Two strategic and complementary goals that both the EU and SEE countries are pursuing are political factors related to the supply of Russian natural gas and the transition from coal to gas. However, these goals have always undermined the composition of energy mixes, the degree of integration of energy supplies with the EU's energy hubs, the degree of integration of energy markets in the region, and the diversification of existing gas supplies since the late 1990s [17].

Overall, there is a shift away from coal and ultimately also from gas and oil. Decarbonisation fosters further economic growth and more sustainable forms of economic growth and energy transformation in all domestic studies [18].

Decarbonisation will mean the collapse of significant subsets of existing industries, especially fossil. They will be replaced by new initiatives that will bring about new investments, profitable opportunities, and jobs. It could create fear of energy transition. Issues could become sharply defined in regional and timescale terms, leading to severe social difficulties [19,20]. It is therefore necessary to establish how these processes have been perceived socially.

In recent years, numerous programmes have emerged to reduce the economic inequality between countries and overcome the ecological crisis. Wealthy nations must lead by example by drastically reducing fossil fuel consumption, adopting more sober patterns of natural resources consumption, and helping low-income countries to reduce poverty and improve their environmental technologies [21]. However, each of these moves have been vigorously opposed by leading multinational corporations, which have tremendous economic and political power over governments and international financial institutions. A substantial civil action is required to reduce fossil fuel use and switch to renewable energy while reducing inequalities between and within nations and redefining the global economic development model. Our generation's critical question is whether the mass social movement advocating decarbonisation will be the correct one.

The remainder of this paper is organized as follows. The methodology is introduced in Section 2 and a relevant literature review is provided. Section 3 presents the justification. Section 4 includes the results. The discussion and conclusions are presented in Section 5, which ends the paper.

2. Methods

The purpose of this study is to identify the determinants of the decarbonisation processes in Poland. This study also shows the directions enabling the diffusion of knowledge regarding decarbonisation to develop a sustainable energy strategy for Poland.

This study applies methodological triangulation, which consists of combining qualitative and quantitative methods in many ways, according to a new paradigm in management sciences that advocates combining several approaches and methods to manage open epistemological and methodological attitudes. The choice of research methods and techniques was the result of conceptualisation and operationalisation processes. The questionnaire method was used in the study.

The literature review intends to assess current knowledge concerning the role of information, the information needs of enterprises and their stakeholders, the importance of an integrated information system of a business unit, and determining the place of management accounting in this system.

The survey was conducted online and consisted of 12 research questions. An online survey provides many possibilities to present problems, collect answers, and offer respondents flexibility and convenience. In designing the research tool, we initially adopted the previous literature's assumptions, according to which decarbonisation processes are focused on reducing CO_2 emissions. The design of the research tool was based on standardised and verified tools. The research was based on a survey by the Tyndall Centre for Climate Research (Critical Issues in Decarbonising Transport Final Report of the Theme 2 project T2.22, Ian Skinner1, Malcolm Fergusson and Katharina Kröger2, Institute for European Environmental Policy (IEEP); Charlotte Kelly and Abigail Bristow, Institute for Transport Studies (ITS) University of Leeds, 2003). The survey asked two questions, with responses based on the Likert scale. The questions concern fundamental issues with the determinants supporting decarbonisation processes in Poland and the model of decarbonisation (centralism vs. localism) in the scope of the energy transition. The survey included two open-ended questions about the most effective legal solutions to support Poland's decarbonisation processes and the essential determinants supporting them.

The research was conducted between December 2019 and April 2020. The survey included 444 respondents who filled in the questionnaire, of which 46% (205) were men and 54% (239) were women. The following assumptions were made for statistical research. Confidence level shows how sure the researchers can be of the obtained results, the $\alpha = 0.95$ indicates a level of certainty of 95%. Another indicator is the size of the fraction. In this case, when we estimate that a given characteristic occurs in 60% of the population, we assume 0.6. If we do not know this value, we take the value of this indicator as 0.5. Another indicator is the maximum error. It indicates to us what level of correction we should assume. For example, if we create a 0.03% or 3% error and conduct an election poll among supporters of political parties. When analyzing the results, we observe that a given party achieved a score of 20%, then with our assumption of an error of 3%, real support can vary by 3% up or down.

It brings the minimum sample size to 384, for whole population 38 million people in Poland. The primary coarse static division resulting from parity has been retained. The research group's additional structures are in line with the statistics of social, age and geolocation groups of the most interested. It mainly affects the inhabitants of affected regions, such as Silesia.

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The individual activities indicated in the survey are assigned one of the following grades:

1. no impact;
2. very little/negligible impact;
3. neutral;
4. visible impact; and
5. significant impact.

Another question, "What do you think the EU should introduce in terms of solutions and regulations regarding decarbonisation?" concerns solutions the EU should introduce in decarbonisation. It was an open-ended question in that respondents could give a free, subjective answer, or several answers. When asking open-ended questions, we intended to obtain as many attitudes and opinions as possible to analyse the studied phenomenon, including decarbonisation.

The research was exploratory, conducted to determine the nature of the problem, and was not intended to provide conclusive evidence but to understand the issue better [22].

The sampling was focused on respondents dealing with the problem of decarbonisation. Table 1 presents the structure of the sample.

Table 1. Sample characteristics.

Age	No
1961–1981 (Generation X)	122
1982–2000 (Generation Y)	301
2001–Present (Generation Z)	8
1943–1960 (Baby boomers (BB))	13
Place of residence	**No**
City	317
Village	127
Sex	**No**
Male	205
Female	239

Source: Own research.

Among the respondents, most people were aged up to 25, while one-quarter were aged 26–35. The smallest group was comprised of people aged over 35. Such an age distribution can be explained by the fact that the direct survey was performed via mail. As for the respondents' education, almost half of them had higher vocational education and 20% had MBAs.

According to Poovey (p. 84), "there are limits to what the rationalised knowledge epitomised by statistics can do." Qualitative research can draw strong attention to detail, covering both verbal and nonverbal behaviour and uncovering nuances [22] (pp. 454–462).

3. Justification

As we mentioned, this study aims to identify the determinants of decarbonization processes in Poland [23,24]. We believe that our research contributes to the literature because, even though decarbonization has been discussed in both EU and international literature, there is no reference to knowledge-diffusion processes as the causative factors for those changes.

Climate change and environmental degradation pose a threat to Europe and the rest of the world. To meet these challenges, Europe needs a new growth strategy to transform the energy market into a modern, resource-efficient, and competitive economy with the following characteristics [25,26]:

- zero net greenhouse gas emissions by 2050;
- economic growth decoupled from resource consumption; and
- no person or region left behind.

Successful implementation of the EU decarbonisation action plan requires the consideration of technologies, policy concepts, and social aspects, which are closely intertwined. For example, technological solutions are needed for emissions at an acceptable cost from a global perspective. The development of an appropriate policy is necessary to transfer climate policy benefits to the EU macro level and, further, to the local government or even to the consumer level. Markets can adapt by postponing investment until conditions are favourable for decarbonisation. It seems necessary to keep low-carbon subsidies for longer than expected [27,28]. In this sense, the EU hopes that its example will encourage other regions of the world to follow suit. Such a strong drive could develop new industries based on cutting-edge clean and low-carbon technologies, strengthen the EU, and help overcome the economic crisis by initiating the necessary changes for a more sustainable policy. To this end, the EU has set itself the overarching goal of reducing the greenhouse effect by 2050 [29].

In the article, the authors analysed various determinants influencing the decarbonisation of electricity by 2050 from a social point of view. The first determinant to be examined is mining. More than 25 countries, especially in Asia, have revised their fossil fuel subsidies in recent years. However, according to the International Monetary Fund, the cost of these subsidies, including environmental and health damage, amounts to approximately US$5.3 trillion annually. These subsidies distort prices to the detriment of decarbonisation. They harm the environment, curb the spread of greener technologies, and burden national budgets [30,31].

Contrary to popular belief, subsidising fossil fuels is not an effective way to increase competitiveness and help the poor. Instead, according to the World Bank, these subsidies benefit the rich. However, despite the abolition of subsidies, it tends to promote equality, while at the same time increasing the prices of energy and other goods, lowering the purchasing power of lower-income households, and leading to an industrialisation-based energy slowdown. Therefore, the savings obtained by abolishing subsidies must be used to compensate for the loss of income among the poor and strengthen the network's social security [32].

The second determinant is subsidies for local governments (e.g., decommissioning of furnaces), as investments in renewable energy sources are supported by the subsidy system. For this reason, renewable energy is still more expensive than conventional energy. For investment projects in renewable energy sources to provide investors with an appropriate return on the invested capital, the subsidy system must be stable. When the subsidy system is destabilised, investment risk and credit risk increase immeasurably, which may significantly slow down planned investments in the renewable energy system. The system of financial support renewable energy system (RES) should be stabilised to develop green energy.

Poland will follow in the footsteps of other EU countries that subsidise electricity production from wind, solar, biomass, or biogas. In the EU, renewable energy sources are developing. Countries are guaranteed a fixed price for RES (the feed-in tariff system), or energy distributors are obliged to buy securities from producers of green energy (so-called green certificates); thus, compliance is a legal requirement. In both cases, consumers ultimately pay for RES support.

Proconsumer solar photovoltaic development programmes are a crucial element of decarbonisation, related to government policy and bottom-up initiatives. When energy consumers see that they can obtain energy from renewable sources practically for free, the post-renewable energy system stage is likely to continue indefinitely. In this case, the stability of both regulations and planning is necessary. Of course, the pace of abandoning fuel will differ in different sectors. It is one thing to, for example, stop using coal in households; it is quite another to replace a heating system in an energy enterprise [31].

The next determinant, the market capacity, does not directly affect the development of renewable sources. The level of renewable energy system ambition depends on political decisions. However, indirectly, the capacity market will create new possibilities for integrating variable sources in the system. There is a chance that energy storage will develop within the capacity market. Warehouses most often supplement wind installations and store energy when it blows, and the market demand is small. In periods of high market demand for energy, batteries can be discharged and the national energy system can be powered for 4 h. The wind energy storage facility meets the availability requirements as well as conventional installations.

One of the most critical determinants influencing decarbonisation is opening up the EU energy market. In 2018 EU institutions and Member States' governments decided to impose stricter targets on renewable energy regulations. In November 2018, the Commission presented its updated vision for building a low-carbon economy by 2050: "A Clean Planet for all—A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy." The document provides a detailed analysis of the changes needed to achieve the envisaged emission reductions. This vision is more ambitious than the EC's 2011 "Roadmap for moving to a competitive low-carbon economy in 2050": it is not limited to reducing emissions by 80%, outlines the possibility of achieving climate neutrality by 2050. Europe's planned transition to a net-zero economy by 2050 implies the need to change national policies. It is also Poland. The country should formulate a long-term strategy for a low carbon economy including not only electricity generation but also other sectors. [31].

Another element influencing decarbonisation is energy efficiency; one of the drivers of this development is annual electricity production, which increased from 6300 Mt to 11,700 Mt in 1990–2013 [9] (pp. 56–63). Policymakers have introduced restrictions and trading systems (e.g., the European Emissions Trading System) or initiated support schemes for renewable energy (e.g., tariffs).

When it comes to renewable energy sources, irregular supply is a challenge for decarbonisation [32,33]. Complementary technologies that can respond to rapid changes in the supply of renewable energy and provide the necessary flexibility on the supply side include coal or gas plants, biomass plants (which are rarely suitably located), batteries and gas (which are still too expensive), and short-term demand response.

Thus, there is increasing emphasis on long-term demand response measures, such as energy efficiency, which reduces the overall electricity demand that needs to be met. For example, the International Energy Agency calculates that improving energy efficiency reduced carbon emissions by 12.5% between 2000 and 2016 [34] (p. 27).

This study addresses the scientific problem of decarbonisation and changes in diffusion in the practice of that process and attempts to find a solution to it. Many determinants condition the decarbonisation of national economies. It is difficult to assess what kind of determinants play a crucial role in decarbonisation processes in many cases. Schmidt and Weight further observe that, within energy studies, interdisciplinary works are rare: “despite the pre-dominantly socio-economic nature of energy demand, such inter-disciplinary viewpoints–albeit on the rise–are still the minority within energy-related research” [22] (pp. 206–219). That is why the authors have tried to carry out such studies.

The traditional energy market is currently in transition towards a more flexible energy system in where energy production is decentralized and based on renewable energy sources, technical platforms are smart and multiple actors can participate in the energy process. The role of end-user is evolving from a consumer to a prosumer, i.e., a producer and consumer of energy. The energy consumers and prosumers are expected to become significant players in the future energy ecosystem, enabling a new type of innovation and value creation opportunities for a variety of actors. It is important to investigate how individuals recognize determinants of decarbonization. The findings highlight how determinants of decarbonization can play an active role in the transformation of the traditional energy market.

In the literature on decarbonisation processes, no broad theoretical explanations indicate the crucial determinants supporting such operations.

4. Results

The research yields answers to the following research question: Which of the following do you think has the most impact on decarbonisation?

1. Subsidies for mining.
2. Subsidies for local governments (e.g., the decommissioning of furnaces).
3. Prosumer solar photovoltaics development programmes.
4. Capacity market.
5. Opening up the EU energy market.

The answers to the questions are presented in Figure 1.

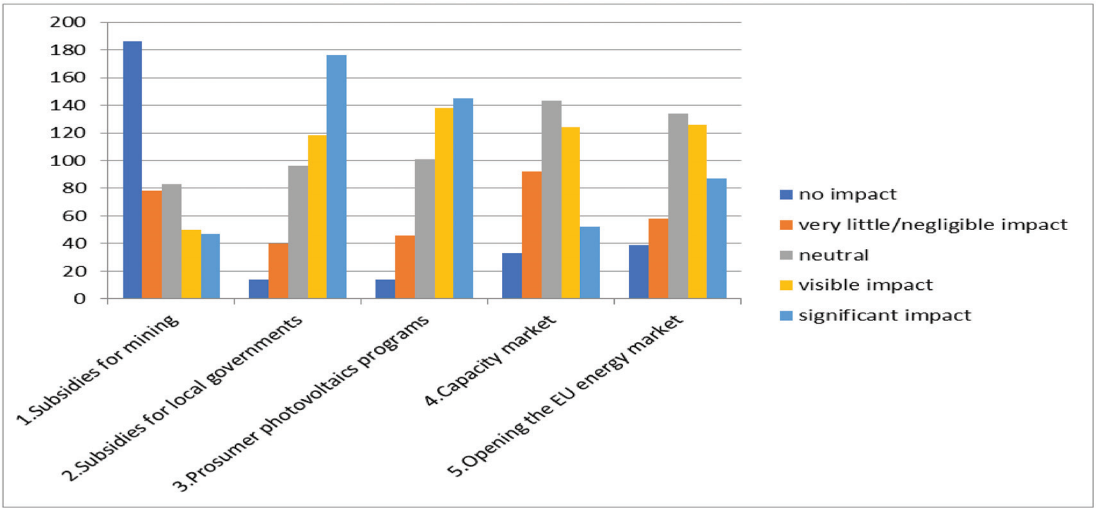

Figure 1. Respondents' opinions on the activities determining decarbonisation processes. Source: Own research based on the results of an online survey, *n* = 444.

Of the respondents, 42% stated that mining subsidies had no impact on the decarbonisation process; 19% believed that mining subsidies were a factor increasingly influencing the decarbonisation process, and 11% thought that the mining subsidy policy had a significant impact on decarbonisation.

The opposite situation was observed with respondents' responses to the question "Which of the following measures has the greatest impact on decarbonisation, in your opinion?" Forty percent of participants stated that subsidies for local governments (e.g., decommissioning of furnaces) significantly impacted decarbonisation, while 22% believed that such subsidies increasingly affected measures to reduce CO_2 emissions. According to 3% of respondents, subsidies for local governments had no impact on the decarbonisation process.

For 64% of respondents, the development programmes for prosumer solar photovoltaics had a significant or reasonably large impact on eliminating CO_2 emissions due to their harmfulness to the environment. Only 3% of respondents believed that these programmes did not affect decarbonisation (Figure 1).

Another topic in the survey concerned the power market, which constitutes regulatory solution stabilizing the electricity supply to households and industries as part of a long-term plan. Therefore, it is a guarantee of uninterrupted electricity supply to all electricity consumers. The capacity market in Poland was introduced in 2017 and is expected to operate until 2046. The security of covering the forecast demand of consumers for power in a given year is contracted several years in advance; therefore, respondents were asked whether, in their opinion, the capacity market influenced decarbonisation.

The responses of the survey participants were quite similar to each other and were as follows (Figure 1):

- no impact (7%);
- very little/negligible impact (21%);
- hard to tell (32%);
- visible impact (28%); and
- significant impact on decarbonisation (12%).

The last question in the survey concerned the EU free energy market. The participants answered this question similarly to the previous ones. Fifty-eight percent believed that the EU free energy market would increasingly impact the elimination of CO_2 emissions, 20%

considered that it had a significant impact on decarbonisation, and only 9% believed that it would make no difference.

When respondents answered the second question, of which of the following activities should be transferred from the central level to the local level, nearly 86% stated that subsidies for local governments and photovoltaics development programmes significantly impact decarbonisation (Figure 2).

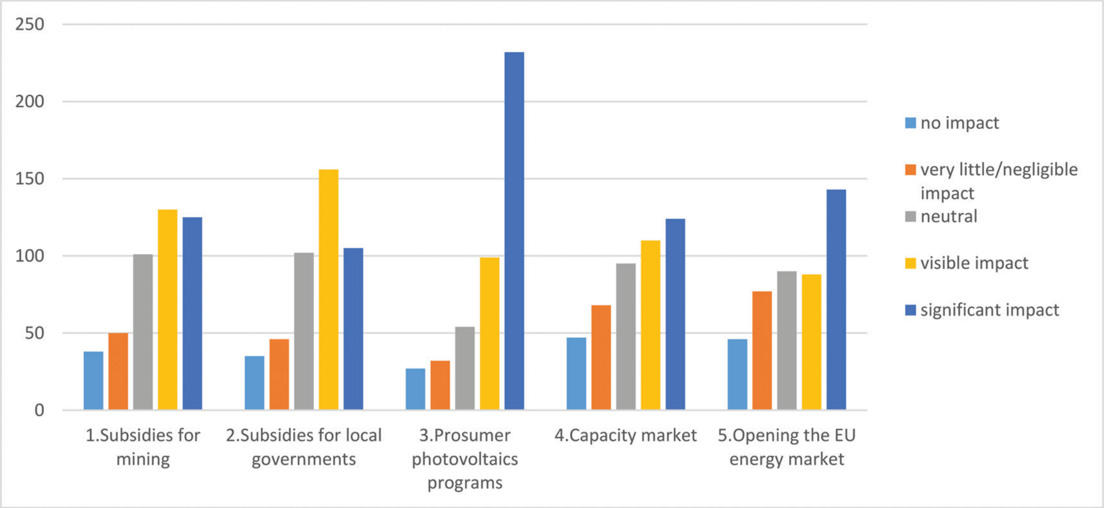

Figure 2. Respondents' opinions on the activities determining decarbonisation processes (Question 2: (Which of the following activities should be transferred from central to local regulation?). Source: Own research based on the results of an online survey, $n = 444$.

The responses of the survey participants were quite similar to each other and were as follows (Figure 2):

- no impact (14%);
- very little/negligible impact (15%);
- hard to tell (41%);
- visible impact (7%); and
- significant impact on decarbonisation (23%).

According to the answers received in the study, 59 respondents believe that activities related to the decarbonisation of the economy, including granting subsidies to residents/recipients (e.g., for the liquidation of the back) should not be transferred from the central to the local level. Fifty-four respondents indicated that it is difficult for them to assess this phenomenon, and 99 people participating in the study did not have a firm opinion on the subject. In response to this question, the dominant opinion (232 respondents) was that activities refering to the decarbonisation of the economy, i.e., the granting of subsidies to residents/recipients (e.g., for the liquidation of furnaces) should be transferred from the central level to the local level.

Another area of scientific research on the transfer of activities related to the economy's decarbonisation from the central to the local level was prosumer photovoltaic development programmes. Eighty-one respondents answered that, in their opinion, these programmes should not be transferred from the central to the local level; 102 people taking part in the survey found it difficult to assess this phenomenon. It can be assumed that these people do not have adequate knowledge of the subject. As many as 105 people did not have a precise opinion, and 156 respondents believed that activities related to the decarbonisation of the economy, including the management of programmes for the development of prosumer photovoltaics, should be transferred from the central to the local level.

According to 19.81% of respondents, activities related to the decarbonisation of the economy, including energy compensation, energy storage, and production by day and night, should not be transferred from the central to the local level (8.55% of respondents had a strong opinion in this respect). According to the data presented in Figure 2, it was difficult for the respondents to assess this phenomenon as they did not have a firm opinion on the subject (27.74%). As many as 57.42% of respondents thought that such activities related to the decarbonisation of the economy as energy compensation, energy storage, daytime energy production, and night-time consumption should be transferred from the central level to the premises (28.15% of respondents had a strong opinion in this respect).

The data from Table 2 are presented in Figure 3. They are the means of all responses obtained in the studies. They show that subsidies for mining are the least important factor for all generations. They have no or a minimal impact on decarbonisation. This is illustrated by the lowest average response value for all ages (especially the youngest, Generation Z) regarding the opening of the EU energy market. Older generations pay attention to local subsidies and the development of photovoltaics. However, Generation Z was the least numerous group. Therefore, it can be assumed that the responses obtained from Generations X and Y are the most representative (Table 3).

Table 2. Respondents' opinions on the average importance of the impact on decarbonisation.

	Average of Importance of Impact on Decarbonisation				
Age	**A**	**B**	**C**	**D**	**E**
1943–1960 (Baby boomers (BB))	2.15	3.85	3.92	2.69	3.23
1961–1981 (Generation X)	2.08	3.84	3.93	3.08	3.44
1982–2000 (Generation Y)	2.40	3.96	3.75	3.20	3.33
2001–Present (Generation Z)	2.75	3125	3.5	3.5	4.0
Total	2.31	3.91	3.80	3.16	3.37

Source: Own research. A—Subsidies for mining; B—Subsidies for local governments; C—Prosumers' photovoltaics development programme; D—Capacity market; E—The opening-up of the EU energy market.

Advanced Statistical Analysis

The median is calculated, assuming what follows:

Assumption:

$$x_1 \le x_2 \le \ldots \le x_n \tag{1}$$

DI:

$$m_e = \begin{cases} x_{(n+1)/2} \\ \frac{1}{2}(x_{n/2} + x_{n/2+1}) \end{cases} \tag{2}$$

for n-odd; for n-even.

SzR:

$$m_e = \overline{x_m} + \frac{d}{n_m}\left(\frac{n - n_m}{2} - \sum_{j=1}^{m-1} n_j\right) \tag{3}$$

The variances from the sample were calculated (s^2-sample variance):

DI:

$$s^2 = \frac{1}{n}\sum_{i=1}^{k}(x_i - \overline{x})^2 \tag{4}$$

SzR:

$$s^2 = \frac{1}{n}\sum_{j=1}^{k} n_j(\overline{x_j} - \overline{x})^2 \tag{5}$$

Thus, s is the standard deviation.

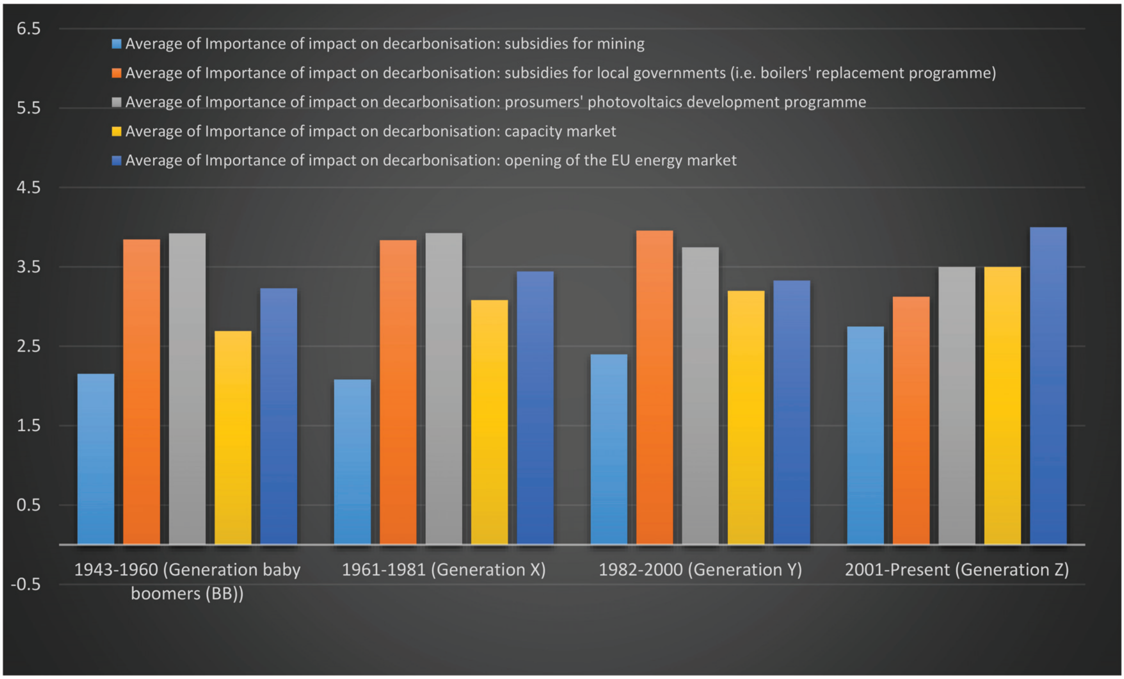

Figure 3. Average importance of impact on decarbonisation. Source: Own research based on the results of an online survey, $n = 444$.

Table 3. Count of the importance of impact on decarbonisation.

Importance of Impact on Decarbonisation: Subsidies for Mining							
Age	**City**		**City Total**	**Village**		**Village Total**	**Total**
	Female	**Male**		**Female**	**Male**		
1943–1960 (Baby boomers (BB))	5	4	9	1	3	4	13
1	2	3	5		1	1	6
2	1		1	1	1	2	3
3	1		1				1
4	1		1		1	1	2
5		1	1				1
1961–1981 (Generation X)	32	64	96	13	13	26	122
1	16	38	54	3	10	13	67
2	4	10	14	2	2	4	18
3	4	7	11	3		3	14
4	3	1	4	1	1	2	6
5	5	8	13	4		4	17
1982–2000 (Generation Y)	111	94	205	71	25	96	301
1	39	41	80	18	12	30	110
2	18	21	39	14	4	18	57
3	24	16	40	22	4	26	66
4	18	7	25	13	2	15	40
5	12	9	21	4	3	7	28
od 2001–Present (Generation Z)	5	2	7	1		1	8
1	2	1	3				3
3	1	1	2				2
4	2		2				2
5				1		1	1

Source: Own research.

Standard deviation is one of the measures of dispersion (variability, dispersion) intended for testing the degree of variation in the value of a variable. Generally, the standard deviation reflects how much the variable's values in the studied population deviate from the arithmetic mean of the studied variable's value. High values of standard deviation indicate that the variable's values are forcefully dispersed around the mean (considerable differentiation), while low values indicate small dispersion (low differentiation).

The standard deviation is strongly related to the arithmetic mean. We have already noted that the arithmetic mean is useful for examining a population with a low degree of differentiation of the variable feature. At the same time, its disadvantages include distorting the result of the mean by adding extreme values. Groups that are not characterised by homogeneity are often a focus of study; in our case, the arithmetic mean has a low cognitive value. So, the standard deviation comes to our aid.

We can also calculate the standard deviation as follows:

$$s = \sqrt{\frac{(x_1 - \overline{x})^2 + (x_2 - \overline{x})^2 + \ldots + (x_n - \overline{x})^2}{n - 1}} \quad (6)$$

where s symbolises the standard deviation and $n - 1$ is the number of samples minus 1.

Figure 4 presents the means obtained from the answers to the impact of decarbonisation and standard deviations. They clearly show that all standard deviations are in the range from 1.5 to 2.6. The respondents' most unambiguous answers from Generation Z, however, cannot be taken into account due to their small size. Yet, also for baby boomers, very high and singular recognition (with a low standard deviation) was given to the proconsumer photovoltaic development programmes.

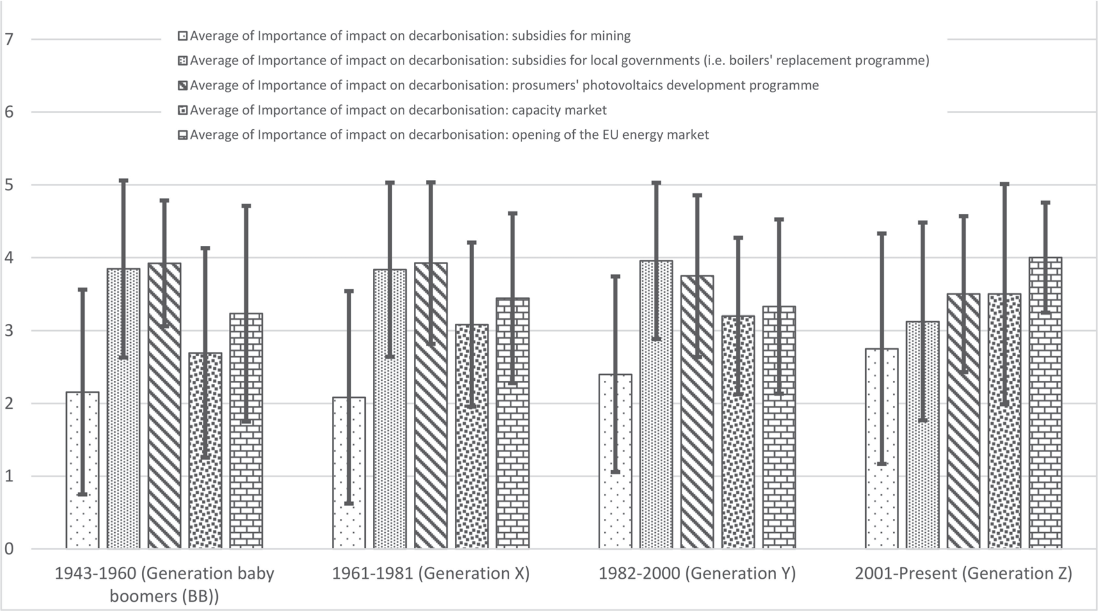

Figure 4. Average importance of impact on decarbonisation with marked standard deviations. Source: Own research based on the results of an online survey, n = 444.

Figure 5 presents the distribution of the number of respondents depending on age and sex, with an additional indication of the place of residence. Generations X and Y are representative, so their results are taken into account in particular.

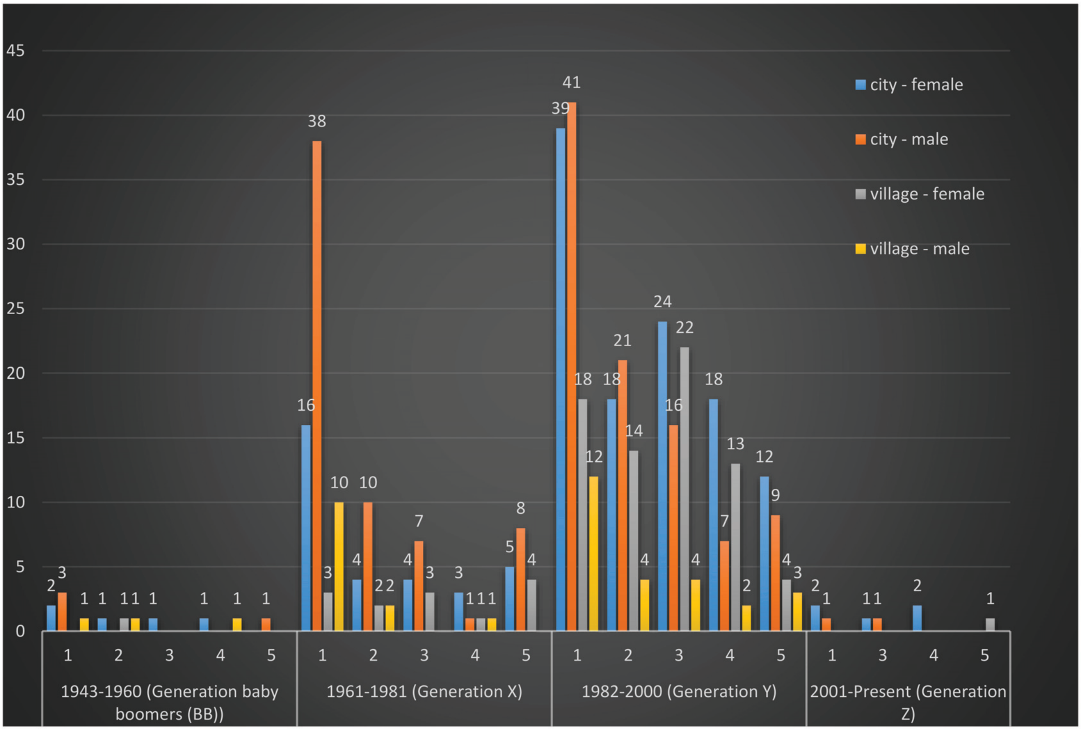

Figure 5. Distribution of responses by sex and localisation by age. Source: Own research based on the results of an online survey, $n = 444$.

Figure 6 and Table 4 show the average levels of answers to the question about the necessity of transferring activities directly to local levels, and standard deviations. Generations X and Y, which we consider due to them representing the majority of respondents, responded unanimously. For them, priority is given to local support programmes of furnace replacement and programmes related to photovoltaics.

Table 4. Mean values in responses to the question of necessity, scored from 1 to 5; sorted by age.

	Average of Necessity of Transferring Actions from the Central to the Local Level				
Age	**A**	**B**	**C**	**D**	**E**
1943–1960 (Baby boomers (BB))	4.23	4.08	3.31	4.00	3.85
1961–1981 (Generation X)	4.24	3.96	3.43	3.63	3.43
1982–2000 (Generation Y)	4.01	3.56	3.63	3.33	3.44
2001–Present (Generation Z)	3.62	3.12	3.87	3.75	4.12
Total	4.07	3.68	3.57	3.44	3.46

Source: Own research. A—Subsidies for the residents/end users (i.e., boilers' replacement programme); B—Prosumers' photovoltaics development programme; C—Compensation for electricity, energy storage, production during the daytime, and consumption at night; D—Funds for environmental protection; E—Support of development of modern power sources (CHP bonus, renewable energy sources).

It is assumed that the standard deviation, being one-third of the mean, indicates a narrow distribution (Tables 5 and 6).

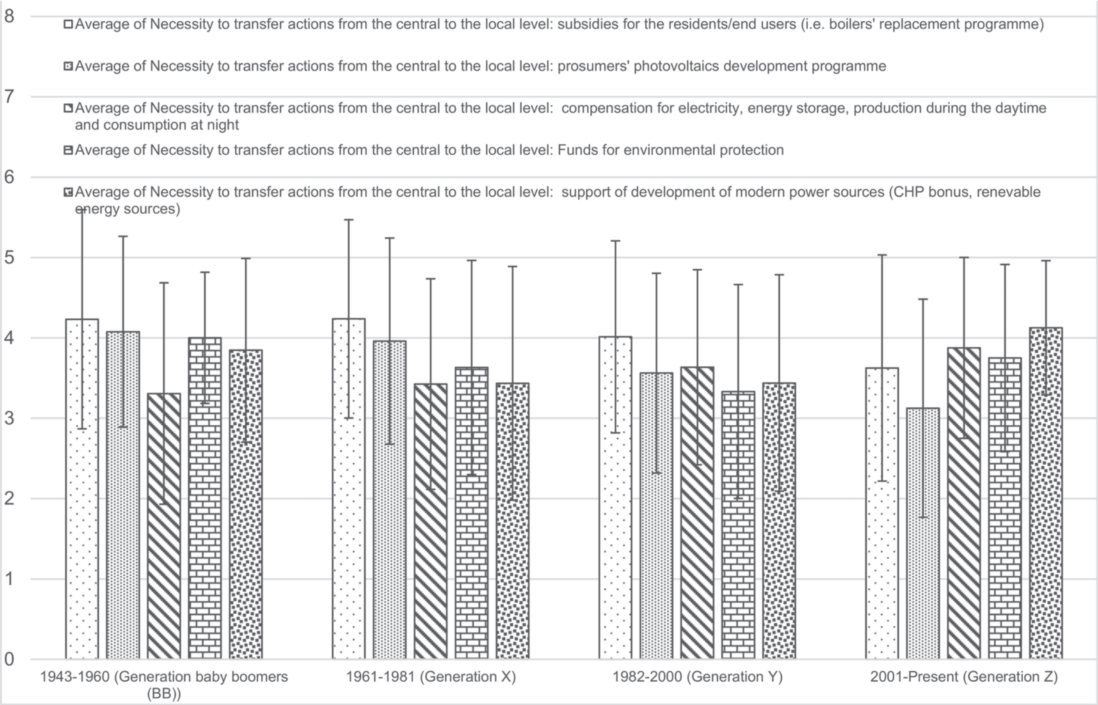

Figure 6. Average of necessity of transferring activities directly to local levels. Source: Own research based on the results of an online survey, *n* = 444.

Table 5. Mean values in responses to the question of necessity, scored from 1 to 5; sorted by age, with marked standard deviations.

	i1	i2	i3	i4	i5
Average	2.31	3.90	3. 80	3.16	3.37
Standard deviation	1.38	1.12	1.11	1.11	1.19

Source: Own research. Notes: The answers to the first question were ranked in importance from 1 to 5, and numbers provided from 1 to 5 for subsequent responses.

Table 6. Average values and standard deviation to the responses n1–n5.

	n1	n2	n3	n4	n5
Average	4.07	3.68	3.57	3.44	3.46
Standard deviation	1.21	1.27	1.24	1.32	1.36

Source: Own research. Notes: The answers to the second question were ranked in Necessity from 1 to 5, and numbers provided from 1 to 5 for subsequent answers.

Table 7 summarises the obtained covariance levels for questions 1 and 2, respectively, for answers from i1 to i5 and from n1 to n5.

The highest covariance of 0.68 is for the answer to the question about photovoltaics and its support in questions 1 and 2. This covariance confirms that the calculations are correct and that the data obtained from the study are accurate.

Table 7. Covariances for the response set for i1–i5 through n1–n5.

Covariation	n1	n2	n3	n4	n5
i1	0.25	0.06	0.17	0.20	0.14
i2	0.59	0.45	0.33	0.18	0.17
i3	0.41	0.68	0.26	0.22	0.30
i4	0.13	0.25	0.31	0.33	0.37
i5	0.13	0.17	0.38	0.49	0.42

Source: Own research.

The second-largest covariance (0.59) is for the answer to the question about the support of local government and the transfer of support to local areas from the central level, both in questions 1 and 2. This also confirms the correctness of the obtained data and the correctness of the answers provided. This covariance is graphically presented in Figure 7.

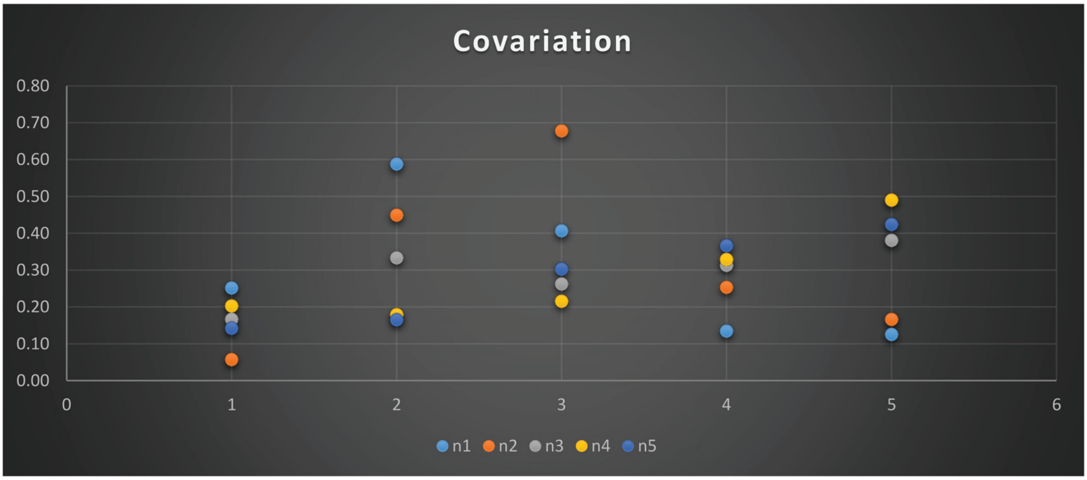

Figure 7. Covariation. Source: Own research based on the results of an online survey, $n = 444$.

Both covariation and strong correlation can indicate a strong relationship where the result is above 0.5. In the case of i3n2, robust covariation is confirmed (0.68), and the correlation (0.49) is sufficiently strong (Figure 6). The results from the sample of 444 indicate that the strongest covariation and correlation concerns the importance of the impact on the decarbonisation of the prosumer solar photovoltaics development programme.

The correlation was also calculated, which confirmed the above conclusions for the covariance. The correlations are presented graphically in Figure 8.

Table 8 shows two correlation coefficients that are higher than the remaining ones. Correlation at the level of 0.43 in response to questions i2 and n1 suggests that the voters were in favour of entrusting the actions to local government rather than centralising them. They reasoned that the local authorities would know their residents better (Figure 8).

At the level of 0.49, an even stronger correlation is visible in responses to questions i3 and n2. This correlation between answers to these two questions suggests that voters, who think that photovoltaics is a crucial factor in the decarbonisation process, would prefer local governments to distribute the subsidies instead of there being centrally controlled distribution of funds. These two coefficients suggest strong support for the local governments by the community (Figure 9).

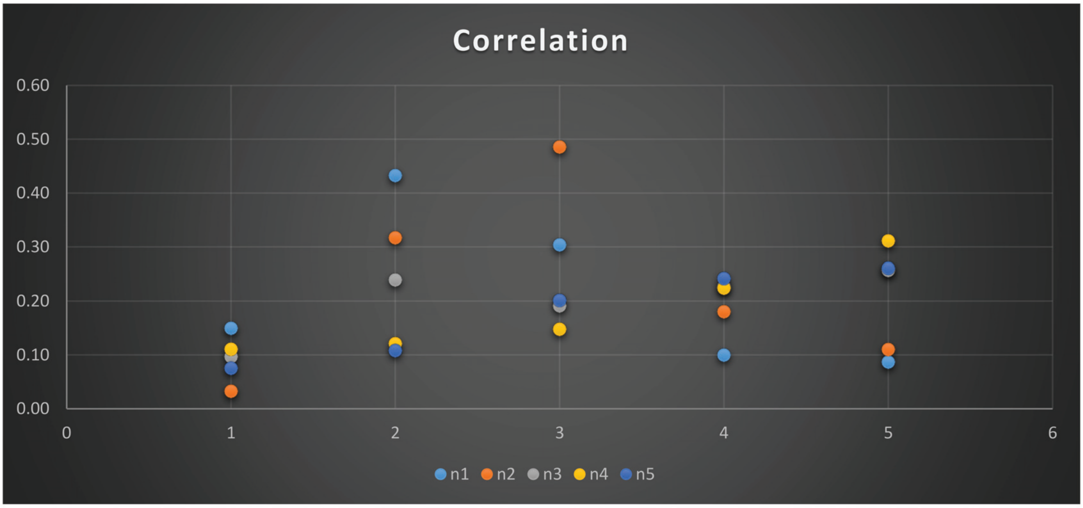

Figure 8. Covariation. Source: Own research based on the results of an online survey, *n* = 444.

Table 8. Correlations for the response set for i1–i5 through n1–n5.

Correlation	n1	n2	n3	n4	n5
i1	0.15	0.03	0.10	0.11	0.08
i2	0.43	0.32	0.24	0.12	0.11
i3	0.30	0.49	0.19	0.15	0.20
i4	0.10	0.18	0.23	0.22	0.24
i5	0.09	0.11	0.26	0.31	0.26

Source: Own research.

The next question was about the solutions that the EU should introduce in the field of decarbonisation. Respondents could give a free, subjective answer, or several answers, to this open-ended question. The aim was to obtain as many attitudes and opinions as possible to analyse the decarbonisation further. It should be emphasised that this phenomenon is still poorly understood in society. Of the respondents, only 238 answered this question; about 20% of the participants indicated that they had no opinion, could not judge, did not know, or found it hard to assess.

The respondents' answers to the question "What solutions do you think the EU should introduce for regulations regarding decarbonisation?" were categorised into four groups. It should be following sentence in the Table 9 common responses to the survey are shown.

In addition to the solutions mentioned above, other respondents suggested that there should be a standard energy policy and a uniform EU position toward natural gas suppliers. Survey participants also pointed out that no country in the EU without extensive financial and technical capabilities in hydroelectric power and geothermal energy had decarbonised its energy sector without a nuclear power plant.

Another proposal concerned a change in the law, namely, a new EU regulation defining a binding prospect for the coal industry's liquidation and establishing a special decommissioning fund for mining in the EU. According to the respondents, the problem of the existing EU solutions is the lack of appropriate bonuses (incentive bonuses) for countries ahead of schedule to reduce CO_2 emissions. The European Commission should develop its own, independent, individual national schedules, based on its analyses in this study.

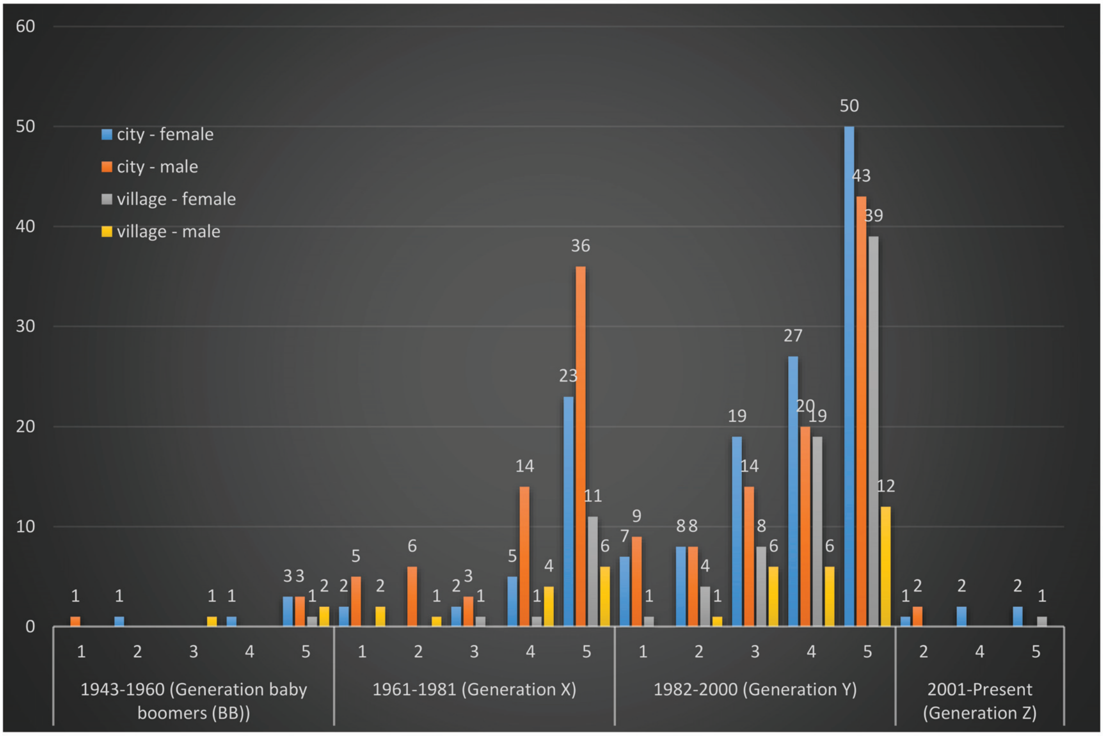

Figure 9. Distribution of responses by sex and localisation by age. Source: Own research based on the results of an online survey, *n* = 444.

While analysing what regulations the EU should introduce in decarbonisation, a small group of respondents suggested that the energy market should not be controlled and should not receive subsidies, with energy policy left as a national policy under the control of each country. These respondents also stated that the largest EU countries were the ones that set the standards for decarbonisation.

Another respondent suggested transforming the energy sector toward large zero-emission sources, such as nuclear, offshore wind, or hydropower. However, another respondent indicated that Poland had a high degree of afforestation.

The respondents also highlighted the following issues:

- introduction of CO_2 certificates;
- introduction of emission limits for households;
- mandatory end to solid fuel stoves (coal);
- increasing the awareness of society and consumers about the positive impact of renewable energy sources on the natural environment and human health;
- elimination of own contribution through EU subsidies;
- elimination of tedious procedures (minimising formalities) for replacing heating devices; and
- making member states accountable for the effects of decarbonisation.

In conclusion, although the results were based on the respondents' subjective opinions, individuals' views and attitudes within the external environment for decarbonisation are fundamental, especially when looking at the best way to reduce CO_2 emissions.

Table 9. EU solutions in the field of decarbonisation: Implementation possibility by individual member states, according to respondents.

No.	Action	Characteristics and Specification
1	Coal management	- coal import ban - high customs duties - no smoking of coal - the use of coal as fuel is prohibited - reduction of coal extraction in mines - a total ban on the production of energy from fossil fuels - introduction of high penalties
2	Grants	- granted to households and entrepreneurs - subsidies for prosumer solar farms- dedicated EU programmes - reduction of subsidies to energy - intensive industries - for renewable energy sources - subsidies for households to replace old stoves - subsidies for the use of other energy sources besides solar—in particular, biomass and wind energy
3	Nuclear energy	- common projects - conduct/implement a low-emissions nuclear policy - the example of France - develop and promote nuclear energy - the EU should allow the construction of nuclear power plants from EU funds - recognition of nuclear energy as an effective decarbonisation mechanism
4	RES technologies	- support and assistance- legal and technical support - penalties for the lack of RES investments - subsidising small RES installations of various types - growing the share of renewable power sources in total power production
5	Taxes	- CO_2 taxation, including the aviation industry - impose charges and emission duties - introduce a carbon footprint tax for products imported from outside the EU - introduction of high carbon taxes, including for households

Source: Own research based on the results of an online survey, *n* = 238.

Considering the results of the assessment of the main factors influencing the decarbonisation process in Poland, in which 249 respondents provided detailed answers, around 20% of the survey participants did not give any answer, indicating that they had no response, did not know, or could not judge.

The responses to the questionnaire indicated that the main factors in the decarbonisation process, according to the respondents, were subsidies and nuclear energy (approximately 50% of the respondents mentioned nuclear points). Among the most frequent answers were replacing coal-fired energy plants with substitute like e.g., energy plants and the decommissioning of old solid fuel stoves. Considering that the respondents were asked an open-ended question and each had the opportunity to provide long answers, the most frequently indicated determinants affecting the elimination of CO_2 emissions are presented in Figure 10.

Respondents seem to be aware that there is no single, simple solution to reducing fossil fuel consumption and CO_2 emissions. Divesting from fossil fuels is a great challenge for Poland. The largest sources of CO_2 emissions are the combustion of fossil fuels in power plants, transport (cars and planes), processes related to the production of industrial goods, and deforestation. Poland has to face these problems to transition to a low-carbon future [35–37].

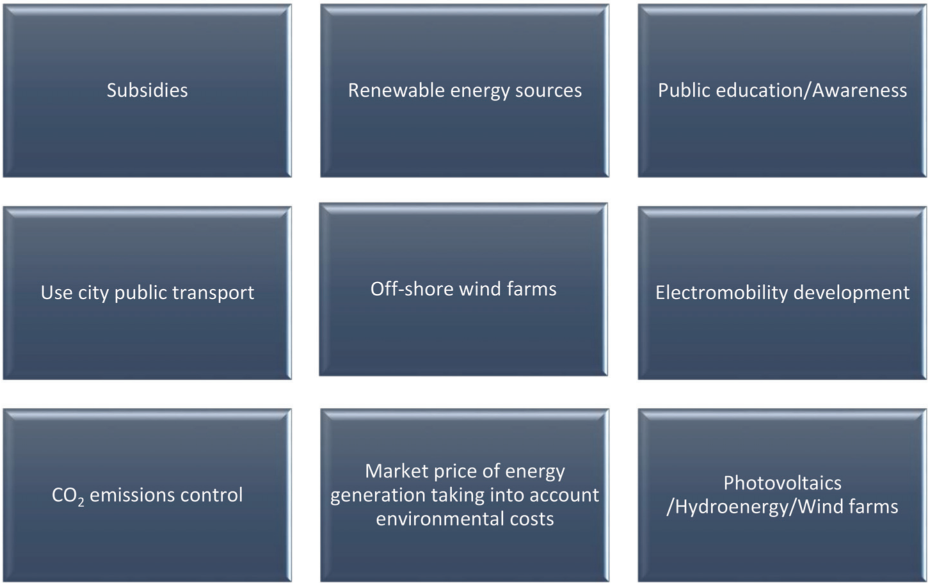

Figure 10. Main determinants of decarbonisation according to the respondents. Source: Own research based on the results of an online survey, $n = 249$.

5. Discussion and Conclusions

The study's main aim was to reveal the determinants of decarbonisation influencing the energy transformation in Poland. Poland is one of the countries whose energy is still based on carbon (the others are China, Russia, Australia, Ukraine, and the USA). Currently, the politics of the whole world resists decarbonisation. In Poland's case, the coal share is decreasing, but it is still the most important fuel for electricity production. Governments must implement policies that are environmentally friendly, cost-effective, and socially acceptable. Social acceptance risk plays a significant role in Poland, so it is crucial to know the factors influencing decarbonisation and energy transformation. The authors conducted a survey, the results of which should be of benefit to policy-makers and researchers worldwide. In our opinion, it is novel research and has important results concerning energy and climate change. It also presents the directions enabling the diffusion of knowledge regarding decarbonisation to develop a sustainable energy strategy for Poland.

The authors investigated phenomena that have not been studied in the literature so far. The following determinants impact decarbonisation: subsidies for mining, subsidies for local governments (e.g., decommissioning of furnaces), prosumer solar photovoltaics development programmes, market capacity, and opening up the EU energy market. The authors were interested in social support for these determinants. Research has shown that mining subsidies had no impact on the decarbonisation process. The respondents stated that the development programmes for prosumer solar photovoltaics had a significant impact on eliminating CO_2 emissions due to their harmfulness to the environment. Local governments provide better support for the decarbonisation process, and should support such activities. Poland was generally seen as a clean energy laggard, but it shot up the solar energy charts by adding 2.2 GW, more than double its capacity last year. Unleashing this potential is crucial for sustaining momentum in the EU solar sector and meeting European Green Deal climate and energy targets. To make the most of this golden opportunity, the rate of deployment for solar needs to increase exponentially, with innovative applications such as floating solar, agricultural photovoltaics, and building-integrated photovoltaics showing significant potential to foster further demand and growth.

Now is not the time for complacency, but for action to ensure a green recovery from the pandemic and a just global transition towards a decarbonised and renewable future.

We suggest that the main pathways in the decarbonisation process in Poland could include the following:

- facilitating investments in wind, solar, geothermal, and hydroelectric energy;
- consciously improving energy policy and energy security;
- coordinating the development of the most effective types of RES;
- construction of a nuclear power plant;
- regulating energy prices and prices for products with high carbon content; and
- transformation of Silesia.

Based on the survey results, we can draw similar or even the same specific conclusions about the critical determinants of Poland's energy market transformation process—education, knowledge, and awareness for both society and business. Other factors include the use of renewable energy, the construction of a nuclear power plant, subsidies for renewable energy sources, the replacement of furnaces, the development of new technologies, the inclusion of transmission infrastructure, and changes in people's deeply rooted beliefs. The study reviewed the international literature on the theory and practice of decarbonisation, emphasising the experiences of other countries, including the USA and China. The authors also rely on German and Scandinavian experiences. However, the carbon dioxide emissions resulting from burning coal are still a major problem in other countries. The USA and China were used as examples because they still use significant amounts of coal for energy production and locally for heat production. Germany has long been marginalizing this problem through programmes for the development of renewable resources. Scandinavia, on the other hand, does not use coal at all to produce energy and coal. The selection of the present comparisons at the current stages of the development of decarbonisation was deliberate. To reduce greenhouse gas emissions in Poland by 2050, the decarbonisation of the economy should occur four times faster than in recent years. In the years 2030–2050, our actions should double in intensity, and the social perceptions of this phenomenon are essential. For the environment, the replacement of coal by gas is of enormous importance. Gas is the next step to stop emissions completely. Gas burns exceptionally cleanly (even without exhaust gas treatment), emitting twice as much CO_2 as the calorically equivalent amount of carbon. The energy conversion efficiency is high. Even small engine installations offer electrical efficiency comparable to the largest coal installations (~45%), and the ceiling of large gas-steam units (~60%) is unattainable for coal-fired power plants. Gas blocks are cheap in terms of investment, and are quick to build and flexible (quick start-up/shutdown). We can find an analogy with the analysis in Sadik-Zada and Gatto [38]. In order to account for the differences between advanced and developing/transition economies, we have included a dummy variable, which takes the value "1" for all developing and transition economies and the value "0" for advanced economies. This volatility reflects the partially differentiated influence of the energy sector on the rest of the economy in these two groups. There is a difference between developing/transition economies and advanced economies in terms of public debt levels.

This study concluded that several paths lead to decarbonisation and energy market transformation and, thus, to climate neutrality. These empirical results could be used to diagnose the state's level of use of instruments to implement its sustainable development goals. Such analytical research has not yet been presented for Poland; this study is the first to attempt to identify the determinants of the decarbonisation process in Poland. This study can be used as a basis for further research on this topic. When we compare natural gas with fuels such as coal and oil, it has a lower carbon intensity. The use of gas as a fuel therefore leads not to total elineation, but only to a reduction in carbon dioxide emissions. As widely known, this emission is mostly responsible for the anthropogenic changes in our global climate. Therefore, natural gas used as a fuel is considered only as a temporary source of energy on the way to the complete elimination of carbon dioxide emissions. This is particularly evident in energy mixes dominated by coal [39]. However, significant criticisms are being made against this view. One of the more famous researchers is Howarth's (2014) argues that both energy extracted from gases which are extracted from shale rocks is very harmful to the environment. According to this view, these sources have a greater impact on climate change than the burning of coal and oil. Only natural gas-based electricity generation has a moderate impact on the change in emissions. this varies from sector to sector of the economy. In the heating and mobility sector, for example, natural gas has a higher level of gas share, GHGs. Howarth argues, and gives this as the main argument that methane is particularly harmful. Natural gas has lower carbon dioxide emissions compared to shale gas. However, it is more harmful that it has a higher methane emission factor. According to his view, even small amounts of methane are more harmful to global warming than carbon dioxide emissions. Nevertheless, this argument is no longer important when we consider the development of energy technologies that significantly reduce methane emissions [38].

Additionally the Authors have to add in the case of no decarbonisation significant part of the existing energy infrastructure, regardless of climate change, will need to be renewed in the next 20 to 30 years. More than 50% of the capacity of centrally dispatched generation units will most likely be decommissioned by 2035.1At the same time, more than three quarters of the aerial high- and medium voltage lines that form the basis of the transmission system are now over 25 years old.16 This reality provides an opportunity to design and build with a zero-carbon mindset instead of retrofitting or prematurely shutting down existing assets. In addition, Poland, with its large forest area, has a net carbon sink (capturing 34 MtCO2e in 2017)17 that the country could use to offset emissions from hard-to-abate economic activities such as agriculture [40].

Future research should concern confirmation of whether the Polish government deals with the decarbonisation process accordingly with social expectations. Moreover, a detailed study should be carried out as to whether the Polish government is willing to act on this matter. Poland's zero-carbon economy shift should be a long-term and stable plan ideally working by 2050. What is more, this should also be coherent with a medium-term reference aim for objectives and undergoing legislative changes. Are the Polish government and society willing to accept the sunset of the mining sector? What is more, are they accepting the actual need to decrease the conventional coal-fired power production in up to 30 years? How about accepting the urging need of pushing the debate on the electricity generation's future in Poland? It would be crucial to, before 2050, explore feasible methods to a near zero-carbon system which would deliver double the amount of energy as today? Research should also be provided in terms of the social acceptance of a low-carbon transition plan for the mining industry in Poland. It should also ensure a consistent regulatory framework taking into account inclusion of the global climate regulations issues in both foreign and export-oriented policies and also the early breakthrough procedures innovations distribution nationwide.

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References

1. Kiuila, O. Decarbonisation perspectives for the Polish economy. *Energy Policy* **2018**, *118*, 69–76. [CrossRef]
2. *Global Economic Prospects, June 2020*; Global Economic Prospects; The World Bank: Washington, DC, USA, 2020; ISBN 978-1-4648-1553-9.
3. Zenghelis, D. Securing Decarbonisation and Growth. *Natl. Inst. Econ. Rev.* **2019**, *250*. [CrossRef]
4. Knobloch, F.; Pollitt, H.; Chewpreecha, U.; Daioglou, V.; Mercure, J.F. Simulating the Deep Decarbonisation of Residential Heating for Limiting Global Warming to 1.5 °C. *Energy Effic.* **2019**, *12*. [CrossRef]
5. Victoria, M.; Zhu, K.; Brown, T.; Andresen, G.B.; Greiner, M. Early Decarbonisation of the European Energy System Pays Off. *SSRN Electron. J.* **2020**. [CrossRef]
6. Hübler, M.; Löschel, A. The EU Decarbonisation Roadmap 2050 What Way to Walk? *Energy Policy* **2013**, *55*, 190–207. [CrossRef]
7. Oyewunmi, T.; Crossley, P.; Talus, K.; Sourgens, F.; Jones, K.B.; Jervey, B.B.; Roche, M. *Decarbonization and the Energy Industry: An Introduction to the Legal and Policy Issues*. Tulane Public Law Research Paper No. 20-9. 2020. Available online: https://ssrn.com/abstract=3548837 (accessed on 1 February 2021). [CrossRef]
8. Ang, B.W.; Su, B. Carbon Emission Intensity in Electricity Production: A Global Analysis. *Energy Policy* **2016**, *94*. [CrossRef]
9. Blyth, W.; Bunn, D.; Chronopoulos, M.; Munoz, J.; Bunn, D.W. Systematic Analysis of the Evolution of Electricity and Carbon Markets under Deep Decarbonisation, Norwegian School of Economics. 2014, pp. 1–36. Available online: https://openaccess.nhh.no/nhh-xmlui/handle/11250/227052 (accessed on 1 February 2021).
10. Zimon, G. An Assessment of the Strategy of Working Capital Management in Polish Energy Companies. *Int. J. Energy Econ. Policy* **2019**, *9*. [CrossRef]
11. Åhman, M.; Nilsson, L.J.; Johansson, B. Global Climate Policy and Deep Decarbonization of Energy-Intensive Industries. *Clim. Policy* **2017**, *17*, 634–649. [CrossRef]
12. Cheema-Fox, A.; Laperla, B.R.; Serafeim, G.; Turkington, D.; Wang, H. *Decarbonization Factors*. Harvard Business School Working Paper, No. 20-037. September 2019. Available online: https://www.hbs.edu/faculty/Pages/item.aspx?num=56840 (accessed on 1 February 2021).
13. Hildingsson, R.; Kronsell, A.; Khan, J. The Green State and Industrial Decarbonisation. *Environ. Politics* **2019**, *28*. [CrossRef]
14. Leal-Arcas, R. Towards Sustainability in Trade, Energy and Climate. *Mod. Environ. Sci. Eng.* **2020**, *6*, 1–30. [CrossRef]
15. Marx, C. Climate Change and Financial Sustainability: A Regulator's Perspective. *ERA Forum* **2020**, *21*, 171–175. [CrossRef]
16. Tsakalidis, A.; Gkoumas, K.; Pekár, F. Digital Transformation Supporting Transport Decarbonisation: Technological Developments in EU-Funded Research and Innovation. *Sustainability* **2020**, *12*, 3762. [CrossRef]
17. Saługa, P.W.; Grzesiak, P.; Kaminski, J. Valuation of Decision Flexibility and Strategic Value in Coal Gasification Projects with the Option-to-Switch between Different Outputs. *Energies* **2020**, *13*, 2826. [CrossRef]
18. Olszewski, R.; Pałka, P.; Wendland, A.; Kaminski, J. A Multi-Agent Social Gamification Model to Guide Sustainable Urban Photovoltaic Panels Installation Policies. *Energies* **2019**, *14*, 3019. [CrossRef]
19. Hadfield, P.; Cook, N. Financing the Low-Carbon City: Can Local Government Leverage Public Finance to Facilitate Equitable Decarbonisation? *Urban Policy Res.* **2019**, *37*. [CrossRef]
20. Spencer, T.; Pierfederici, R.; Sartor, O.; Berghmans, N.; Samadi, S.; Fischedick, M.; Knoop, K.; Pye, S.; Criqui, P.; Mathy, S. Tracking Sectoral Progress in the Deep Decarbonisation of Energy Systems in Europe. *Energy Policy* **2017**, *110*, 509–517. [CrossRef]
21. Barrett, J.; Cooper, T.; Hammond, G.P.; Pidgeon, N. Industrial Energy, Materials and Products: UK Decarbonisation Challenges and Opportunities. *Appl. Therm. Eng.* **2018**, *136*, 643–656. [CrossRef]
22. Gephart, R.P. What Is Qualitative Research and Why Is It Important? *Acad. Manag. J.* **2004**, *47*. [CrossRef]
23. Hoppe, T.; de Vries, G. Social Innovation and the Energy Transition. *Sustainability* **2018**, *11*, 141. [CrossRef]
24. Svensson, O.; Khan, J.; Hildingsson, R. Studying Industrial Decarbonisation: Developing an Interdisciplinary Understanding of the Conditions for Transformation in Energy-Intensive Natural Resource-Based Industry. *Sustainability* **2020**, *12*, 2129. [CrossRef]
25. Capros, P.; Tasios, N.; de Vita, A.; Mantzos, L.; Paroussos, L. Model-Based Analysis of Decarbonising the EU Economy in the Time Horizon to 2050. *Energy Strategy Rev.* **2012**. [CrossRef]
26. Mullally, G.; Byrne, E. A Tale of Three Transitions: A Year in the Life of Electricity System Transformation Narratives in the Irish Media. *Energy Sustain. Soc.* **2015**. [CrossRef]
27. Antadze, N.; Westley, F.R. Impact Metrics for Social Innovation: Barriers or Bridges to Radical Change? *J. Soc. Entrep.* **2012**. [CrossRef]
28. Schmidt, S.; Weigt, H. Interdisciplinary Energy Research and Energy Consumption: What, Why, and How? *Energy Res. Soc. Sci.* **2015**, *10*, 206–219. [CrossRef]
29. de Leon Barido, D.P.; Avila, N.; Kammen, D.M. Exploring the Enabling Environments, Inherent Characteristics and Intrinsic Motivations Fostering Global Electricity Decarbonization. *Energy Res. Soc. Sci.* **2020**, *61*. [CrossRef]
30. Immink, H.; Louw, R.T.; Brent, A.C. Tracking Decarbonisation in the Mining Sector. *J. Energy S. Afr.* **2018**, *29*. [CrossRef]
31. Leal-Arcas, R. New Frontiers of International Economic Law: The Quest for Sustainable Development. *Univ. Pa. J. Int. Law* **2018**, *40*, 83.

32. Kulovesi, K.; Oberthür, S. Assessing the EU's 2030 Climate and Energy Policy Framework: Incremental Change toward Radical Transformation? *Rev. Eur. Comp. Int. Environ. Law* **2020**, *29*. [CrossRef]
33. International Energy Agency (IEA). *World Energy Outlook 2015*; International Energy Agency: Paris, France, 2015.
34. International Energy Agency (IEA). *World Energy Outlook 2018*; International Energy Agency: Paris, France, 2018.
35. Szczepańska-Woszczyna, K. Strategy, corporate culture, structure and operational processes as the context for the innovativeness of an organization. *Found. Manag.* **2018**, *10*, 33–44. [CrossRef]
36. Saługa, P.W.; Szczepańska-Woszczyna, K.; Miśkiewicz, R.; Chłąd, M. Cost of Equity of Coal-Fired Power Generation Projects in Poland: Its Importance for the Management of Decision-Making Process. *Energies* **2020**, *13*, 4833. [CrossRef]
37. Kinelski, G. The main factors of successful project management in the aspect of energy enterprises' efficiency in the digital economy environment. *Energy Policy J.* **2020**, *23*, 5–20. [CrossRef]
38. Sadik-Zada, E.R.; Gatto, A. The Puzzle of Greenhouse Gas Footprints of Oil Abundance. *Socio-Econ. Plan. Sci.* **2020**. [CrossRef]
39. Sadik-Zada, E.R. Distributional Bargaining and the Speed of Structural Change in the Petroleum Exporting Labor Surplus Economies. *Eur. J. Dev. Res.* **2020**, *32*, 51–98. [CrossRef]
40. Engel, H.; Purta, M.; Speelman, E.; Szarek, G.; van der Pluijm, P. *Carbon-Neutral Poland 2050. Turning a Challenge into an Opportunity*; McKinsey Company: Warsaw, Poland, 2020. Available online: https://www.mckinsey.com/pl/~{}/media/mckinsey/locations/europeandmiddleeast/polska.raporty/carbonneutralpoland2050/carbonneutralpoland_mckinseyreport.pdf (accessed on 1 February 2021).

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Article

Central and Eastern European CO_2 Market—Challenges of Emissions Trading for Energy Companies

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Abstract: The aim of this article was to identify challenges of emissions trading that the Polish and CEE Central and Eastern Europe energy industry will face, as well as to indicate key implications for the competitiveness of the companies from the energy sector resulting from that trading. The EU Emissions Trading Scheme (ETS) is the emissions trading system, which results from the EU policy concerning climate change. It is a tool for reducing greenhouse gas emissions (GHG). The system regulates an annual allocation of the allowances. The price of CO_2 emission allowances is subject to constant fluctuations because it depends on various macroeconomic factors as well as is an effect of proprietary trading by global investment banks. Polish energy companies have an increasing share in the emission of CO_2 in the European market. This is due to the fact that other European countries are rapidly moving away from fossil fuel-fired sources. The cost per MWh related to CO_2 price has been growing in the last 10 years from ca. 5 up to 30 EUR/MWh at the beginning of 2021. From an electric power utilities perspective, the ability to set up a proper strategy in trading CO_2 will be crucial to be competitive in the wholesale power market. The higher price of CO_2 (and electric power) at the domestic market in relation to more green (more renewable energy sources RES in energy mix) surrounding countries translates into a worse competitive position.

Keywords: EU ETS; CO_2; emissions trading; energy companies from Central and Eastern Europe

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1. Introduction

The EU ETS is the emissions trading system, which results from the EU policy concerning climate change [1]. It is the key tool for reducing greenhouse gas emissions (GHG). It contributes to achieving the EU's target of cutting GHG emissions [2].

The system regulates an annual allocation of the allowances. Under it the European Union has committed to reducing GHG emissions successively in subsequent periods: Phase I (2005–2007), phase II (2008–2012), phase III (2013–2020), and IV (2021–2030). The emissions trading system has been widely discussed in the scientific literature [3–10]. The authors introduced the present status and process of changing the EU Emissions Trading Scheme (ETS) and the market mechanisms and instruments for CO2 EA [3–10]. In some of those articles, the models have been built to predict behavior and changes in this market [3,4,8–10]. Some take the perspective of the post-Kyoto agreement [3]. The addressees of the research are also different: Some research is aimed at decision-makers creating institutional operating conditions [3,7,9]. Others take a more entrepreneurial point of view, regarding corporate CO2 strategies [5,6].

The EU ETS functions in the 31 countries of the European Economic Area (EEA). It limits emissions from nearly 11,000 power plants and manufacturing installations as well as over 500 aircraft operators flying between EEA's airports. According to the EU Commission, it covers around 39% of the EU's GHG emissions [2].

The EU ETS system is now in phase III which has different rules than phases I and II. First of all, the previous national caps system on emissions was replaced by a single

EU-wide cap. As a result, the primary method of allowances' allocation is auctioning, instead of the free allocation used before. Enterprises have to buy emission allowances on the market according to their demand. The total number of allowances is limited every year so that allowances have a price that is valued by the market. According to the EU administration, "Trading brings flexibility that ensures emissions are cut where it costs least to do so. A robust carbon price also promotes investment in clean, low-carbon technologies" [2].

The importance of trading CO_2 emissions is directly related to the cost of electricity at the wholesale market. For example, when a coal-fired power plant produces electricity, the cost of CO_2 at the beginning of 2021 is almost half of the price. In the long run, very high electricity prices translate into the worse competitive position of the whole country's economy. So-called heavy industries like steel production, car production, or manufacturing, in general, will change the location of the factories [11].

The share of Polish emissions in the EU is growing, while at the same time the total volume of emissions is decreasing. It is caused by the fact that, while other countries such as Germany, the Netherlands, and Italy are moving away from fossil fuel-fired sources, emissions in Poland have seen little change. As a result of that, the Polish and Central and Eastern Europe CEE energy industry will face several challenges concerning emissions trading. This article aimed to identify these challenges faced by the Polish and CEE energy industries. Until now, the majority of articles have mainly taken into account the prospect of decision-makers, which could be identified with a macro perspective [4]. This paper aimed to contribute to the existing knowledge concerning the EU emissions trading system bearing in mind the perspective of energy companies from CEE, i.e., the micro context. Therefore, in the beginning, a literature review was conducted to identify the current research on CO_2 emissions allowance (CO_2 EA) trading. Then, the CO_2 emissions market was analyzed and a critical analysis of literature was carried out to isolate the factors that can affect the trading conditions and the price of CO_2 EA. Finally, the case study of PKN Orlen, which is the biggest company in the CEE region, listed on the Fortune 500, was examined. This paper aimed to contribute to the existing knowledge concerning the EU emissions trading system, taking into account the perspective of companies.

2. CO_2 Emissions—Poland and CEE Countries

As part of the European Green Deal, the commission proposed in September 2020 to raise the 2030 greenhouse gas emission reduction target, including emissions and removals, to at least 55% compared to 1990. The commission has a plan to come forward with the proposals by June 2021. The previous target for 2030 GHG emissions was to cut them by 40% [2].

Figure 1 shows greenhouse gas emission targets and trends for EU countries according to MMR (Monitoring Mechanism Regulation)projections [12]. In the nearest future, further reductions in greenhouse gas emissions are expected partially because of the COVID-19 crisis; however, increased energy efficiency and renewable energy use are required across all sectors.

Poland, the largest economy of Central Eastern Europe is one of the European Union's largest emitters of carbon dioxide, following countries such as Germany, the United Kingdom, France, and Italy.

Figure 2 illustrates the emissions of the EU as well as CEE countries and Poland [13]. It has to be mentioned that the rate of reduction of EU emission has slowed down in the period 2014–2018 compared to previous years.

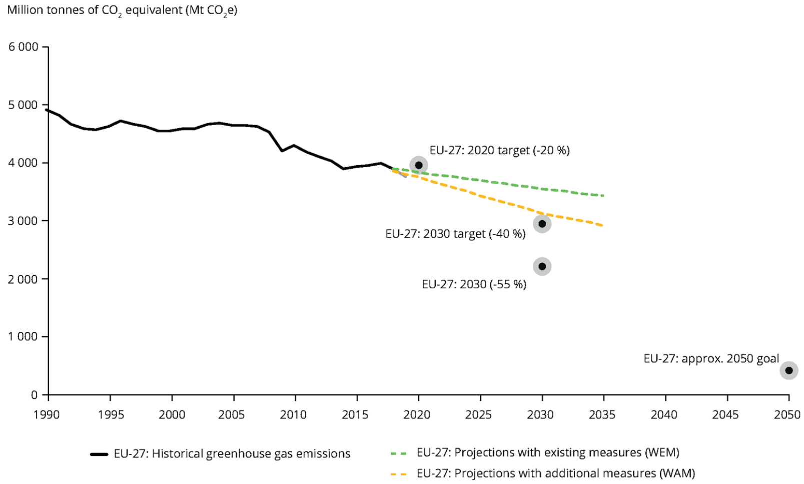

Figure 1. Greenhouse gas emission targets and trends for the EU-28 Member States (EU-28 and after 2020 EU-27) according to MMR (Monitoring Mechanism Regulation)projections (million tonnes of CO_2). Source: European Environment Agency (EEA) (2020).

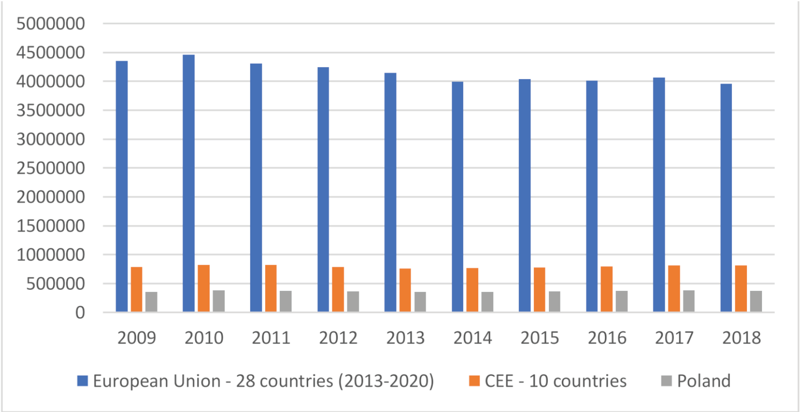

Figure 2. Greenhouse gases—total (CO_2, N_2O in CO_2 equivalent, CH4 in CO_2 equivalent, HFC in CO_2 equivalent, PFC in CO_2 equivalent, SF6 in CO_2 equivalent, NF3 in CO_2 equivalent) (thousand tonnes of CO_2). Source: Own calculations based on Eurostat database (2020).

The EU-28 is the abbreviation of the European Union (EU) which consists of a group of 28 countries (Belgium, Bulgaria, Czech Republic, Denmark, Germany, Estonia, Ireland, Greece, Spain, France, Croatia, Italy, Cyprus, Latvia, Lithuania, Luxembourg, Hungary, Malta, Netherlands, Austria, Poland, Portugal, Romania, Slovenia, Slovakia, Finland, Sweden, and the United Kingdom). CEE is the abbreviation for a group of countries which consist of Bulgaria, the Czech Republic, Estonia, Hungary, Lithuania, Latvia, Poland, Romania, Slovenia, and Slovakia.

The most significant sector in terms of emissions is commercial power engineering: Commercial power plants, combined heat and power plants, and heating plants. Figure 3 and Table 1 depicts greenhouse gas emissions from the energy sector in UE, CEE and Poland.

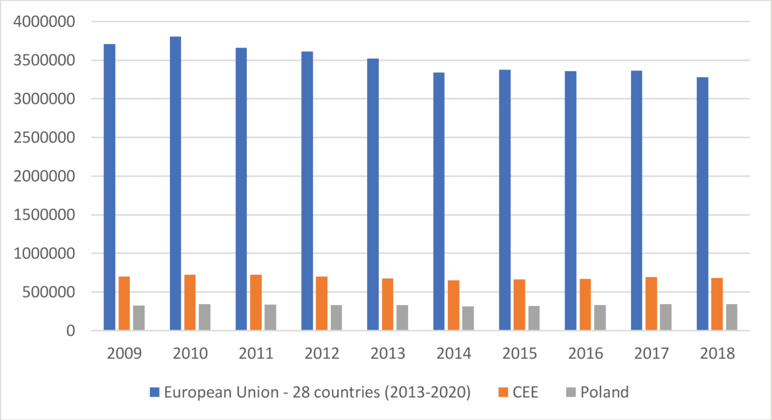

Figure 3. Greenhouse gases—energy (CO_2, N_2O in CO_2 equivalent, CH_4 in CO_2 equivalent, HFC (Hydrofluorocarbon) in CO_2 equivalent, PFC (Perfluorocarbons) in CO_2 equivalent, SF6 in CO_2 equivalent, NF3 in CO_2 equivalent) in thousand tonnes. Source: own calculations based on Eurostat database (2020).

Table 1. Greenhouse gases—total and in energy sector (CO_2, N_2O in CO_2 equivalent, CH_4 in CO_2 equivalent, HFC in CO_2 equivalent, PFC in CO_2 equivalent, SF6 in CO_2 equivalent, NF3 in CO_2 equivalent) in thousand tonnes.

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018
Total									
EU	4464 048	4308 864	4244 734	4145 286	3990 237	4033 917	4013 970	4063 118	3953 006
CEE	18%	19%	18%	18%	19%	19%	20%	20%	20%
Poland	8%	9%	9%	9%	9%	9%	9%	9%	9%
Energy									
EU	3807 924	3657 507	3614 453	3521 931	3337 425	3377 394	3356 515	3362 611	3279 195
CEE	19%	20%	19%	19%	20%	20%	20%	21%	21%
Poland	9%	9%	9%	9%	9%	9%	10%	10%	10%

Source: Own calculations based on Eurostat database (2020).

In 2018, the 30 highest emitting power plants alone were responsible for emitting 30% of the total combustion emissions. The top-emitting power plants are located mainly in Poland and Germany. The largest emitter of all the EU ETS installations is the lignite-fired power plant in Bełchatów, Poland, which emitted 38.3 $MtCO_2$ in 2018 [14].

The power plants from CEE countries that were among the 30 highest emitting power plants in the EU in 2018 are listed in the Table 2 [14].

Polish power plants, including Kozienice (hard coal), Połaniec (hard coal), Turów (lignite), Rybnik (hard coal) and Opole (hard coal), as well as Bełchatów (lignite), account for 23% of the emissions from this top 30 list of installations [14]. Most of the biggest emitters in the EU are already planned to be decommissioned by the end of 2040. As mentioned earlier, the EU Commission plans to achieve a zero net carbon footprint by 2050 [2]. The shift from fossil fuels to green electricity will take decades. However, Germany, which has consistently been the EU's biggest emitter of carbon dioxide (CO_2) emissions, has a long-term strategy to decrease emissions faster than other neighboring countries, and especially faster than Poland. From an economic perspective, it means that Germany will gain a more competitive advantage because of the cheaper electricity for final customers (business users). A long-term strategy for electric utilities should be focused on how to decrease emissions (average per MWh and in total) in the shortest time possible. From the buyers' perspective, it is very important to do the pricing of the emission allowances. The accurate forecast of the CO_2 prices is one of the most important things in large scale utilities that have exposure to CO_2 prices.

Table 2. Power plants from CEE countries that were among the 30 highest emitting power plants in the EU in 2018.

Power Plant	Fuel	Installed Capacity 2018 (MV)	Verified Emissions 2018 Mt CO_2	Verified Emissions 2018 vs. 2017 (%)
Bełchatów (PL)	Lignite	5472	38.3	2%
Kozienice (PL)	Hard coal	2941	9.7	−13%
Maritsa East 2 (BG)	Lignite	1604	9.6	−9%
Połaniec (PL)	Hard coal	1882	8.2	17%
Narva (EE)	Oil Shale	1369	7.8	−7%
Opole (PL)	Hard coal	1532	7.5	19%
Turów (PL)	Lignite	1488	6.9	−3%
CEZ a.s. (CZ)	Lignite	930	5.5	−2%
Oddział w Rybniku (PL)	Hard coal	1790	5.2	−19%
Mátrai Eromu ZRt (HU)	Lignite, Natural Gas	950	5.2	−9%

Source: Healy; Graichen; Graichen; Nissen; Gores; Siemons. Trends and projections in the EU Emissions Trading Scheme (ETS) in 2019, the EU Emissions Trading System in numbers, and European Topic Centre on Climate Change Mitigation and Energy, 2019.

3. CO_2 Emissions Allowance (CO_2 EA) Trading—Literature Review

In order to identify all the challenges faced by the Polish and CEE energy industries, the literature review had two goals: To diagnose the CO_2 emissions market in Poland and CEE countries, as well as to identify determinants for the price of the CO_2 emission allowances.

Understanding the classification of emission allowances and emission allowance prices and the methods of their modeling, and above all, the determinants that researchers introduced into the models (considering them important) is of fundamental importance for understanding the challenges faced by the Polish and EU energies industries.

Therefore, the literature review conducted below is aimed at identifying in the existing studies all kinds of factors that have an impact on emission allowance prices. Every single factor identified in this way may pose a potential challenge for companies in the energy sector. What is more, some of the factors may have been underestimated or not taken into account at all when considering the competitiveness of companies in this sector.

3.1. Classification of Emission Allowances and Emission Allowance Prices

Benz and Trück [15] indicated that the emission allowances are not the "normal goods", i.e., classical resources. Demand (the price) for the "normal goods" depends on the profit that is expected from the usage of those goods. However, allowance price depends directly on the expected market deficiency resulting from the imbalance of current demand and supply. That is why CO_2 emission allowances are specified rather as "factors of production". Companies may decide to change the method of production to reduce CO_2 emissions and thus control their demand (and have a real impact on the price of emission allowances, i.e., less demand–lower allowance price). It means that companies have a significant impact on market liquidity and price dynamics.

It should be remembered that the annual numbers of allowances are limited according to the EU Directives. As there is a ban for intertemporal banking of allowances, they become worthless at the end of each ban period.

The emissions hence become either an asset or a liability for the obligation to deliver allowances to cover those emissions. Accordingly, it seems more adequate to compare the right to emit CO_2 with other operating materials or commodities than with a traditional equity share [15].

The prices of emission allowances are subject to constant fluctuations. Until 2018 (years 2012–2017), these fluctuations were in the range between 2 to 10 EUR. There was a sharp increase in the prices in 2018—up to 25 EUR. In the years 2019–2020, prices have shown a much greater amplitude of fluctuations—between 15 and 30 EUR. Details of the prices of CO_2 emission allowances in 2012–2020 are shown in Figure 4.

Figure 4. The prices of CO_2 emission allowances in 2012–2020 (EUR/t). Source: own analysis based on the data from CIRE, https://www.cire.pl/ [16].

EU allowances (EUAs) are expected to average 37.86 in 2021 and 41.61 EUR/t in 2022 [17]. In 2030 expected prices are 80 and 120 EUR/t in 2040.

As the emission allowances are an important factor of production, the prediction of their prices is crucial for many industries—both in short and in long terms. Unfortunately, according to Borak et al. [18], the literature on the EU-ETS and price behavior or hedging with CO_2 spot or futures contracts is very sparse.

In the literature, we can find various models regarding directly or indirectly the CO_2 emission allowance price. Two main types of models can be distinguished: Models in which the CO_2 emission allowance is a determinant influencing the broadly understood energy market [19], and models where the main goal is to analyze the CO_2 emission allowance price and the determinants that influence this price [20,21].

According to Bariss et al. [22] integration of energy supply within the European system aims at improving the security of power supply, but at the same time, it makes forecasting the CO_2 emission (both amount and price) more complicated.

Bariss et al. [22] estimated the carbon market effect (including CO_2 emissions allowance) on power prices by the method of multiple regression analysis. In those models, the CO_2 emission allowance price is characterized as a "vary changing variable" so the monthly average of a daily closing price has been taken to the model. In addition, Daskalakis et al. [23] indicated that emission allowance spot prices are likely to be characterized by jumps and non-stationarity.

Boersen and Scholtens [24] investigated how electricity markets are related to CO_2 emission allowance prices. They used the generalized autoregressive conditional heteroskedasticity (GARCH) model.

Criqui et al. [25] analyzed the operation of a tradable emission permit market between states in a competitive environment, the price of the permit, and the marginal abatement costs exchanges level. The POLES (Prospective Outlook on Long-term Energy Systems) model was used. Authors confronted their research with the MIT's Joint Program on the Science and Policy of Global Change [26], within which the general equilibrium model of global economic activity, energy use, and carbon emissions were analyzed with the usage of the emissions prediction and policy assessment (EPPA) model. In this article, two models (POLEC and EPA) were compared.

It is worth mentioning that many other researchers also constructed models for describing the emission allowance price dynamics. For example, Chesney and Taschini [27] used the model with the assumption of the potential presence of asymmetric information in the market; Benz and Trück [15] used a regime-switching model to describe the dynamics emission allowance spot prices; Chang-Yi Li et al. [20] used a regime-switching jump-diffusion model (RSJM) with a hidden Markov chain to capture not only a volatility clustering feature but also the dynamics of the spot EUA returns; Paolella and Taschini [28] used a parametric GARCH model for the analysis of emission allowance spot market returns; Carmona and Hinz [29] developed a risk-neutral reduced-form model for allowance futures prices; Isenegger et al. [30] developed models for the pricing of exotic option contracts based on observed carbon spot and futures prices. They used the standard of the GARCH model.

The above-mentioned models differ significantly from each other. They use different assumptions, different determinants (drivers), and thus different databases. They are based on a variety of econometric tools. Their goals are also varied. In the next section, groups of determinants and drivers that affect the price of CO_2 emissions are identified.

3.2. Determinants for the Price of the CO_2 Emission Allowances

Costs of CO_2 are directly correlated with wholesale energy prices for countries based on fossil-fuels. The higher purchasing cost of CO_2 means a higher cost of electricity at power exchanges. The emissivity of the generating units concerned then manifests itself in increasing CO_2 costs. For example, lignite power plants emit approx. 1100, hard coal power plants approx. 930–950, and gas power plants approx. 500–600 kg/MWh. The higher the share of coal in the energy mix, the higher the purchase costs of CO_2, and therefore of electricity. When adopting a long-term strategy, one should take into account the development of emission allowance prices until 2030 and 2040.

The most frequently mentioned determinants that affect CO_2 emission allowance price are those connected with the electricity and resources related to the production of energy [22]. According to Boersen and Scholtens [24], nine sectors are the subject of the EU ETS (i.e., are involved in CO_2 emission), but 70% of the permits go to combustion installations, mainly in the energy sector. That is why the main important determinants are those connected with electricity production, especially with the costs, such as supply and demand for energy or the prices of natural resources (coal, oil, gas).

Boersen and Scholtens [24] stated that not only are the prices of natural resources important, but also the switching possibilities between gas and coal for electricity generation.

Technologies used to produce energy in the local and regional markets are also of great importance. For example, the price of CO_2 emission allowance significantly affects the production of one MWh of energy produced from hard coal, lignite, or gas, but not using the solar, biomass, or wind technology [22].

The price of CO_2 emission allowance depends strictly on the demand for such emissions, and this directly depends on macroeconomic factors. The higher the global economic growth, the greater the gross domestic product growth, the decrease in unemployment, the increase in investment, etc., the higher the demand for CO_2 emissions. Such research was conducted by Barassi and Spagnolo [31]. They provided some empirical evidence on the causality links between per capita CO_2 emissions and economic growth both in the short and long term.

There is no consensus among researchers whether the weather affects the emission and the price of CO_2 emission. Convery and Redmund [32] suggested that weather was not a major factor, in contrast with for example Rickels et al. [33] and Alberola et al. [34]. For them, low temperatures determine the demand for power, as well as for CO_2 emission allowance.

Not only market factors, such as energy production costs or production factors prices, affect the prices of CO_2 emission. Institutional factors are equally important determinants. Benz and Trück [9] categorize the principal determinants for market and institutional ones (policy and regulatory issues). The supply of CO_2 allowances depends on policymakers and their political decisions.

For some researchers [35] due to the strong financialization of the market, the CO_2 emission allowance becomes a financial instrument and their prices depend on the situation on the financial market. Since the financial crisis of 2007–2008, the majority of the investment banks do not trade physical energy commodities as they used to do before. However, they are allowed to trade financial products such as CO_2 emissions.

Taking into account the case of Poland, Krawiec [36] analyzed the monthly reports of the National Center for Balancing and Management of Emissions for 2013–2016. The analysis showed that the most common growth factors in the price of allowances in Poland were:

- Increase in prices of energy carriers;
- Increase in electricity prices;
- Good situation on financial markets;
- Favorable macroeconomic situation;
- The approaching end of the billing period;
- Plans to increase emission reductions (tightening reduction targets);
- Lower supply of energy from renewable sources;
- Reduction of subsidy for renewable energy;
- Higher costs of reducing CO_2 emissions (including replacement costs low-emission);
- Weather conditions (e.g. extreme temperatures, such as hot summers, cold winters) translating into the demand for electricity (cooling/heating);
- The introduction of backloading options/introduction of MSR (Market Stability Reserve);
- Reduction of the number of auctions;
- Delay in issuing free allowances/reduction of the pool of free allowances.

In conclusion, the drivers that affect the price of CO_2 emission allowance can be divided into the following groups:

- Electricity production costs;
- Energy price;
- Fossil fuel price;
- Technologies for power production;
- Demand and supply of electricity;
- Macroeconomic factors;
- Financial factors;

- Institutional issues (policy and regulatory issues);
- Weather condition.

A complete analysis of the groups of factors and individual drivers that determine the CO_2 emission allowances price is presented in Table 3.

Table 3. Determinants and drivers of the CO_2 emission allowances price according to conducted literature review.

Group of Determinants	Drivers	Example of References
Electricity production costs	Price of technologies Price of resources Marginal energy carrier costs	Bariss et al. [22] Boersen and Scholtens [24] Chung et al. [37] Böing and Regett [38]
Energy price	Global and local relations between energy supply and energy demand Local energy taxes	Hammoudeh [39] Bredin and Muckley [40] Reinaud [41] Bunn [42] Keppler [43] Sadorsky [44] García–Martos et al. [45]
Fossil fuel price	Price of carbon Price of oil Price of gas The switching possibilities between gas and coal for electricity generation	Bariss et al. [22] Boersen and Scholtens [24] Mansanet–Bataller, Pardo, Valor [46] Chevallier and Carbon [47] Rickels et al. [33] Convery and Redmund [32] Chung et al. [38] Seifert et al. [21] Lin and Jia [48]
Technologies for power production	Share of electricity production technologies (fossil fuel versus hydro, nuclear, wind, solar, biomass) Electromobility Investments in the energy sector	Bariss et al. [22] Tucki et al. [49]
Demand and supply of electricity	Internal (regional or local) demand and supply of electricity The seasonal and daily variations of supply and demand	Bariss et al. [22] Seifert et al. [21] Wagner and Uhrig–Homburg [50]
Macroeconomic factors	Economic indicators, e.g., GDP, consumption, unemployment rate, investments, stock market growth	Barassi and Spagnolo [31] Hintermann [51] Chung et al. [38] Seifert et al. [21] Benz and Trück [4] Paramati [19]
Financial factors	Relationship between spot and futures prices returns from various financial investments financialization of the market, e.g., Nordpool and APX-UK spot prices	Benz and Trück [4] Lovcha et al. [35] Gorenflo [52] Dasgupta et al. [53] Niblock and Harrison [54] Ozturk and Acaravci [55] Shahbaz et al. [56] Zhang [57]
Institutional issues (policy and regulatory issues)	State subsidy schemes for power–law system regulations, transaction costs, certified emission reduction, emission of CO2 rate, uncertainties in international agreements, market stability reserve, decisions of the European Commission (e.g., on National Allocation Plans), explicit trading rules (e.g., intertemporal trading), the linkage of the EU ETS with the market of project-based mechanisms	Ellerman et al. [26] Chung et al. [38] Seifert et al. [21] Krawiec [36] Boersen and Scholtens [24] Conrad et al. [58] Benz and Trück [4] De Perthuis and Trotignon [59] Kim et al. [60]
Weather	Atmospheric conditions: Temperature, precipitation, windiness (wind force)	Rickels et al. [33] Alberola et al. [34] Hintermann [52] Seifert et al. [21]

Source: Own study.

The literature analysis identified the main factors that influence the price changes of both energy and CO_2 EA prices. The analysis of those factors can constitute the basis for identifying the challenges faced by both Polish and Eastern European energy companies. The inclusion of those factors in the companies' strategies may determine the competitiveness of these companies in the European market. However, this analysis prompted several reflections:

(1) Most of the factors can be classified as external ones, i.e., those to which the company has to adapt; however, there is no great possibility of influencing them. Such determinants include especially those related to macroeconomic and institutional factors;

(2) It draws attention to the fact that although the drivers include those related to the weather, climate change—one of the main problems of the modern world—was not directly among the problems considered to energy prices and CO_2 EA prices. This factor seems to be definitely underestimated;

(3) It is also characteristic that many drivers/events that lead to the displayed price development are characterized not by a predictable factor, but rather by a "black swan" factor. The COVID-19 pandemic has shown this. The pandemic lockdown has unexpectedly changed energy demand. Such "black swans" can also be violent weather phenomena related to climate change, political phenomena related, e.g., to trade wars between superpowers on world markets, or technological changes. This is an extremely difficult challenge for companies in the energy sector.

4. Case Study of PKN Orlen

PKN Orlen, which is listed at Global 500, is the largest capital group in the "oil and gas" sector that comes from Central and Eastern Europe. In 2019, company revenues amounted to 28,977 million USD and the profit reached 1120.5 million USD [61].

The ORLEN Group operates on six home markets which are Poland, the Czech Republic, Germany, Lithuania, Slovakia, and Canada. The concern is vertically integrated and is exposed to fluctuations in prices of several energy commodities that include crude oil, petroleum products, natural gas, CO_2, electricity, coal, property rights, biomass.

Currently, PKN ORLEN owns combined heat and power units in Płock and Włocławek. Additionally, it has taken over the energy company "Energa", as well as its plans of acquiring Lotos [62] and PGNiG [63] in the nearest future. From the managerial point of view, these acquisitions will be an important step to build a single multi-utility group with a strong position in Europe and global coverage. Taking into account the pan-European market, several key financial hubs where transactions on the CO_2 market are made can be distinguished. The most important of them are London, Amsterdam, and Geneva, followed by Dusseldorf and Frankfurt. As presented above, Polish energy companies and especially PKN ORLEN have an increasing share in the emission of CO_2 in the European market. Due to the fact that other countries, such as Germany, the Netherlands, and Italy, are rapidly moving away from fossil fuel-fired sources, the share of the Polish energy sector will increase in the nearest future. It can be predicted that in the years 2030-2035 it will reach over 20% and after 2040 it will be nearly 30–40% of the EU ETS market [16].

As part of its strategy, PKN Orlen will seek to cut the carbon dioxide (CO_2) emissions from its current refining and petrochemical assets by 20% and emissions of CO_2/MWh from power generation by 33% by 2030, as well as it has aspirations to achieve emission neutrality by 2050 [63].

In the nearest future, PKN ORLEN will have an emission efficiency of 30–40 million tons of allowances per year. With a cost of 30 EUR/tone, the total portfolio may reach 1.2 or 2.5 billion EUR if the issue price in 2030 is 60 EUR/tone. The key issue that should be addressed by the group is how to manage the first-degree margin in the case of generation (gas, coal) and how to buy emission allowances in the cheapest way.

The key players on the market of allowances for emitting carbon dioxide and other greenhouse gases market can be divided into two categories: Utilities and investment banks. This market has a kind of duality. Firstly, one can distinguish the physical CO_2 emission allowances (property rights) that the issuers have to surrender each year. Secondly, there is a whole financial market based on SPOT quotations for physical allowances. It has to be mentioned that there are two main exchanges for these allowances which are intercontinental exchange (ICE) and European energy exchange (EEX). Additionally, there is an over-the-counter OTC market with investment banks. Large investment banks may have open positions reaching even 300–500 million tons of allowances, which is roughly the same as the 10-year demand for allowances of PKN Orlen or Polska Grupa Energetyczna SAPGE. From the point of view of energy companies operating in the region of Central and Eastern Europe, it is difficult to gain a competitive advantage in purchasing allowances without the presence of key hubs. For example, large Polish energy groups should have trading companies at least in London, Amsterdam, and Geneva. That is why a huge challenge for PKN ORLEN will be to create such a business entity.

From PKN ORLEN and other Polish energy groups' perspective, managing the trade and purchase of emission allowances will become key factors affecting their profitability. The indicator that measures the profit of a coal plant is the generation margin called a market spread or clean dark spread (CDS). Coal plant generation margins, commonly referred to as clean dark spread (CDS) or clean spark spread, are driven by the premium of power prices over plant variable operating costs. Variable costs are driven by coal and carbon prices as well as the cost of CO_2 emissions. It means that the cost of CO_2 emissions is a crucial factor affecting the margin of Polish energy groups.

Typically, the commercial strategy of energy groups is based on the simultaneous sale of electricity and the purchase of emission allowances and fuel. However, there are strategies for delaying or accelerating the purchase of emission allowances. For example, it is possible to purchase 10% of the portfolio of emission allowances a few months earlier if the price is low enough. It has to be mentioned that energy companies in the majority of cases realize these actions through dedicated trading companies, such as Enea Trading Sp. z o.o. in Poland. Each trading company has departments that deal with financial risk as well as a trading department that is divided into individual boards. In most cases, the trader has a trading specialization (commodity), such as coal, natural gas, CO_2, and electricity. From a risk management perspective, asset-backed trading should be separated from proprietary trading, which is necessary from the point of view of asset management. This is due to several factors. Firstly, when trading for own account, the trader should anticipate the movements of the competition as well as forecast prices. It has to be underlined that there are psychological differences between speculative trade seeking hedging or speculative gains and trade that has non-speculative reasons [64]. Secondly, the goal of the proprietary trading team is to gain knowledge about competitors on the market and to predict prices. As a result thanks to speculative trading, better forecasts can be built for teams trading capital group assets.

To conclude, after the acquisitions, PKN ORLEN should centralize its commercial activities for the entire group, including Lotos and PGNiG in one trading company. Considering the fact the company operates in the area of crude oil and natural gas, the trading company (or trading branch) should be registered for example in Geneva which remains a trading hub for crude oil. Another crucial issue for PKN ORLEN will be to predict the changes in the price of emission allowances for the needs of trading because these prices are the key factor affecting generation margin.

5. Conclusions

Summarizing this article, it should be stated that the role and importance of emissions trading for companies emitting CO_2 grows with the increase in the cost per MWh. There are three major challenges related to emission trading from electric power utility points of view: Pricing models, qualified traders, location, and organizational structure, as well as lobbying staff.

First of all, as was highlighted in the article, pricing models are an important issue. Major price drivers are linked to regulations given by the European Commission. Pricing the CO_2 market is mostly related to financial derivatives of pricing models. As discussed in the article, predicting the changes of the price of emission allowances for the needs of trading is a very complex process that requires the identification of many determinates that affect this price as well as a quick reaction to their changes. That is why future research should focus on statistical methods such as the latent root analysis to identify the components affecting the allowance price.

Secondly, one of the most important aspects is the human factor. Traders who have a deep understanding of the market and experience in carbon emissions trading are a key point for being successful in hedging margins in the electricity market. There are not many potential employees in the CEE region who are familiar at the same time with proprietary trading and hedging strategies in this particular commodity.

The third challenge is directly related to environmental product trading hubs in Europe and organizational structure. As was highlighted, there is more than one trading location which important in CO_2 trading. The company should be located at least in Geneva, London, and Amsterdam with small local originators. The organizational structure should be smart and flexible to respond fast. Having a team of experienced staff in the CO_2 area can be decisive in gaining a competitive advantage for energy companies.

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References

1. EU ETS Handbook, European Commission. 2010. Available online: https://ec.europa.eu/clima/sites/clima/files/docs/ets_handbook_en.pdf (accessed on 20 November 2020).
2. EU Commission, Report on the Functioning of the European Carbon Market, Brussels. 2020. Available online: https://ec.europa.eu/clima/sites/clima/files/news/docs/com_2020_740_en.pdf (accessed on 20 November 2020).
3. Anger, N. Emission trading beyond Europe: Linking schemes in a Post-Kyoto World. *Energy Econ.* **2006**, *30*, 2028–2049. [CrossRef]
4. Benz, E.; Trück, S. Modeling the price dynamics of CO_2 emission allowances. *Energy Econ.* **2009**, *31*, 4–15. [CrossRef]
5. Christiansen, A.; Arvanitakis, A.; Tangen, K.; Hasselknippe, H. Price determinants in the EU emissions trading scheme. *Clim. Policy* **2019**, *5*, 15–30. [CrossRef]
6. Egenhofer, C. The making of the EU emissions trading scheme: Status, prospects and implications for business. *Eur. Manag. J.* **2007**, *25*, 453–463. [CrossRef]
7. Uhrig-Homburg, M.; Wagner, M. Derivative instruments in the EU emissions trading scheme: An early market perspective. *Energy Environ.* **2008**, *19*, 635–655. [CrossRef]
8. Carmona, R.; Fehr, M.; Hinz, J.; Porchet, A. Market design for emission trading schemes. *SIAM Rev.* **2010**, *52*, 403–452. [CrossRef]
9. Jiménez-Rodríguez, R. What happens to the relationship between EU allowances prices and stock market indices in Europe? *Energy Econ.* **2019**, *81*, 13–24. [CrossRef]
10. Chevallier, J.; Nguyen, D.K.; Reboredo, J.C. A conditional dependence approach to CO_2-energy price relationships. *Energy Econ.* **2019**, *81*, 812–821. [CrossRef]
11. Guðbrandsdóttir, N.H.; Haraldsson, H.O. Predicting the price of EU ETS carbon credits. *Syst. Eng. Procedia* **2011**, *1*, 481–489. [CrossRef]
12. European Environment Agency. Available online: https://europa.eu/european-union/about-eu/agencies/eea_pl (accessed on 20 November 2020).
13. Eurostat Database. Available online: https://ec.europa.eu/eurostat/data/database (accessed on 16 February 2020).
14. Healy, S.; Graichen, V.; Graichen, J.; Nissen, C.; Gores, S.; Siemons, A. Trends and projections in the EU ETS in 2019, The EU Emissions Trading System in Numbers, European Topic Centre on Climate Change Mitigation and Energy. 2019. Available online: https://www.eionet.europa.eu/etcs/etc-cme/products/etc-cme-reports/etc-cme-report-3-2019-trends-and-projections-in-the-eu-ets-in-2019 (accessed on 20 November 2020).

15. Benz, E.; Trück, S. CO_2 emission allowances trading in Europe—Specifying a new class of assets. *Probl. Perspect. Manag.* **2006**, *4*, 30–40.
16. CIRE. Available online: https://www.cire.pl (accessed on 20 November 2020).
17. Reuters. Available online: https://www.reuters.com/article/us-eu-carbon-poll-idUSKBN2711HK (accessed on 25 November 2020).
18. Borak, S.; Härdle, W.K.; Trück, S.; Weron, R. *Convenience Yields for CO_2 Emission Allowance Futures Contracts*; SFB 649 Discussion Paper, No. 2006; SSRN: Rochester, NY, USA, 2006.
19. Paramati, S.R.; Mo, D.; Gupta, R. The effects of stock market growth and renewable energy use on CO_2 emissions: Evidence from G20 countries. *Energy Econ.* **2017**, *66*, 360–371. [CrossRef]
20. Chang-Yi, L.; Son-Nan, C.; Shih-Kuei, L. Pricing derivatives with modeling CO_2 emission allowance using a regime-switching jump diffusion model: With regime-switching risk premium. *Eur. J. Financ.* **2016**, *22*, 887–908.
21. Seifert, J.M.; Uhrig-Homburg, M.; Wanger, M. Dynamic behavior of CO_2 spot prices. *J. Environ. Econ. Manag.* **2008**, *56*, 180–194. [CrossRef]
22. Bariss, U.; Avenitis, E.; Junghans, G.; Blumberga, D. CO_2 emission trading effect on baltic electricity market. *Energy Procedia* **2016**, *95*, 58–65. [CrossRef]
23. Daskalakis, G.; Psychoyios, D.; Markellos, R.N. Modeling CO_2 Emission allowance prices and derivatives: Evidence from the European trading scheme. *J. Bank. Financ.* **2009**, *33*, 1230–1241. [CrossRef]
24. Boersen, A.; Scholtens, B. The relationship between European electricity markets and emission allowance futures prices in phase II of the EU (European Union) emission trading scheme. *Energy* **2014**, *74*, 585–594. [CrossRef]
25. Criqui, P.; Silvana, M.; Laurent, V. Marginal abatement costs of CO_2, emission reductions, geographical flexibility and concrete ceilings: An assessment using the POLES model. *Energy Policy* **1999**, *27*, 585–601. [CrossRef]
26. Ellerman, A.D.; Decaux, A. *Analysis of Post-Kyoto CO_2 Emissions Trading Using Marginal Abatement Curves*; Joint Program Report Series Report 40; Massachusetts Institute of Technology: Cambridge, MA, USA, 1998; pp. 1–24.
27. Chesney, M.; Taschini, L. The endogenous price dynamics of emission allowances and an application to CO_2 option pricing. *Appl. Math. Financ.* **2012**, *19*, 447–475. [CrossRef]
28. Paolella, M.; Taschini, L. An econometric analysis of emission trading allowances. *J. Bank. Financ.* **2008**, *32*, 2022–2032. [CrossRef]
29. Carmona, R.; Hinz, J. Risk-neutral models for emission allowance prices and option valuation. *Manag. Sci.* **2011**, *57*, 1453–1468. [CrossRef]
30. Isenegger, P.; Wyss, R.; Marquardt, S. *The Valuation of Derivatives on Carbon Emission Certificates*; Working Paper; Swiss CFA Society: Zug, Switzerland, 2013.
31. Barassi, M.; Spagnolo, N. Linear and non-linear causality between CO_2 emissions and economic growth. *Energy J.* **2012**, *233*, 23–38. [CrossRef]
32. Convery, F.J.; Redmond, L. Market and price developments in the European Union emissions trading scheme. *Rev. Environ. Econ. Policy* **2007**, *1*, 88–111. [CrossRef]
33. Rickels, W.; Georlich, D.; Oberst, G. *Explaining European Emission Allowance Price Dynamics: Evidence from Phase*; Kiel Working Paper No. 1650; Kiel Institute for the World Economy: Kiel, Germany, 2010.
34. Alberola, E.; Chevallier, J.; Cheze, B. Price drivers and structural breaks in European carbon prices 2005–2007. *Energy Policy* **2008**, *36*, 787–797. [CrossRef]
35. Lovcha, Y.; Perez-Laborda, A.; Sikora, I. *The Determinants of CO_2 Prices in the EU ETS System*; Working Papers 2072/376031; Universitat Rovira i Virgili: Tarragona, Spain, 2019.
36. Krawiec, W. Determinanty cen uprawnień do emisji CO_2 na rynku europejskim w latach 2013–2016. *Finanse, Rynki Finansowe Ubezpieczenia* **2017**, *2*, 231–239. [CrossRef]
37. Chung, C.; Jeong, M.; Young, J. The price determinants of the EU Allowance in the EU emissions trading scheme. *Sustainability* **2018**, *10*, 4009. [CrossRef]
38. Böing, F.; Regett, A. Hourly CO_2 emission factors and marginal costs of energy carriers in future multi-energy systems. *Energies* **2019**, *12*, 2260. [CrossRef]
39. Hammoudeh, S.; Nguyen, D.K.; Sousa, R.M. Energy prices and CO2 emission allowance prices: A quantile regression approach. *Energy Policy* **2014**, *70*, 201–206. [CrossRef]
40. Bredin, D.; Muckley, C. An emerging equilibrium in the EU emissions trading scheme. *Energy Econ.* **2011**, *33*, 353–362. [CrossRef]
41. Reinaud, J. *CO2 Allowance & Electricity Price Interaction*; IEA: Paris, France, 2007.
42. Bunn, D.W.; Fezzi, C. *Interaction of European Carbon Trading and Energy Prices*; Working Paper No. 63; FEEM: Milano, Italy, 2007.
43. Keppler, J.H.; Mansanet-Bataller, M. Causalities between CO_2, electricity, and other energy variables during phase I and phase II of the EU ETS. *Energy Policy* **2010**, *38*, 3329–3341. [CrossRef]
44. Sadorsky, P. Correlations and volatility spillovers between oil prices and the stock prices of clean energy and technology companies. *Energy Econ.* **2012**, *34*, 248–255. [CrossRef]
45. García-Martos, C.; Rodríguez, J.; Sánchez, M.J. Modelling and forecasting fossil fuels, CO_2 and electricity prices and their volatilities. *Appl. Energy* **2013**, *101*, 363–375. [CrossRef]
46. Mansanet-Bataller, M.; Pardo, A.; Valor, E. CO_2 prices, energy and weather. *Energy J.* **2007**, *28*, 67–86. [CrossRef]
47. Chevallier, J. Carbon futures and macroeconomic risk factors: A view from the EU ETS. *Energy Econ.* **2009**, *31*, 614–625. [CrossRef]

48. Lin, B.; Jia, Z. Impacts of carbon price level in carbon emission trading market. *Appl. Energy* **2019**, *239*, 157–170. [CrossRef]
49. Tucki, K.; Orynycz, O.; Świć, A.; Mitoraj-Wojtanek, M. The development of electromobility in poland and EU States as a tool for management of CO_2 emissions. *Energies* **2019**, *12*, 2942. [CrossRef]
50. Wagner, M.W.; Uhrig-Homburg, M. Futures price dynamics of CO_2 emission certificates—An empirical analysis. *J. Deriv.* **2006**, *17*, 73–88.
51. Hintermann, B. Allowance price drivers in the first phase of the EU ETS. *J. Environ. Econ. Manag.* **2010**, *59*, 43–56. [CrossRef]
52. Gorenflo, M. Futures price dynamics of CO_2 emission allowances. *Empir. Econ.* **2013**, *45*, 1025–1047. [CrossRef]
53. Dasgupta, S.; Laplante, B.; Mamingi, N. Pollution and capital markets in developing countries. *J. Environ. Econ. Manag.* **2001**, *42*, 310–335. [CrossRef]
54. Niblock, S.; Harrison, J. Do dynamic linkages exist among European carbon markets? *Int. Bus. Econ. Res. J.* **2012**, *11*, 33–44. [CrossRef]
55. Ozturk, I.; Acaravci, A. The long-run and causal analysis of energy, growth, openness and financial development on carbon emissions in Turkey. *Energy Econ.* **2013**, *36*, 262–267. [CrossRef]
56. Shahbaz, M.; Hye, Q.M.A.; Tiwari, A.K.; Leitão, N.C. Economic growth, energy consumption, financial development, international trade and CO_2 emissions in Indonesia. *Renew. Sustain. Energy Rev.* **2013**, *25*, 109–121. [CrossRef]
57. Zhang, Y. The impact of financial development on carbon emissions: An empirical analysis in China. *Energy Policy* **2011**, *39*, 2197–2203. [CrossRef]
58. Conrad, C.; Rittler, D.; Rotfuss, W. Modeling and explaining the dynamics of European Union allowance prices at high-frequency. *Energy Econ.* **2012**, *34*, 316–326. [CrossRef]
59. De Perthuis, C.; Trotignon, R. Governance of CO_2 markets: Lessons from the EU ETS. *Energy Policy* **2014**, *75*, 100–106. [CrossRef]
60. Kim, H.; Kim, M.; Kim, H.; Park, S. Decomposition analysis of CO_2 emission from electricity generation: Comparison of OECD countries before and after the financial crisis. *Energies* **2020**, *13*, 3522. [CrossRef]
61. Fortune. 2020. Available online: https://fortune.com/fortune500/ (accessed on 23 December 2020).
62. EU Commission. Available online: https://ec.europa.eu/commission/presscorner/detail/en/IP_20_1346 (accessed on 27 December 2020).
63. PKN ORLEN. Available online: https://www.orlen.pl/EN/InvestorRelations/Pages/default.aspx (accessed on 27 December 2020).
64. Barberis, N. Psychology-based models of asset prices and trading volume. In *Handbook of Behavioral Economics: Applications and Foundations*; Elsevier: Amsterdam, The Netherlands, 2018; Volume 1, pp. 79–175.

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Energy Consumption in Central and Eastern Europe (CEE) Households in the Platform Economics

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Abstract: The ongoing digitization of the economy has led to the creation and functioning of platform model socio-economic systems. It is also reflected in the changes in patterns of energy consumption in households. In the first cross-section, it is an industrial revolution, with environmental benefits. However, platforms are primarily a revolution in the consumption sphere, and here, the effects of digitization are not fully recognized. Our social needs are increasingly met "through accessibility" without us leaving our home. Due to the home's multifunctionality, based on the availability of platform services, household energy consumption should be viewed differently today than before. The article aims to show the changes in Central and Eastern Europe (CEE) household energy consumption between 2008–2018 and their assessment through the prism of the economy's platformization methods. The study presents the changes in energy consumption in households and determines the correlations between platformization (the author's index) and changes in energy consumption in households with the use of taxonomic methods. The platformization leaders—Estonia and Lithuania—were subjected to a more detailed analysis. The presented method(s) may be useful in predicting the changes in households' energy consumption caused by the digitization of other countries in the region (countries under transformation and outsiders-Bulgaria, Romania), in implementing household energy management systems, and in a better adjustment of regulations directed at these consumers.

Keywords: households; energy consumption; platform

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1. Introduction

The socio-economic systems of the current platform business model are a consequence of continuous digitization of the economy [1]. Platforms help the market forces of supply and demand work together. In the first cross-section, we are dealing with an industrial revolution (industry 4.0). Less energy and natural resources consumed and fewer greenhouse gases emitted are just a few of the environmental benefits [2–6]. Here platforms primarily revolutionize consumers' market, so the effects of digitization are not fully recognized. This reduced level of resource consumption broadly affects socio-economic activity, that is the consumption of energy. The emphasis is attached to the energy-intensive industry and transport sectors [7–11]. Yet digitization has brought about significant changes to both the labor market [12–14] and the way we live [15,16]. Thanks to digital competencies and advances in technology, work environments are becoming more virtual. These virtual offices are supported by both open or closed platforms. Due to the different activities that take place in the modern residence, the energy consumption in today's households should be viewed differently than in the industrial era. The problem gained importance by 2020. The COVID-19 pandemic has significantly changed socio-economic life, with households wired for digital platforms that will take an increasing share of energy consumption.

The issues of energy consumption in households are not new [17,18]. There is plenty of space in the subject literature dedicated to them in the context of digitization [19].

The literature indicates the household is better and better equipped with digital consumer devices (e.g., personal computers, mobile phones, TV sets, and home entertainment systems [20], it also shows the increasing energy efficiency of these devices [21] and the optimization of energy consumption [22]. The considerations disregard the digital competences which, when better developed, allow us to understand how to implement and operate energy-efficient digital household solutions based on platforms. The article aims to try to show the changes in energy consumption in households in 2008–2018 in Central and Eastern Europe (CEE) countries, and, using taxonomic methods, to identify the correlation between energy consumption and platform adoption by these economies.

The article begins with the literature review that consists of three steps: (1) the platforms' specificity, (2) key factors influencing the amount of energy consumption in households, (3) digitization versus location's multifunctionality. It aims to show how the residence's multifunctionality which is continuously growing thanks to platforms can affect the energy consumption in households.

In the context of changes in energy models, it is subject to debate what has a greater role: technologies or behavioral factors [23]. The influence of behavioral and technological factors is not linear [24]. Our activities are often routine and our practices are interrelated [25]. Similar observations result from digital competences.

The third section is methodological. For the purposes of this article, we constructed an indicator of economic platformization. Synthetic indicators of the digitization of the economy and society are encountered in practice. They are based on indicators of the availability of digital infrastructure and digital competences (e.g., DESI [26] and IMG [27]). In contrast, the proposed platformization indicator is based on the actual use of platform tools, and not only their availability, in three sections: society, economy, and administration. The platformization index is a new, original research perspective on changes in energy consumption in households.

The taxonomic methods used in the study–section fourth, based on Euclidean distance matrices (EDMs) [28,29], are classified as important data mining techniques [30]. They are used, among others, to study the development of phenomena in spatial terms [31] and to classify objects based on data identifying these objects. Although the first applications of EDMs date back to the 1930s [32], these methods are gaining momentum due to new applications, in particular in research based on machine learning [33,34]. Agglomeration methods made it possible to divide the CEE countries into three groups. Their separation was based on similarities in terms of the interdependencies between the level of platformization and changes in energy consumption in households. The platformization leaders, Estonia and Lithuania, were subjected to a detailed analysis explaining the obtained regularities.

The approach presented may also be useful in (a) predicting changes in household energy consumption caused by digitization, (b) implementing energy management systems, and (c) better adjustment of regulations addressed to platform users.

2. Literature Review

2.1. Internet Platforms

The dynamic development of the platform-based economy creates a new landscape for the global economy and affects the lives of citizens around the world [35]. The very term "platform" is defined very differently [36–38]. Gawer [38] defines platforms as evolving organizations or meta-organizations that: (1) bring together and coordinate the activities of constitutive, innovative, and competing agents; (2) create value, generate and use benefits from the supply and/or demand side of the market; (3) are characterized by a modular technological architecture that consists of a core and a periphery [39]. A platform is typically recognized as a set of subsystems and interfaces (in the broader sense, the Internet [40]), that makes up the company's own business ecosystem for customers, partners, programmers, institutions, or is used by them. Platforms operate on the so-called multi-sided market-on multilateral platforms, sometimes referred to as a two-sided market [41]. Platforms are generally recognized as a meeting place that facilitates interactions between individuals [42].

Platforms operate in production and consumers' markets concurrently. In the context of production, we are dealing with the industrial revolution (industry 4.0) [43], according to which the reduction of costs, improvement of efficiency, and quality of products are achieved through automation employing real-time data exchange and artificial intelligence. Industry platforms are open to external connections, which facilitate innovation into their ecosystems [44]. Digital transformation brings environmental benefits such as lower consumption of energy, lower use of natural resources, and reduced greenhouse gas emissions.

Platforms also play an important role in the energy sector [45], most importantly, in the distribution of energy [46]. However, platforms are primarily a revolution in exchange [36]. They completely change how we think, work, and learn. At work and home, we increasingly meet our needs through available and open platforms. The price we pay for it is our data [47]. The more data platforms have about their customers, the more they can offer them. The most famous 1.0 platforms (Amazon, Facebook, and Google) are investing heavily in and developing artificial intelligence and blockchain technologies which are expected to become the basis of 2.0 platforms. Algorithms based on machine learning and deep learning supported by artificial intelligence not only meet our needs to an increasingly better extent but also create them (they know faster and better what we need). To use their services, all you need is the Internet, a computer (more and more often a smartphone), and digital competences. The latter is a set of knowledge, skills, and attitudes necessary for active participation in social life. The Digital Competence 2.0 framework, defined by the European Commission, covers five areas: information and data literacy, communication and collaboration, digital content creation, security, and problem solving [48]. Thanks to them, we navigate through the virtual network provided to us by platforms with growing efficiency.

2.2. Energy Consumption in Household Factors

Households have for a long time been assigned an important role in the implementation of a country's energy policy, in the literature that has been written on the subject, as well as in the economic practice. In the EU, the strategic goal of improved climatic conditions is sought through energy transformation, primarily industry, transport, and construction sectors [49]. In Europe, the housing sector is responsible for approx. 30% of energy consumption and 16% of total CO2 emissions [50]. These values are influenced not only by the state of the construction industry and the energy demand related to its operation (although it is responsible for the most important part of energy consumption in this cross-section [51]) but also by household energy consumption models. The latter, along with technological progress [52], may play an important role in the transition of European economies to the path of sustainable development.

The factors influencing the amount of energy consumption in households are extremely diverse. They are the result of individual decisions made under the influence of socio-economic and contextual conditions. The role of behavioral factors (attitudes, beliefs, norms) is widely recognized in the field of social and environmental psychology [53–57]. It is often emphasized that consumer decisions are often irrational and routine. Their declarations, for example, on the importance attached to the problem of climate change, do not translate into practical actions, such as saving energy or changing the sources of energy [58]. Consumers' environmental "awareness" is important, but not sufficient to implement the principles of sustainable development at the household level [58,59]. Consumers' energy-related behavior is strongly embedded in their environment [60,61]. The latter are sometimes seen through the prism of institutional economics [62]. According to North's approach [63], the institutional environment consists of (a) formal institutions-legal regulations (tax incentives, regulations, standards), (b) informal institutions-customs, culture, fashion (e.g., ecology [64]), and (c) a mechanism for implementing and enforcing formal and informal rules of the game (e.g., enforcement of penalties for air pollution).

In explaining household consumption patterns, much attention is paid to contextual factors. These are permanent or temporary factors influencing the energy usage behavior of individuals or households, specific to place and time of energy consumption [65,66]. The Covid-19 pandemic should be recognized as a contextual factor. Contextual factors play an important role in energy management [67], i.e., ensuring: (a) energy availability, (b) energy security, (c) household energy efficiency. The implementation of the above objectives requires many coordinated actions, such as assessment of the real needs of the household, selection of an energy mix adequate to the needs and possibilities, and monitoring of equipment operation based on safety and efficiency standards in accordance with the country's energy policy [68].

The complexity and interdependence of household energy consumption model factors prompt many authors to treat them holistically and interdisciplinary [17,18,62,69]. One of the most comprehensive and, at the same time, structured classification of factors influencing energy consumption in households is the approach of Frederiks et al. [69]. Individual prognostic factors and situational factors are distinguished in their classification. There are two categories in the first group: (a) socio-demographic factors (e.g., age, gender, education, employment status, household type, or location) and (b) psychological factors (e.g., values, motivation, vulnerability). According to this approach, situational factors, in turn, are legal regulations, available technology, prices, infrastructure, as well as all other unmentioned political, economic, social, and cultural factors influencing the environment. The above-mentioned factors are interdependent and change over time. Household energy consumption models evolve over time [70]. The digital revolution appears to be a substantial driving force behind these changes. In the second decade of the 21st century, attention is paid primarily to the so-called intensifying technologies. They are characterized by wide application (they can be used in various contexts), easy to adapt to individual needs, and practically trouble-free updating [71–73]. The group of important supporting technologies driving the digital economy includes Internet of Things (IoT), cloud computing, artificial intelligence algorithms, robotics, and blockchain.

Digitization has also penetrated individual prognostic factors shaping household energy consumption patterns (see Figure 1). This point of view broadens the holistic approach of Frederiks et al. to include digital components [69]. In the group of socio-demographic factors, these are digital competences-not always dependent on age or education level. Digital competences can be acquired formally through training courses, and informally [74,75]. The daily use of generally available platforms is part of the second source-informal. Research confirms that even using Wikipedia can increase our digital competences [76]. Thanks to them, the Internet and the media are an important source of information. They strongly influence the consumption decisions we make, also in the area of shaping pro-ecological practices [76,77].

Digitization also affects the human psyche. The negative phenomena include computer addiction, Internet addiction, addiction to social networks, cybersickness problems of perception of reality [78,79].

2.3. Digital Transformation of Households

The digital transformation of households has two interdependent dimensions: (a) a technological one, (b) and a social dimension, which are expressed through the growth of digital competencies and the increase of family online daily activity thanks to platforms [80]. The first dimension consists primarily of digital solutions that can lead to a reduction in household energy consumption and a change in their consumption patterns [22,81]. Intensifying technologies play an important role in households' technological digital transformation. IoT-the network of connections between physical objects equipped with sensors enables the data to flow between them.

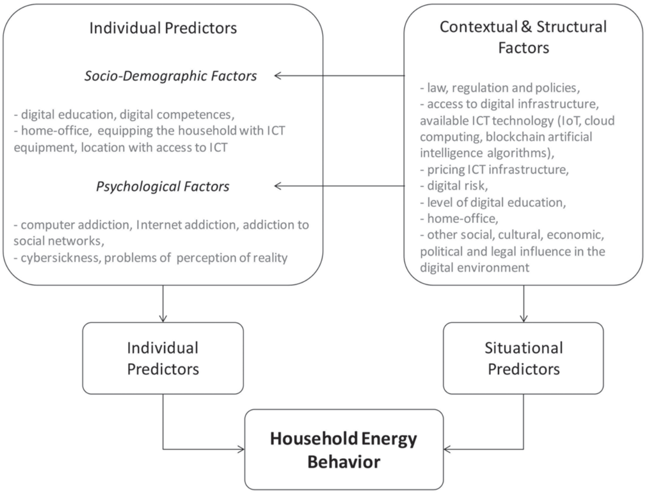

Figure 1. Household energy behavior in the digital era main factors.

The objects that belong to the network identify one another and communicate digitally with other devices-the objects "talk to each other" behind the scenes [82]. Thus IoT technology, supported by artificial intelligence, allows us to monitor all devices that use energy in the household and optimize the energy consumption at the same time [83–85]. The projects implemented in the EU, namely USmartConsumer [86] and E-Balance [87] are good examples thereof. These projects spent significant financial resources to help the end-user [88]. These digital solutions fit into the concept of the so-called "smart homes". Their popularity is largely determined by environmental awareness [89]. The main barriers to the dissemination of this concept (i.e., smart homes), however, are the complexity and variety of systems and their price.

The methods for forecasting household energy consumption are based on new technological possibilities (IoT, cloud computing, algorithms) and disregard the impact of social transformation. They focus on the technological possibilities of the measure only [90]. The social digital transformation before the pandemic was slow. Working remotely was reserved for the so-called liberal professions and not for full-time workers [91]. Digital competences were most often perceived through the prism of institutional solutions-study and work [92]. As a result of the covid-19 pandemic and the need to keep social distance, the social digital transformation has accelerated significantly. During the Covid-19 pandemic, the home has become a workplace for many. An estimated 40% of Europeans have moved to work remotely during the pandemic, while only about 15% had ever done it before its outbreak [93]. Not only work, but also learning takes place online. We satisfy various types of our needs—shopping, entertainment, and social contacts—through publically accessible platforms. The result is a drastic decline in total energy consumption [94,95], its growth in households [96], and, due to it, a noticeable increase in the cost of living for households [97]. Consumption of electricity has become the primary concern. It has been observed in all regions of the world affected by the pandemic [98–100]. Surveys show that the increase in energy consumption in households varies according to their size. In small families-up to 2 members in 2018–2019, this is an increase of approx. 10.8%, 18% in medium-sized families (3–4 people) and as much as 37% in large families (over 4 people) [101]. Research also shows that consumers are afraid of an increase in energy expenditure, especially while there is a decline in their income [102]. With the increasing platformization of the economy, access to household energy, energy management, and its affordability are the elements that are taking on a slightly different meaning than they had in the past [103]. They determine not only the basic conditions of life, but also work, study, and the fulfillment of higher-order needs (e.g., culture).

On the other hand, the accelerated digital social transformation implies a significant increase in digital competences. We increase digital competences not only through remote working and learning but also through routine activities (such as paying bills online). Zoom data shows that from March to April 2020 alone, the daily number of users of this platform increased from 200 to 300 million, compared to about 10 million in December 2019. That's a 30-fold increase in just four months. In turn, Microsoft Teams announced that the user base in April 2020 was 44 million compared to 20 million in March of the same year [104]. Acquiring digital competences does not apply to everyone equally. Their lack may even lead to digital exclusion [105].

3. Data and Methodology

The research methodology consists of three stages.

Stage 1—volatility in household energy consumption in 2008–2018 for the following developed CEE countries: Bulgaria, Estonia, Lithuania, Latvia, Poland, Czech Republic, Romania, Slovakia, Slovenia, and Hungary [29]. A similar level of development allows for a wider inference. The basis of the statistical analysis is the Eurostat database [106]. Due to its limitations (the latest data most often comes from 2018), as well as the possibility of making comparisons of the phenomena included in the study, the analysis covered the years 2008–2018.

The study covered changes in energy consumption in households in general and per capita. Patterns, including similarities and differences between CEE countries, were assessed in a wider context. The benchmark for this assessment was the trends in changes in total energy consumption, energy prices, and the level of socio-economic development of the surveyed countries.

Stage 2—platformization of CEE economies and the amount of energy consumption.

To synthetically assess the level of platformization of the CEE countries, the taxonomic method of the development pattern, initiated by Professor Zdzisław Hellwig [107], was applied. This method is one of the taxonomic methods included in the clustering methods group [29]. It is based on the study of Euclidean distances between the studied objects [108,109]. Taxonomic methods are used to assess the level of differentiation of objects (in this case countries) in terms of the statistical features assigned to them. This approach provides the basis for grouping like objects based on similar properties [110]. Objects that have similar characteristics are grouped in the same group.

The research algorithm categorized the CEE countries into groups (i.e., high, medium, and low) based on their level of economic platformization, using the following approach:

1. Selection of variables. When selecting partial measures, the criteria used in spatial research were taken into account, including (a) significance from the point of view of the analyzed phenomenon and exhausting its scope, (b) maintaining proportionality in the representation of partial phenomena, (c) measurability, availability, and completeness of statistical information.

The degree of platformization of the CEE countries was determined based on the selection of 45 diagnostic variables covering various aspects of digitization, both of society (natural persons) and enterprises. The variables presented both the technical and social dimensions of digitization.

The independence of selected features was set by determining the Pearson linear correlation coefficient (r) between all variables [111]. It is one of the most frequently used coefficients (the correlation coefficient of zero means no relationship between the variables, and the further it reaches +1 or −1, the stronger the relationship between the variables, positive or negative, respectively).

The criterion of a strong correlation of variables was r^3 0,7 (with such a correlation one variable explains 50% of the variability of the other). The application of the above criterion has made it possible to eliminate the mutually strongly correlated features.

As a result of the correlation analysis, 11 variables were omitted in the further study: X4, X5, X7, X12, X15, X20, X30, X33, X34, X37, X43. This meant that a total of 34 variables were used to evaluate the synthetic index, which are presented in Table 1 (their description below the table). As a result of the correlation analysis, 11 variables were omitted in the further study: X4, X5, X7, X12, X15, X20, X30, X33, X34, X37, X43. This meant that a total of 34 variables were used to evaluate the synthetic index, which are presented in Table 1.

Variables description:

X1	Individuals carried out free online training or self-study to improve skills relating to the use of computers, software, or applications in total,
X2	Individuals carried out training paid by themselves to improve skills relating to the use of computers, software, or applications in total,
X3	Enterprises that employ ICT specialists as % of all enterprises without the financial sector, and employing 10 or more people,
X4	The development of web solutions is mainly performed by own employees as % of all enterprises without the financial sector, and employing 10 or more people—omitted in the further study,
X5	Enterprises with e-commerce sales of at least 1% turnover,
X6	Enterprises' total turnover from e-commerce sales,
X7	Use enterprise's blog or microblogs (e.g., Twitter, Present.ly, etc.) (as of 2014),
X8	Use social media to develop the enterprise's images or market products,
X9	Use social media to share opinions of customers,
X10	Involve customers in the innovation of goods or services through social media,
X11	Involve customers in the development or innovation of goods or services through social media,
X12	Enterprises that have ERP software package to share information between different functional areas,
X13	Enterprises that bought cloud computing services,
X14	Enterprises that bought Customer Relationship Management software (as a CC service),
X15	Enterprises analyzing big data from social media,
X16	Individuals used a laptop, notebook, netbook, or tablet computer to access the internet away from home or work,
X17	Individuals used a mobile phone (or smartphone) to access the internet,
X18	Individual's main job tasks changed as a result of the introduction of new software or computerized equipment,
X19	Individuals needed further training to cope well with the duties relating to the use of computers, software, or applications at work,
X20	Individuals' skills correspond well to the duties related to the use of computers, software, or applications at work,
X21	Individuals choosing, modifying, or testing new software or computer equipment at work,
X22	Individuals whose main job tasks changed as a result of the introduction of new software or computer equipment,
X23	Individuals had to learn how to use new software or computer equipment at work
X24	Individuals needed further training to cope well with the duties relating to the use of computers, software, or applications at work,
X25	Individuals used social media at work,
X26	Individuals created or supported IT software or programs,
X27	Individuals used specialized software at work,
X28	Individuals created or edited electronic documents in their work,
X29	Individuals used computers, laptops, smartphones, tablets, or other portable devices at work,
X30	Individuals used computers, laptops, smartphones, tablets, other portable devices, or other computerized equipment or machinery,

X31 Individuals' satisfaction level on the usefulness of available information: greatly satisfied,
X32 Individuals carried out at least one financial activity over the internet,
X33 Individuals used smartphones with some security system, installed automatically or provided with the operating system,
X34 Individuals used smartphones with some security system, installed by them or provided with the subscription,
X35 Individuals already lost information, pictures, documents, or other kinds of data on the smartphone as a result of a virus or other hostile type of programs,
X36 Individuals never restricted or refused access to personal data, when using or installing an app on the smartphone,
X37 Individuals did not know it was possible to restrict or refuse access to personal data when using or installing an app on the smartphone,
X38 Individuals used the internet to interact with public authorities,
X39 Households-level of internet access,
X40 Individuals used computers, laptops, smartphones, tablets, or other portable devices away from home and work,
X41 Internet use: seeking transportation service,
X42 Internet use: seeking housing service,
X43 Internet, phone, video call use,
X44 Individuals using social media (creating profiles, publishing information, posting on Facebook, Twitter, etc.),
X45 Internet use: seeking health information.

2. Standardization [111] of variables performed to obtain the comparability of variables. Standardization was performed using the formula:

$$z_{ik} = \frac{x_{ik} - \overline{x}_k}{S_k};\ S_k = \left[\frac{1}{w}\sum_{i=1}^{w}(x_{ik} - \overline{x}_k)^2\right]^{\frac{1}{2}} \tag{1}$$

where: w–number of units (country) and $i \in 1 \ldots w,\ x_{ik}$–value of the k-th variable in the i-th unit, $\overline{x}_k$–arithmetic mean of the kth variable, S_k–standard deviation of kth variable, z_{ik}–standardized value of k-th variable in i-th unit.

3. Setting a pattern of development P_0-combining all the best features of the surveyed units. The basis for the construction of an abstract pattern of development is a normalized matrix of features (Z). To distinguish the stimulant and destimulant subsets from the set of features (s), the vector P_0 is defined, where:

$$P_0 = [z_{01}, z_{02}, \ldots z_{0s}, \ldots z_{01}],\ z_{0s} = \underset{i}{max} z_{is} \Rightarrow s \in Iz\_0s = (min)iz\_is \Rightarrow s \notin I \tag{2}$$

The diagnosis of the diagnostic variables adopted in the study shows that all of them turned out to be stimulants.

4. Calculation of taxonomic distances between the studied units and the development pattern.

$$c_{i0} = \left[\sum_{s=1}^{n}(z_{is} - z_{0s})^2\right]^{\frac{1}{2}} \tag{3}$$

where: n–number of features, z_{is}–value of the s-th variable in the i-th unit.

Table 1. Diagnostic variables in platformization study of the CEE countries after verification * in 2018.

Kraj	X1	X2	X3	X6	X8	X9	X11	X12	X14	X15	X17	X18	X20	X23	X24	X26	X28	X29	X30	X31	X32	X33	X34	X35	X36	X37	X38	X39	X40	X41	X42	X43	X44	X45
Bulgaria	8	1	20	4	74	21	14	23	2	2	72	12	21	2	35	8	9	11	2	82	4	30	7	6	27	6	25	75	25	2	9	58	53	30
Czechia	24	2	20	32	88	26	21	38	5	3	77	17	15	2	56	23	29	20	5	78	16	27	23	3	46	3	54	87	31	6	5	45	59	56
Estonia	8	1	15	14	93	21	24	26	7	6	80	29	27	12	43	26	30	40	8	94	50	29	13	2	14	4	80	90	33	29	25	53	65	60
Latvia	7	1	20	7	92	26	39	32	3	3	69	11	17	4	51	19	27	20	4	91	30	30	19	3	27	3	70	85	16	8	8	57	65	48
Lithuania	14	2	15	13	81	33	25	48	6	8	76	19	25	6	43	18	19	16	4	91	20	40	6	3	27	9	55	82	28	14	14	61	61	61
Hungary	5	2	26	24	77	20	16	14	5	3	77	20	11	5	46	16	15	29	8	88	11	52	17	8	20	3	53	86	47	6	23	61	69	60
Poland	6	2	23	18	89	23	26	29	3	2	66	16	20	4	43	13	14	18	5	86	7	35	9	4	24	3	40	87	34	7	20	49	53	47
Romania	12	1	10	7	84	18	26	23	-	5	77	18	22	7	21	7	7	10	2	63	2	31	8	4	19	7	12	84	32	4	9	49	60	31
Slovenia	15	3	18	17	70	23	13	33	5	3	79	21	18	9	52	19	27	23	13	92	8	40	7	3	21	6	53	89	22	7	9	42	52	48
Slovakia	12	3	18	21	67	23	18	31	6	3	71	19	18	3	47	10	7	17	2	72	10	31	12	3	21	4	59	82	40	15	21	55	59	53

5. Determining the di * development measure on the basis of taxonomic distances:

$$d_i^* = \frac{c_{i0}}{c_0}, \text{ where } c_0 = \bar{c}_0 + 2S_0,\ \bar{c}_0 = \frac{1}{w}\sum_{i=1}^{w} c_{i0},\ \ S_0 = \left[\frac{1}{w}\sum_{i=1}^{w}(c_{i0} - \bar{c}_0)^2\right]^{\frac{1}{2}} \tag{4}$$

The development index (di) is in the range of 0–1 and the closer the value of the measure approaches zero, the higher the level of development of a given unit. This allows the ranking of the CEE countries according to the degree of development of platformization. This ranking was the basis for the division of the surveyed countries into three groups that differ least in terms of the studied characteristics. A group was selected with a high, medium, and low level of economic platformization. A detailed analysis of the studied regularities is presented based on Lithuania and Estonia.

Stage 3—Lithuania and Estonia-case study taking into account the Global Connectivity Index (GCI) indicator.

The Global Connectivity Index (GCI) indicator was used to conduct a comprehensive approach in assessing the digitization of the economy, including the advancement of the implemented technologies and the possibility of their different impact on the level of energy consumption (also as a result of various digital competences) in countries with the highest level of platformization, namely Lithuania and Estonia [112]. GCI consists of four pillars: the supply of ICT products and services, the demand for these products, the experience of the end-users (individuals and organizations), and the ICT potential. It comprises 40 indicators measuring the impact of ICT on the economy, digital competitiveness, and future growth. Their selection was aimed at capturing the development of ICT and digital transformation in terms of four levels of technology, i.e., broadband, cloud, IoT, and AI. The comparability of indicators between countries was ensured by relating them to the potential of the economy (e.g., GDP), the number of households, or the population. Each indicator is rated on a scale of 1 (low) to 10 (high). The final total GCI level (10–100) is an aggregation of indicators from the four segments indicated above.

Given the above, the analysis of the relationship between platformization and energy consumption in households will be embedded in the differences in the digitization of the different examples of Lithuania and Estonia.

4. Results

4.1. Changes in Household Energy Consumption

The changes taking place in societies and the economy, largely caused by the digital revolution, mean that there are significant shifts in the structure of energy consumption, i.e., between its main consumers. Hence, in the search for answers to the questions posed in the article, it is important to analyze changes in energy consumption in the countries in the study. Among the CEE countries, households account for a significant share of the total energy consumption. In 2018, it ranged from approx. 1/5 of total consumption in countries such as Slovakia, Slovenia, and Bulgaria to approx. 30–33% of total consumption in Latvia, Estonia, Hungary, and Romania [113]. Between 2008 and 2018, most CCE countries saw a decline in total household energy consumption. The highest was recorded in Latvia (by 15.2%), the remaining countries recorded a decline of 0–5% (see Figure 2). Only in Bulgaria and the Czech Republic, we saw an increase (by 5.5% and 8.2%, respectively). It is worth adding that these changes took place in the context of a decrease in total energy consumption in the CEE countries. It amounted to approx. 6%, except for Poland, Lithuania, Hungary, and Bulgaria, where actually an increase in total energy consumption was recorded (the highest in Poland, reaching almost 15% in 2008–2018).

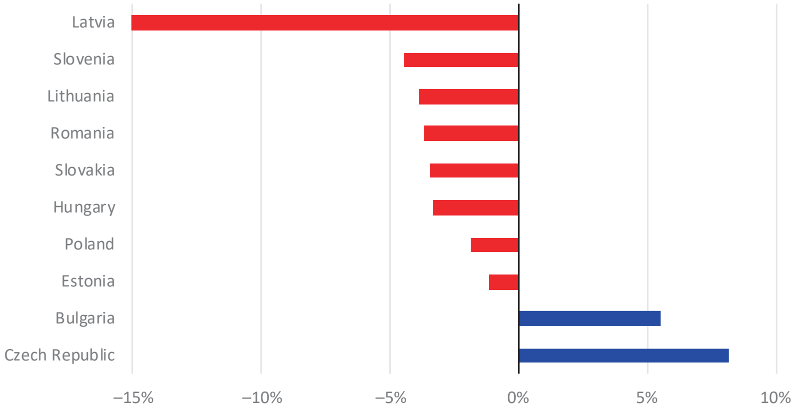

Figure 2. Total changes in energy consumption in households in CEE countries in 2008–2018.

At the same time, the CEE countries with the highest energy consumption in households per capita include Estonia, the Czech Republic, and Lithuania, where in 2018 it was at a level exceeding 600 thousand tons (in oil equivalent—TOE) [113,114]—see Figure 3. The smallest consumption, on the other hand, was characteristic of Bulgaria, Slovakia, and Romania, where it did not exceed 400 thousand tons of energy per capita.

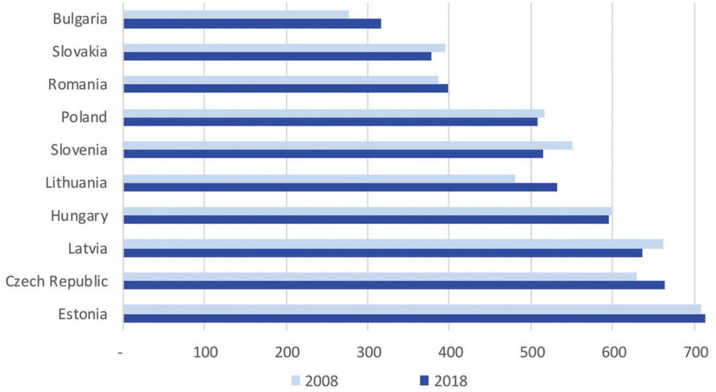

Figure 3. Changes in energy consumption in households per capita in the CEE countries in 2008–2018.

It was related to the level of socio-economic development and a different course of the political and energy transformation [115,116]. The group of countries with the highest energy consumption includes countries with the highest level of socio-economic development among the CEE countries. Countries with the lowest energy consumption were also characterized by a relatively low level of development-Figure 4.

In the analyzed period, there was a decrease in this consumption in half of the analyzed countries (the largest in Slovenia, slightly lower in Slovakia and Latvia). In turn, a large increase in per capita household energy consumption was recorded in Bulgaria and Lithuania, (i.e., about 10–15%), i.e., countries representing both high and low levels of this consumption.

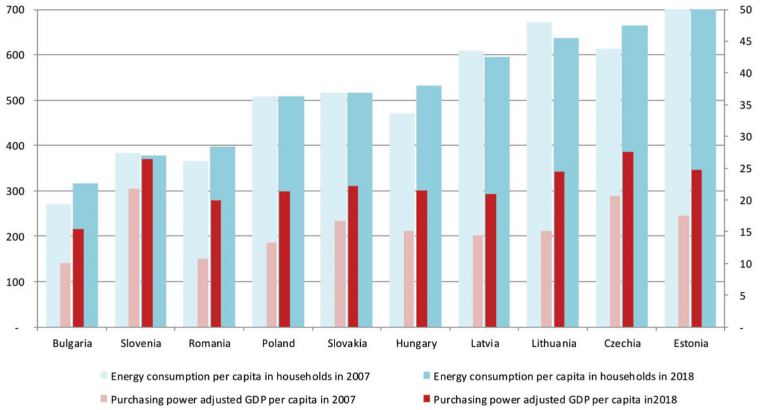

Figure 4. Energy consumption in households per capita and GDP per capita in the CEE countries in 2007 and 2018.

Also, in the case of electricity consumption, one of the forms of energy consumption in households (expressed in thousands of tons of oil equivalent) in 2008–2018, in most CEE countries we saw an increase (except for Latvia and Hungary). It ranged from approx. 1−2% (Estonia, the Czech Republic), through 5–9% (Slovenia, Poland, Bulgaria, Lithuania) to approx. 12% in Slovakia and the largest amount was 22% in Romania [117]. Only in 2015–2020, it was accompanied by an increase in energy prices in households (euro per kilowatt excluding taxes and charges). The highest increase was recorded in Lithuania (by 28.7%) as well as the Czech Republic and Romania (14.6% and 11.4% respectively) [117]. In turn, their highest level in this period (2015–2020) was characteristic in 2018 for the Czech Republic, Slovenia, Latvia, Estonia (0.13–0.10 EUR) and in 2020 for the Czech Republic, Lithuania, Slovakia, Slovenia and Romania (from 0.13 to 0.10 euro).

Countries such as Estonia, the Czech Republic, Latvia and Lithuania are also countries with a high level of energy consumption in households per capita-Figure 5.

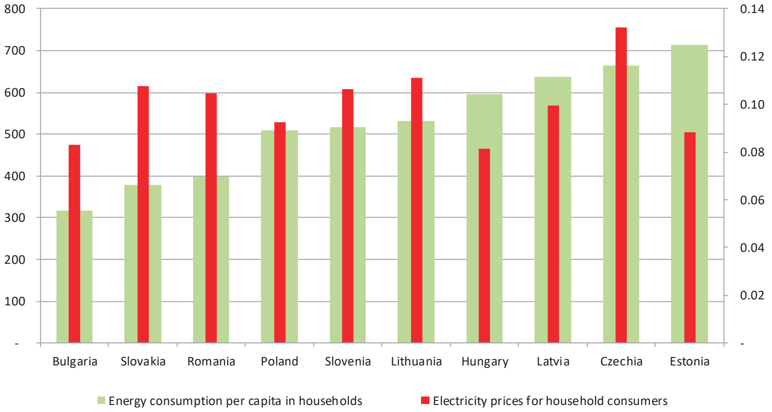

Figure 5. Electricity prices and energy consumption per capita in households in CEE countries in 2020.

In 2018, in the Czech Republic, Slovenia, Estonia, Poland, Romania, and Latvia, the price of electricity was higher in households than in other sectors of the economy [118,119]. In 2020, it was characteristic of the Czech Republic (5.89), Slovenia (2.52), Lithuania (2.40), and Estonia (2.07). Only in Hungary, the price of electricity in households was lower than that offered to other users by (0.37).

4.2. The Platformization of CEE Economies and the Amount of Energy Consumption

Taking into account the applied research approach, i.e., the taxonomic method of distance from the pattern, which was used to classify the CEE countries in terms of the level of platformization, the highest level was achieved by Lithuania and Estonia. As a result, they were included in the first group (Figure 3). The average level of platformization was characteristic of the Czech Republic, Hungary, Slovenia, Poland, Slovakia, and Latvia. The lowest level of digitization as defined above (group III) was achieved by Romania and Bulgaria. Among the CEE countries, they recorded the lowest level of socio-economic development measured by GDP per capita and expressed both according to the official exchange rate and purchasing power. Only countries with a high level of platformization showed relatively low energy consumption in total and in households. In other groups distinguished in terms of platformization, it is difficult to notice the relationship between the level of platformization and the above-mentioned energy consumption (e.g., Bulgaria, representing the 3rd platformization group, has a level of energy consumption in total and in households similar to Slovakia's from group II, and Latvia's level, from group II, is lower than Lithuania's, included in group I).

Taking as the reference point energy consumption per capita total, one can state that relatively more often its higher level is observed in the countries with a higher level of platformization. Such a tendency, however, cannot be observed in the case of energy consumption in households per capita (see Figure 6). The levels of implementation of digital solutions are varied in these countries. Their level of modernization varies as well. This translates in turn into different energy efficiency and is associated with different ranges of skills needed to use digital solutions. These countries also show large differences in demographic and economic potentials and their structures.

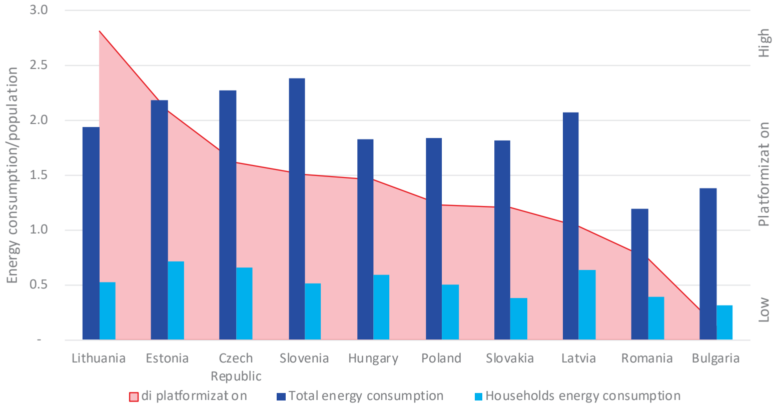

Figure 6. Platformization of CEE countries and the level of energy consumption in total and in households in 2018 per capita (in thousand tons of oil equivalent).

The trends in energy consumption outlined above do not clearly indicate dependence and appear to result from many conditions, including the force of individual factors, internal or external in nature. The percentage of people who worked remotely during the pandemic (2020) confirms cardinally the emerging trends. The percentage of people surveyed shows differences among the CEE countries. It ranges from about 1/5 in Poland, Slovakia, Bulgaria, and Hungary, through about 1/4 in Romania and the Czech Republic, to about 1/3 in Lithuania (Estonia, Latvia and Slovenia were excluded in the study due to insufficient case studies).Moreover, the research shows that these people indicated the regular performance of work-related duties also in their free time more often than those, who worked at their employer's premises or in various places away from home (this concerned approx. 1/5 of the respondents, while in the case of working at the employer's or other places away from home-6% of respondents in both cases) [93].

Taking into account the progress in the digitalization of societies and the economy (platformization), it would seem that the increase in household energy consumption will mostly affect the countries that show its greatest advancement, i.e., Estonia and Lithuania. Yet no clear tendency emerges, in this respect, from the analysis of the current trends in the changes in household energy consumption, including per capita. The overall growth of consumption (only in the Czech Republic and Bulgaria), high level per capita (in Slovenia, Estonia, and Latvia), and changes in the latter (the largest in Lithuania, Latvia, and Poland) refer to the countries that differ from one another in terms of their level of platformization. Moreover, these trends result from factors that interpenetrate or even "cancel" themselves at times.

5. Case-Study-Lithuania and Estonia

The GCI data for 2015–2019 show that of the 79 countries that study the impact of ICT on the economy (they collectively generate 95% of global GDP), Estonia (21) ranked highest among the CEE countries-indicator value at 62, followed by Czech Republic (25)-indicator value 58, Lithuania (28, 56, respectively), Slovenia (29, 56), Hungary (31, 54), Slovakia (32, 53), next Bulgaria (34, 51), Poland (36, 51), and Romania (37, 51) [112].

Estonia, known as 'e-Estonia', achieved particularly high positions, exceeding the global average for broadband technologies (84 against the average of 63 for the countries in the study), but also for IoT (42 against 35, respectively). Taking into account the examined pillars included in the GCI, Estonia stands out in particular in terms of the users' demand and experience in the use of communications (70 against 53 and 75 against 61, respectively). The development of broadband technology and its high accessibility level were associated with great affordability, much higher than the world average. High-speed broadband has been widely available and used in providing digital public services, including tax system support. Recognition of Estonia as a pioneer of the electronic transformation of public services ensured the implementation of Government Cloud solutions. A certain drawback in this area is the lower level of saturation of less urbanized areas with broadband connections. Their implementation in rural areas may improve general access to such a network and reduce costs for its users. The modernization of the information systems in use is aimed at maintaining the efficiency in providing e-services by government agencies and also by other service providers. In Estonia, much of the local data is stored in the cloud and the use of the cloud is widely accepted. The created legal provisions relating to individual ICT areas, including digital signatures, consumer protection, and e-commerce have built a base for the dynamic development of ICT. The level of their implementation was rated above the average of the surveyed countries (9 against 7).

Similarly, among the partial indicators in the delivery pillar, the level of subscription of 4G services is highly rated, i.e., mobile devices of people and organizations giving access to the 4G network (8 vs. 6), as well as Internet capacity in relation to the total capacity of the international internet band (in Mb/s)-(5 against 3). Values above average, often reaching the maximum value (i.e., at the level of 9–10 points), are also characteristic in the procurement pillar for the share of smartphones in overall connections, mobile broadband subscription, server security, as well as the number of households with access to a computer.

In the area of user experience in using connectivity, Estonia records higher levels of indicators in most of the indicators included in this pillar (mobile broadband availability, e-government services, percentage of inhabitants using the Internet, awareness of cybersecurity, and affordability of access to fixed broadband) than the average among the surveyed countries. The indicators in the potential pillar were scored slightly higher than those in the supply pillar. This concerned in particular the impact of ICT on the implementation of new business models, the assessment of the forecast of the annual growth rate on the IoT and AI market, and the number of programmers per capita. The latter was reflected in the level of indicators (within 5–8 points), still above the average level of the surveyed countries.

The indicators of GC for Lithuania, ranked 28th, are also above the world average. It especially refers to users' demand for connectivity and their experience in this area (68 with an average of 62 and 62 against 53, respectively). On the other hand, in the case of basic technologies for the development of GCI, higher than average level of indicators is recorded (in particular) in the area of broadband technologies and access to the cloud (84 against the average of 63 and 54 against 51, respectively). Lithuania has performed particularly well in smartphone penetration and mobile broadband subscriptions (availability and affordability stimulate demand while network security and speed build a good experience) and has reached a level exceeding the global average. User interest in the areas of e-commerce and server security has also increased. In the demand area, a high level (above the world average) was recorded in the number of households with Internet access (8 vs. 7), apart from the broadband network subscription and connection penetration dominated by smartphones. In the area of experience, Lithuania stands out in terms of the cost-effective subscription for mobile and wired broadband, the development of e-government services, the universal use of the Internet by citizens, and also the quality of services available in the cloud.

To a large extent, the basis for a good user experience are the activities in the supply pillar, especially investments in modern network infrastructure (7 vs. 4). They manifested, among others, through an increase in 4G coverage in 2019, high quality of services provided by access to the 4G network (7 vs. 6), and the adequacy of regulations related to the development of ICT (global average). As mentioned above, in terms of the development of technologies crucial for the development of communications, the global average was exceeded by investments in "cloud" technologies (54 against 51). However, Lithuania still lags behind in the area of factors enabling the development of advanced information and communication technologies. Investments in the potential area are among the lowest, especially those relating to the implementation of artificial intelligence and IoT. These investments are below average, especially in AI, with a slightly better rating of IoT (18 against 27 and 33 against 35, respectively).

Lithuania is taking steps to increase state expenditure on the development of infrastructure that provides access to the Internet of new generation and support for this type of investment undertaken by the private sector. Such initiatives are manifested by, among others, support by the National Digital Agenda for investments in broadband infrastructure, also in cases where the limitation is the low economic profitability of the investment. An important task in increasing Lithuania's digitalization is to improve the digital skills of Lithuanians, apart from stimulating the demand for access to high-quality communication. The goal is to achieve 100% coverage of the country with the Internet with a speed of 30 Mb/s and 50% of households with a network with a speed of 100 Mb/s by 2020.

When comparing the two countries with the highest level of platformization among the CEE countries surveyed, it is Estonia that has generally achieved a higher level of the implementation of key technologies underpinning the digital economy (high-speed broadband, cloud services, AI, and IoT). This difference applies in particular to IoT and AI technologies-(Figure 7) (i.e., 42 against 33 in Lithuania, respectively, with the world average being 35, and 27 against 18 in Lithuania, with an average of 27). Estonia, in the group of CEE countries, also records large investments in the cloud. As a result, Estonia is included in the group of adapters (after the beginners and ahead of the leaders in the three-tier classification in the GCI ranking), also in terms of achievements in the field of IoT technology. The development of AI requires a solid foundation in the field of cloud technology and IoT. In the list of adapters in the general classification of GCI, Estonia took 1st place, Lithuania was 8th.

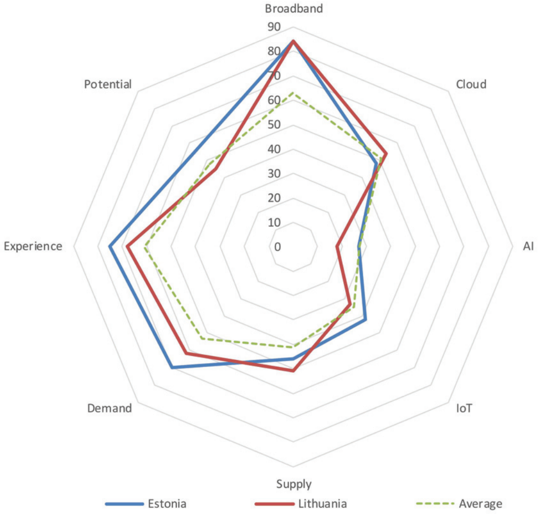

Figure 7. The level of digitization of Lithuania and Estonia based on GCI by types of technology (Broadband, Cloud, IoT, and AI) and digitization pillars (SDEP–Supply, Demand, Experience, and Potential) in 2019 compared to the average of the surveyed countries.

Lithuania, on the other hand, has made more progress in the field of technologies related to cloud services. The highest level amidst the indicated technologies was achieved in the development of broadband technologies; it is at the same level in both countries.

Taking the pillars of the digital economy, i.e., demand, supply, experience, as a point of reference, it is worth noting that both countries exceeded the global average in these areas, but only Estonia has exceeded it in the potential pillar. Taking into account the individual indicators included in the pillars of the digital economy, one must note Estonia’s advantage in accessing the 4G network, regulations on ICT technology, equipping farms with the necessary equipment, server security, development of e-administration services, awareness of cybersecurity as well as activities for the development of the IoT market. On the other hand, when compared to Estonia, Lithuania has had greater achievements recorded in terms of telecommunications investments and equipping households with optical fiber, as well as the quality of services available in the cloud and the created potential of the IoT market.

6. Conclusions and Perspectives for Further Research

In 2008–2018, in most CEE countries, we observe a decrease in energy consumption by households (except Bulgaria and Romania). In the case of energy consumption in households per capita, it concerns already half of the studied group of CEE countries, with a significant increase in energy consumption in Lithuania and Bulgaria. However, we cannot clearly evaluate these trends from the point of view of the ongoing economic platformization underway in these countries. On the one hand, platformization, the impact of which is exacerbated by the pandemic, may lead to an increase in energy consumption, especially electricity consumption in households. Digital technologies based on freely available networks create new opportunities for companies: they delegate more tasks to consumers, tighten their relationship with the customer thanks to complex and integrated applications, and deliver personalized product packages at any time and place. As a result, we can do many more routine activities remotely at home, and, if there are any infrastructure limitations in the office, we perform more of them at work too. Similar observations are made regarding working remotely and the wider growth of the home office, especially at the present requirements of social distancing.

Working from home blurs the boundaries between the workspace and family life. It also leads to an increase in costs imposed on households. In the case of work performed at the company's premises, these costs are borne by the employer. We include among them the costs of water consumption, waste disposal, and also energy costs. This type of phenomenon may, at least in the short term, lead to an increase in energy consumption in households, which can be verified already at the beginning of 2021 (there are no comprehensive post-covid statistics at present).

On the other hand, the expected increase in energy consumption does not have to be a long-term trend. Although the home use of many different types of devices for activities related to work, study, entertainment, or simply social contacts is increasing, its impact on the energy costs of households can be verified by various factors. This is due to technologies that contribute to the introduction of more effective solutions reducing energy consumption, as well as the increased demand for work organization management systems. Moreover, the accelerated digitization leads to an increase in digital competences and so-called "smart" solutions are becoming much more affordable than in the past. In other words, platformization has a positive long-term effect on energy consumption in households, provided that its level is high and is based on the latest solutions.

There are tangible benefits for enterprises. These are: (1) costs passed on to the customer (e.g., online transactions via financial platforms), advertising (e.g., opinions about the product, the seller posts by customers in social networks), product testing, etc. In return, the customer receives "attractive " affordable offers. By entering into more and more advanced relations with various types of organizations (e.g., e-commerce companies, e-administration), the client increases his digital competences in an informal manner.

The above interdependencies are confirmed by an in-depth analysis of countries with the highest level of platformization, namely Lithuania and Estonia. In these countries, changes in energy consumption in households are associated with different progress in the digitization of society and the economy. It is reflected in the level of platformization, as well as the GCI index used in the study. Estonia appears to be an example of an earlier entry into the digitization processes and thus shows smaller increases in this respect. As a consequence, we observe a relatively small decrease in energy consumption in households and a slight increase in energy consumption per capita. In turn, Lithuania has been catching up with digital backlogs revealed by their dynamic development, has achieved both a high level of platformization and associated with it increase in energy consumption in households per capita. This increase in the burden of costs on households (the largest increase among CEE countries) is related to a greater inclination of the Lithuanians to bear these costs by individuals working from home. It also results from the introduction of large-scale working from home. In this crisis situation, the Lithuanians used their savings to a greater extent, which allowed them to maintain the current standard of living (only 10% of teleworkers and 15% of partial teleworkers indicated no savings during the pandemic, compared to 28% of employees working at employer's premises) [76].

The above analysis does not give a full picture of the impact of the transfer of our professional and private activity via platforms onto households and their energy consumption. It shows, however, that in the long run, platformization can reduce this consumption, but it does not happen automatically. The two key elements responsible for the course of this process are: (1) the level of platformization and quality of digital infrastructure (in general, not limited to energy distribution), and (2) digital competences. These are promising research areas from the point of view of energy management in the household and energy policy. In the first cross-section, the main question is: how do platformization and digital competences affect household implementations of intelligent energy management systems? The issues related to the impact of platformization on energy consumption in households constitute one of the potential dimensions of energy policy in the 21st century. The Covid-19 pandemic also creates new challenges. The basic insight relates to solving this dilemma: should the states support subsidies to the rising energy costs in households or invest in science and digital competences and publicly available digital infrastructure, that actively counteracts digital exclusion? These questions are important because, even though the pandemic should be seen as a contextual, time-related factor, our digital habits might not go back to the times before the pandemic. Platformization is our future.

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References

1. Kenney, M.; Zysman, J. The rise of the platform economy. *J. Sci. Technol.* **2016**, *32*, 61–69.
2. International Institute for Applied Systems Analysis (IIASA). TWI2050: Transformations to Achieve the Sustainable Development Goals. Report Prepared by the World in 2050 Initiative. 2018. Available online: https://iiasa.ac.at/web/home/research/twi/Report2018.html (accessed on 22 November 2020).
3. International Institute for Applied Systems Analysis (IIASA). TWI2050: The World in 2050. The Digital Revolution and Sustainable Development: Opportunities and Challenges. Report Prepared by the World in 2050 Initiative. 2019. Available online: https://iiasa.ac.at/web/home/research/twi/Report2019.html (accessed on 22 November 2020).
4. Ordieres-Meré, J.; Remón, T.P.; Rubio, J. Digitalization: An Opportunity for Contributing to Sustainability From Knowledge Creation. *Sustainability* **2020**, *12*, 1460. [CrossRef]
5. George, G.; Merrill, R.K.; Schillebeeckx, S.J.D. Digital Sustainability and Entrepreneurship: How Digital Innovations Are Helping Tackle Climate Change and Sustainable Development. *Entrep. Theory Pract.* **2020**. [CrossRef]
6. Snooks, G. New perspectives on the industrial revolution. In *Was the Industrial Revolution Necessary?* Routledge: Abingdon, UK, 1994; pp. 13–38.
7. Rossotto, C.M.; Das, P.L.; Ramos, E.G.; Miranda, E.C.; Badran, M.F.; Licetti, M.M.; Murciego, G.M. Digital platforms: A literature review and policy implications for development. *Compet. Regul. Netw. Ind.* **2018**, *19*, 93–109. [CrossRef]
8. Margetts, M. Makers: The New Industrial Revolution; The New Industrial Revolution; Consumers, Globalisation and the End of Mass Production. *J. Mod. Craft* **2017**, *10*, 107–109. [CrossRef]
9. Ideas. Global Economic Review: Special issue on new industrial platform and innovation in east asia: Economics of the 4th industrial revolution. *Glob. Econ. Rev.* **2019**, *48*, 111. [CrossRef]
10. Baron, R.; Zintel, M.; Zieries, M.; Mikulla, D. Digital Platforms in Freight Transportation. A True Industry Disraptor? Arthur D. Little. 2017. Available online: https://www.adlittle.com/en/insights/viewpoints/digital-platforms-freight-transportation (accessed on 21 January 2021).
11. OECD. Going Digital: Shaping Policies, Improving Lives. 2019. Available online: https://www.oecd.org/publications/going-digital-shaping-policies-improving-lives-9789264312012-en.htm (accessed on 23 January 2021).
12. Perrons, D. The new economy, labour market inequalities and the work life balance. In *Geographies of Labour Market Inequality*, 1st ed.; Martin, R., Morrison, P.S., Eds.; Routledge: London, UK, 2002; pp. 129–148.
13. Dengler, K.; Gundert, S. Digital Transformation and Subjective Job Insecurity in Germany. *Eur. Sociol. Rev.* **2021**. [CrossRef]
14. Udd, E. Digital leisure, the internet and popular culture: Communities and identities in a digital age, by Karl Spracklen. *Leisure* **2016**, *40*, 245–246. [CrossRef]
15. Denegri-Knott, J.; Molesworth, M. Concepts and practices of digital virtual consumption. *Consum. Mark. Cult.* **2010**, *13*, 109–132. [CrossRef]
16. Kalogeropoulos, A. Online News Video Consumption. *Digit. J.* **2017**, *6*, 651–665. [CrossRef]
17. Costanzo, M.; Archer, D.; Aronson, E.; Pettigrew, T. Energy conservation behavior: The difficult path from information to action. *Am. Psychol.* **1986**, *41*, 521–528. [CrossRef]
18. Stern, P.C. New Environmental Theories: Toward a Coherent Theory of Environmentally Significant Behavior. *J. Soc. Issues* **2000**, *56*, 407–424. [CrossRef]
19. Martiskainen, M.; Coburn, J. The role of information and communication technologies (ICTs) in household energy consumption—Prospects for the UK. *Energy Effic.* **2010**, *4*, 209–221. [CrossRef]
20. Corcoran, P.; Desbonnet, J.; Bigioi, P.; Lupu, I. Home network infrastructure for handheld/wearable appliances. *IEEE Trans. Consum. Electron.* **2002**, *48*, 490–495. [CrossRef]
21. Andrae, A.S.G.; Edler, T. On Global Electricity Usage of Communication Technology: Trends to 2030. *Challenges* **2015**, *6*, 117–157. [CrossRef]
22. Erdmann, L.; Hilty, L.; Goodman, J.; Arnfalk, P. *The Future Impact of ICTs on Environmental Sustainability*; Institute for Prospective Technological Studies: Seville, Spain, 2014.

23. Gram-Hanssen, K. Efficient technologies or user behaviour, which is the more important when reducing households' energy consumption? *Energy Effic.* **2012**, *6*, 447–457. [CrossRef]
24. Aune, M. Energy comes home. *Energy Policy* **2007**, *35*, 5457–5465. [CrossRef]
25. Gram-Hanssen, K. Understanding change and continuity in residential energy consumption. *J. Consum. Cult.* **2011**, *11*, 61–78. [CrossRef]
26. European Commission. The Digital Economy and Society Index (DESI). 2020. Available online: https://ec.europa.eu/digital-single-market/en/digital-economy-and-society-index-desi (accessed on 10 January 2021).
27. Bris, A.; Cabolis, C. The IMD World Digital Competitiveness Ranking. How Does Your Country Rank? 2019. Available online: https://www.imd.org/research-knowledge/articles/the-imd-world-digital-competitiveness-ranking/ (accessed on 10 December 2020).
28. Iglesias, F.; Kastner, W. Analysis of Similarity Measures in Times Series Clustering for the Discovery of Building Energy Patterns. *Energies* **2013**, *6*, 579–597. [CrossRef]
29. Kumar Malhotra, V.; Kaur, H.; Alam, M.A. An Analysis of Fuzzy Clustering Methods. *Int. J. Comput. Appl.* **2014**, *94*, 9–12. [CrossRef]
30. Rokach, L.; Maimon, O. Clustering Methods. In *Data Mining and Knowledge Discovery Handbook*, 1st ed.; Maimon, O., Rokach, L., Eds.; Springer: Boston, MA, USA, 2005; pp. 321–352.
31. Munandar, T.A.; Musdholifah, A.; Arsyad, L. Modified agglomerative clustering with location quotient for identi-fication of regional potential sector. *J. Theor. Appl. Inform. Technol.* **2017**, *95*, 1191–1199.
32. Young, G.; Householder, A.S. Discussion of a set of points in terms of their mutual distances. *Psychometrika* **1938**, *3*, 19–22. [CrossRef]
33. Turk, M.; Pentland, A. Eigenfaces for Recognition. *J. Cogn. Neurosci.* **1991**, *3*, 71–86. [CrossRef] [PubMed]
34. Alfakih, A.Y.; Khandani, A.; Wolkowicz, H. Solving Euclidean distance matrix completion problems via semidefinite programming. *Comput. Optim. Appl.* **1999**, *12*, 13–30.
35. Evans, P.C.; Gawer, A. The Rise of the Platform Enterprise: A Global Survey, The Center for Global Enterprise. 2016. Available online: https://www.thecge.net/app/uploads/2016/01/PDF-WEB-Platform-Survey_01_12.pdf (accessed on 10 January 2020).
36. Parker, G.G.; Van Alstyne, M.W.; Choudary, S.P. *Platform Revolution: How Networked Markets Are Transforming the Economy—And How to Make Them Work for You*; W.W. Norton & Company Inc.: New York, NY, USA, 2016.
37. Evans, D.; Hagiu, A.; Schmalensee, R. *Invisible Engines: How Software Platforms Drive Innovation and Transform Industries*; The MIT Press: Cambridge, MA, USA, 2006.
38. Gawer, A.; Cusumano, M.A. Platforms and Innovation. In *The Oxford Handbook of Innovation Management*; Dodgson, M., Gann, D.M., Phillips, N., Eds.; Oxford University Press: Oxford, UK, 2014; pp. 649–656.
39. UNCTAD. The 'New' Digital Economy and Development. Technical Note. 2017. Available online: https://unctad.org/system/files/official-document/tn_unctad_ict4d08_en.pdf (accessed on 12 January 2020).
40. Evans, D.; Schmalensee, R. *The Antitrust Analysis of Multi-Sided Platform Businesses*; Working Paper 18783; National Bureau of Economic Research: Cambridge, MA, USA, 2013. [CrossRef]
41. Rysman, M. The Economics of Two-Sided Markets. *J. Econ. Perspect.* **2009**, *23*, 125–143. [CrossRef]
42. Evans, D.S.; Schmalensee, R.; Noel, M.D.; Chang, H.H.; Garcia-Swartz, D.D. Platform Economics: Essays on Multi-Sided Businesses. In *Platform Economics: Essays On Multi-Sided Businesses*; Evans, D.S., Ed.; Competition Policy International: Brussels, Belgium, 2011. Available online: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=1974020 (accessed on 10 February 2020).
43. Nowicka, K.; Szymczak, M. Logistyka i łańcuchy dostaw w obliczu czwartej rewolucji przemysłowej. *STUDIA Bas.* **2020**, *3*, 61–84. [CrossRef]
44. Gawer, A. Bridging differing perspectives on technological platforms: Toward an integrative framework. *Res. Policy* **2014**, *43*, 1239–1249. [CrossRef]
45. Kloppenburg, S.; Boekelo, M. Digital platforms and the future of energy provisioning: Promises and perils for the next phase of the energy transition. *Energy Res. Soc. Sci.* **2019**, *49*, 68–73. [CrossRef]
46. Van Dijck, J.; Poell, T.; De Waal, M. *The Platform Society: Public Values in a Connective World*; University Press Oxford: Oxford, UK, 2018.
47. Steel, E.; Locke, C.; Cadman, E.; Freese, B. How Much Is Your Personal Data Worth? *Financial Times*, 12 June 2013. Available online: https://ig.ft.com/how-much-is-your-personal-data-worth/(accessed on 1 November 2019).
48. European Commission. The Digital Competence Framework 2.0. 2020. Available online: https://ec.europa.eu/jrc/en/digcomp/digital-competence-framework (accessed on 1 November 2020).
49. European Commission. Communication from the Commission to the European Parliament, The Council, The European Economic and Social. Committee and the Committee of the Regions. 2020. Available online: https://ec.europa.eu/clima/sites/clima/files/eu-climate-action/docs/com_2030_ctp_en.pdf (accessed on 1 November 2020).
50. Energy Information Administration (EIA). International Energy Outlook. 2016. Available online: https://www.eia.gov/outlooks/ieo/pdf/0484 (accessed on 5 June 2020).
51. Brounen, D.; Kok, N.; Quigley, J.M. Energy literacy, awareness, and conservation behavior of residential households. *Energy Econ.* **2013**, *38*, 42–50. [CrossRef]

52. European Commission. *A Roadmap for Moving to a Competitive Low Carbon Economy in 2050*; Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee of the Regions; European Commission: Brussels, Belgium, 2011.
53. Kaiser, F.G.; Wölfing, S.; Fuhrer, U. Environmental attitude and ecological behaviour. *J. Environ. Psychol.* **1999**, *19*, 1–19. [CrossRef]
54. Abrahamse, W.; Steg, L. How do socio-demographic and psychological factors relate to households' direct and indirect energy use and savings? *J. Econ. Psychol.* **2009**, *30*, 711–720. [CrossRef]
55. Lindenberg, S.; Steg, L. Normative, Gain and Hedonic Goal Frames Guiding Environmental Behavior. *J. Soc. Issues* **2007**, *63*, 117–137. [CrossRef]
56. Yeboah, F.K.; Kaplowitz, M. Explaining Energy Conservation and Environmental Citizenship Behaviors Using the Value-Belief-Norm Framework. *Hum. Ecol. Rev.* **2016**, *22*, 159–237. [CrossRef]
57. Frederiks, E.R.; Stenner, K.; Hobman, E.V. Household energy use: Applying behavioural economics to understand consumer decision-making and behaviour. *Renew. Sustain. Energy Rev.* **2015**, *41*, 1385–1394. [CrossRef]
58. Schipper, L.; Bartlett, S.; Hawk, D.; Vine, E. Linking Life-Styles and Energy Use: A Matter of Time? *Annu. Rev. Energy* **1989**, *14*, 273–320. [CrossRef]
59. Gram-Hanssen, K. New needs for better understanding of household's energy consumption-behaviour, lifestyle or practices? *Arch. Eng. Des. Manag.* **2013**, *10*, 91–107. [CrossRef]
60. Barr, S.; Gilg, A.W.; Ford, N. The household energy gap: Examining the divide between habitual- and purchase-related conservation behaviours. *Energy Policy* **2005**, *33*, 1425–1444. [CrossRef]
61. Guagnano, G.A.; Stern, P.C.; Dietz, T. Influences on Attitude-Behavior Relationships. *Environ. Behav.* **1995**, *27*, 699–718. [CrossRef]
62. Vasseur, V.; Marique, A.-F.; Udalov, V. A Conceptual Framework to Understand Households' Energy Consumption. *Energies* **2019**, *12*, 4250. [CrossRef]
63. North, D.C. Institutions. *J. Econ. Perspect.* **1991**, *5*, 97–112. [CrossRef]
64. Owens, S.; Driffill, L. How to change attitudes and behaviours in the context of energy. *Energy Policy* **2008**, *36*, 4412–4418. [CrossRef]
65. Tanner, J.F., Jr.; Raymond, M.A. Principles of Marketing, Version 2.0. May 2012. Available online: https://catalog.flatworldknowledge.com/catalog/editions/tanner_2-0-principles-of-marketing-2-0 (accessed on 10 June 2020).
66. Wambugu, H.W. Effects of situational factors and packaging characteristics on the outcome of shoppers' behaviour in Kenyan supermarkets. *Eur. J. Bus. Manag.* **2015**, *7*, 47–60.
67. Kuhe, A.; Bisu, D.Y. Influence of situational factors on household's energy consumption behaviour. *Int. J. Energy Sect. Manag.* **2019**, *14*, 389–407. [CrossRef]
68. International Energy Agency (IEA). Developing Energy Efficiency Indicators to Track Efficiency Progress: Why? 2014. Available online: https://www.iea.org/reports/energy-efficiency-market-report-2014 (accessed on 18 July 2020).
69. Frederiks, E.R.; Stenner, K.; Hobman, E.V. The Socio-Demographic and Psychological Predictors of Residential Energy Consumption: A Comprehensive Review. *Energies* **2015**, *8*, 573–609. [CrossRef]
70. Kolk, A. The role of consumers in EU energy policy. *Carbon Manag.* **2012**, *3*, 175–183. [CrossRef]
71. Bresnahan, T.F.; Trajtenberg, M. General purpose technologies 'Engines of growth'? *J. Econ.* **1995**, *65*, 83–108. [CrossRef]
72. Teece, D.J. Profiting from innovation in the digital economy: Enabling technologies, standards, and licensing models in the wireless world. *Res. Policy* **2018**, *47*, 1367–1387. [CrossRef]
73. Seufert, S.; Scheffler, N. Developing Digital Competences of Vocational Teachers. *Int. J. Digit. Lit. Digit. Competence* **2016**, *7*, 50–65. [CrossRef]
74. Treglia, E.; Tomassoni, R. The Development of Digital Competences and Emotional Skills Through the Use of Audio-Visual Technologies. *Int. J. Digit. Lit. Digit. Competence* **2019**, *10*, 55–60. [CrossRef]
75. Petrucco, C. Wikipedia as Training Resource for Developing Digital Competences. *Int. J. Digit. Lit. Digit. Competence* **2010**, *1*, 29–35. [CrossRef]
76. Young, W.; Russell, S.V.; Robinson, C.A.; Barkemeyer, R. Can social media be a tool for reducing consumers' food waste? A behaviour change experiment by a UK retailer. *Resour. Conserv. Recycl.* **2017**, *117*, 195–203. [CrossRef]
77. Sujata, M.; Khor, K.-S.; Ramayah, T.; Teoh, A.P. The role of social media on recycling behaviour. *Sustain. Prod. Consum.* **2019**, *20*, 365–374. [CrossRef]
78. Mukhamedova, D.; Rakhimova, I.; Nigmatullina, L.; Majidov, N.; Abdullayev, B. Psychological aspects of addiction to social media, computer and computer games. *Int. J. Psych. Rehab.* **2020**, *24*, 319–324.
79. van Emmerik, M.L.; de Vries, S.C.; Bos, J.E. Internal and external fields of view affect cybersickness. *Displays* **2011**, *32*, 169–174. [CrossRef]
80. OECD. An Introduction to Online Platforms and Their Role in the Digital Transformation. 2019. Available online: https://www.oecd.org/innovation/an-introduction-to-online-platforms-and-their-role-in-the-digital-transformation-53e5f593-en.htm (accessed on 22 July 2020).
81. Miller, P.; Wilsdon, J. Digital Futures—An Agenda for a Sustainable Digital Economy. *Corp. Environ. Strateg.* **2001**, *8*, 275–280. [CrossRef]
82. Arthur, W.B. The second economy. *McKinsey Q.* **2011**, *4*, 1–9.

83. Miller, B.; Nixon, T.; Tai, C.; Wood, M. Home networking with Universal Plug and Play. *IEEE Commun. Mag.* **2001**, *39*, 104–109. [CrossRef]
84. Digital Living Network Alliance (DLNA). Networked Device Interoperability Guidelines. 2006. Available online: http://docshare04.docshare.tips/files/11856/118566774.pdf (accessed on 22 November 2019).
85. Naus, J.; Spaargaren, G.; Van Vliet, B.J.; Van Der Horst, H.M. Smart grids, information flows and emerging domestic energy practices. *Energy Policy* **2014**, *68*, 436–446. [CrossRef]
86. European Commission. Smart Consumer—Smart Customer—Smart Citizen. FP7-ENERGY—Specific Programme "Coopera-tion": Energy. 2015. Available online: https://cordis.europa.eu/project/id/308765/pl (accessed on 11 November 2019).
87. European Commission. Balancing Energy Production and Consumption in Energy Efficient Smart Neighbourhoods FP7-ICT—Specific Programme "Cooperation": Information and Communication Technologies. 2017. Available online: https://cordis.europa.eu/project/id/609132 (accessed on 11 November 2019).
88. Acuner, E.; Kayalica, M. Özgür A review on household energy consumption behavior: How about migrated consumers? *Environ. Econ.* **2018**, *9*, 8–21. [CrossRef]
89. Kastner, W.; Neugschwandtner, G.; Soucek, S.; Newman, H.M. Communication systems for building automation and control. *Proc. IEEE* **2005**, *93*, 1178–1203. [CrossRef]
90. Li, J.; Just, R.E. Modeling household energy consumption and adoption of energy efficient technology. *Energy Econ.* **2018**, *72*, 404–415. [CrossRef]
91. European Commission. Telework in the EU before and after the COVID-19: Where We Were, Where We Head to. 2020. Available online: https://ec.europa.eu/jrc/sites/jrcsh/files/jrc120945_policy_brief_-_covid_and_telework_final.pdf (accessed on 10 November 2019).
92. Novichenko, N. Digital competences in the system of key human competences for lifelong learning: Development trends in Europe and Ukraine. *Public Adm. Asp.* **2020**, *8*, 54–59. [CrossRef]
93. Eurofound. Living, Working and COVID-19, COVID-19 Series. 2020. Available online: https://www.eurofound.europa.eu/publications/report/2020/living-working-and-covid-19 (accessed on 10 November 2019).
94. Hook, L.; Raval, A. Coronavirus Leads to 'Staggering' Drop in Global Energy Demand. *Financial Times*, 29 April 2020. Available online: https://www.ft.com/content/ee88c064-2fac-4a08-aad5-59188210167b(accessed on 10 November 2020).
95. International Energy Agency (IEA). Global Energy Demand to Plunge This Year as a Result of the Biggest Shock since the Second World War. 2020. Available online: https://www.iea.org/news/global-energy-demand-to-plunge-this-year-as-a-result-of-the-biggest-shock-since-the-second-world-war (accessed on 19 September 2019).
96. European Parliament. Energy Poverty in Europe and Support for Families Following the COVID-19 Pandemic. 2020. Available online: https://www.europarl.europa.eu/doceo/document/E-9-2020-004352_EN.html (accessed on 10 November 2020).
97. Meinrenken, C.J.; Modi, V.; Mckeown, K.R.; Culligan, P.J. New Data Suggest COVID-19 Is Shifting the Burden of Energy Costs to Households. 2020. Available online: https://blogs.ei.columbia.edu/2020/04/21/covid-19-energy-costs-households/ (accessed on 10 November 2020).
98. Household Electricity Consumption during the COVID-19 Lockdown. 2020. Available online: https://www.prayaspune.org/peg/blogs/household-electricity-consumption-in-india-during-the-covid-19-lockdown-insights-from-metering-data.html (accessed on 10 November 2020).
99. Using Electricity Data to Understand COVID-19 Impacts. 2020. Available online: https://www.abs.gov.au/AUSSTATS/abs@.nsf/mf/4661.0 (accessed on 10 November 2020).
100. European Commission. Market Reports for 2nd Quarter Highlight Impact of Covid Lockdown on Electricity and Gas Markets. 2020. Available online: https://ec.europa.eu/info/news/market-reports-2nd-quarter-highlight-impact-covid-lockdown-electricity-and-gas-markets-2020-oct-12_en (accessed on 22 November 2020).
101. Chhetri, R. Effects of COVID-19 Pandemic on Household Energy Consumption at College of Science and Technology. *Int. J. Sci. Res. Eng. Dev.* **2020**, *3*, 1383–1387.
102. Consumers' Experiences with Energy During the Covid-19 Pandemic—Summary of Research Findings. 2020. Available online: https://www.ofgem.gov.uk/publications-and-updates/consumers-experiences-energy-during-covid-19-pandemic-summary-research-findings (accessed on 22 November 2020).
103. Birol, F. The Coronavirus Crisis Reminds Us That Electricity Is more Indispensable than Ever. IEA. 2020. Available online: https://www.iea.org/commentaries/the-coronavirus-crisis-reminds-us-that-electricity-is-more-indispensable-than-ever (accessed on 10 November 2020).
104. 54 Zoom Statistics. Available online: https://usefyi.com/zoom-statistics/ (accessed on 10 May 2020).
105. Pięta, P. Development of social capital by strengthening of digital competences among groups exposed to social exclusion. *Ann. Mark. Manag. Econ.* **2018**, *4*, 73–87. [CrossRef]
106. Eurostat. Database. Available online: https://ec.europa.eu/eurostat/data/database (accessed on 1 September 2020).
107. Hellwig, Z. Zastosowanie metody taksonomicznej do typologicznego podziału krajów ze względu na poziom ich rozwoju oraz zasoby i strukturę wykwalifikowanych kadr. *Przegląd Stat.* **1968**, *4*, 307–326.
108. Liao, T.W. Clustering of time series data—A survey. *Pattern Recognit.* **2005**, *38*, 1857–1874. [CrossRef]
109. Fahad, M.; Shahid, A.; Manumachu, R.R.; Lastovetsky, A. A Novel Statistical Learning-Based Methodology for Measuring the Goodness of Energy Profiles of Applications Executing on Multicore Computing Platforms. *Energies* **2020**, *13*, 3944. [CrossRef]

110. Sharma, N.; Bajpai, A.; Litoriya, R. Comparison the various clustering algorithms of weka tools. *Int. J. Emerg. Technol. Adv. Eng.* **2012**, *2*, 73–80.
111. Milligan, G.W.; Cooper, M.C. Methodology Review: Clustering Methods. *Appl. Psychol. Meas.* **1987**, *11*, 329–354. [CrossRef]
112. Huawei. Global Connectivity Index. Methodology. 2020. Available online: https://www.huawei.com/minisite/gci/en/methodology.html (accessed on 20 July 2020).
113. Eurostat. Final Energy Consumption by Sector Thousand Tonnes of Oil Equivalent. Available online: https://ec.europa.eu/eurostat/databrowser/view/TEN00124/bookmark/table?lang=en&bookmarkId=2d41074e-914c-4d80-bdd1-109e9b56c1f6 (accessed on 10 November 2020).
114. Eurostat. Population. 2020. Available online: https://ec.europa.eu/eurostat/databrowser/view/tps00001/default/table?lang=en (accessed on 10 November 2020).
115. Cornillie, J.; Fankhauser, S. The energy intensity of transition countries. *Energy Econ.* **2004**, *26*, 283–295. [CrossRef]
116. Markandya, A.; Pedroso-Galinato, S.; Streimikiene, D. Energy intensity in transition economies: Is there convergence towards the EU average? *Energy Econ.* **2006**, *28*, 121–145. [CrossRef]
117. Eurostat. Share for Transmission and Distribution in the Network Cost for Gas and Electricity—Annual Data. 2020. Available online: https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_pc_206&lang=en (accessed on 10 November 2020).
118. Eurostat. Electricity Prices for Household Consumers—Biannual Data (from 2007 Onwards). 2020. Available online: http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_pc_204 (accessed on 10 November 2020).
119. Eurostat. Electricity Prices for Non-Household Consumers—Biannual Data (from 2007 Onwards). 2020. Available online: https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_pc_205&lang=en (accessed on 10 November 2020).

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Article

Coopetitive Nature of Energy Communities—The Energy Transition Context

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Abstract: The decentralization of the large-scale energy sector, its replacement with pro-ecological, dispersed production sources and building a citizen dimension of the energy sector are the directional objectives of the energy transformation in the European Union. Building energy self-sufficiency at a local level is possible, based on the so-called Energy Communities, which include energy clusters and energy cooperatives. Several dozen pilot projects for energy clusters have been implemented in Poland, while energy cooperatives, despite being legally sanctioned and potentially a simpler formula of operation, have not functioned in practice. This article presents the coopetitive nature of Energy Communities. The authors analysed the principles and benefits of creating Energy Communities from a regulatory and practical side. An important element of the analysis is to indicate the managerial, coopetitive nature of the strategies implemented within the Energy Communities. Their members, while operating in a competitive environment, simultaneously cooperate to achieve common benefits. On the basis of the actual data of recipients and producers, the results of simulations of benefits in the economic dimension will be presented, proving the thesis of the legitimacy of creating coopetitive structures of Energy Communities.

Keywords: energy cooperatives; coopetition; renewable energy sources; Renewable Energy Communities; management

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1. Introduction

The decentralization of large-scale energy, its replacement with pro-ecological, distributed generation sources, and building a civic dimension of the energy sector are the directional objectives of the energy transformation in the European Union (Clean Energy Package—CEP). Community legislation does not impose a precise formula for achieving these goals, giving individual member states freedom of action. Building energy self-sufficiency at a local level is possible on the basis of formulas called Energy Community (EC). The first is the energy community defined in the Renewable Energy Directive REDII [1] and focusing on the area of renewable energy, including the Renewable Energy Community. Citizens Energy Community (CEC) [2], which is implemented within the so-called Market Directive, is the second form of activity. Both of these concepts serve the development of distributed energy in the local dimension, have legal personality and are characterised by voluntary and open participation. The main goal of their operation is to run activities that bring economic and environmental benefits in the local and regional dimension, which are aimed at building self-sufficiency and energy independence [3,4].

The EU direction of transformation of the energy market has also been reflected in Polish law, where, similarly to the Community regulations, two concepts were created that introduce the civic dimension of energy [5]. These include energy clusters and energy cooperatives—with the latter being the latest form of support for distributed civic energy are the subject of this article. Energy cooperatives are voluntary associations of energy consumers and producers, who jointly declare and implement the goals of building energy independence. Thanks to which we are able to achieve additional benefits together [3,6].

In practice, the realization of additional benefits is associated with the coopetitive interaction of players. Coopetition is a deliberate strategy of mixing cooperation and competition [7] at different stages and arenas in order to achieve better individual and collective results [8]. The term coopetition has been present in strategy literature for many years now, allowing for several threads of research to exploit or investigate it. Firstly, a theoretical view of coopetition has been developed as related fields theory extension. Game theory brought into light the need to deliberately transform inter-organizational market relations into a positive sum game or reshape competition structure [9]. The strategic behaviour perspective attracted attention to the rent appropriation issue, which is far more in a manager's scope than mere rent generation, and it has syncretic forms beyond those discussed in literature [10]. Inter-organizational dynamics in turn provided theoretical grounds for showing that coopetition is a dynamic process that emerges between cooperating parties and leads to intertwining rent maximization and rent appropriation behaviours [11]. Secondly, a growing body of empirical investigation has brought a substantial body of mainly case-study based evidence that provides rich insights into both coopetition's nature and its dynamics. Several industries have been under scrutiny, most notably: professional football [12], insurance [13], cultural institutions [14], information and communication technologies [15], transportation industry [16], banking [17], purchasing groups [18], and electro-mobility [19]. Another thread of research has a clearly theoretical inclination because it expects coopetition to appear between market players [13], or it suggests that this option is in their best interest [9]. Therefore, coopetition is seen as a collective and individual ideal strategy. Those actors that do not deliberately use it fall into a non-equilibrium or suboptimal option. Under-performing competitive strategies have the traits of individual rationality. which is not optimal in a multi-actor context typical to coopetition under scrutiny. Those claims remain broadly grounded in game theoretical applications to cooperative settings. Rational collective decision making models, such as the prisoner's dilemma repeated game, suggest that cooperation between competitors clearly yields best results for all players. Yet, empirical findings suggest that many managers choose to remain outside coopetitive strategies. The theoretical underpinnings of this thread of research rely heavily upon collective strategies models using game theoretical mathematics.

The aim of this paper is to advance coopetition empirical findings by addressing the case study of energy communities. The individual and innovative contribution of the authors to research in this area is the element of empirical research that clearly demonstrates the legitimacy of the application of coopetition strategies. Combining the context of energy communities with the analysis of the effects of coopetition (both joint and individual) has never been the subject of empirical analyses.

The hypothesis reflects the statement that coopetition seems to be favourable for all the actors involved, while functioning on ones' own gives worse results both the individual and collective level. The paper is organized into four sections. First, the characteristics of the functioning of an energy cooperative are being presented in order to identify their background and identify the benefits. Second, simulation assumptions for research on cooperatives are listed, showing the details of the empirical analysis background. Third, an economic analysis focusing on the main findings is shown. The fourth one presents the results and conclusions also stressing the limitations of the paper and a further research agenda.

2. Background—Characteristics of the Functioning of an Energy Cooperative with the Identification of Benefits

2.1. Energy Cooperative as a Response to REC and CEC

Poland is a country where the energy sector is still dominated by worn-out system units fuelled by hard coal and lignite. On the other hand, there is strong legislative pressure as well as pressure formulated in terms of social expectations to carry out difficult but necessary energy transformation processes. One of the three pillars of the strategic direction document—Poland's Energy Policy until 2040, concerns the issue of a zero-emission energy system. This area assumes the need for a strong development of local and civic energy, and the measure of the goal is to increase the share of recipients that are actively participating in the market. It is assumed that 300 energy sustainable areas and a million prosumers will be created by 2030 [20].

One of the solutions enabling the acceleration of Poland's green transformation is the popularization of local energy communities and the consequent decentralization of the energy sector. The definition of an energy cooperative appeared in Polish law in 2019 during the amendment to the Act on Renewable Energy Sources [21]. According to this legal act, an energy cooperative is a cooperative within the meaning of the provisions of the Cooperative Law [22] and the Act on farmers' cooperatives [23] (in the case of agricultural cooperatives), the subject of which is the production of electricity, heat, or biogas only for the own needs of an energy cooperative and its members.

Energy cooperatives:

- may be established in the area of a rural or urban-rural commune or in the area of not more than three adjacent communes of this type,
- they can operate in the area of operation of a single distribution system operator supplying electricity to producers and customers who are members of this cooperative, whose installations are connected to the network of a given operator. The area of operation of an energy cooperative is determined on the basis of the places of connection of producers and customers who are members of this cooperative to the distribution network,
- operate within low and medium voltage networks,
- may have from three to 999 members inclusive,
- where their object of activity is the production of:
    - electricity, total installed electrical capacity of all renewable energy installations:
        - makes it possible to cover not less than 70% of the own needs of an energy cooperative and its members during the year,
        - does not exceed 10 MW,
    - heat, the total achievable thermal power does not exceed 30 MW, and
    - biogas, the annual capacity of all installations does not exceed 40 million m^3.
- may be created only by natural or legal persons.

The main goals of establishing energy cooperatives include:

- building local energy self-sufficiency,
- increasing the energy independence of mainly rural areas and small towns,
- improving the living conditions and running a business in rural areas, including increasing the competitiveness of the agro-food sector, achieved thanks to cheaper energy media, and
- increasing the use of locally occurring renewable resources.

2.2. Principles of Operation and Settlement in an Energy Cooperative

Energy cooperatives operate on the basis of a prosumer system that consists of an energy settlement that is based on the so-called discounts. An energy seller only settles accounts with an energy cooperative for the difference between the amount of electricity that is introduced to the electricity distribution network and the amount of electricity collected from this network for its own needs by the cooperative (its members) in the ratio of the corrected quantitative factor of 1 to 0.6 (in the case of prosumers, depending on the power of the installation, the coefficients 1 to 0.8 or 1 to 0.7 apply) [24,25]. In other words, for 1 MWh of energy produced by the cooperative and not used at the moment by the members of the cooperative, i.e., fed into the distribution network (the network in this situation acts as a storage for energy not used by the cooperative), 0.6 MWh of energy can be obtained from it. This can happen at any time within the billing period when the cooperative's generation sources do not meet the current demand. This settlement applies to electricity that is introduced and taken from the distribution network by all electricity producers and consumers who are members of an energy cooperative. The same principle applies if the subject of the cooperative's activity is heat or biogas. Therefore, it should be assumed that the more it is possible to "synchronize" the amount of energy that is produced with its receipt at a given moment within the cooperative entities, so as not to discharge the surplus energy production into the grid, the greater the economic effects of the energy cooperative will be. It can be said that the distribution network will, in such a situation, only "secure" the internal energy economy of the cooperative.

As a prosumer, an energy cooperative functions in the power system under a comprehensive agreement that is signed with an external energy supplier. This agreement regulates the issues of both distribution and sale of possible energy shortages to the cooperative. For an energy seller, an energy cooperative is one collective end-user subject to a single settlement. For the needs of internal settlements of an energy co-operative between its individual members, the seller provides the amount of energy that is introduced and taken from the grid by individual members of the co-operative. The cooperative settles them in accordance with internally adopted rules. The amount of unused energy remains to be collected (compensated) within the given 12-month billing period. The functioning of an energy cooperative is associated with specific benefits at the cooperative level, which can then be cascaded onto its members. The seller carries out the settlement of the energy cooperative, in the discount model, on the basis of measurement data that are provided by the distribution system operator (DSO). The first of the benefits is:

- maximization of energy self-consumption—achieved thanks to the daily-hourly balancing of the amount of electricity that is introduced to and taken from the distribution network by all producers and consumers belonging to an energy cooperative after prior summary balancing of the amount of energy introduced and taken from the distribution network from all installation phases.

From the settled amount of electricity, an energy cooperative:

- does not pay settlement fees to the seller and
- does not pay distribution service fees, the amount of which depends on the amount of electricity consumed by all producers and consumers of the cooperative (variable distribution component).

For the amount of electricity that is generated in all renewable energy installations of an energy cooperative and then consumed by all electricity consumers of the energy cooperative:

- is not charged and charged:
    - ○ RES charges referred to in Art. 95 paragraph. 1 of the Act on Renewable Energy Sources,
    - ○ capacity fee, as defined in the provisions of the Act of 8 December 2017 on the capacity market,
    - ○ cogeneration fee within the meaning of the provisions of the Act of 14 December 2018 on the promotion of electricity from high-efficiency cogeneration,
    - ○ excise duty, provided that the total installed electric capacity of all renewable energy installations of the energy cooperative does not exceed 1 MW, and
- the obligations to redeem the certificates of origin or to pay the substitution fee referred to in Art. 52 sec. 1 (green and blue certificates), nor those resulting from Art. 10 of the Energy Efficiency Act (white certificates).

The model of internal settlements of produced and consumed electricity can be carried out for any time horizon—e.g., for an hour.

3. Materials and Methods

The basic methodological approach presented in this article is a case study analysis of energy communities and it was based on an economic analysis of real market data.

A case study includes:

- background introduction—characteristics of the functioning of an energy cooperative with the identification of benefits,
- defining the simulation assumptions for research on cooperatives,
- economic analysis, and
- effects of coopetition within the energy communities.

3.1. Simulation Assumptions for Research on Cooperatives

It was necessary to prepare simulation scenarios reflecting the energy cooperative that could function in reality and the relations between its members in order to simulate and test the hypothesis. Actual data on producers and consumers of energy in rural areas were adopted for analytical and simulation activities due to the definition indicating that an energy cooperative is a solution aimed, in particular, at stimulating the construction of energy communities in rural areas. An energy cooperative was created for simulation purposes, reflecting various: (i) location character, (ii) level of demand for electricity, (iii) nature of economic activity of cooperative members, (iv) electricity consumption profile for each member of the cooperative, (v) production potential among cooperative members, and (vi) the level of voltage supplying cooperative members. The construction of an energy cooperative also takes the formal and legal aspects resulting from the applicable regulations into account. In particular, the location criterion regarding the allocation of members in the area of up to three adjacent rural or rural urban communes was maintained, as well as the need to balance at least 70% of the demand from own generation sources.

The simulation process was carried out in several stages in order to thoroughly examine the effects of establishing an energy cooperative:

1. In the first stage, 11 farms meeting the criteria described above were selected and the actual costs of purchasing electricity along with the distribution service were calculated, taking the current tariff rates into account. The obtained results constituted a reference for the results of further simulations.
2. The second stage assumed that each farm would build its own power source, adjusted to the demand profile with the generation profile. For the prosumers created in this way, the calculation of the costs of purchasing the missing energy along with the distribution service was carried out in the same way as for the first stage. The obtained results illustrate the benefit of becoming an individual prosumer. The selection of generation sources, i.e., generation technology and source power, was optimized in terms of the target combination of receiving and generating facilities into a cooperative. The objective function was to minimize the sum of energy that is drawn from the grid from outside the grid storage and the state of the energy storage at the end of the billing period.
3. The third stage assumed the consolidation of farms–prosumers within the framework of an energy cooperative, and the calculation of the effects of self-balancing, an increase in self-consumption, and the costs of purchasing missing energy. The result of simulations and calculations was to be the cost seen from the perspective of the entire cooperative, which was ultimately to be decomposed for each of its members. The results of the decomposition were to make it possible to evaluate the profitability of joining the cooperative for all of its members.

3.1.1. Assumptions for Stage 1

The purpose of the selection of farms was to reflect:

- location character—the simulation was made for entities located in the Silesia Voivodeship, and the selection additionally took different locations of communes in the voivodeship into account. The choice of this voivodeship was also aimed at reproducing the level of insolation typical for the country, and thus the generation efficiency,
- different levels of demand for electricity—under this criterion, participants were selected taking into account the diversity of individual energy demand of each of them.

The cooperative was composed of participants with low consumption of 52 MWh/year, up to the level of 3574 MWh/year,

- the nature of the economic (agricultural) activity—the selection of participants reflected the division in force in Polish law by the so-called PKD (Polish Classification of Activities) codes that are appropriate for typical agricultural activities, i.e., agricultural crops, vegetable cultivation, cereal cultivation, poultry, pig, and cattle breeding, as well as services for the agricultural sector. The full classification is included in the commentary to Table 1,
- electricity consumption profile for each member of the cooperative—the tariff diversity in force in Poland, and which may occur among members of energy cooperatives, was taken into account. Entities belonging to one, two, or three zone tariffs were selected, thanks to which the diverse nature of energy consumption was reproduced,
- electricity consumption profile for each member of the cooperative—the tariff diversity in force in Poland, and which may occur among members of energy cooperatives, was taken into account. Entities belonging to one, two or three zone tariffs were selected, thanks to which the diverse nature of energy consumption was reproduced,
- different levels of supply voltage for farms—consumers supplied at the medium (MV) and low (LV) voltage level, and
- production potential among cooperative members—the selection of municipalities took into account the possibility of building renewable energy sources in each of the technologies: wind, photovoltaic, biogas, biomass, and water.

Table 1. Characteristics of the selection of farms.

Characteristics	Cooperative 1
Voivodeship	Silesia
Number of members	11
Agricultural activity profile and number of members	01.46.Z; ż (3) 01.13.Z; (3) 01.47.Z; (5)
Voltage level (LV/MV) and number of members	LV (4) MV (7)
Tariff group and number of members	C11 (2) C12a (1) C22b (1) B21 (1) B23 (6)
Electricity demand [MWh/year]	9 757
Minimum, average and maximum energy consumption by a cooperative member [MWh/year]	min: 52 mean: 887 max: 3 574

Where:

Agricultural activity profile:

- 01.13.Z—Growing vegetables, including melons, and growing root crops and tubers,
- 01.46.Z—Pig rearing and breeding, and
- 01.47.Z—Poultry Farming and Breeding

For economic analyses, the tariff rates for both the sale of electricity as a commodity and distribution were used. The rates of DSO—Tauron Distribution and Tauron Sales for 2020 were taken into account, being additionally increased by the capacity fee related to the introduction of the capacity market in Poland from 1 January 2021. Tables 2 and 3 present the individual price components.

Table 2. Distribution tariffs included in the calculation [26].

Tariff Group	All Day	Day/ Peak	Night/ Offpeak	1st Peak	2nd Peak	Rest of the Day	Qualitative Rate	Capacity Fee
	PLN/MWh						PLN/MWh	PLN/MWh
B11	67.27						13.33	76.2
B21	55.26						13.33	76.2
B22		53.48	53.48				13.33	76.2
B23				35.13	35.13	35.13	13.33	76.2
Tariff Group	PLN/kWh						PLN/kWh	PLN/kWh
C21	0.1422						0.0133	0.0762
C22a		0.1422	0.1422				0.0133	0.0762
C22b		0.1422	0.1422				0.0133	0.0762
C23				0.1564	0.2274	0.1138	0.0133	0.0762
C11	0.1401						0.0133	0.0762
C12a		0.1315	0.1315				0.0133	0.0762
C12b		0.1315	0.1315				0.0133	0.0762

Table 3. Sales tariffs included in the calculations [27].

Tariff Group	All Day	Peak	Offpeak	Day	Night	1st Peak	2nd Peak	Rest of the Day
	PLN/MWh							
B11	447.00							
B21	437.00							
B22		506.00	390.00					
B23						500.00	586.00	359.00
Tariff Group	PLN/kWh							
C21	0.471							
C22a		0.585	0.425					
C22b				0.541	0.365			
C23						0.602	0.644	0.380
C11	0.489							
C12a		0.600	0.422					
C12b				0.591	0.364			

3.1.2. Assumptions for Stage 2

The purpose of the selection of farms was to reflect:

- the selection of generation sources, both in terms of generation technology and capacity, was aimed at achieving the effect of minimizing the sum of energy that is purchased from the grid outside the grid storage and the stock at the end of the billing period. For the purposes of the simulation, it was assumed that the total annual energy production in each farm cannot exceed 120% of the annual energy demand. This level guarantees the full balance of each farm in the annual settlement period, while not guaranteeing an hourly balance,
- Poland has moderately favourable sun exposure conditions, however, the prosumer energy industry is almost 100% based on photovoltaic sources. For the purposes of the simulations, it was assumed that at least 25% of energy production in all farms comes from solar energy. Additionally, the power limitations for a single PV farm were adopted from 0 to 1000 kW with increments of 50 kW,
- due to unfavourable hydrological conditions, it was assumed that ultimately a maximum of one hydroelectric power plant may operate within an energy cooperative. An assumption was made, which is reflected in practice, that a small hydropower plant is characterised by a low power of several dozen to several hundred kW. Therefore, the simulation takes the power limitations of a single source from 0 to 500 kW in increments of 50 kW into account, and it was assumed that it would be only in one farm,
- rural and rural-urban areas are very often undeveloped or low-built areas. This location is favourable for the construction of low-mast, low, and medium power wind

sources. For the needs of analytical and simulation works, it was assumed that the participants of the cooperative could build sources with a capacity from 0 to 1000 kW with an increment of 250 kW,

- agricultural land is also a space for the construction of biogas and biomass sources, guaranteeing high generation efficiency and stability of the production profile. For the simulation, for both biomass and biogas, power limitations of the sources from 0 to 600 kW with increments of 200 kW were assumed, and
- due to the fact that the installation of new sources is associated with significant costs, it was assumed that one farm has at most two sources of energy production when selecting production sources to optimally balance the demand.

For the assumptions that are indicated for stages 1 and 2, an optimization process was carried out in order to select the type and capacity of generating sources based on a dedicated mathematical model using the mixed integer programming technique. GLPK software was used for modelling, in particular, the GMPL high-level language made available. The presentation of the mathematical model and the detailed analysis of the results are not the subject of this work and constitute separate publication material [28]. The results presented in Table 4 were obtained as a result of the optimization.

Table 4. Characteristics of the sources and obtained results of generation simulation.

Id	Production		Consumption		Capacity [kW]				
	Total [GWh/Year]	Average Daily [kWh/Day]	Total [GWh/Year]	Average Daily [kWh/Day]	PVPP	SWPP	WPP	BMPP	BGPP
Total	8.760	997	9.757	1111	3810	200	3750	400	600
Farm1	0.175	44	0.190	22	175				
Farm2	0.105	27	0.104	12	105				
Farm3	0.270	31	0.255	29	70	200			
Farm4	1.245	149	1.102	125	495		750		
Farm5	0.540	62	0.501	57	140			400	
Farm6	2.000	239	3.574	407	1000		1000		
Farm7	1.960	234	1.809	206	960		1000		
Farm8	1.370	164	1.124	128	370		1000		
Farm9	0.905	105	0.900	102	305				600
Farm10	0.140	35	0.146	17	140				
Farm11	0.050	13	0.052	6	50				

Where: PVPP—Photovoltaic power plant; SWPP—Small hydro power plant; WPP—Wind power plant; BMPP—Biomass power plant; BGPP—Biogas power plant.

4. Economic Analysis

Based on the above-mentioned assumptions, an analysis of the costs of energy purchase was carried out along with the distribution service for each of the three stages. In the first stage, in which each farm purchased all electricity from the seller—Tauron Sales GZE on the basis of a comprehensive contract (energy and distribution), it was possible to observe the level of personalized annual costs from PLN 35,000 to over PLN 1.85 million. The total cost for all farms exceeded 5.14 million PLN/year, of which 4.28 million PLN (85%) is the cost of energy as a commodity, and the remaining 0.87 million PLN (15%) is the cost of distribution and power fee. The calculations were made while taking the actual number of hours and energy for each hour zone in each of the tariff groups into account. Table 5 presents the detailed calculation results. The second stage included the settlement of each farm that is equipped with its own source or generation sources with the power and generation technology that is presented in Table 4. Having a separate generation of each farm allowed for obtaining the status of a prosumer and reducing the amount of energy that is purchased from the seller. Depending on the effectiveness of the source selection, the total level of self-consumption obtained for all prosumers amounted to 5.84 GWh, which, in relation to the total level of demand of 9.76 GWh, constituted nearly 60%. This energy and the energy collected in the discount model from the network storage are both not subject to distribution and sales fees. Full payment for energy and distribution only occurs in the event of an imbalance of each prosumer. The total amount of energy purchased from the seller for balance purposes by all prosumers amounted to 2.14 GWh. This purchase was associated with a cost of PLN 1.12 m, of which PLN 0.94 m (84%) was the cost of energy, and PLN 0.18 m was the cost of distribution and power charges.

Table 5. Economic calculations results.

Stage	Users [1]	Self-Consumption	Collection from the Network Storage	Loss on the Network Storage	Consumption from the Network (Outside the Storage)	Energy Cost	Distribution Cost	Capacity Market	Total
		kWh/Year				PLN			
1	F1	-	-	-	-	88,669	27,552	6721	122,941
	F2	-	-	-	-	49,043	16,191	3255	68,489
	F3	-	-	-	-	111,380	17,482	10,091	138,953
	F4	-	-	-	-	480,833	53,400	38,133	572,366
	F5	-	-	-	-	218,677	24,286	17,342	260,305
	F6	-	-	-	-	1,559,584	173,204	123,684	1,856,472
	F7	-	-	-	-	789,190	87,645	62,587	939,423
	F8	-	-	-	-	490,443	54,467	38,895	583,806
	F9	-	-	-	-	392,840	43,628	31,155	467,622
	F10	-	-	-	-	71,262	22,355	4866	98,484
	F11	-	-	-	-	25,392	7966	1734	35,091
	T(1)	-	-	-	-	4,277,313	528,175	338,464	5,143,952
2	P1	65,555	76,611	0	48,109	22,910	6966	1406	31,282
	P2	32,634	47,963	2693	23,527	10,682	3658	541	14,881
	P3	188,672	42,922	14,008	23,280	10,173	1597	1078	12,848
	P4	731,788	303,503	55,756	66,651	29,633	3230	2562	35,425
	P5	421,531	55,368	27,568	24,250	11,185	1175	819	13,179
	P6	1,701,672	208,830	0	1,663,653	723,439	80,621	47,803	851,862
	P7	1,155,359	504,022	59,235	149,234	66,120	7232	5124	78,475
	P8	777,016	318,016	97,093	28,934	12,694	1402	1014	15,110
	P9	703,174	126,986	14,302	70,125	31,827	3398	2118	37,343
	P10	49,230	63,539	0	32,961	16,118	5056	894	22,068
	P11	17,551	22,714	0	11,661	5702	1789	318	7809
	T(2)	5,844,183	1,770,474	270,655	2,142,384	940,483	116,124	63676	1,120,283
3	M1	-	-	-	-	18,147	5481	1220	24,848
	M2	-	-	-	-	8446	2872	474	11,793
	M3	-	-	-	-	9208	1445	1031	11,685
	M4	-	-	-	-	29,930	3385	2673	35,989
	M5	-	-	-	-	10,228	1045	750	12,023
	M6	-	-	-	-	594,082	78,209	46,298	718,589
	M7	-	-	-	-	67,245	7578	5389	80,211
	M8	-	-	-	-	11,875	1460	1020	14,354
	M9	-	-	-	-	25,970	2809	1887	30,666
	M10	-	-	-	-	12,262	3847	738	16,847
	M11	-	-	-	-	4366	1370	263	5998
	C (3)	6,237,022	1,446,487	67,317	2,073,532	791,760	109,500	61,744	963,004
	(2)–(1)	-	-	-	-	−3,336,830	−412,051	−274,788	−4,023,669
	(3)–(1)	-	-	-	-	−3,485,553	−418,676	−276,720	−4,180,948
	(3)–(2)	392,839	−323,988	−203,338	−68,851	−148,722	−6625	−1932	−157,279

[1] Where: F—Farm; P—Prosumer; M—Member of cooperative; T—Total; C—Cooperative.

The third stage involved the settlement of an energy cooperative that consists of 11 farms with the status of a prosumer. The illustration of the synthetic model showing the calculation method is as follows:

$$Cost_T = \sum_{n=1}^{c}\left(\sum_{d=1}^{365}\left(\sum_{t=1}^{k}(V_{Et} \times (P_{Et} + P_{Dt})) + \sum_{h=7}^{22}(V_{Eh} \times P_{CM})\right)_d\right)_n \tag{1}$$

where:

$Cost_T$—total cost of electricity purchase
t—number of tariff zones
h—hours 7:00 a.m.–10:00 p.m.
c—number of customers (1—for individual or prosumer, 11—for cooperative)
V_{Et}—volume of electricity consumption in each of scenarios (discount model for prosumer: 1/0.8 or 1/0.7; for cooperative 1/0.6)

V_{Eh}—volume of electricity consumption in peak hours in working days
P_{Et}—electricity price in tariff zone '*t*'; $t_{\max} = 4$
P_{Dt}—price of electricity distribution in tariff zone '*t*'
P_{CM}—Settlement price on capacity market 76.20 PLN/MWhv [29].

A detailed model of settlements for energy cooperatives is described in the draft of legal regulation [30]. The financial results broken down into cost streams: energy purchase, distribution, and capacity market are presented in Table 5.

The merging of the demand–supply profiles of prosumers allowed for self-consumption at the level of 64%, i.e., 393 MWh more than in the case of individual prosumer settlement (Stage 2). The amount of electricity charged and subject to charges has also decreased, from 2.142 GWh (Stage 2) to 2.073 GWh. The above elements contributed to the reduction of the total cost of energy purchase and distribution services, which, for the entire energy cooperative, amounted to 0.963 million PLN/year, of which nearly 0.792 million PLN (82%) was the cost of energy. It is also worth emphasizing that the optimization of the selection of generation sources for individual participants was aimed at minimizing the sum of the volume purchased from the seller and the stock of network storage at the end of the settlement period. For this reason, energy losses that could not be used within the 12-month billing period were minimized. The reduction was achieved from 270 MWh for stage 2 to 67 MWh for stage 3.

5. Results and Discussion

The conducted profitability analysis of an energy cooperative, the results of which are presented in Table 5, allows for concluding that the creation of an energy cooperative on the basis of farms with the prosumer status additionally affects the emergence of benefits in the form of over 157 kPLN per year. Such a good result is obtained, despite a worse discount rate. In the case of a farm–a prosumer, this ratio is 1/0.7 and, for a cooperative, it is 1/0.6 (introduced to the 1 MWh network results in the possibility of free collection of 0.7 or 0.6 MWh). The financial effect that is obtained by the cooperative should be transferred to its individual members. In order to simulate such a separation, a key was used, depending on the share of each member of the cooperative in generating savings. The greater the daily-hourly profile of a cooperative member was correlated with the instantaneous generation of electricity and condition of the network warehouse, the greater its share in the profit distribution was obtained. Table 6 presents the results of such a division and they correspond to the model specified in the draft of legal regulation [30]. It shows that two members of the cooperative achieved a deterioration of the financial result in relation to the scenario, when they were only farms with a prosumer status. It is worth emphasizing that this happened, despite the fact that the financial result obtained by the entire cooperative was in favour of the cooperative.

Table 6. Economic effect for an energy cooperative.

Users	Total Cost for Stage 2	Total Cost for Stage 3	Stage 3–Stage 2
		PLN	
Member1	31,282	24,848	−6434
Member2	14,881	11,793	−3088
Member3	12,848	11,685	−1163
Member4	35,425	35,989	564
Member5	13,179	12,023	−1156
Member6	851,862	718,589	−133,272
Member7	78,475	80,211	1736
Member8	15,110	14,354	−756
Member9	37,343	30,666	−6678
Member10	22,068	16,847	−5221
Member11	7809	5998	−1811
Total	1,120,283	963,004	−157,279

In the context of the results obtained, one can ask whether if the cooperative did not include four and seven members, the obtained result for the entire cooperative and for its other members would still be favourable. For this purpose, the same profitability analysis was carried out for the entire cooperative with nine members (excluding farms with the prosumer status marked with numbers 4 and 7). Table 7 presents the results that were obtained for the original scenario of the cooperative (stage 3a) and for the cooperative with a reduced number of members (stage 3b).

Table 7. Decomposition of the cooperative's result into its members.

Stage	Users	Energy Cost	Distribution Cost	Capacity Market	Total	Advantage	Loss
		PLN					
3a	Member1	−4762	−1485	−186	−6434	−6434	
	Member2	−2235	−786	−67	−3088	−3088	
	Member3	−965	−151	−47	−1163	−1163	
	Member4	297	155	111	564		564
	Member5	−957	−130	−69	−1156	−1156	
	Member6	−129,357	−2412	−1504	−133,272	−133,272	
	Member7	1125	346	265	1736		1736
	Member8	−819	58	6	−756	−756	
	Member9	−5857	−590	−231	−6678	−6678	
	Member10	−3856	−1210	−156	−5221	−5221	
	Member11	−1336	−419	−55	−1811	−1811	
	Cooperative (3)	−148,722	−6625	−1932	−157,279	−159,579	2300
3b	Member1	−3911	−1222	−149	−5281	−5281	
	Member2	−1819	−660	−51	−2529	−2529	
	Member3	−310	−49	38	−321	−321	
	Member4	-	-	-	-	-	
	Member5	−441	−82	−32	−555	−555	
	Member6	−130,791	−3435	−731	−134,957	−134,957	
	Member7	-	-	-	-	-	
	Member8	−934	15	−10	−929	−929	
	Member9	−4459	−444	−133	−5037	−5037	
	Member10	−3242	−1017	−123	−4382	−4382	
	Member11	−1120	−351	−44	−1515	−1515	
	Cooperative (3)	−147,027	−7245	−1235	−155,506	−155,506	

6. Conclusions

- Eliminating members of cooperatives 4 and 7 does not have a positive effect on the final benefit for the whole cooperative.
- For step 3b, the distribution of benefits indicates that only members numbered 6 and 8 gain as compared to scenario 3a. The remaining seven members have a worse financial result.
- The financial effect that is obtained in stage 3b is PLN 4,073 worse than in stage 3a. Therefore, it can be concluded that the departure of two members of the cooperative, for whom it was unprofitable to participate in it, deteriorates, as a rule, the results of other members. At this point, it becomes reasonable to leave members 4 and 7 in the coopetitive actions aimed at financing the loss recorded by them, by other members. Such an approach, apart from covering the loss, allows for the generation of benefits of PLN 1773 (as compared to scenario 3b), which can be distributed with the appropriate key to all members of the cooperative.

The results of the conducted research and simulations, which constitute an individual and pioneering contribution of members of the authors' team, very faithfully reflecting the specificity of the operation of energy cooperatives and based on actual data, confirm that the profitability of energy cooperatives is very dependent on the nature and supply-demand profile of its members. The profitability of the energy cooperative is additionally lowered, due to the less favourable discount rate when compared to the standard prosumer scenario. However, the analyses that were carried out clearly indicate that it is possible to obtain benefits within the cooperative both on the global and individual level. This statement confirms the realization of article's goal as well as positively tests the hypotheses.

It is worth emphasizing that not all energy consumers may become owners of their own generation sources and be prosumers. This is the case, for example, due to location limitations, a lack of space to develop the source, or high investment costs. The model of an energy cooperative guarantees very tangible benefits in each of such cases for each of the members. Additionally, within the energy community, it becomes possible to build ties and relationships that aimed at searching for the best financial effect, as seen from the perspective of the community and translating into individual benefits.

Many empirical papers clearly demonstrate that competitors either purposefully use cooperative behaviours to generate and capture rents, or should behave so. The founding achievement of coopetition research community is much more than coining a term for a complex phenomenon. This brings attention to attitudes, behaviours that prevent actors from coopetition strategy implementation.

This paper limitations may be attributed to selective case study presentation. This study does not have exhaustive ambitions, but, in turn, it might be biased by the omission of many theoretical and empirical works. Theoretical sampling satisfies for listing empirical case studies analysed by other coopetition researchers, but it does not provide representative results. Instead, it creates a sharp picture of the research community's current efforts. Moreover, the analysis case study is also selective. While those reasons suggest a prudent use of findings, their formulation remains straightforward. Yet, whether coopetition is a theory or just another dynamic capability as well their positive impact on individual and collective results remains to be tested.

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References

1. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the Promotion of the Use of Energy from Renewable Sources; European Union: (OJ L 328). 21 December 2018. Available online: http://data.europa.eu/eli/dir/2018/2001/oj (accessed on 9 January 2021).
2. Citizens Energy Communities: Recommendations for a Successful Contribution to Decarbonisation; Eurelectric Position Paper—Dépôt Légal: D/2019/12.105/13. 2019. Available online: https://www.apren.pt/contents/publicationsothers/eurelectric--citizens-energy-communities.pdf (accessed on 9 January 2021).
3. Ghiani, E.; Giordano, A.; Nieddu, A.; Rosetti, L.; Pilo, F. Planning of a Smart Local Energy Community: The Case of Berchidda Municipality (Italy). *Energies* **2019**, *12*, 4629. [CrossRef]
4. Hussain, H.I.; Slusarczyk, B.; Kamarudin, F.; Thaker, H.M.T.; Szczepańska-Woszczyna, K. An investigation of an adaptive neuro-fuzzy inference system to predict the relationship among energy intensity, globalization, and financial development in major ASEAN economies. *Energies* **2020**, *13*, 850. [CrossRef]

5. Sokołowski, M.M. Renewable and Citizen Energy Communities in the European Union: How (Not) to Regulate Community Energy in National Laws and Policies. *J. Energy Nat. Resour. Law* **2020**, *38*, 289–304. [CrossRef]
6. Neagu, B.-C.; Ivanov, O.; Grigoras, G.; Gavrilas, M.; Istrate, D.-M. New Market Model with Social and Commercial Tiers for Improved Prosumer Trading in Microgrids. *Sustainability* **2020**, *12*, 7265. [CrossRef]
7. Czakon, W.; Mucha-Kuś, K.; Rogalski, M. Coopetition Research Landscape—A Systematic Literature Review 1997–2010. *J. Econ. Manag.* **2014**, *17*, 121–150.
8. Czakon, W.; Mucha-Kuś, K.; Sołtysik, M. Coopetition strategy—What is it in for all? *Int. Stud. Manag. Organ.* **2016**, *46*, 80–93. [CrossRef]
9. Brandenburger, A.M.; Nalebuff, B.J. *Co-Opetition*; Doubleday Currency: New York, NY, USA, 1996.
10. Lado, A.; Boyd, N.; Hanlon, S. Competition, Cooperation and the Search for Economic Rents: A Syncretic Model. *Acad. Manag. Rev.* **1997**, *22*, 110–141. [CrossRef]
11. Tidström, A. Perspectives on Coopetition on Actor and Operational Levels. *Manag. Res.* **2008**, *6*, 207–218. [CrossRef]
12. Robert, F.; Marques, P.; Le Roy, F. Coopetition between SMEs: An empirical study of French professional football. *Int. J. Entrep. Small Bus.* **2009**, *8*, 23–43. [CrossRef]
13. Okura, M. Coopetitive Strategies of Japanese Insurance Firms—A Game Theory Approach. *Int. Stud. Manag. Organ.* **2007**, *37*, 53–69. [CrossRef]
14. Mariani, M. Coopetition as an Emergent Strategy. Empirical Evidence from an Italian Consortium of Opera Houses. *Int. Stud. Manag. Organ.* **2007**, *37*, 97–126. [CrossRef]
15. Ritala, P.; Hallikas, J.; Sissonen, H. Coopetitive Networks in ICT Sectors. *Int. J. Bus. Environ.* **2008**, *2*, 1–16. [CrossRef]
16. Tidström, A. Causes of Conflict in Intercompetitor Cooperation. *J. Bus. Ind. Mark.* **2009**, *24*, 506–518. [CrossRef]
17. Czakon, W. Power Asymmetries, Flexibility and the Propensity to Coopete: An Empirical Investigation of SME's Relationships with Franchisors. *Int. J. Entrep. Small Bus.* **2009**, *8*, 23–43. [CrossRef]
18. Mucha-Kuś, K. Measurable Effects of Metropolitan Gas Purchasing Group in the Light of Gas Market Functioning in Poland. *Resources* **2020**, *9*, 36. [CrossRef]
19. Mucha-Kuś, K.; Stęchły, J.; Zamasz, K. The role of coopetition in development of electromobility. *Zesz. Nauk. Politech. Śląskiej Organ. Zarządzanie* **2018**, *21*, 357–369. [CrossRef]
20. Polish Energy Policy until 2040. Available online: https://www.gov.pl/attachment/e585942a-af9a-45f6-a580-dc607b4c0d22 (accessed on 29 December 2020).
21. Act on Renewable Energy Sources 'Ustawa z Dnia 20 Lutego 2015 r. o Odnawialnych Źródłach Energii, Dz. U. 2015 poz. 478 z Późn. Zm. Available online: http://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=wdu20150000478 (accessed on 9 January 2021).
22. The Cooperative Law Act 'Ustawa z Dnia 16 Września 1982 r. Prawo Spółdzielcze, Dz. U. 1982 nr 30 Poz. 210 z Późn. Zm.'. Available online: https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU19820300210 (accessed on 9 January 2021).
23. Act on Farmers' Cooperatives 'Ustawa z Dnia 4 Października 2018 r. o Spółdzielniach Rolników, Dz. U. 2018 Poz. 2073 z Późn. Zm.'. Available online: https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20180002073 (accessed on 9 January 2021).
24. Wróbel, J.; Sołtysik, M.; Rogus, R. Selected elements of the Neighborly Exchange of Energy—Profitability evaluation of the functional model. *Energy Policy J.* **2019**, *22*, 53–64.
25. Saługa, P.W.; Szczepańska-Woszczyna, K.; Miśkiewicz, R.; Chłąd, M. Cost of Equity of Coal-Fired Power Generation Projects in Poland: Its Importance for the Management of Decision-Making Process. *Energies* **2020**, *13*, 4833. [CrossRef]
26. Tariff for Electricity Tauron Dystrybucja S.A. for 2020. Available online: https://www.tauron.pl/-/media/offer-documents/firma/taryfa-msp/gze-podstawowe/taryfa_dystrybucyjna.ashx (accessed on 17 December 2020).
27. Tariff for Electricity Tauron Sprzedaż GZE Sp. Z o.o. Available online: https://www.tauron.pl/-/media/offer-documents/firma/taryfa-msp/gze-podstawowe/01022020-gze-taryfa-sprzedaz-gze-taryfy-abcor-pdf-k.ashx (accessed on 17 December 2020).
28. Jasiński, J.; Kozakiewicz, M.; Sołtysik, M. Determinants of Energy Cooperatives' Development in Rural Areas—Evidence from Poland. *Energies* **2021**, *14*, 319. [CrossRef]
29. Energy Reulatory Ofiice. Available online: https://www.ure.gov.pl/pl/energia-elektryczna/rynek-mocy/informcjepure/9164,Informacja-nr-632020.html (accessed on 30 January 2021).
30. Draft Regulation of the Minister of Climate and Environment of 9/12/2020 on the Registration, Balancing and Sharing of Measurement Data and Settlements of Energy Cooperatives. Available online: https://legislacja.rcl.gov.pl/projekt/12333808/katalog/12687355#12687355 (accessed on 30 January 2021).

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Article

Green Energy in Central and Eastern European (CEE) Countries: New Challenges on the Path to Sustainable Development

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Abstract: In the conditions of climate change and the scarcity of natural resources, the future of energy is increasingly associated with the development of the so-called green energy. Its development is reflected in the European Commission strategic vision to transition to a climate-neutral economy. This is a challenge that the Central and Eastern European (CEE) countries, members of the EU, are also trying to meet. In recent years, these countries have seen an increase in the share of renewable energy and a reduction in greenhouse gas emissions (GGE). On the other hand, basing the energy sector on unstable energy sources (photovoltaics and wind technologies) may imply new challenges on the way to sustainable development. These are old problems in a new version (ecology, diversification of supplies) and new ones related to the features of renewable energy sources (RES; instability, dispersion). The aim of the article was to classify, on the basis of taxonomic methods, the CEE countries from the point of view of green energy transformation (original indicator) and to predict new threats to Romania, Poland, and Bulgaria, the countries representing different groups according to the applied classification. The issues presented are part of a holistic view of RES and can be useful in energy policy.

Keywords: renewable energy sources (RES); green energy transformation; sustainable development

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1. Introduction

Given the conditions of climate change [1] and the scarcity of natural resources, the future of power engineering is increasingly associated with the development of the so–called green, renewable energy. However, the concept of green energy does not always refer only to the renewable energy sources (RES). Its key feature is the lack of negative impact on the environment. This is what characterizes not only renewable energy, namely, solar, wind, hydro, geothermal, biomass, and biofuels, but also nuclear energy [2]. Nevertheless, in most research studies, green energy is perceived as renewable green energy [3]. It constitutes a strategic direction for the EU on its path towards sustainable development [4]. In 2009, the EU adopted a broad package of 2020 commitments: a 20% increase in energy efficiency, a 20% reduction in greenhouse gas emissions (GGE) (compared to 1990 levels), and a 20% increase in renewable energy [5,6]. The assumption is that in 2050 more than 80% of electricity will come from RES [7]. For some member states, these ambitious targets may be difficult to meet [8].

Transition to a climate-neutral economy by 2050 is a major challenge overall, but especially for Central and Eastern European (CEE) countries that show a certain "delay" in relation to the more developed countries of Western Europe. It has roots in their former economic system—their energy was largely based on solid fuels, and little importance was given to the economy's energy intensity and negative environmental effects. Political transformation and accession of these CEE states to the EU have brought about some significant changes in their energy structure and energy intensity. Consequently, they have been developing solar and wind energy dynamically. This trend has led to a significant GGE reduction. On the other hand, basing the energy sector on unstable energy sources (such as the sun and wind) may imply new challenges on the path to sustainable development.

These are old problems in a new form (i.e., ecology and diversification of supplies) and new problems related to the very features of RES (such as their instability or dispersion).

This article aims to classify CEE countries by their transformation towards green energy and to predict new threats (if any) to Romania, Poland, and Bulgaria, countries representing different groups, according to the applied classification. The issues presented are part of a holistic view of RES and can be useful in energy policy.

2. Methodology

The research methodology consists of 4 stages. The first stage is the literature review presenting (1) the specificity of the process of energy transformation in CEE countries; (2) features of solar and wind energy, i.e., the most dynamically developing sectors of green renewable energy in CEE countries; (3) new (old) challenges of the energy transformation of the CEE countries on the way to sustainable development.

Stage 2 presents the energy structure of select CEE countries. The empirical analysis was limited to the following socio-economically homogeneous countries: Bulgaria, Estonia, Lithuania, Latvia, Poland, the Czech Republic, Romania, Slovakia, Slovenia, and Hungary. Having undergone through the process of transformation of their economic and political systems, these countries are classified, nowadays, as highly developed [9], and have similar challenges with regards to green energy transformation. The calculations in stage 2 were carried out on the basis of the International Renewable Energy Agency [10].

Stage 3 is the classification of CEE countries according to the green energy transformation index. For the classification of countries, we used the distance from the pattern method and the Ward's method (cluster analysis). They are included in the group of clustering methods [11] recognized as important data mining techniques. They are applicable (also in social sciences) in assessing the similarities and differences between the studied objects (countries) [12,13]. In both methods used, the classification is based on the Euclidean distance matrices (EDMs) [14,15]. These methods lead to the determination of clusters of objects (countries), i.e., obtaining homogeneous classes of objects due to the objects' features [16]. On this basis, we were able to assess the level of participation of each country in the studied group, the internal homogeneity of the group, and its cohesion and stability of development [17]. The method of distance from the pattern, included in the taxonomic methods of linear ordering, allows us to define the hierarchy of objects. On the other hand, the Ward's method (non-linear ordering) allows us to determine the similarity of objects without establishing their hierarchy [18].

In the construction of the synthetic index of energy transformation (STEP A), we used an algorithm of the taxonomic method of distance from the pattern [19,20], which provided the basis for the classification of countries with different levels of energy transformation. The research algorithm included

1. Selection of partial indicators describing the manifestations of key importance for this transformation. In the authors' approach, the partial indicators were (1) energy productivity (being the reciprocal of the economy's energy consumption), expressed in purchasing power standard (PPS) per kilogram of oil equivalent (kgoe); (2) share of renewable energy in gross final energy consumption; and (3) growth index of GGE in relation to the year 2000. The selection of indicators was dictated by the policy pursued in the EU. In the field of energy transformation, great emphasis is also placed on reduction of GGE [21], energy from renewable sources [22], and improvement of energy efficiency [23]. This approach is in line with the ambitious goals of the European Green Deal [24]. The adopted partial indicators reflect only the basic directions of changes characteristic of the energy transformation of the CEE countries.

An incomplete database (e.g., Eurostat), especially in the long term, constituted a major limitation in selecting a larger number of indicators for this group of countries. Using different databases (e.g., national) limited the possibility of full comparisons due to inconsistent methodology. There are no linear relationships between the partial indicators. The increase in energy productivity is not synonymous with the increase in the green transformation. However, from the point of view of the EU's priorities, the achievement of both goals, i.e., both an increase in energy productivity and an increase in the share of RES in energy consumption, is a desired effect. Increasing the share of RES without improving energy productivity would be contrary to the EU directive and the European Green Deal's assumptions.

The assessment of the level of energy transformation in CEE countries was carried out at 2 time points, i.e., in 2008 and 2018, and included data averaged over 5 years (2004–2008 and 2014–2018). The aim of such a procedure was to eliminate the impact of random events [3]. Determination of the degree of independence of selected partial measures was performed using the Pearson linear correlation coefficient (r) [25,26]. This coefficient ranges from -1 to +1, where 0 means no relationship between the variables, and the closer the absolute value of the coefficient is to 1, the greater the relationship. A level below 0.7 was adopted as a determinant of the independence of factors. Coefficient r (greater than or equal to 0.7) was considered a criterion for the correlation of variables [27,28]. The correlations of partial indicators are shown in Figure 1.

2. Standardization [29] of variables in order to obtain their comparability, which was done according to the formula

$$z_{ik} = \frac{x_{ik} - \overline{x}_k}{S_k} \text{ for } x_k = \frac{1}{w}\sum\nolimits_{i=1}^{w} x_{ik};\ S_k = \left[\frac{1}{w}\sum\nolimits_{i=1}^{w}\left(x_{ik} - \overline{x}_k\right)^2\right]^{\frac{1}{2}}, \tag{1}$$

where

w—number of units (countries) $i \in \langle 1 \ldots w \rangle$;
$k \in \langle 1 \ldots n \rangle$, n—number of features;
x_{ik}—value of the k-th variable in the i-th unit;
$\overline{x}_k$—arithmetic mean of the kth variable;
S_k—standard deviation of kth variable;
z_{ik}—standardized value of k-th variable in i-th unit.

3. Separating the stimulant and destimulant subsets from the set of standardized features (s) in order to determine the development pattern P_0 (units combining the best features of the studied units). Among the partial indicators adopted in the study, 2 indices, PPS/kgoe and RES, are stimulants. The third indicator, GGE, has a negative impact on the energy transition. The pattern was constructed on the basis of the normalized feature matrix (Z) and the vector P_0 was used, where

$$P_0 = \left[z_{01}, z_{02}, \ldots z_{0s}, \ldots z_{01}\right],\ z_{0s} = \max_i z_{is} \Rightarrow s \in I z_{0s} = \min_i z_{is} \Rightarrow s \notin I, \tag{2}$$

I—stimulant subset;
z_{0s}—the best value of s-th variable;
z_{is}—standardized value of s-th variable in i-th unit.

4. Calculation of taxonomic distances, using the Euclidean method, between the studied units and the development pattern (c_{i0}):

$$c_{i0} = \left[\sum_{s=1}^{n}\left(z_{is} - z_{0s}\right)^2\right]^{\frac{1}{2}} \tag{3}$$

5. Determining the measure of development (d_i) on the basis of taxonomic distances:

$$d_i = \frac{c_{i0}}{c_0},\ \text{where } c_0 = \overline{c}_0 + 2S_0,\ \overline{c}_0 = \frac{1}{w}\sum\nolimits_{i=1}^{w} c_{i0},\ S_0 = \left[\frac{1}{w}\sum\nolimits_{i=1}^{w}\left(c_{i0} - \overline{c}_0\right)^2\right]^{\frac{1}{2}} \tag{4}$$

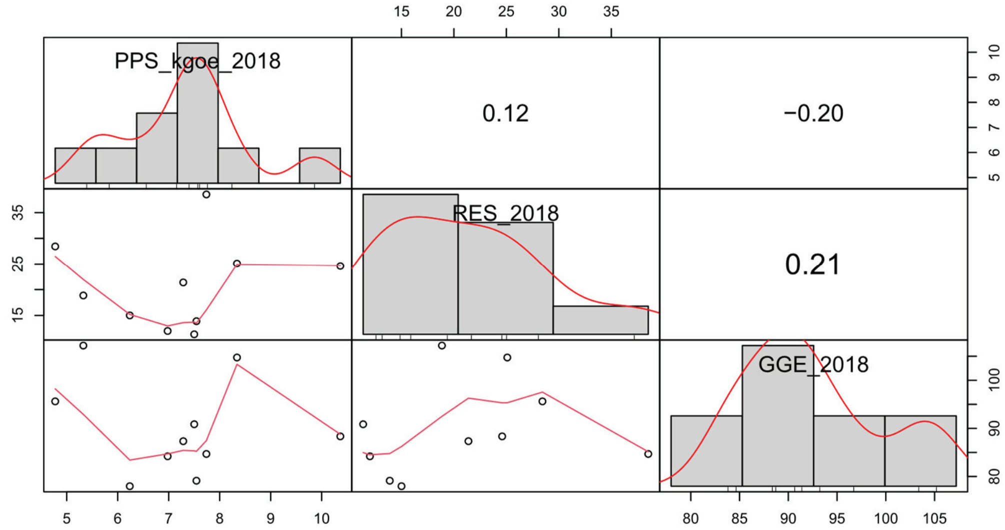

Figure 1. Pearson correlation coefficients between partial indicators purchasing power standard (PPS)/kgoe, renewable energy sources (RES), and greenhouse gas emissions (GGE) in 2018.

The synthetic indicator (d_i) is within the range 0–1. The more a given unit is at a higher level of development, the more the measure value approaches zero. The development pattern method thus enables ranking CEE countries according to the degree of green energy transformation, on the basis of the calculated taxonomic indicators/synthetic values of development indicators (d_i).

STEP B—Classification of CEE countries in terms of energy transformation according to Ward's minimum variance clustering method.

Ward's method belongs to the agglomeration grouping methods. It is considered one of the most effective in creating homogeneous clusters [30]. The group consists of units (countries) for which the variance of the studied variable, which is a measure of cluster diversity, is the smallest. The method minimizes the sum of the squared distances inside the clusters after the group is created in a given step.

$$s = \sum_{s=1}^{k} (x_i - \overline{x})^2, \tag{5}$$

x_i—the value of the variable being the segmentation criterion for the *i*-th object;
k—number of objects in a cluster.

The procedure is repeated many times until the group includes all the elements of the set subject to the cluster analysis. The results of grouping units using the Ward method (CEE countries according to the level of energy transformation) are presented in the form of a dendrogram. Cluster groups of the analyzed countries were determined using the ward2 procedure of R.

The calculations in stage 3 were performed using the Eurostat statistical database [31] and IRENA [10].

Stage 4 is an attempt to assess the challenges related to the development of renewable sources for Bulgaria, Poland, and Romania on selected examples that include (a) an increase in the use of solar panels, (b) import of components for the development of solar and wind energy, and (c) connections between Information and Communication Technology (ICT) and the development of green renewable energy.

First of all, the basis for this assessment was the impact of solar energy development on the environment through (a) forecasting the amount of waste generated by exhausted solar photovoltaic (PV) panels and (b) prediction of the surface of non–recycled waste from solar photovoltaics panels. Both the forecasting and prediction were carried out in the examined CEE countries on the basis of (a) trends in the development of solar energy net generation capacity (electricity production capacities for renewables and wastes) expressed in MW, (b) e-waste recycling rate [32], (c) technical data of PV cells (used to convert energy production capacity to the surface of PV panels) [33–35], and (d) forecasted 20-year service life.

The prediction was performed in two cases. The first case is less favorable to the environment as it assumes the level of PV utilization to be maintained at the level of the current e-waste disposal capacity of the CEE countries. The year 2018 was the baseline [31]. In the second case, it was assumed that the utilization of e-waste would increase to 68% (growth case)—the level of the best performers in e-waste recycling from Western Europe [31]. The increase in energy efficiency may contribute to the reduction of waste generated. However, it does not change the very mechanism of their formation. Due to the lack of predictions in the literature regarding new technological solutions that bring about an increase in energy efficiency, we did not address this issue in the study.

The study of the relationship between the increase in solar and wind energy production capacity and the import of components necessary for their development constitutes another cross-section of the assessment of the challenges accompanying the development of energy from RES. The study used data from Trade Map International Trade Statistics concerning products used to a large extent in the installation of green energy production facilities (products classified to group 84, i.e., machines, mechanical devices, nuclear reactors, boilers; their parts) [36].

The assessment of the challenges resulting from the development of green energy also includes the search for dependencies between the dynamics of its development and technological needs. The verification of the relationships between the indicated phenomena was carried out on the basis of the dynamics of changes in their development, i.e., total renewable energy, solar energy, and wind energy in relation to the expenditure on ICT. It was only an attempt to capture the dependencies between these phenomena or lack thereof. The Eurostat data were used in this analysis [31].

3. Results

3.1. Literature Review

3.1.1. Energy Transformation of CEE Countries

Energy is an important part of the life of every person, every country, and the planet, but the way energy is perceived changes with the development of civilization. In the industrial era, the focus was on meeting the needs of rapidly industrialized economies and societies [37]. Little importance was given to social development or public goods such as environment, security, equality, or sovereignty [38]; in the new paradigm of development, equated with sustainable development, these goods have been playing a key role [39]. The UN Conference in Stockholm in 1972 confirmed the aforementioned transformations. Sustainable development was defined then as development that meets the needs of the present without diminishing the chances of future generations to meet their own needs.

While significant changes in the economic development paradigm were taking place in the world, the CEE countries pursued a policy of energy-intensive industrialization, and then underwent political transformation. Historical conditions contributed to a certain “delay” in the process of energy transformation of the CEE countries compared to the Western European states. The systemic transformation/liberalization of the economy, privatization, restructuring of enterprises, and the resulting changes in the structure of the economy did not proceed in the same way in individual CEE countries and in the same period [40]. It resulted in a strong decline in the energy intensity of CEE economies (even higher than the EU average [40]), but it was due to slightly different reasons. For example, in the years 1992–1998, Bulgaria and Romania experienced a decrease in the energy intensity of the economy in the conditions of increasing energy intensity of industry.

In the Baltic states, the decrease in energy intensity of industry was responsible in as much as 50% for the decrease in energy intensity of their economies in general [41].

Central and Eastern European countries have different potentials for the development of green energy. These varied conditions determined a different business climate for the development of renewable energy during the systemic transformation. Bulgaria, Romania, and Slovakia were considered the most attractive countries for its development [42]. Romania is especially noteworthy, as it is characterized by high hydropower [43]. Although it invests in solar and wind energy, water is still the most important resource in Romania's group of renewable resources [44]. In Slovakia, Hungary, Bulgaria, and the Czech Republic, investments in nuclear energy made in the past had an impact on the course of the energy transformation. It is not a renewable energy, but an energy with a low environmental impact, enabling the achievement of the assumed climate goals much faster than in Poland (traditionally dependent on cheap coal).

The membership in the EU structures, in whose policy sustainable and green development has had a strategic place [45,46] for many years, has proven to be a factor intensifying the energy transformation of the CEE countries. In 2019, the European Green Deal was adopted to deal with numerous climate and social problems [47]. It assumes that high and growing energy efficiency should be accompanied by energy transformation (increasing the share of renewable energy in total energy consumption [48,49]. In CEE countries, government programs actively support the development of green energy and these actions have already brought some tangible results. Experts predict an above-average and long-term growth of new investments in RES in this region, mainly in terms of the sun [50] and wind [51].

3.1.2. Solar and Wind Energy—Pros and Cons

The increase in the share of RES in the production of primary energy leads to a decrease in the energy consumption of the economy [52,53] and an increase in their use in electricity production. In the case of CEE countries, this is the result of applying relatively newer technologies in comparison with those used in traditional power engineering. It is estimated that as early as 2025, RES will be the largest source of electricity generation in the world. From this point of view, solar energy has the greatest development potential [54–56]. It can be used in two ways. The first is obtaining heat with the use of solar collectors, the second is electricity production [57,58]. Solar energy is developing in four sectors: commercial, utilities, industrial, and residential. Apart from solar energy, the popularity of wind energy is also growing. Wind farms capture the energy of the wind flow with the help of turbines and convert it into electricity. The windmills are located on and off land. Due to the varying power, they can be used in both households and for industrial purposes [59].

Solar and wind energy, which are clean, inexhaustible, and environmentally friendly, are perceived as excellent sources of energy production [60]. Photovoltaics, together with new solutions in the field of wind technologies [61], are characterized by a radical reduction of costs [62] thanks to more efficient technologies and better materials [63]. Moreover, thanks to R&D investments [64] and new patents, the costs of these technologies are expected to drop even further [65].

Some authors argue that the producers of photovoltaics and wind technologies can even compete in terms of costs with those who generate power from fossil fuels [66]. Dissemination of solar energy, apart from the decrease in costs, is additionally favored by its high social acceptance [67,68], which is reflected in loyal initiatives promoting the use of this energy source [69]. Contrary to solar energy, wind energy is sometimes negatively perceived from the environmental point of view, in terms of disturbance of ecosystems, noise, and unfavorable landscape. Wind energy also poses some technological challenges aimed at eliminating the limitations of the technology used thus far, e.g., the emission of harmonic currents [70].

Solar and wind energy as energy sources are not faultless. First, they are heavily dependent on weather and climate change. However, as technology advances, their limitations can be minimized. An example is the forecasting of sun exposure using satellite data [71]. Second, unlike fossil fuel power generation, most renewable energies (except hydro, geothermal, concentrated solar, and biomass) are intermittent. This means that technologies such as PV and wind turbines cannot generate electricity on demand [72].

The above features of unstable energy sources are new challenges in the field of energy storage [73–75] and in the integration of green renewable energy with shaped energy systems [76–78]. Energy systems need to be more flexible. This applies in the first place to systems where the combined share of wind and photovoltaic energy accounts for over 30% of total energy, and the share of PV in the mix of RES is between 20 and 30% [79]. Integration problems (technical and political [80]) are noticed in the EU. The way to meet them is to adopt a green energy strategy based on a concentrated intelligent energy network, enabling the flow of information and the use of various energy sources [81,82]. High expectations in solving the above problems are associated with technological progress and digital solutions [83,84]. Digital energy platforms that coordinate and manage energy demand and supply in real time are rapidly developing in the European energy system. In the group of CEE countries, two platforms are located in Lithuania and single platforms are in Bulgaria, Estonia, and Hungary [85].

3.1.3. New (Old) Challenges of the Energy Transformation

The development of green renewable energy means climate benefits and greater productivity in energy and other economic sectors, especially construction, industry, and transport [86]. From the perspective of achieving the goals of green energy transformation, a relatively new research approach has emerged recently—its aim is to identify the threats resulting from a rapid transition to RES [87]. In the conditions of climate change and scarcity of natural resources, the international community undertakes numerous activities aimed at limiting energy consumption and reduction of GGE [88–90]. The aim of the new EU growth strategy is to transform the European Union (EU) into a modern, resource-efficient, and competitive economy [89,91].

However, new environmental challenges emerge with the dynamic development of green renewable energy. One of them is a dynamic increase in waste from PV cells expected in the coming years [92]. There is a need for supervision over the course of the management of used PV [93]. Technological and institutional support in the recovery of used raw materials is also necessary [94,95].

The development of renewable energy is associated with the independence of individual national economies from external supplies, which is part of a wider issue of energy security [96–98]. Political factors have always played an important role in the geographical diversification of energy supplies [99–102]. It is reflected in CEE countries by their striving to become independent of raw materials from Russia [78].

In 2019, the global production of solar panels was estimated at approximately EUR 57.8 billion, of which only 12.8% was in the EU. Among the 10 largest producers of photovoltaic cells and modules, the vast majority are located in Asia. Among the wind technology producers, it gets better—while there are no large companies from CEE countries among them, there are three from Germany (Siemens, Senvion, Gamesa Renewable Energy—with Spanish participation) [87]. In light of the above facts, there is a risk of replacing the dependence on oil and natural gas from Russia with products from China and highly developed European countries.

Green energy transformation, in line with the European Green Deal, is supposed to generate an increase in the competitiveness of EU countries in the future [103]. The digitization of the energy sector and the dissemination of digital technologies and communications will help with this goal's realization [104]. It brings about new challenges in terms of supporting the development of green energy. They are expressed in the transition in energy policy from focusing on the energy sector in the strict sense to approaching it broadly, taking into account universal digital connectivity and the development of new digital tools. Digital energy systems also need digital security [105,106]. Big new opportunities are related to Internet of Things (IoT) and blockchain technology. However, the market of equipment for sensors and IoT monitoring devices is dominated by global companies (e.g., Hitachi ABB 193, IBM) [79], and there are no CEE companies in this group.

3.2. Energy Structure of CEE Countries

Central and Eastern European countries, due to the large differentiation of their socio-economic potential, show significant differences in terms of the size and structure of energy production. The leaders in terms of the volume of total primary energy supply include Poland, the Czech Republic, Romania, and Hungary (respectively, from 4374.3 thousand TJ to 1115.6 thousand TJ in 2017). The lowest values have been recorded in the Baltic states and Slovenia (below 300.1 thousand TJ). These states also have the lowest economic and demographic potential among the CEE countries.

Non-RES still play an important role in the energy structure of many CEE countries, especially Poland, Slovakia, the Czech Republic, Bulgaria, and Hungary. Latvia and Lithuania have been found to be the countries with the highest share of renewable energy.

The use of RES for the production of electricity is of great importance in the EU and its CEE member states. In 2019, the RES had the largest share in the total electricity capacity in Latvia (approximately 62% of the total), Romania (48.5%) and Bulgaria (39.4%) [107–109]. It is worth noting that the highest potential of electricity obtained from RES is characteristic of Romania (11.2 thousand MW), Poland, and Bulgaria (approximately 4.5 thousand MW) 10]. There is some kind of specialization among CEE countries in the structure of electricity generated from RES. In Latvia, Slovenia, Slovakia, Romania, and Bulgaria, hydropower is of great importance (from 87% to 56%) [10]. In the case of wind energy, such an observation can be applied to Lithuania and Poland (64 and 63%). Hungary and the Czech Republic stand out in terms of the power generated from solar energy (59% and 48%, respectively; Figure 2).

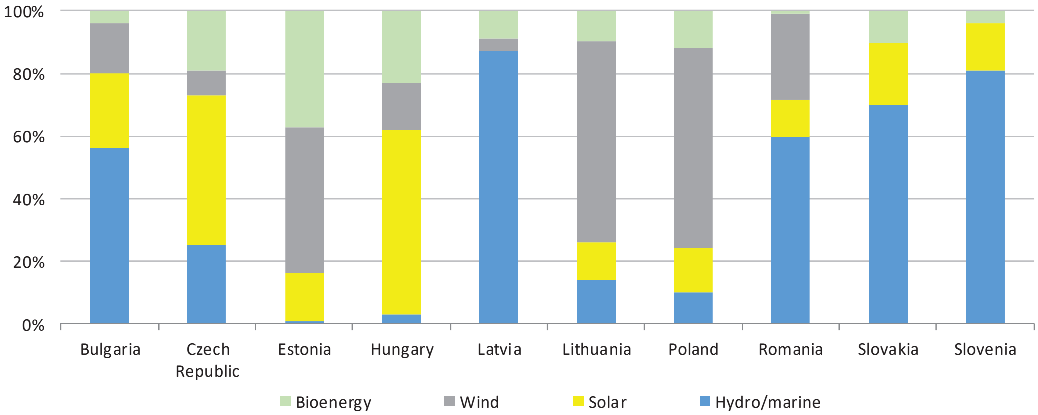

Figure 2. Electricity capacity structure obtained from RES (in %) in 2019.

3.3. Classification of CEE Countries According to the Green Energy Transformation Index

In 2018, according to the taxonomic method of linear ordering (distance from the pattern), Latvia and Romania achieved the highest level of energy transformation (Figure 3). These countries, including Slovenia, are included to the first group in terms of the level of the energy transformation index in 2008. However, the level of energy transformation in these countries, except Romania, has slightly deteriorated in the studied period (there is a slightly greater distance from the pattern).

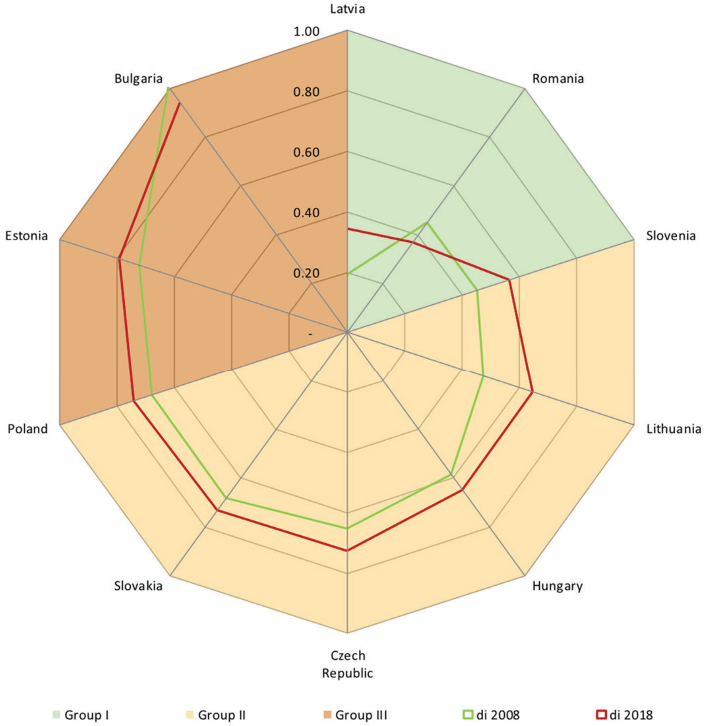

Figure 3. Classification of Central and Eastern European (CEE) countries according to energy transformation based on the synthetic index (di) in 2008 and 2018.

The most numerous group—group II—was formed by countries with an average level of energy transformation. In 2018, it included Lithuania, Hungary, the Czech Republic, Slovakia, and Slovenia.

On the other hand, Bulgaria showed the lowest advancement of the energy transformation in 2018, while Estonia and Poland performed slightly better than Bulgaria.

In 2008–2018, there was a decrease in the distance from the development pattern in Romania and Bulgaria, i.e., countries belonging to different groups in terms of energy transformation. On the other hand, the greatest increase took place in Lithuania, Latvia, and Slovenia, i.e., countries with relatively high advancement in energy transformation. The processes related to the introduction of new solutions in the energy sector are not yet fully stable.

Using Ward's method, these countries can be divided into three groups (of two, five, and three countries) from the point of view of energy transformation (Figure 4). The two-element group is made up of Bulgaria and Estonia, classified in terms of the green transformation, measured by the distance from the pattern to the third group—the lowest group (variant II).

The three-element group is composed of Lithuania and Romania and joined in the next iteration by Latvia. Finally, the five-element group comprises Hungary and Slovakia, joined next by the Czech Republic, and then Poland and Slovenia. It is noteworthy that the clusters at the lowest iteration level were made up of countries that were included in the same group in terms of energy transformation measured by the distance from the pattern method, regardless of the adopted variant of the synthetic indicator (variants I and II).

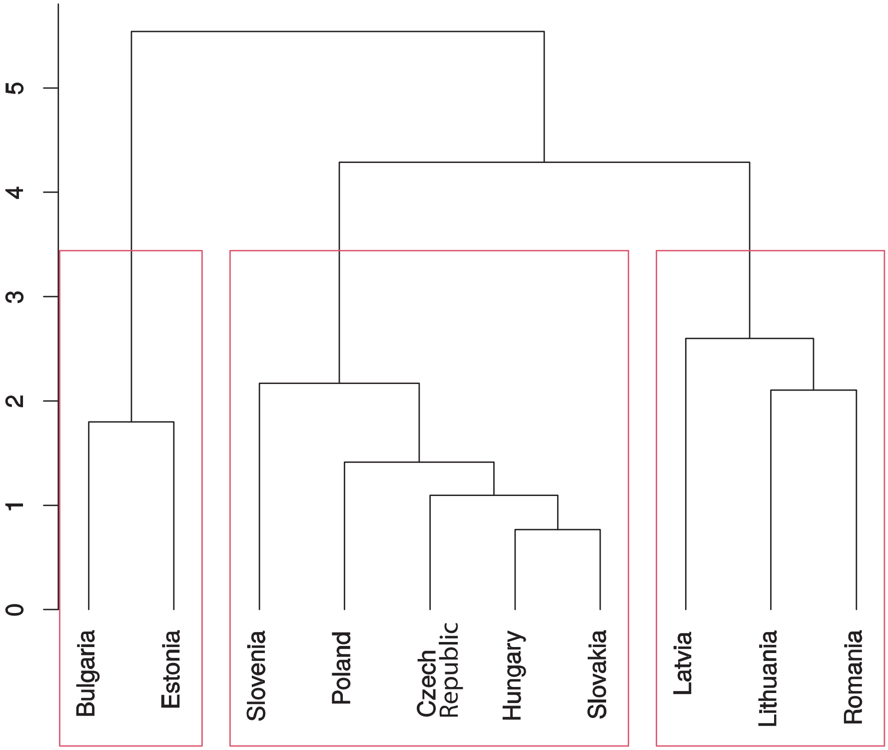

Figure 4. Classification of CEE countries in 2018 in terms of the level of energy transformation according to Ward's method.

From the point of view of energy transformation, the CEE countries showed both certain similarities and differences. They resulted from different trends in the development of green energy that were visible in the size of the partial indicators adopted for the construction of the synthetic indicator of energy transformation, i.e.,

1. Energy productivity, which increased in 2008–2018 in all countries. The undisputed leaders in 2018 included Romania (10.4 PPS/kgoe) and Lithuania (8.3). The lowest level of productivity was characteristic of Bulgaria and Estonia, i.e., countries representing a relatively low level of energy transformation (Figure 5).
2. Percentage share of RES in total energy consumption (the increase of RES in the total energy consumption was recorded in all countries). The group with the greatest importance of green energy in consumption included both the countries that represent the most and the least advanced energy transformation (Latvia at 38.5% and Estonia at 28.4%) (Figure 6). Renewable energy consumption was found to still play a minor role in Poland, Slovakia, and Hungary (from 11.4 to 13.9%).
3. GGE intensity from energy consumption (100 = emissions in the year 2000). The worst situation in this respect in 2018 was recorded in Bulgaria and Lithuania, where GGE exceeded the level recorded in the year 2000 (107 and 105, respectively) (Figure 7). In Lithuania, an increase in emissions was also recorded in comparison to 2008. In 2009, the last reactor of the Ignalina Nuclear Power Plant was closed in Lithuania. This resulted in an increase in the energy sector based on solid fuels (natural gas and oil) and the accompanying increase in CO_2 emissions. In addition, taxes on transport are among the lowest in the EU, which is not conducive to reducing CO_2 emissions [110].

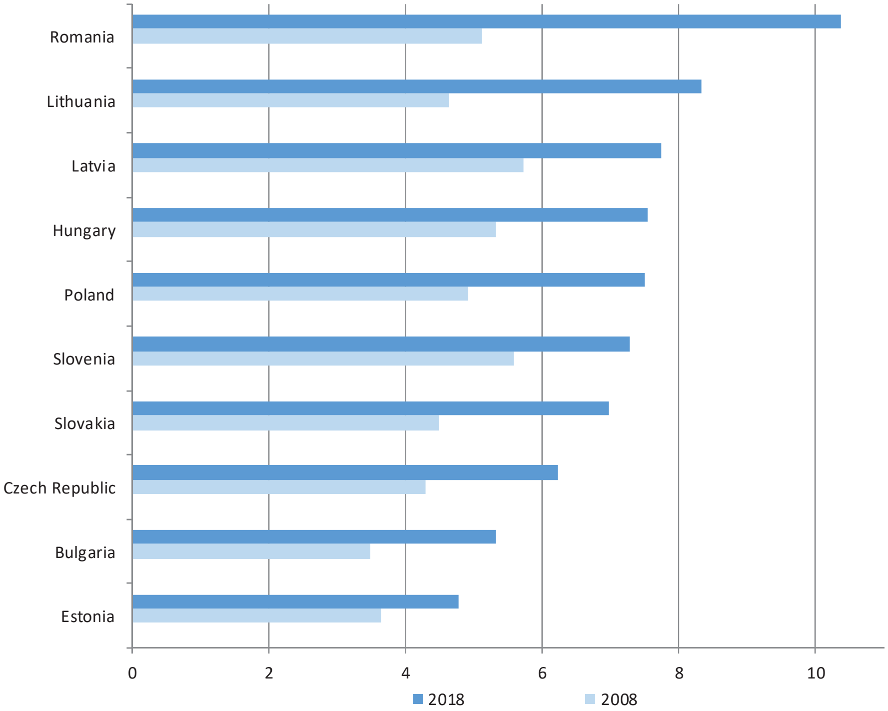

Figure 5. Energy productivity in CEE countries in 2008 and 2018 in PPS/kgoe.

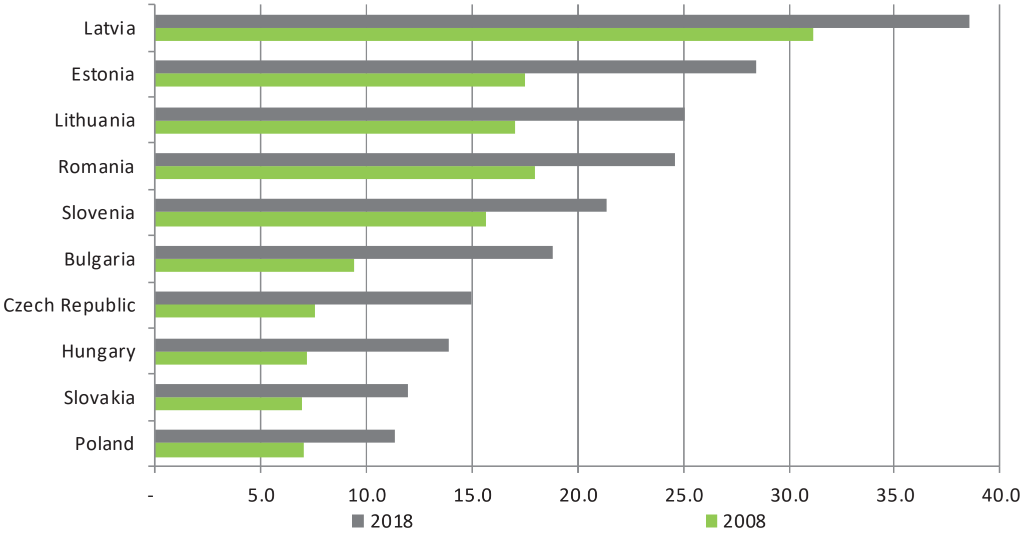

Figure 6. The share of RES in energy consumption in CEE countries in 2008 and 2018 as percentages.

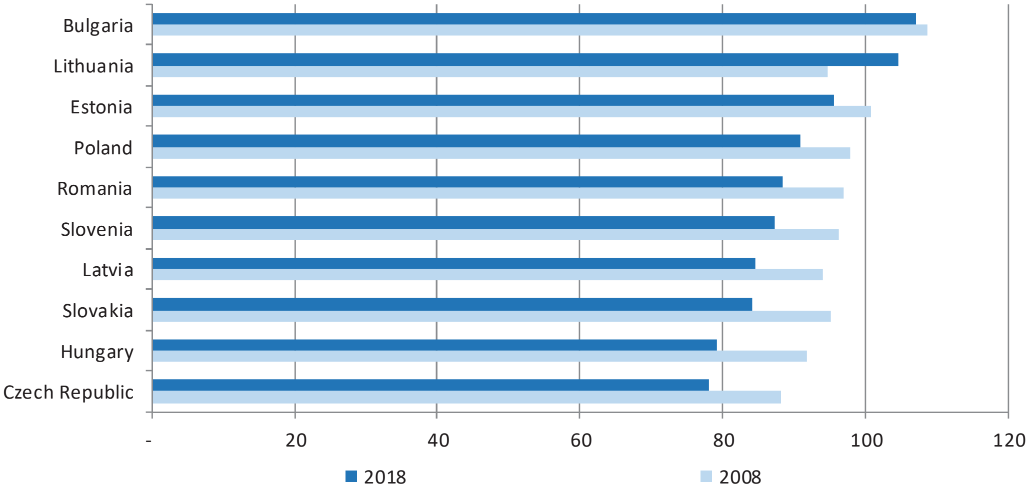

Figure 7. GGE from energy consumption (100 = emissions in 2000) in CEE countries in 2008 and 2018.

In other CEE countries, a positive, downward trend in GGE was recorded. It was significant, exceeding 10 percentage points, in the Czech Republic, Slovakia, and Hungary.

3.4. RES and New Challenges on the Path to Sustainable Development—Examples of Bulgaria, Poland, and Romania

Countries representing various groups of energy transformation are Romania (I), Poland (II), and Bulgaria (III). This is connected with slightly different challenges of the energy transformation and the intensions to achieve the goals of energy policy.

3.4.1. Environmental Challenges

The dynamic development of solar energy prompts reflection on PV panels' utilization and reuse (the principles of closed economy). According to the prediction of the growth of PV panels (on the basis of the dynamics of the increase in solar energy production capacity), it is possible to attempt to measure their impact on the environment and the degree of their utilization, and, consequently, to assess the environmental impact after their use is completed [111–116].

In accordance with the method adopted in the forecast, their surface area in 2020–2030 will be the highest in Poland (15,980,000 to 17,954,000 m^2), lower in Romania (6580–7,393,000 m^2), and the lowest in Bulgaria (5,170,000 to 5,919,000 m^2) [115]. The 20-year average lifetime of PV cells means that the disposal of panels from 2010 will start in 2030.

In each subsequent year (in the study below in the next 5-year period), this will cover collectors that will have completed their 20-year life cycle (e.g., the expected number of panels installed Poland by 2025 will amount to 16,779,000 m^2, and disposal in 2045 will cover 799,000 m^2, according to power gained from PV s installed in 2025). This means that the largest number of panels for disposal in Poland will be in 2040 (15,472,000 m^2), and in Bulgaria and Romania in 2035 (4,705,000 and 6,228,000 m^2, respectively). Maintaining the existing production capacity requires the expenditure on panels at a level that compensates for those intended for disposal, or even a higher expenditure depending on the policy for the development of photovoltaic energy.

The following observations result from the scenarios of solar energy development and utilization of PV panels adopted in the study:

1. The baseline scenario assumes that recycling in the countries in the study will be maintained at the 2018 level, i.e., 68% for Bulgaria, 36% for Poland, and 26% for Romania (Eurostat online data code: CEI_WM050) [116]. The assumptions made (an increase

in production capacity and the related prediction of an increase in the PV surface area, the life cycle of PV panels) lead to a conclusion that the area of recycled panels in the period 2030–2050 will be the highest in Bulgaria and Romania in 2035 (approximately 3,200,000 and 1,620,000 m^2 respectively) and in Poland in 2040 (5,570,000 m^2). As a consequence, the area of non-recycled panels in cumulative terms will reach the highest level in Poland in 2050 (approximately 11,500,000 m^2). A twofold lower level of non-recycled waste is expected in Romania (approximately 5,470,000 m^2), and the lowest level will be achieved in Bulgaria (less than 1,900,000 m^2).

2. Growth scenario in which it was assumed that recycling would reach the level typical in this regard for the best Western European countries (at 68%, which also means no change in Bulgaria's case). In this scenario, the largest panel area will be utilized in Poland in 2040 (approximately 10,520,000 m^2), Bulgaria (approximately 3,200,000 m^2), and Romania in 2035 (4,235,000 m^2). The negative impact of PV on the environment will decrease significantly if a higher recycling level was adopted and is related to the base case. The area of non-recycled panels by 2050 (increasing approach) in Poland will decrease to approximately 5,750,000 m^2 (the highest among the countries in the study), and in Romania to approximately 2,370,000 m^2 (Figure 8).

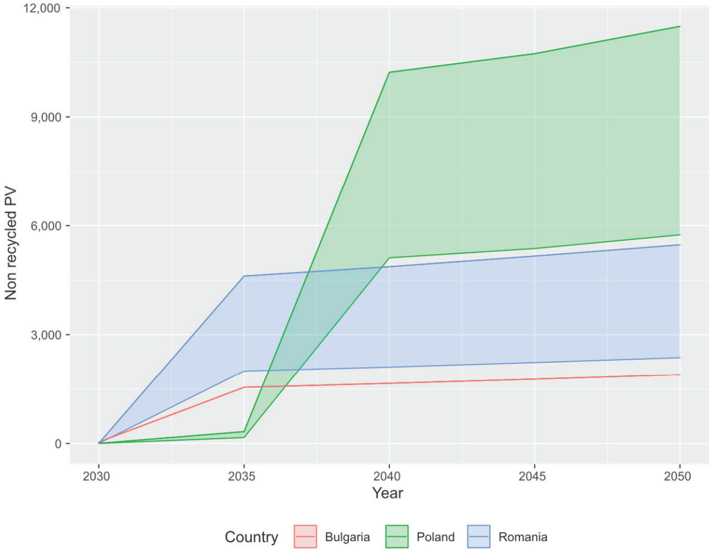

Figure 8. Prediction of non-recycled panels (area in thousand m^2)—cumulatively in the years 2030–2050.

3.4.2. Supply Diversification

Among the countries studied, Poland is the largest recipient of the components necessary for the development of green energy; its imports amounted to approximately USD 33.1 million in 2018 [36]. The main supplier of these components to Poland is Germany, which, in 2018, was responsible for approximately 28% of Poland's total imports (and in 2015–2018, more than a quarter of the total, with an upward trend). China is also a large supplier (18.2% of total supplies). Together, these two countries account for almost half of Poland's supplies of components for green energy production. Significantly lower than in Poland (approximately three times), the supply of components for green energy production was recorded in Romania (in 2018, approximately USD 11.6 million), and even lower in Bulgaria (USD 3.9 million). The different degrees of dependence on suppliers in these countries is a symptom of differences in the structure of renewable energy production and the directions of its development. It is reflected in the different dynamics of growth of solar and wind energy production capacity.

In the case of solar energy growth, it is very high in Poland (in 2015–2018 by 421%) compared to a slight growth rate in Romania (approximately 4.5%), and even more marginal rate in Bulgaria (by 0.4%). This very dynamic growth in Poland is undoubtedly the effect of its lower level in the base year of 2015 (approximately 10 times lower production capacity than in Bulgaria and approximately 12 times less than in Romania). A similarly high growth dynamics was recorded in wind energy in Poland—it amounted to approximately 420% in 2010–2018.

A higher growth was recorded in Romania (approximately 680%), while in Bulgaria it amounted to approximately 43%. It is worth noting that this high increase in wind energy in Poland took place despite the high level of production capacity in the base year 2010. At the same time, the growth dynamics of the import of components necessary for green energy production is similar in the countries in the study, i.e., it reached about 33% in Poland and Bulgaria and about 32% in Romania between 2015 and 2018.

3.4.3. Technology in Energy Transformation

New digital solutions offer great opportunities for the integration of energy from renewable sources with other energy sources. Their development determines the development of the ICT sector. ICT expenditure in Poland in 2010–2018 increased from approximately EUR 11.5 billion to approximately EUR 17.8 billion, reaching the highest level among the CEE countries in this study (Eurostat –TIN00074) [31]. In 2018, in Romania, these expenditures amounted to approximately EUR 7.65 billion and in Bulgaria they were more than twice as low (approximately 3.4 billion EUR). Their particularly high growth dynamics were recorded in Romania (approximately 95% increase), while the lowest growth happened in Poland (approximately 55%). When the changes in the volume of expenditures were compared to the dynamics of the development of renewable energy production capacities (including solar and wind), we found that in each of the analyzed countries there were positive relationships between them (confirmed by Pearson's correlation), ranging from 0.81 (Romania) to 0.86 (in Poland) to 0.89 (Bulgaria). At the same time, the growth rate of ICT expenditure was found to be disproportionately low in relation to the dynamic growth of solar and wind energy, especially in Poland and Romania.

4. Conclusions and Perspectives for Further Research

The energy structure formed in the past, country's own energy resources, political decisions, and technological possibilities lead to different paths of CEE countries, moving towards the assumed climate goals. Non-RES still play an important role in many of the countries, namely, Poland, Slovakia, the Czech Republic, Bulgaria, and Hungary. However, all of these countries are undergoing a green energy transition. Its most visible manifestation is the increase in the use of RES for the production of electricity. In 2019, electricity capacity from RES in Latvia, for example, exceeded 60%. There are different models in the structure of power generated by RES in the CEE group of countries. In Latvia, Slovenia, Slovakia, Romania, and Bulgaria, hydropower plays a dominant role, while wind energy is dominant in Lithuania and Poland. In Hungary and the Czech Republic, on the other hand, it is the solar energy that makes them stand out in terms of the power generated from RES.

The constructed energy transformation indicator shows the analyzed phenomenon in a slightly wider perspective than that of the energy structure or electricity production. Its three main components, i.e., energy productivity, the share of RES in total energy consumption, and the intensity of GGE, fit in with the answer to the following question: Does the increase in energy consumption from RES lead to an increase in total energy productivity in the conditions of lower GGE?

From this point of view, the synthetic index of energy transformation allows us to divide the CEE countries into three groups of different sizes. The first group includes leaders—Latvia and Romania. Bulgaria is an unequivocal outsider creating the third group, and to a lesser extent Estonia and Poland. The remaining countries form the second group.

The energy transition to a zero-emission economy is not a simple transition, both from social and technical point of view. It is a challenge in terms of social costs and risk. The latter can be seen through the characteristics of RES. In this case, the greatest risk of changes is associated with unstable sources, i.e., solar and wind energy. Countries with an advanced energy transformation process, in which the sun and wind play a very important role, will have to face them first of all. These problems concern technology, finances, and integration with energy distribution networks.

The second group of issues regards the goals of green transformation, i.e., the environmental benefits of raw material independence as well as the improvement of the competitiveness of the energy sector and the economy related to it. There is e–waste instead of GGE and dependence on imports of solar and wind energy components in lieu of oil and gas imports. The perception of energy efficiency and the competitiveness of the economy is also changing. The relations between them must be supported by digital solutions, i.e., Artificial Intelligence (AI), IoT, and big data. Unfortunately, the growth rate of ICT expenditure is disproportionately low in relation to the dynamic growth of solar and wind energy, especially in Poland and Romania.

A European Green Deal strategy requires a new, holistic view. Limiting the economy to strictly technological conditions may lead to economic disturbances in the long run. It is a challenge to the economic policy of the CEE countries—energy policy is its integral part. New investments are necessary for creating national energy technologies, building production lines for renewable energy, and development of ICT. They should be accompanied by investments in e-waste disposal, in line with the increase in the share of RES in the energy structure. These tasks are particularly important for the CEE countries, which develop their renewable energy based on imported products, and in terms of e-waste, they rank at the bottom of the EU.

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References

1. Gonzalez-Perez, M.; Neuerburg, K. Climate Change as Critical Security Threat. *Int. J. Clim. Change* **2019**, *11*, 1–14. [CrossRef]
2. WTI. What Is Green Energy? (Definition, Types and Examples). Available online: https://www.twi-global.com/technical-knowledge/faqs/what-is-green-energy (accessed on 11 January 2020).
3. Herrero, C.; Pineda, J.; Villar, A.; Zambrano, E. Tracking progress towards accessible, green and efficient energy: The Inclusive Green Energy index. *Appl. Energy* **2020**, *279*, 115691. [CrossRef]
4. European Commission. The EU Approach Towards Implementing the UN's 2030 Agenda for Sustainable Development Together with Its Member Countries. Available online: https://ec.europa.eu/info/strategy/international-strategies/sustainable-development-goals/eu-approach-sustainable-development_en (accessed on 11 November 2020).
5. European Commission. Communication from the Commission. Clean Energy for All Europeans. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52016DC0860 (accessed on 11 November 2020).
6. Hatzigeorgiou, E.; Polatidis, H.; Haralambopoulos, D. Energy CO_2 Emissions for 1990–2020: Decomposition Analysis for EU25 and Greece. *Energy Source Part A* **2010**, *32*, 1908–1917. [CrossRef]
7. European Commission. Communication from the Commission. A Clean Planet for All. A European Strategic Long-Term Vision for a Prosperous, Modern, Competitive and Climate Neutral Economy. Available online: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=COM%3A2018%3A773%3AFIN (accessed on 15 October 2020).
8. Kemfert, C. Green Deal for Europe: More Climate Protection and Fewer Fossil Fuel Wars. *Intereconomics* **2019**, *54*, 353–358. [CrossRef]

9. Unctad. Development Status Groups and Composition 2017. Available online: https://unctadstat.unctad.org/EN/Classifications/DimCountries_DevelopmentStatus_Hierarchy.pdf (accessed on 19 November 2020).
10. IRENA. Available online: https://www.irena.org/Statistics/Statistical-Profiles (accessed on 19 December 2020).
11. Thevenon, O. Family Policies in OECD Countries: A Comparative Analysis. *Pop. Dev. Rev.* **2011**, *37*, 57–87. [CrossRef]
12. Munandar, T.A.; Azhari, S.N. Analysis of Regional Development Disparity with Clustering Technique Based Perspective. *Int. J. Adv. Res. Comp. Sci.* **2015**, *6*, 137–141.
13. Joopudi, S.; Rathi, S.S.; Narasimhana, S.; Rengaswamyb, R. A New Cluster Validity Index for Fuzzy Clustering. *IFAC Proc.* **2013**, *46*, 325–330. [CrossRef]
14. De Souto, M.; De Araujo, D.; Costa, I.; Soares, R.; Ludermir, T.; Schliep, A. Comparative study on normalization procedures for cluster analysis of gene expression datasets. In Proceedings of the 2008 IEEE International Joint Conference on Neural Networks (IJCNN 2008), Hong Kong, China, 1–8 June 2008; pp. 2792–2798.
15. Řezanková, H. Cluster Analisys of Economic Data. *Staistika* **2014**, *94*, 73–86.
16. Kopczewska, K.; Kopczewski, T.; Wójcik, P. *Quantitative Methods in R, Economic and Financial Applications*; CeDeWu: Warszawa, Poland, 2009.
17. Młodak, A. *Taxonomic Analysis in Regional Statistics*; Difin: Warszawa, Poland, 2006.
18. Mischke, M. Types of Public Family Support: A Cluster Analysis of 15 European Countries. *J. Comp. Policy Anal.* **2011**, *13*, 443–456. [CrossRef]
19. Hellwig, Z. Zastosowanie metody taksonomicznej do typologicznego podziału krajów ze względu na poziom ich rozwoju oraz zasoby i strukturę wykwalifikowanych kadr. *Przegląd Stat.* **1968**, *4*, 307–326.
20. Suchecki, B. *Ekonometria Przestrzenna: Metody i Modele Analizy Danych Przestrzennych*; C.H. Beck: Warszawa, Poland, 2010.
21. European Parliament. Regulation (Eu) 2018/842 of the European Parliament and of The Council. On Binding Annual Greenhouse Gas Emission Reductions by Member States from 2021 to 2030 Contributing to Climate Action to Meet Commitments Under the Paris Agreement and Amending Regulation (EU) No 525/2013. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32018R0842 (accessed on 10 November 2020).
22. European Parliament. Directive 2018/2001 of the European Parliament and of the Council on the Promotion of the Use of Energy from Renewable Sources. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001&from=fr (accessed on 10 November 2020).
23. European Parliament. Directive (EU) 2018/2002 of the European Parliament and of the Council Amending Directive 2012/27/EU on Energy Efficiency. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.328.01.0210.01.ENG&toc=OJ:L:2018:328:TOC (accessed on 10 November 2020).
24. Kulovesi, K.; Oberthür, S. Assessing the EU's 2030 Climate and Energy Policy Framework: Incremental change toward radical transformation? *Rev. Eur. Community Int. Environ. Law* **2020**, 151–166. [CrossRef]
25. Kuzma, J.W. *Basic Statistics for the Health Sciences*, 3rd ed.; Mayfield Publishing Company: Mountain View, CA, USA, 1998.
26. Milligan, G.; Cooper, M. An examination of procedures for determining the number of clusters in a data set. *Psychometrika* **1985**, *50*, 159–179. [CrossRef]
27. Taylor, R. Interpretation of the Correlation Coefficient: A Basic Review. *J. Diagn. Med. Sonogr.* **1990**, *6*, 35–39. [CrossRef]
28. Schober, P.; Boer, C.; Schwarte, L.A. Correlation Coefficients: Appropriate Use and Interpretation. *Anesth. Analg.* **2018**, 1763–1768. [CrossRef] [PubMed]
29. Milligan, G.W.; Cooper, M.C. A study of standardization of variables in cluster analysis. *J. Classif.* **1998**, *5*, 181–204. [CrossRef]
30. Grabiński, T. *Analiza Taksonomiczna Krajów EUROPY w Ujęciu Regionalnym*; Akademii Ekonomicznej w Krakowie: Kraków, Poland, 2003.
31. Eurostat. Available online: https://ec.europa.eu/eurostat/data/database (accessed on 17 November 2020).
32. European Commission. EU Energy Trends to 2030—Update 2009. Available online: https://ec.europa.eu/energy/sites/ener/files/documents/trends_to_2030_update_2009.pdf (accessed on 17 December 2020).
33. Sunpower. Technical Specifications. Available online: https://us.sunpower.com/solar-resources/products/datasheets (accessed on 17 December 2020).
34. QCells. Q Cells Q.Antum Duo Solar Panels. Available online: https://www.q-cells.co.uk/products/solar-panels.html (accessed on 17 December 2020).
35. Solaria. Technical Documents & Literature Library. Available online: https://www.solaria.com/additional-product-information (accessed on 17 December 2020).
36. International Trade Statistics. Available online: https://www.importgenius.com/?utm_source=google&utm_medium=9061067&utm_campaign=&utm_term=international%20trade%20statistics&utm_content=107111299575&gclid=Cj0KCQiAw_H-BRD-ARIsALQE_2MrQHBN-VpeGFXKFAepycRvBZJo6Dg-xwENMXMUbF_TDWLMzdRNTr0aAkNCEALw_wcB (accessed on 18 December 2020).
37. Helm, D. *Energy, the State, and the Market: British Energy Policy Since 1979*; Oxford University Press Inc.: Oxford, UK, 2004.
38. Clapp, J. Development as Freedom. *Int. J.* **1999**, *55*, 160–162. [CrossRef]
39. Dunning, J.H. Towards a new paradigm of development: Implications for determinants of international business. *Transnatl. Corp.* **2006**, *15*, 173–227.

40. Markandya, P.-G.S.; Streimikiene, D. Energy intensity in transition economies: Is there convergence towards the EU average? *Energy Econ.* **2006**, *28*, 121–145. [CrossRef]
41. Cornillie, J.; Fankhauser, S. The energy intensity of transition countries. *Energy Econ.* **2004**, *26*, 283–295. [CrossRef]
42. Fankhauser, S.; Lavric, L. The investment climate for climate investment: Joint Implementation in transition countries. *Clim. Policy* **2003**, *3*, 417–434. [CrossRef]
43. European Commission. Renewable Energy Directive. Available online: https://ec.europa.eu/energy/en/topics/renewable-energy/renewable-energy-directive (accessed on 14 November 2020).
44. Oncioiu, I.; Petrescu, A.; Grecu, E.; Petrescu, M. Optimizing the Renewable Energy Potential: Myth or Future Trend in Romania. *Energies* **2017**, *10*, 759. [CrossRef]
45. Ossewaarde, M.; Ossewaarde-Lowtoo, R. The EU's Green Deal: A Third Alternative to Green Growth and Degrowth? *Sustainability* **2020**, *12*, 9825. [CrossRef]
46. Markus, R. Checking In: Renewable Energy in CEE. Available online: https://ceelegalmatters.com/analysis/14539-checking-in-renewable-energy-in-cee (accessed on 7 December 2020).
47. European Commission. The European Green Deal. Available online: https://ec.europa.eu/info/sites/info/files/european-green-deal-communication_en.pdf (accessed on 14 October 2020).
48. Simionescu, M.; Păuna, C.B.; Diaconescu, T. Renewable Energy and Economic Performance in the Context of the European Green Deal. *Energies* **2020**, *13*, 6440. [CrossRef]
49. Child, C.; Breyer, C. Transition and transformation: A review of the concept of change in the progress towards future sustainable energy systems. *Energy Policy* **2017**, *107*, 11–26. [CrossRef]
50. UE Market Outlook. For Solar Power 2019–2023. Available online: https://www.solarpowereurope.org/eu-market-outlook-for-solar-power-2019-2023/ (accessed on 14 October 2010).
51. Prospects for the Renewable Energy Development in CEE. Available online: http://www.forum-ekonomiczne.pl/prospects-for-the-renewable-energy-development-in-cee/?lang=en (accessed on 7 November 2020).
52. Sun, J.W. Three types of decline in energy intensity—An explanation for the decline of energy intensity in some developing countries. *Energy Policy* **2003**, *31*, 519–526. [CrossRef]
53. Samargandi, N. Energy intensity and its determinants in OPEC countries. *Energy* **2019**, *186*, 115803. [CrossRef]
54. Rourke, F.O.; Boyle, F.; Reynolds, A. Renewable energy resources and technologies applicable to Ireland. *Renew. Sustain. Energy Rev.* **2009**, *13*, 1975–1984. [CrossRef]
55. West, L. Top Renewable Energy Sources. Available online: https://www.treehugger.com/top-renewable-energy-sources-1204190 (accessed on 7 December 2020).
56. Global Energy Statistical Yearbook 2020. Share of Wind and Solar in Electricity Production. Available online: https://yearbook.enerdata.net/renewables/wind-solar-share-electricity-production.html#:~{}:text=In%202019%2C%20the%20share%20of,%2Dfired%20%E2%80%93%20power%20generation%20declined (accessed on 15 March 2020).
57. Good, C.; Andresen, I.; Hestnes, A.G. Solar energy for net zero energy buildings—A comparison between solar thermal, PV and photovoltaic–thermal (PV/T) systems. *Sol. Energy* **2015**, *122*, 986–996. [CrossRef]
58. Urban, F.; Geall, S.; Wang, Y. Solar PV and solar water heaters in China: Different pathways to low carbon energy. *Renew. Sustain. Energy Rev.* **2016**, *64*, 531–542. [CrossRef]
59. Letcher, T.M. *Wind Energy Engineering: A Handbook for Onshore and Offshore Wind Turbines*; Academic Press: Cambridge, MA, USA, 2013.
60. Yang, H.; Wei, Z.; Chengzhi, L. Optimal design and techno-economic analysis of a hybrid solar–wind power generation system. *Appl. Energy* **2009**, *86*, 163–169. [CrossRef]
61. Lindman, Å.; Söderholm, P. Wind energy and green economy in Europe: Measuring policy-induced innovation using patent data. *Appl. Energy* **2016**, *179*, 1351–1359. [CrossRef]
62. Trancik, J.E.; Cross-Call, D. Energy technologies evaluated against climate targets using a cost and carbon trade-off curve. *Environ. Sci. Technol.* **2013**, *47*, 6673–6680. [CrossRef] [PubMed]
63. Kavlak, G.; McNerney, J.; Trancik, J.E. Evaluating the causes of cost reduction in photovoltaic modules. *Energy Policy* **2018**, *123*, 700–710. [CrossRef]
64. Breyer, C.; Birkner, C.; Meiss, J.; Goldschmidt, J.C.; Riede, M. A top-down analysis: Determining photovoltaics R&D investments from patent analysis and R&D headcount. *Energy Policy* **2013**, *62*, 1570–1580. [CrossRef]
65. Comello, S.; Reichelstein, S.; Sahoo, A. The road ahead for solar PV power. *Renew. Sustain. Energy Rev.* **2018**, *92*, 744–756. [CrossRef]
66. Hansen, K.; Breyer, C.; Lund, H. Status and perspectives on 100% renewable energy systems. *Energy* **2019**, *75*, 471–480. [CrossRef]
67. Kim, J.; Park, S.-Y.; Lee, J. Do people really want renewable energy? Who wants renewable energy? Discrete choice model of reference-dependent preference in South Korea. *Energy Policy* **2018**, *120*, 761–770. [CrossRef]
68. Cavallaro, F.; Ciraolo, L. A multicriteria approach to evaluate wind energy plants on an Italian island. *Energy Policy* **2005**, *33*, 235–244. [CrossRef]
69. Dóci, G.; Vasileiadou, E.; Petersen, A.C. Exploring the transition potential of renewable energy communities. *Futures* **2015**, *66*, 85–95. [CrossRef]
70. Bollen, M.H.J.; Yang, K. Harmonic aspects of wind power integration. *J. Mod. Power Syst. Clean Energy* **2013**, *1*, 14–21. [CrossRef]

71. Mazorra Aguiar, L.; Pereira, B.; David, M.; Díaz, F.; Lauret, P. Use of satellite data to improve solar radiation forecasting with Bayesian Artificial Neural Networks. *Sol. Energy* **2015**, *122*, 1309–1324. [CrossRef]
72. Dowds, J.; Hines, P.; Ryan, T.; Buchanan, W.; Kirby, E.; Apt, J.; Jaramillo, P. A review of large-scale wind integration studies. *Renew. Sustain. Energy Rev.* **2015**, *49*, 768–794. [CrossRef]
73. Blarke, M.B.; Lund, H. The effectiveness of storage and relocation options in renewable energy systems. *Renew. Energy* **2008**, *33*, 1499–1507. [CrossRef]
74. Mourant, A. Energy storage research advances. *Renew. Energy Focus* **2015**, *16*, 28–29. [CrossRef]
75. Denholm, P.; Mai, T. Timescales of energy storage needed for reducing renewable energy curtailment. *Renew. Energy* **2019**, *130*, 388–399. [CrossRef]
76. Oprea, S.-V.; Bâra, A.; Majstrović, G. Aspects Referring Wind Energy Integration from the Power System Point of View in the Region of Southeast Europe. Study Case of Romania. *Energies* **2018**, *11*, 251. [CrossRef]
77. Hirth, L.; Ueckerdt, F.; Edenhofer, O. Integration costs revisited—An economic framework for wind and solar variability. *Renew. Energy* **2015**, *74*, 925–939. [CrossRef]
78. Akhmatov, V. System stability of large wind power networks: A Danish study case. *Int. J. Electr. Power Energy Syst.* **2006**, *28*, 48–57. [CrossRef]
79. Huber, M.; Dimkova, D.; Hamacher, T. Integration of wind and solar power in Europe: Assessment of flexibility requirements. *Energy* **2014**, *69*, 236–246. [CrossRef]
80. International Electrotechnical Commission. Grid Integration of Large-Capacity Renewable Energy Sources and Use of Large-Capacity Electrical Energy Storage. Available online: http://www.iec.ch/whitepaper/pdf/iecWP-gridintegrationlargecapacity-LR-en.pdf (accessed on 7 February 2020).
81. Kulatilaka, N. Green Revolution 2.0: Opportunities and Challenges in the Green Economy. *SSRN Electron. J.* **2013**. [CrossRef]
82. Boie, I.; Fernandes, C.; Frías, P.; Klobasa, M. Efficient strategies for the integration of renewable energy into future energy infrastructures in Europe—An analysis based on transnational modeling and case studies for nine European regions. *Energy Policy* **2014**, *67*, 170–185. [CrossRef]
83. Franki, V.; Višković, A. Energy security, policy and technology in South East Europe: Presenting and applying an energy security index to Croatia. *Energy* **2015**, *90*, 494–507. [CrossRef]
84. Shum, K.L. Renewable Energy Technology—Is it a Manufactured Technology or an Information Technology? *Sustainability* **2010**, *2*, 2382–2402. [CrossRef]
85. Duch-Brown, N.; Rossetti, F. Digital platforms across the European regional energy markets. *Energy Policy* **2020**, *144*, 111612. [CrossRef]
86. Kaygusuz, K. Renewable Energy Sources: The Key to a Better Future. *Energy Sources* **2002**, *24*, 787–799. [CrossRef]
87. European Parliament. Report from The Commission to The European Parliament and The Council on Progress of Clean Energy Competitiveness. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1602695747015&uri=COM:2020:953:FIN (accessed on 10 January 2021).
88. Ulli-Beer, S.; Bosshardt, M.; Dietrich, P.; Wokaun, A. What Alternative Drive-train Technologies and Policies are Needed to Meet a 50% CO_2 Reduction Target? The Case of the EU-Fleet. *SAE Tech. Pap.* **2009**. [CrossRef]
89. Niederhafner, S.; Chan Song, L. Different Paths Towards the Same Goal? Comparing the Implementation and Performance of CO_2 Emissions Reduction Regulations in the EU and South Korea. *SSRN Electron. J.* **2013**. [CrossRef]
90. European Commission. A New Industrial Strategy for Europe. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0102 (accessed on 24 November 2020).
91. Asafu-Adjaye, J.; Mahadevan, R. Implications of CO_2 reduction policies for a high carbon emitting economy. *Energy Econ.* **2013**, *38*, 32–41. [CrossRef]
92. Bogacka, M.; Pikoń, K.; Landrat, M. Environmental impact of PV cell waste scenario. *Waste Manag.* **2017**, *70*, 198–203. [CrossRef]
93. Hocine, L.; Mounia Samira, K. Optimal PV panel's end-life assessment based on the supervision of their own aging evolution and waste management forecasting. *Sol. Energy* **2019**, *191*, 227–234. [CrossRef]
94. Fiandra, V.; Sannino, L.; Andreozzi, C.; Graditi, G. End-of-life of silicon PV panels: A sustainable materials recovery process. *Waste Manag.* **2019**, *84*, 91–101. [CrossRef]
95. Ardente, F.; Latunussa, C.E.L.; Blengini, G.A. Resource efficient recovery of critical and precious metals from waste silicon PV panel recycling. *Waste Manag.* **2019**, *91*, 156–167. [CrossRef]
96. Kruyt, B.; van Vuuren, D.P.; de Vries, H.J.M.; Groenenberg, H. Indicators for energy security. *Energy Policy* **2009**, *37*, 2166–2181. [CrossRef]
97. Winzer, C. Conceptualizing energy security. *Energy Policy* **2012**, *46*, 36–48. [CrossRef]
98. Kamble, S.P. Editorial: Sustainability for Energy and Environment. *Curr. Environ. Eng.* **2018**, *5*, 2–3. [CrossRef]
99. Deese, D.A. Energy: Economics, Politics, and Security. *Int. Secur.* **1979**, *4*, 140. [CrossRef]
100. Cohen, G.; Joutz, F.; Loungani, P. Measuring energy security: Trends in the diversification of oil and natural gas supplies. *Energy Policy* **2011**, *39*, 4860–4869. [CrossRef]
101. Weiner, C. Security of Energy Supply and Gas Diversification in Poland. *SSRN Electron. J.* **2018**. [CrossRef]
102. Pawluszko, T. Energy Security and the Problem of Peripherality: Case study of the CEE region between Russia and the EU. *Can. J. Polit. Sci.* **2018**, *2*, 61–82. [CrossRef]

103. European Commission. The Green Deal and Competition Policy. Available online: https://ec.europa.eu/commission/commissioners/2019-2024/vestager/announcements/green-deal-and-competition-policy_en (accessed on 10 December 2020).
104. IEA. Digitalisation and Energy. Technology Report—November 2017. Available online: https://www.iea.org/reports/digitalisation-and-energy (accessed on 12 December 2020).
105. Brouthers, K.D.; Geisser, K.D.; Rothlauf, F. Explaining the internationalization of ibusiness firms. *J. Int. Bus. Stud.* **2015**, *47*, 513–534. [CrossRef]
106. Hazarbassanova, D.B. The value creation logic and the internationalisation of internet firms. *Rev. Int. Bus. Strategy* **2016**, *26*, 349–370. [CrossRef]
107. International Renewable Energy Agency. Energy Profile Latvia. Available online: https://www.irena.org/IRENADocuments/Statistical_Profiles/Europe/Latvia_Europe_RE_SP.pdf (accessed on 12 December 2020).
108. International Renewable Energy Agency. Energy Profile Romania. Available online: https://www.irena.org/IRENADocuments/Statistical_Profiles/Europe/Romania_Europe_RE_SP.pdf (accessed on 12 December 2020).
109. International Renewable Energy Agency. Energy Profile Bulgaria. Available online: https://www.irena.org/IRENADocuments/Statistical_Profiles/Europe/Bulgaria_Europe_RE_SP.pdf (accessed on 12 December 2020).
110. Smith, L.; Velten, E.K.; Donat, L.; Duwe, M. *Assessment of Climate Change Policies in the Context of the European Semester: Country Report: Lithuania*; Ecologic Institute Eclareon: Berlin, Germany, 2013.
111. IEA. Renewables 2019. Market Analysis and Forecast from 2019 to 2024. Available online: https://www.iea.org/reports/renewables-2019 (accessed on 10 November 2020).
112. European Commission. European Energy and Transport Trends to 2030. Directorate-General for Energy. Available online: http://bookshop.europa.eu (accessed on 11 November 2020).
113. Shivakumara, A.; Dobbinsb, A.; Fahlb, U.; Singh, A. Drivers of renewable energy deployment in the EU: An analysis of past trends and projections. *Energy Strategy Rev.* **2019**, *26*, 100402. [CrossRef]
114. Eurostat Database. Electricity Production Capacities by Main Fuel Groups and Operator. Available online: https://ec.europa.eu/eurostat/databrowser/view/nrg_inf_epc/default/table?lang=en (accessed on 2 December 2020).
115. Eurostat Database. Electricity Production Capacities for Renewables and Wastes. Available online: https://ec.europa.eu/eurostat/databrowser/view/nrg_inf_epcrw/default/table?lang=en (accessed on 2 December 2020).
116. Eurostat Database. Recycling Rate of e-Waste %. Available online: https://ec.europa.eu/eurostat/databrowser/view/cei_wm050/default/table?lang=en (accessed on 12 December 2020).

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Discounting for Energy Transition Policies—Estimation of the Social Discount Rate for Poland

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Abstract: The transition of the energy system in Poland has a long time horizon and demands a substantial investment effort supported by proper economic evaluation. It requires a precise Social Discount Rate (SDR) estimation as discounting makes the present value of long-term effects extremely sensitive to the discount rate level. However, Polish policymakers have little information on SDR: the predominant practice applies *a priori* fixed 5% discount rate, while studies devoted only to Poland are quite rare. To eliminate this research gap, our paper aims at estimating SDR for Poland, applicable in energy transition policies. We derive SDR for three datasets varying in length, twofold: using market rates via Consumption Rate of Interest (CRI) and Social Opportunity Cost (SOC) of capital, and prescriptive Ramsey and Gollier approaches based on Social Welfare Function (SWF). The results indicate that the rates based on CRI and SOC deviate substantially with changing data timeframes and market conditions, while prescriptive methods show much higher time stability. Due to long-term planning horizons for energy policies, we argue for adopting, as SDR in Poland, the longest dataset's Ramsey-based rate of 4.72% which can be reduced to 4.39% by Gollier's precautionary term (reflecting the uncertainty over future consumption growth), which are our main findings.

Keywords: energy policy; economic appraisal; social discount rate; Ramsey formula; consumption rate of interest; social opportunity cost

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1. Introduction

The issue of energy sector transition is a conglomerate of many issues as well as methods of analysis in search of effective solutions. This paper concentrates on the problems of economic evaluation of investment projects, whose implementation is in line with the priorities of Poland's long-term energy policy, and particularly the issue of discount rate estimation that should be adopted to improve the appraisal process of such investments.

The necessity of using discounting in the appraisal methods is not subject to discussion and it is not our intention to question its necessity. However, an important issue is the methodology of estimating the level of this rate that should be adopted for long-term projects with a significant share of positive externalities. In commercial investment projects, the commonly used method of discount rate estimation is the investor's cost of capital. This method in regard to the analysed projects cannot be effectively applied for at least two reasons.

First, investments in energy transition are not commercial investments in the strict sense of the word. The effectiveness of these investments is more of a social nature rather than a specifically financial one. Second, the time perspective of such investments is very long (e.g., the European Green Deal perspective reaches 2050 [1] or energy transitions fighting global warming operating with time horizons over centuries [2]) which makes the classic approach to discount rate entirely inapplicable, as it leads to an excessive depreciation of long-term effects, which may, therefore, wrongly indicate ineffectiveness. By the same token, a Social Discount Rate (SDR) should be used instead of a commercial one for the appraisal of this type of investment.

In this context, the paper presents the methodology and results of estimating the level of the SDR for evaluation of the social effectiveness of long-term energy investment projects. Considering the fact that the prevailing practice in Poland is the application of a fixed 5% SDR value based on the EU recommendation for CEE countries, the findings can fill the gap and improve the process of energy investment evaluation, particularly in light of the substantial expenditures needed to meet the goals of the European Green Deal. The results can also be found relevant for policymakers, private and public investors as well as researchers, as the number of studies in this area is still insufficient.

1.1. Policy of Energy Sector Transition in Poland—The Timeframe and Financing Requirements

The plans for energy transition policy in Poland give two premises to focus particularly on the discount rate needed at the evaluation stage: long timeframe and substantial investment needs.

Any sectoral policy, by defining its priorities, covers a specific time horizon. The 2040 perspective is most often mentioned for the transition policy of Poland's energy sector. It has therefore been assumed that the temporal turning point of the analysis is the perspective of the year 2040 as the time by which Poland's energy policy will practically have been established and implemented. In November 2018, the document "Poland's energy policy until 2040" was published [3]. The document is a guidance project, which was refined and updated in September 2020. According to this document, Poland's policy of changes in the broadly understood energy sector has been based on three pillars: fair transition, zero-emission energy system, and significant improvement in air quality. The main areas of energy policy transition in Poland [4] include such aims as reduction in greenhouse gas emissions by 40% by 2030 (compared to 1990), increase in the share of renewable energy to 32%, increase in energy efficiency by energy saving at the level of 23% by 2030, which, apart from long-term horizons, are inextricably linked with substantial investment needs.

An important and costly goal to be reached is the reduction in CO_2 emissions. Poland has a particularly difficult task in this regard. The country ranks 5th in Europe among the largest emitters of carbon dioxide; moreover, after a significant decline in 1990s (by approx. 27.4% compared to 1989), since 2002, CO_2 emissions have remained relatively stable and no further improvement can be observed, especially when compared to other top CO_2 emitters in the EU (Figure 1). Not only does it illustrate the scale of the problem, but also the scale of necessary expenditure to be made.

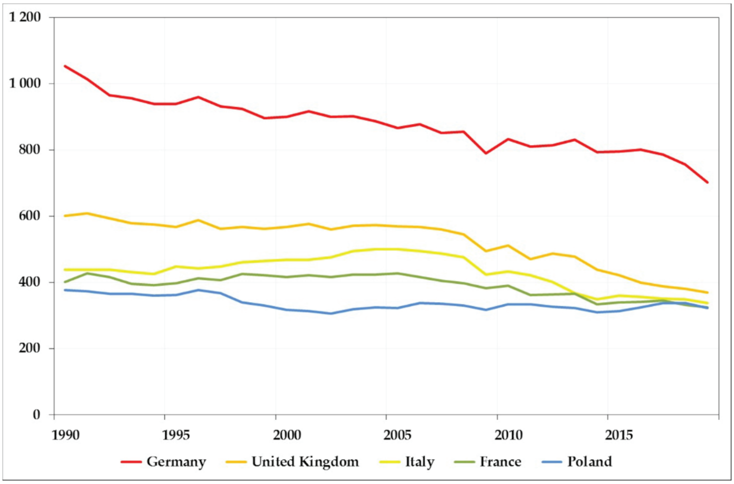

Figure 1. EU countries with the highest level of CO_2 emissions (in Mt) [5].

Poland has to accomplish substantial tasks in the field of renewable energy, both for the current period and from the 2040 perspective. Eurostat has published records on the share of renewable energy sources (RES) in the markets of the Community countries [6]. They confirmed the concerns that Poland has failed to fulfil EU guidelines regarding the 20% share of RES in energy consumption by the end of 2020. In 2019, this level was 12.2%, with significantly higher shares of hard coal, lignite, crude oil, and natural gas (see Figure 2 to compare the energy mix structure for Poland and the EU in 2019). The forecasts for 2040 are also not particularly optimistic; the assumed minimum value of 32% will be difficult to achieve and very capital-intensive.

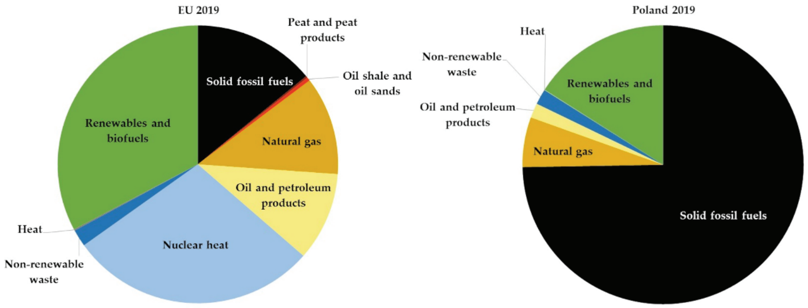

Figure 2. Primary energy production by source in Poland and the EU in 2019 [7].

Four basic indicators have been defined for Poland’s energy transition and they should be achieved by 2030 as an implementation stage of the 2040 adopted policy [3]:

- Share of hard coal in electricity generation at a level not higher than 56% (target for 2030);
- RES share in final energy consumption at a level of not less than 23%;
- Implementation of nuclear energy (target for 2033);
- Reduction in greenhouse gas (GHG) emissions by 30% compared to 1990 emissions.

In the strategic area of increasing energy efficiency for Poland, it is assumed that the final energy savings in the period between 1 January 2021 and 31 December 2030 should amount to no less than 5.6 million tonnes of oil equivalent, and the total cumulative final energy savings in the years 2021−2030, calculated in accordance with the guidelines of the amended EED Directive (Energy Efficiency Directive) with the use of forecasts on the average annual final energy consumption for 2016−2018, will amount to 3.6 thousand tonnes of oil equivalent [4]. This comes from Directive 2018/2002/EU, which aims at saving the final energy by 32.5% compared to the reference scenario. This means that in the years 2021−2030, the total savings in final energy consumption should be equivalent to annual new savings of 0.8% of the average annual final energy consumption in 2016−2018. In the ten-year time perspective, the cost of implementing the tasks set out in the amended Energy Efficiency Act is to amount to approximately EUR 1.5 billion [8].

Key activities will consist of targeted investments that will allow the assumed goals to be attained. The main priorities of capital expenditure are: transition of coal regions, reduction in energy poverty, new industries related to RES and nuclear energy, offshore wind energy, local and prosumer energy, transition of heating, electrification of transport. For Poland, the key issue is the departure from hard coal as the basic energy carrier. Due to the adopted assumptions, the use of hard coal to generate electricity is expected to drop to 37% in 2030 (from the current level of 70%), while in 2040—up to 11%. In urbanized areas, coal should be abandoned as a heat source by 2030, and in rural areas—by 2040.

Implementation of the adopted policy for Poland will require a very wide range of activities and very significant investment expenditure. About EUR 50 billion will be allocated to the national energy and climate transition from EU and national funds under various mechanisms by 2030, including e.g., Cohesion Policy (allocation for Poland of approx. EUR 20 billion), Recovery and Resilience Facility (allocation for Poland of approx. EUR 7 billion), The Just Transition Fund (allocation for Poland of approx. EUR 3.5 billion) [9], or new instruments that will support the transition of the energy system in Poland, such as the Modernization Fund and the National Target Fund, supplied with funds from the sale of CO_2 emission allowances. Initial estimates indicate the possibility of obtaining over EUR 10 billion [10].

Assuming investment expenditure at the level of around EUR 50 billion in the next 10 years and accepting an equal spending rate for each year, we have an estimated level of investment expenditure of around EUR 100 billion by the end of 2040, in 2020 prices, for the implementation of Poland's energy transition strategy. On the other hand, these investments will increase GDP by approx. EUR 50−77 billion, according to the report of the Jagiellonian Institute [11]. However, these estimates are not unambiguous due to the time perspective and complexity of the problem. According to, for example, the Polish Electricity Association, the investment expenditure that will have to be incurred for the transition of the energy sector by 2030 will be in the range of EUR 60−70 billion, and in the perspective of 2050, EUR 130−175 billion [12].

1.2. Social Discount Rate—Methods and Application in Energy Investments

The range of tasks and the anticipated level of investment expenditure presented in the preceding section as well as the unique political, technological, and financial complexity of the expected benefits of energy transition require a number of questions to be asked. In the context of the economic effectiveness of these undertakings, it needs to be highlighted that, first, such projects are not typical commercial activities, where market prices fully reflect the fair value of inputs and outputs due to a considerable amount of externalities, and second, the time frame of energy-related projects in many cases extends far beyond the reach of the financial markets perspective, which is usually not more than 30 years, e.g., green transformation to cut down carbon dioxide emissions or nuclear power plants echo for centuries.

These efficiency questions are usually managed by evaluation via cost–benefit analysis (CBA), which allows for proper adjustments aimed at reflecting social effectiveness instead of private effectiveness. This also includes the price of capital reflecting the social view on how future benefits and costs should be valued against present ones, represented by Social Discount Rate. All those costs and benefits are given in shadow prices used in CBA to reflect their true value for society [13]. What must be highlighted is the fact that choosing an appropriate discount rate is an important stage for any investment project evaluation process. The widely accepted process of evaluation rests on a discounted cash flow approach represented by the Net Present Value criterion that summarises all cash inflows and outflows generated by the project, transforming them first into the present value equivalent. The choice of discount rate may be decisive for the outcome in the analysis where outlays (born today therefore remaining undiscounted) are confronted with future (therefore, discounted) cash flows. For energy-related projects, this task is even more meaningful due to the long timeframe of evaluation as it makes present value extremely sensitive to slight variances in discount rate values (e.g., effect of EUR 1 appearing after 30 years is reduced by 3/4 when discounted at 5%; raising the rate to 7% makes present value lower by 7/8 and these discrepancies soar for longer periods) [14].

This transformation via discounting is an essential part of economic analysis as it reflects the returns of alternative opportunities that are lost due to choosing the project being evaluated. In a perfectly competitive economy (complete set of perfectly competitive markets), free from any market distortions, the marginal social opportunity cost of funds (and SDR) would be reflected by market interest rates, equalising the supply side reflected by the social rate of time preference (SRTP) and demand—by the social opportunity cost of capital (SOC). Since the economy and markets are distorted, the price of capital diverges from the optimum and needs to be estimated [15]. However, while SDR is widely applied in the public investment evaluation and its definition seems to be clear and unequivocal, the theoretical approaches to the estimation as well as empirical results to achieve "the proper" value are still widely discussed in the literature and no consensus has been achieved so far [16,17]. This paper concentrates on the two sides of the capital market: SRTP and SOC form two main strands in the literature, making the effort of delivering the proper measure of SDR.

The Social Rate of Time Preference represents discounting appropriate for benefits and costs measured in consumption units [18]. Using this approach for discounting in project evaluation, we implicitly assume that public investments are financed from savings (therefore, crowding out current consumption). Then, the SRTP approach serves for intertemporal exchange in consumption. Some solutions concentrate on intertemporal preferences observed via financial instruments and are based on the consumption rate of interest (CRI) approximated by the long-term real after-tax return on savings [19,20]. This is justified by the fact that intertemporal preferences of individuals towards saving can be applied to assess the government policy influencing the consumption of those individuals. The alternative is a prescriptive approach exercising social welfare function (SWF) maximised over time to deliver the Ramsey formula, which adds up the pure time preference reflecting society's impatience and the element mirroring the consumption opportunity cost lost by society when investing [15,21]. The latter element is a product of two factors: expected growth rate of per capita consumption and the elasticity of marginal utility of consumption. The prevailing approach across Europe is represented by the Ramsey formula [22], which is also supported by the IPCC [2].

The second branch of the standpoint, the social opportunity cost of capital, focuses on efficiency in using scarce resources. The SOC approach rests on the Pareto criterion where improvement in social welfare is achieved if the investment accepted outperforms the alternatives. The government, while investing, competes for the same lot of funds as the private sector and displaces them in the case of accepting the project. Therefore, to provide welfare maximisation for society, a public investment must yield at least the same level of return as the private one. The return is represented by the marginal rate of return on private investments (return on investments, ROI) [23]. Empirical estimates of SOC use financial market rates, i.e., the real before-tax rate of return on corporate bonds or exercise national income accounts to calculate the profitability of the private sector as a contribution to GDP [24,25].

A separate point of discussion in the literature aims at dealing with the long-term issue, particularly intergenerational investment impacts. In general, these approaches argue for lower discount rates, particularly a declining discount rate (DDR) schedule, as it reduces the sensitivity of distant effects to discounting. However, epistemological roots of the decline vary tremendously. The three of them are the most widely discussed. The enlarged Ramsey formula is a predominant approach to solve this task [2], designed to capture the risk towards level of future consumption via embracing the volatility over future growth rate [26] or certainty equivalent discount factors, referred to as "gamma discounting" [27]. There are two alternative approaches: expert judgements to elicit specific values of long-term SDR [28,29] and questionnaires to investigate the stated intertemporal preferences of the general public [30,31].

While SDR is based on a diversified set of approaches, they also lead to diverging estimates. The highest rates are usually produced by the SOC approach, reaching 6–8% for developed countries [16,23] or even higher for developing countries (e.g., 11% for South Africa [25]). Ramsey-based results vary as well, mainly due to differences in the consumption growth rate, with values of approx. 4% for developed countries, such as the UK, the US, Germany, Italy, or France [32,33], from 2% to over 6% for the EU [34], and for developing countries varying from China's 15% to negative rates for some African countries [2,17]. The lowest estimates come from the CRI approach (1–3%) [16]. Uncertainty in discounting followed by the Gollier proposal leads to estimates lower by approx. 0.3–0.5%

than the regular Ramsey formula [35,36]. In general, DDRs decline to approx. 1%, but the values vary between 0.5% and 4% depending on the approach [29,31,37].

Discounting regimes also vary among official recommendations between countries. The majority of EU countries follow the Ramsey approach [33] (Italy, France, the UK), recommended also in the official EU guidelines [38] or use a CRI regime based on government borrowing rates (Germany, Norway). The US, Australia, and Asian countries generally apply the SOC approach [16,17]. The DDR approach serves for long-term projects (usually with effects ranging above 30 years) in the UK [39], France, and the US (for environmentally-related investments) [36,40].

The majority of works estimating SDR for Poland are based on the Ramsey approach, resulting in values from approx. 3% to 6% [34,41,42]. The official recommendation for SDR applied in Poland, in general, follows a constant 5% discount rate and comes from the EU recommendations on discounting for CBA [38]. Long-term focused discount rates are rare in the literature. Examples include Foltyn-Zarychta [31], who estimates the rate (for intergenerational projects) declining from 5% to 0.4% for a 1000-year perspective, or Saługa [43], who applies the DDR scheme in relation to mining investments.

However, none of those studies focus on the energy sector solely. The EU recommendation of a uniform 5% may reverberate negatively on the number of projects accepted. First, this value is not supported explicitly by any in-depth study concentrating on the economic characteristics of Poland. Second, the recommended value does not account for uncertainty related to long-term intergenerational issues, particularly important for energy-related projects.

1.3. The Aim of the Study

This paper considers the issue of selecting a proper discount rate level in the efficiency calculation. The paper aims at estimating SDR for Poland which can be used for long-term energy sector transition policies. Since the level of discount rate determines the rate of depreciation of future values, and in the case of Poland, we are dealing with the need to incur exceptionally high expenditure with a long period of waiting for effects, adopting the financial discount rate would show the ineffectiveness of such investments. We share the conviction that "(. . .) the discussion about efficiency of energy transition policy cannot be decoupled from the social discount rate and the compensation that society requires to forego current consumption for future benefits", especially if we take into consideration that "Discounting and the discount rate are also central elements for the determination of the social cost of carbon (SCC)" [44]. This viewpoint is supported by Steinbach and Staniaszek [45], who differentiate between individual discount rates and social discount rates in energy system analysis. From their perspective, individual discount rates should be applied in modelling individual investment decision making. However, evaluation of the total costs and benefits of energy systems requires a societal perspective to be adopted and, as a result, social discount rates application. As emphasized by Hermelink and de Jager [46], the adopted level of discount rate is crucial to the evaluation results of energy policy options. They also claim that discount rates employed in the EU Impact Assessment for the 2030 energy and climate policy framework should be significantly lowered, as was done by some EU member states (their proposal assumes calculation of the EU Weighted Average Capital Cost that is supposed to be in the range 3–6%). We investigate these problems in the following sections.

The analysis follows two strands in the literature: descriptive CRI and SOC (both market data-based) and the prescriptive Ramsey formula (social welfare function-based). While the Ramsey formula is the predominant approach of government SDR recommendations in Europe (as mentioned in the preceding section), the paper concentrates on this approach, also investigating CRI and SOC. The overview of approaches undertaken in the paper is summarised by Figure 3.

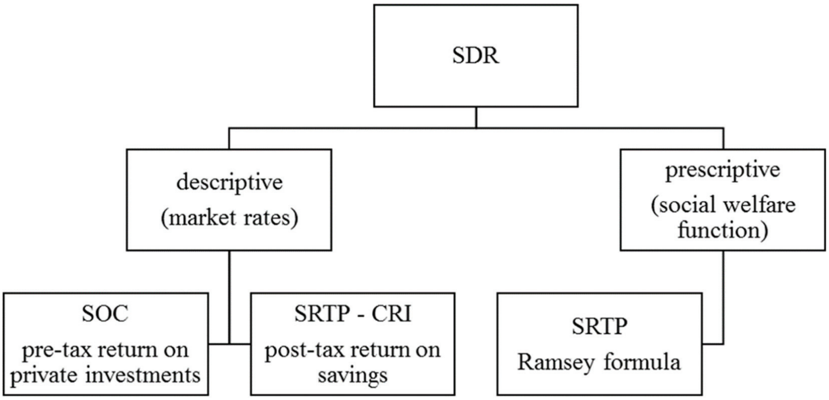

Figure 3. Main approaches to estimate the Social Discount Rate.

The descriptive strand analysed rests on market rates of return that approximate CRI and SOC. As recommended by Zhuang et al. [17] and Boardman et al. [20], these are based on the after-tax rate of return on low-risk financial instruments (reflecting CRI-SRTP) and the pre-tax rate of return on riskless private investments, which represents an alternative approach to SOC. The prescriptive approach delivers the value of SDR based on the social rate of time preference approach according to the Ramsey model, with the elasticity of marginal utility of consumption estimated on the basis of the personal taxation method [47]. Additionally, to deal with long-term energy policy-related impacts, we derive SDR based on Gollier's approach [48] that includes the volatility over the growth rate of per capita consumption. To our knowledge, such combination of methods has not been applied previously for Poland.

The paper is organised as follows: Section 2 starts with describing two market-based approaches (CRI and SOC), followed by insight into the Ramsey formula and its Gollier modification. Next, the sources and treatment of data used in the study are described. The following section presents the results obtained for all approaches for three time horizons reflecting the range of data gathered. This is followed by the discussion including a recommendation of the SDR values that we find the most appropriate to use for energy policy investments. The conclusions section closes the paper.

2. Materials and Methods

2.1. SRTP-CRI Based on Real After-Tax Return on Savings

Consumption Rate of Interest (CRI) takes the angle of capital supply (savers). Boardman et al. [20] as well as Burgess [49] point out that the major distortion that causes the divergence between the demand side (enterprises) and the supply side (consumers) emerges from taxation (apart from such factors as the level of risk, liquidity, or imperfect information). The proper measure of what consumers must forgo to accept the investment is therefore given as their post-tax real returns on savings as these rates represent an agent's postponed consumption opportunity cost.

The literature presents various estimation methods. Moore et al. [13] refer to an average monthly yield on treasury notes with various maturity lengths. Historical real returns on long-term government bonds are recommended by the U.S. Environmental Protection Agency [40] and Zhuang et al. [17], but using other low-risk securities is also possible [18] as well as consumer borrowing rates [49]. The returns to savers are reduced by tax burden in marginal terms and transformed into real rates, with average inflation (inflation forecasts) based on historical data considered [13]. Harberger and Jenkins [50] argue that the real rates for the majority of countries would stay within the range of 2–3%.

2.2. Social Opportunity Cost (SOC) Based on Market Return on Private Investments

SOC rests on the assumption that both sectors, public and private, compete for the same pool of scarce resources, so any additional investment in a public project leads to the diversion of funds from the private sector. In these circumstances, the appropriate Social Discount Rate is determined by the opportunity cost in the private sector [51].

However, it is argued that not all the components of the private marginal rate of return are included in the opportunity cost [17,52], particularly risk premia and transaction costs. The lower limit of the opportunity cost is therefore the marginal cost of government borrowing (assumed to be equal to marginal cost of taxation). The upper bound for the opportunity cost of public projects is the cost of private sector capital reduced by the post-tax differential private risk premium as well as additional transaction and illiquidity costs.

A straightforward consequence of the conducted analysis is the adoption of various market rates as proxies for the Social Opportunity Cost. According to Boardman et al. and Moore et al. [13,20], the best proxy for the upper bound of the opportunity cost is real, pre-tax rate of return on corporate bonds, as enterprises tend to equate (on the margin) the expected pre-tax investment return with the pre-tax bonds rate. It is also emphasised that the actual opportunity cost is probably significantly lower [20]. The opposite extreme of the opportunity cost estimates is the government borrowing rate, as the taxes on private financing are usually higher than those on the public one and the premium for income covariance is negligible (but generally positive). As a result, we obtain an interval for the Social Opportunity Cost.

2.3. Ramsey Approach—The Prescriptive Social Welfare Function Based Regime

SDR measured via the Ramsey model emerges from the criticism of capital market observed rates. The main point raised by the proponent is that capital markets are far from being perfect, i.e., consumers, as well as private sector investors, face a variety of rates due to information asymmetry, differences in creditworthiness, or dual roles as borrowers and lenders for consumers [15]. The Ramsey formula is based on a prescriptive approach, seen as an appropriate risk-free measure for public investments [53], emerging from the aim of intertemporal maximisation of social welfare function [21]:

$$\mathrm{W} = \int_{0}^{+\infty} e^{-\rho t} U(c_t)\,\mathrm{d}t \tag{1}$$

where $U(c_t)$ stands for utility derived by society from consumption in period t and $e^{-\rho t}$ is a discount factor (assuming continuous compounding), with ρ as a utility discount rate that represents pure time preference. Transforming the welfare function to obtain the consumption (instead of utility) rate of discount that optimizes the productivity of capital gives the Ramsey formula (taking the premise of constant elasticity in the utility function) as:

$$SRTP = \rho + \eta g \tag{2}$$

where g is the (anticipated) growth rate of per capita consumption and η is the elasticity of marginal utility of consumption $\eta = -\frac{\mathrm{d}U'(c_t)}{U'(c_t)} / \frac{\mathrm{d}c_t}{c_t}$ (the percentage reduction in the marginal utility of per capita consumption due to a 1% increase in per capita consumption). The product of g and η represents the fact that as society is becoming richer per capita (g), the additional unit of consumption is valued less according to the diminishing marginal utility of consumption (reflected by η), which acts in accordance with the society's view to reduce inequality in consumption flows over time [13,14].

The utility discount rate ρ consists of two elements. The first one reflects the risk of death based on mortality rates for a given country. The second element is the myopia of decisions—the society's impatience to consume sooner than later. However, it should be pointed out that for long-term decisions, some researchers, e.g., Ramsey [21], Eckstein [54], and Parfit [55], suggest to exclude it on ethical grounds, particularly in cases of investments affecting future generations as it makes these generations less important only due to the fact that they are born later.

The growth rate of per capita consumption g is usually based empirically on mean annual growth rates of consumption or GDP, as is done in the works by Evans and Sezer [34], Percoco [56], and Florio and Sirtori [41]; however, more demanding approaches are also used. For instance, Moore et al. [13] as well as Kula [57–59] use extrapolation based on the slope of a relationship between time and the natural logarithm of real per capita private consumption expenditure.

The elasticity of marginal utility of consumption, η, reflects the society's aversion to inequality in consumption level over time or over individuals; however, this can be interpreted also as aversion to risk—the willingness to avoid sudden changes in consumption level. The higher η is, the higher the discount rate is, making current consumption more important than the gains in the future. The estimates of η are usually based on four approaches that include: eliciting stated preferences via surveys [29,60], indirect behaviour evidence based on consumption choices [32], life-cycle behaviour models considering saving choices of individuals or revealed social values based on the level of progressivity of personal tax income [22]. In this paper, we focus on the revealed social values approach, which produces stable estimates, both across time and between countries [33].

Revealed social values, or "the equal sacrifice", approach emerges from the social planner's aversion to inequality which represents the tastes and preferences of the society. Inequality aversion is derived from the progressivity of national personal income tax rates, based on the premise that the tax schedule is designed in such a way that the marginal utility of tax burden is equal for all individuals. This represents society's aversion to inequality and can be transferred from the tax system to other areas as, e.g., intertemporal decisions [61]. The η in the tax method is estimated as [47]:

$$\eta = \frac{\ln(1 - MTR)}{\ln(1 - ATR)} \tag{3}$$

where MTR is the marginal income tax rate, and ATR represents the average tax rate.

The extension of the Ramsey rule via Gollier's approach [26,48] is proposed for long-term projects, e.g., climate change investments reducing greenhouse gas emissions [2,36]. The modification assumes that the consumption level in SWF is uncertain and the consumption growth fluctuations are independently and normally distributed. Then, the discount rate takes the form:

$$SRTP = \rho + \eta\mu_g - 0.5\eta^2\sigma_g^2 \tag{4}$$

where μ_g and σ_g^2 represent the consumption growth rate mean and variance, respectively. The last element of the equation is interpreted as a precautionary term, reflecting the fact that a social planner, when facing the uncertainty, is willing to save more now to benefit in the future [62].

2.4. Data Sources

The analysis presented in this study is based on two general alternative approaches that determine the discount rate applied in public investment projects appraisal. The descriptive approach that adopts the discount rate used to translate future costs and benefits into current ones, as a consumption rate of interest or social opportunity cost of capital, relies heavily on financial data describing particular components of return on savings and private sector cost of financing. A straightforward consequence of this fact is the necessity of using various financial datasets to estimate the Social Discount Rate.

We followed the convention advocated by Moore et al., Boardman et al., and Spackman, [13,20,52] while estimating SDR based on market data by starting our calculations from CRI represented by the post-tax real rate of return which savers are willing to accept. As a result, the most common choice of an observable proxy for this variable is the after-tax real rate of return on government bonds. Thus, we exploited, i.a., time series provided by the Polish Ministry of Finance covering all domestic issues of Treasury bonds [63]. This dataset includes information about all transactions since February 1994 (bonds sold to financial institutions) or since June 1992 (retail bonds). To obtain the monthly time series of average yield in the case of bonds purchased by institutional investors, we calculated a weighted average of yields considering sales transactions conducted in a particular month. We adopted proceeds from sales as the weights. We omitted all the records for which the yield was unavailable (mainly CPI-linked bonds and floating rate bonds). A similar procedure was applied in the case of retail bonds, with a few minor exceptions. First, as retail bonds are generally sold at par, instead of yield, we used the nominal coupon rate (5-year fixed rate bonds were the only exception—they were sold in tranches and below par; in this case, we exploited yield to maturity calculated using average selling price over tranches). Furthermore, all the floating rate bonds and CPI-linked bonds, for which the first-period coupon rate was available, become the basis for calculations.

Bonds used in the previous calculation differed among themselves by the time to maturity. One of the practices followed by researchers is to consider instruments of constant time to maturity [13]. Having adopted this approach, we also used time series of yields on 10-year Polish fixed rate Treasury bonds provided by the Federal Reserve Bank of St. Louis [64]. This dataset covers the period starting from January 2001. At this point, one issue must be raised. As it is noted, e.g., by Moore et al. [13], there are many proxies serving as the rate of return on a riskless asset reflecting the level of real, after-tax return on savings obtainable by postponing current consumption. A government bond yield is only one among various possible choices, not necessarily the best one if a significant part of the population prefers other means of saving. Therefore, we additionally decided to use the average rate of return earned on personal term-deposits (covering all maturities) according to the data provided by the National Bank of Poland [65]. The analysed time series starts from December 1996.

An additional factor which heavily influences the rate of return on savings is the level of capital gains tax. Before December 2001, all capital gains and equivalents (e.g., dividends, interest on fixed-income securities) were not taxed. From March 2002 until December 2003, the tax rate was equal to 20% of the income (during the interim period December 2001–February 2002, income on newly issued instruments and contracts was proportional accounting to the length of the exemption period) [66,67]. Since January 2004, all capital gains and equivalents have been taxed using a flat tax rate of 19% [68].

At the other extreme is the cost of private sector capital: the Social Opportunity Cost. Unfortunately, it is also problematic to find the best proxy reflecting the cost of private funding. Boardman et al. [20] advocate the application of the real, pre-tax rate of return on corporate bonds instead of any measure that considers the equity rate of return. We share their view that this solution might be treated as optimal due to various reasons. First, it allows us to avoid a rather cumbersome estimation of the effective marginal corporate tax rate. This is a result of equating marginal expected pre-tax return on investment with before-tax cost of capital implied by bond yield. Moreover, in the case of equity profitability, we have at our disposal only average rates of return while marginal ones (which might be significantly lower) are needed. The bond yields are also more stable than equity returns and include a significantly lower risk premium to their holders. The advantages mentioned were the main incentive to follow this approach. Unfortunately, the Polish corporate bond market is relatively thin and is mainly composed of floating rate bonds, which makes assessment of the bond yield impossible or vulnerable to various ad hoc assumptions. As a consequence, we decided to use the time series provided by the National Bank of Poland describing the average interest rate paid by companies on their credit liabilities (independently of the maturity) [65]. The data provided by the NBP cover the period starting from December 1996. This approach also seems more advantageous due to the fact that Polish enterprises commonly finance their activities using the credit channel rather than directly via capital markets (according to the data provided by the Warsaw Stock Exchange and NBP, the nominal value of market debt traded on WSE equals to approx. 5%

of total credit to nonfinancial enterprises) [65,69]. What should be highlighted is the fact that the rates of return on Treasury bonds are also used in SOC estimations. The Treasury bond post-tax yield represents the rate for the savers; the pre-tax rate as a proxy for the rate at which the government borrows on the market may represent the cost of capital for policy investments [16]. Although they do not represent SOC in its pure definition, we added them to previously discussed estimates as an approach that links CRI and SOC as well as provides a lower bound for the rates of return on private investments. The calculation of both CRI and SOC, as they are based on market nominal data, requires the consideration of inflation expectations. Unfortunately, despite extensive investigation, we were unable to obtain inflation forecasts of demanded frequency. Therefore, we decided to use as a proxy ex-post inflation rates averaged over 12 consecutive months using geometric rates of return. The database obtained from the Statistics Poland website [70] covers a period starting from January 1982 with monthly frequency. Due to the adopted mechanism of calculating an approximation of expected inflation, the last period for which an appropriate value could have been obtained was October 2019.

The second approach that enables the estimation of Social Discount Rate refers to the Ramsey formula [21]. As this viewpoint rests on optimization of current and future consumption level, the data necessary to evaluate the Social Rate of Time Preference consist of fluctuations in real consumption expenditures. The necessary observations are provided by the Organisation for Economic Co-operation and Development and are available on the OECD Statistics website. In this study, we followed the concept discussed by Groom and Maddison [22] to employ real, quarterly, not seasonally adjusted consumption expenditure on semi-durable goods, non-durable goods, and services per capita. The OECD database provides data about households' consumption expenditure classified as "other goods and services", meaning total goods and services excluding durable ones (expressed in millions, in PLN of 2015). The additional question to answer was whether to analyse total or per capita consumption. On the one hand, we share the view expressed by Feldstein [53] that a social utility consumption function should mirror not only per capita consumption, but also the size of the population (i.e., social welfare should raise when a society enjoys a constant per capita consumption level while the population increases). On the other, this task might hardly be achievable and most of the studies presented in the literature employ per capita consumption. The additional argument in favour of this choice in the case of Poland is the fact that its population remained rather stable during the analysed period (coefficient of variation 0.57%). Unfortunately, due to periodic reassessment of population size after general censuses without backward adjustment, we were unable to exploit the data provided by Statistics Poland. As a consequence, we chose to employ data series prepared by the Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat [71]. The data given as of 1 July for every year were linearly interpolated to obtain end-of-quarter values and then averaged to obtain the quarter mean value. These values were then used to obtain quarterly time series of per capita consumption and to estimate its average rate of change as well as the uncertainty connected with future growth. To obtain the rate of growth of per capita consumption, we followed Kula [57–59] by fitting the equation:

$$\ln C_t = a + gt \tag{5}$$

To avoid possible bias caused by the COVID-19 pandemic, among explanatory variables, we used a dummy variable for Q2 2020 (significant at $p = 0.05$). The variance of the growth rate was estimated as the variance of the error term.

The Ramsey equation also employs the elasticity of marginal utility of consumption, estimated in this study via "the equal sacrifice" method proposed by Stern [47]. The appropriate data are delivered by the OECD Tax Database [72] (also used by other European SDR studies, e.g., [41,42]), including the average and marginal tax rates and wedges for four levels of income expressed as a percentage of the average wage (67%, 100%, 133%, 167%). The applied all-in tax rate combines the central and sub-central government income tax as well as employee social security contribution. Despite controversies of whether the social security contribution should be treated as part of the tax wedge [22], we decided to include it as, in many studies, e.g., Florio and Sirtori's work [41], it is thought to bring the same consequences to the employee as income tax [73,74]. For the highest level of income (167%) at marginal tax levels, we excluded two years from the analysis (2006 and 2008), replacing the original values with the average of two adjacent years due to the extremely high rates provided by the OECD database (40.3% and 37.0% while the average for remaining years was approx. 28%). Although we could not find the details explaining this deviation, we assume that it was caused by introducing a new defined contribution pension system instead of the defined benefit regime. The year 2009 was the first year when the intermedium pensions started to be calculated and paid [75], which could have stimulated individuals with high salaries to retire earlier, benefiting from old pension regulations and thus, increasing the marginal tax rate in a disproportionate manner. It was emphasised by Stern [47] that the most appropriate way to calculate the elasticity of marginal utility of consumption is to weight observations by the number of people to whom they refer. To meet this requirement, we used the data published biannually by Statistics Poland [70] that describe the structure of population while taking into account level of gross salary. As the OECD data are divided into four classes (67%, 100%, 133%, 167%) by level of income expressed as a percentage of average wage, we assigned workers to those classes as well. The first class ("67%") represents workers of gross salary below 75% of the average, the second class ("100%")—workers earning between 75% and 125% of the average, the third class ("133%")—workers of gross salary between 125% and 150%, and the last class ("167%")—the remaining workers. According to the assumption adopted by Stern [47], "the line was constrained to go through the origin (. . .), because for low incomes marginal and average tax rates are zero" and we restricted our analysis to only the zero-intercept case while running regressions. This methodology is followed by many authors [76]. The regressions run using weighted and unweighted observations yield almost the same results.

The last variable needed to estimate the Social Discount Rate using the Ramsey equation is the pure rate of discount. In this study, we assumed after Ramsey and Eckstein [21,54] that its component that reflects the pure individuals' impatience or myopia is equal to zero due to the desire to treat all generations alike and to avoid the introduction of irrationality into the process of decision-making [59], which is particularly important in the case of climate change and energy policy [77]. We consider mortality as the only reason for positive pure discount rate. This component was estimated using death statistics for the entire Polish society since 1946 (restricting analysis to the most recent years does not significantly change the results). The appropriate time series of yearly frequency are provided by Polish Statistics [70].

3. Results

To estimate SDR, we chose:

- The post-tax households' deposits real yield and post-tax retail bonds' real yield as the revealed net rates of return to savers representing the Consumption Rate of Interest.
- The pre-tax Treasury bonds of all maturities real yield as the lower limit for the Social Opportunity Cost (as they represented, on average, 94.4% of central government domestic debt and 65.6% of central government total debt).
- The pre-tax corporate credit liabilities real yield as the upper bound for the Social Opportunity Cost.
- The estimates of the Social Rate of Time Preference obtained using the Ramsey and Ramsey–Gollier approach.

The obtained results on SDR vary between the approaches as well as the period analysed. We estimated the discount rates for three time-horizons: all-available-data horizon (starting from approx. mid-1990s, depending on the approach analysed), EU accession benchmark (July 2004), and—mainly for contrasting purposes—2019.

The CRI approach provides the lowest estimates, ranging from negative rates for a single year (2019), with the lowest value −2.19% for the post-tax real rate on personal deposits, then higher, but still relatively low (from 0.49% for deposits to 1.66% for 10-year Treasuries) estimates for the EU accession taken as a benchmark; to the highest numbers for the all data available horizon, where the lower bound (1.86%) is given by deposits and the higher one by Treasury bonds for all maturities (2.78%). SOC also gives negative values based on the pre-tax government bonds rates for 2019, except for the pre-tax return on credit liabilities (0.34%). The post-accession period is illustrated by SOC rates ranging from 1.91% for retail bonds to 3.40% for companies' loans. Finally, the all available data horizon brings the rate of 5.04% on companies' loans and values from 3.01% to 3.37% for the pre-tax rate on Treasuries. The values of SDR based on Ramsey face much lower discrepancies. The lowest estimates are also calculated for 2019 (2.25% and 2.14% for Ramsey and its Gollier modification, respectively), which is mainly due to lower consumption growth rate predictions. Two other periods are illustrated by the rates more than twice as high, giving the results of 4.46% and 4.17% (EU accession period) and 4.72% and 4.39% (all available data) for Ramsey and including Gollier's precautionary effect, respectively. Our results are summarized in Tables 1 and 2.

Table 1. Estimates of Social Discount Rate for Poland based on market rates.

	All Available Data	**Data Since Q2 2004**	**Data Since January 2019**
Post-tax average rate of return on personal term-deposits	1.86%	0.48%	−2.19%
mean +/− st. dev.	[−1.56%; 5.27%]	[−1.21%; 2.16%]	[−2.81%; −1.58%]
Post-tax average rate of return on government bonds			
Treasury bonds	2.78%	1.35%	−1.78%
mean +/− st. dev.	[−0.62%; 6.18%]	[−0.22%; 2.93%]	[−2.35%; −1.21%]
Retail bonds	2.42%	1.17%	−1.81%
mean +/− st. dev.	[−0.89%; 5.73%]	[−0.53%; 2.86%]	[−2.49%; −1.13%]
10Y Treasury bonds	2.25%	1.66%	−1.54%
mean +/− st. dev.	[−0.10%; 4.61%]	[0.14%; 3.18%]	[−2.06%; −1.02%]
Pre-tax average rate of return paid by companies on credit liabilities	5.04%	3.40%	0.34%
mean +/− st. dev.	[0.92%; 9.15%]	[1.57%; 5.22%]	[−0.35%; 1.02%]
Pre-tax average rate of return on government bonds			
Treasury bonds	3.37%	2.14%	−1.39%
mean +/− st. dev.	[0.08%; 6.66%]	[0.45%; 3.82%]	[−1.95%; −0.84%]
Retail bonds	3.01%	1.91%	−1.43%
mean +/− st. dev.	[−0.21%; 6.23%]	[0.07%; 3.74%]	[−2.12%; −0.74%]
10Y Treasury bonds	3.05%	2.52%	−1.10%
mean +/− st. dev.	[0.84%; 5.25%]	[0.91%; 4.12%]	[−1.6%; −0.6%]

All rates are given as real rates of return.

Table 2. Estimates of Social Discount Rate for Poland based on Ramsey and Ramsey–Gollier equation.

	All Available Data	**Data Since Q2 2004**	**Data Since January 2019**
Mortality component (log)	0.9599%	0.9599%	0.9599%
Elasticity of marginal utility of consumption	1.1174	1.1105	1.0776
Rate of consumption growth (log)	3.2711%	3.0690%	1.1746%
Rate of consumption growth (log) variance	0.0052	0.0046	0.0018
SRTP–Ramsey approach	4.72%	4.46%	2.25%
SRTP–Ramsey–Gollier approach	4.39%	4.17%	2.14%

All rates are given as real rates of return.

Figure 4 additionally illustrates the values of the main variables determining the level of the Social Discount Rate.

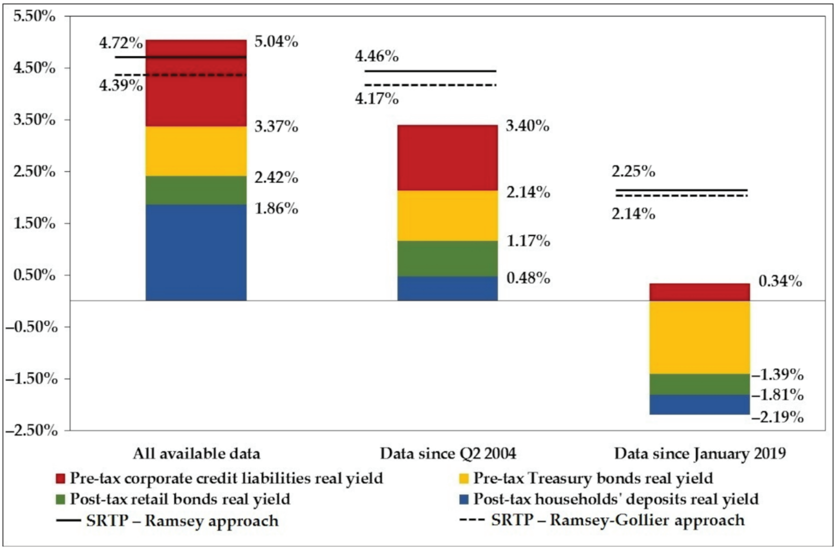

Figure 4. Estimates of Social Opportunity Cost and Social Rate of Time Preference.

Market rates, as we discuss further and as was emphasised by Feldstein [78], despite their alleged objectivity, do not seem to be the most appropriate indicators of the discount rate for public projects due to their observed volatility in this study, particularly clear for 2019 results. The longest horizon based on available data represents the preferred time-range for further discussion, despite the fact that the interval for SDR on the basis of CRI and SOC is definitely substantial. In real terms, the SDR interval is 1.86–5.04%, while considering pre-tax average rate of return on government bonds, it might be contracted to 3.37–5.04%. The average post-tax rate of return on retail bonds, higher by 56 bp, does not take into account that retail bonds represent a very small share of households' portfolio [79] and, in our opinion, is inadequate to measure the society's time preference in Poland. The estimates obtained using the Ramsey equation seem much more stable: 4.72%, or having considered possible fluctuations in growth rates, the Ramsey–Gollier equation: 4.39%. The shift in SDR value estimated using the elasticity of marginal utility of consumption, if we consider only the period after joining the European Union by Poland, is not as large as the discrepancies in SDR evaluated as the opportunity cost. The Ramsey (Ramsey–Gollier) formula provides us with the value of 4.46% (4.17%), i.e., decline by 26 bp (22 bp). At the same time, the interval for the Social Opportunity Cost moves down to 2.14–3.40% (by 160 and 123 bp, respectively). For illustrative purposes only, we also presented estimates based on the data starting from January 2019. In this case, the Social Opportunity Cost lies in the interval from −1.39% to 0.34% (fall by 476 and 470 bp, respectively) while the Social Rate of Time Preference is 2.25% (Ramsey, fall by 247 bp) and 2.14% (Ramsey–Gollier, fall by 225 bp).

4. Discussion

The results obtained consist of three proposals of the values presented above, namely SOC, CRI, and Ramsey-based approaches. This part provides comparison with other studies followed by the limitations of each approach.

In the case of the SRTP approach based on the post-tax return to savers, our results for the all available data time range vary from 1.86% to 2.78%. This stays close in comparison with other estimates ranging around 2–3% [16,50]. However, it should be highlighted that personal rates are difficult to compare with other studies due to country-specific legal frameworks [13]. This difficulty also lies in country-specific determinants of capital supply, such as the variety of saving offered or the propensity to save.

It should be emphasised that the time preference rate derived from market data only partially reflects the real society's attitude towards the exchange of current for future consumption. The calculated values must be treated as a lower limit for the social time preference rate due to various reasons. One of them is the fact that the perception of all individuals as net savers is inappropriate as some are net borrowers facing borrowing rates significantly higher than lending ones. Furthermore, restricted funds availability due to information asymmetry between lenders and borrowers results in a rising demand for government debt (driving the rates down) and a falling demand for private debt (driving the rates up). As overborrowing imposes certain restrictions on borrowers' behaviour, they tend to not increase their debt despite the fact that interest rates might be below time preference rate [52]. Feldstein [78] notices the problems raised as "an individual's marginal borrowing and lending rates may not be equal". We can find that there exists many different borrowing and lending rates which differ due to the transaction's amount, duration, and risk. This observation undermines the assumption of a single marginal equilibrium lending (or borrowing) rate existing.

Finally, some reservations should be expressed in light of energy policies. The first one emerges from the myopia of financial market offers: the longest available maturity of saving instruments reaches up to 30 years [80]. Such a discrepancy may infringe the cohesion between consumer choices and long-term energy policy investments. The longest instruments used in this study are 10-year government bonds, lagging far behind the timeframe of climate change-related issues. Additionally, what Burgess and Zerbe [23] point out is that a possible discrepancy exists between the personal time preference rates and the views about the rates for government policy decisions. The latter rate is marked in the literature as consumer–citizen divergence [81–83].

The main advantage of using the Social Opportunity Cost of capital as a discount rate is the fact that it represents the simple and obvious rule, that "no project should be accepted if its return is less than the return available on alternative projects" [84]. This benchmark estimated in the study ranges from 3.01% to 5.04% for the maximum available period, which is slightly lower than the reported estimates for developed countries, reaching 6–8% [16]; however, this discrepancy can be assigned to the methodology adopted due to the fact that our study employs a return on bonds and loan rates, while Burgess and Zerbe [23] use the National Accounts data to deliver the profitability within the enterprise sector. The main difference seems to lie in the risk premia, lower for credit facilities or equal to zero for Treasury bonds. In the presented method of obtaining the Social Opportunity Cost, we followed the approach excluding the after-tax risk premium for private investors from the opportunity cost while adding a negligible premium for income covariance (Spackman estimated it for the UK at 0.10% [52]). The argument in favour of using the riskless rate of return as the opportunity cost has been stressed by Samuelson [85], who noticed that the government acts as an insurer by pooling multiple various projects and virtually eliminates the idiosyncratic risk.

The problem of including risk premia in the discount rate for the energy generation sector has been raised by Lind [14]. His estimates were based on the methodology implied by the rate of time preference concept (i.e., the after-tax rate of return to savers) and in the case of the whole U.S. economy, oscillated about 4.6% (including market risk premium). The energy industry was an exception. As Lind argued [14], the rates of return in this sector seemed to be non-perfectly but rather weakly correlated with general market returns which lowered the rate to 3% (still above the long-term after-tax rate of return on government bonds equal to 2%). An additional argument in favour of this point of view might be formulated based on legal acts governing Poland's energy generation sector. According to the regulations, the rate of return in this industry is set by the Energy Regulatory Office using the concept of pre-tax Weighted Average Cost of Capital calculated in compliance with the Miller–Modigliani model [86,87]. It should be noticed that the fall in the pre-tax return to equity calculated according to the rules by 3.79 p.p. since 2011 is caused almost entirely by the fall in the riskless rate of return by 3.80 p.p. (the changes in the level of risk premium, target financing structure, and one-time change in methodology were offsetting each other; adjusted R^2, while regressing the pre-tax equity cost against the riskless rate of return and a dummy variable representing a one-time methodological change, equals to 0.964). As a result, the rate of return on invested equity heavily resembles the riskless investment. The implications raised here are the following. First, risk premia can be excluded even if we consider energy investments as purely private. Second, both private and public investments can follow the same discounting regime.

The drawback of the SOC approach is the assumption that public investments crowd out private ones dollar-for-dollar, which is not necessarily true as they are partially financed by funds diverted from consumption or by borrowing from overseas. This objection might be somehow relaxed as Harberger [88] proposed a model which refers to funds diverted from various sources: consumption, private investments, and foreign investors. In this case, the final Social Opportunity Cost is a weighted average of costs of funds of different origin. In this paper, we do not use this method as we rather construct an interval of possible values of the opportunity cost, which serves only as a guideline while our target value is determined using the time preference approach.

Another disputable issue is the alleged objectivity of market-based rates. As observed by Creedy and Passi [89], this approach also requires making certain value judgements, but they are less explicit than in the case of the time preference method and as a result, it is supposed to be more objective. As Creedy and Passi notice, the very decision to employ this approach is based on a hidden assumption that the time preference revealed by the government should be the same as the one revealed by the businesses while making their investment decisions, which differ in terms of aim (maximising the company's value instead of society's welfare) and time range (the majority of commercial investments are limited by a 10-year perspective, also reflected in loan repayment schedules; perspectives longer than 10 years are perceived as long-term) [38].

Finally, the issue that applies to both market-based approaches: volatility of market rates. The problem in our study was shown by applying three time perspectives: all data available (collection starts from approx. mid-1990s), mid-2004 (when Poland joined the European Union), and 2019. The values differ significantly between the timeframes, particularly for 2019 (last pre-pandemic year), where almost all market-estimated rates were negative. Market rates are much more volatile than estimates obtained employing the utility function and in the short term rather reflect current monetary policy decisions than long-term society's preference regarding exchanging future well-being for the current one. Those arguments put into question the effort aimed at estimating the Social Discount Rate as a descriptive variable, based on market rates.

The estimates based on the Ramsey approach give much more stable results both in terms of the time period analysed and international comparisons. Mortality rates (0.96% in this study) are usually estimated at around 1–2% depending on the country and the time period used, but the majority of studies apply 1% as "the most appropriate" value [17,90]. Growth rates vary between countries; however, they stay within the range 3% to nearly 5% in previous studies for Poland [34,41,42]. The η estimates usually stay within the range of 1–2 [17,22] with the average value for Europe suggested to be at 1.5 [41]. Values of η for Poland fall within the range of 1.09 to 1.58 [32,34,41,42]. Our results stay close to the results obtained in 2013 by Florio and Sirtori [41] who used the International Monetary Fund growth forecasts (3.16%), mortality rates (0.97%) as of 2011, and elasticity of marginal utility of consumption equal to 1.09 in 2011. A value similar to ours (4.94%), based on η estimated using the tax method, was obtained by Seçilmiş and Akbulut [42] who analysed transition countries (Czech Republic, Estonia, Hungary, Latvia, Poland, Slovakia); however, their result, received as a panel estimate, is significantly lower (2.75%) mainly due to differences in the method used to estimate the elasticity of marginal utility of consumption (0.48) based on a food demand model. Furthermore, the 2012 results of Addicott et al. [91] based on demographic data are definitely higher than ours (6.69%) as well as the assumed 2002 values obtainable using elasticity of marginal utility of consumption as estimated by Evans [32] (1.38 for the low-income class and 1.58 for the high-income class).

All these results do not take into consideration the issue of uncertainty embedded into future growth rates. Therefore, we recommend, as the most appropriate one, the estimate received by employing the Gollier correction that lowers Ramsey's SDR by 33 bp for the longest available period. The precautionary effect found here is similar to values in other studies, balancing around 0.1–0.3% for the OECD countries [2,36]; however, they are based on historical growth rate data, where volatility (standard deviation) is rather small, e.g., 3.5–5% for the U.S. and up to 5.1% for Italy [33,35], as this effect is much larger for economies in transition, such as Poland or developing countries [2,92].

It must be noticed that the estimated Social Discount Rate will inevitably differ among various countries. It stems from heterogeneous societies' views on utility of future and current consumption as well as its growth rate (Ramsey) or the diversity of different socioeconomic factors influencing investments' efficiency and savers' propensity to invest (SOC and CRI). This leads to huge differences in hurdle rates recommended by energy sector regulators, which sometimes may be as high as 10% in real terms [93], especially if we take into consideration the fact that they may cover risk premia. Recent studies confirm significant dispersion of discount rates applied to energy investments in various countries [94,95], supporting our viewpoint that we cannot assume a uniform international hurdle rate in energy policies.

The Ramsey approach seems to be well fitted to energy-related investments due to their longevity. The 5th IPCC report [2] points out here the flaw of market rates which aggregate the preferences of people living at present and omit those who will be born in the future. Moreover, the very task of investing intergenerationally is mostly a normative problem [31,55] and the choice of η is an ethical issue as raised by Helgeson et al. [60].

However, the prescriptive character has a major drawback that lies in the form of subjectivity, starting from disputable ethical arguments, supporting, e.g., the omission of impatience in calculating the utility discount rate ρ or estimating η based on various domains (inequality represented in the approach undertaken in this study, inter-temporal substitution, substitution between goods, and risk aversion) implying that the aversion to inequality in consumption level is "the same regardless of whether it occurs between individuals today, across time or across risky scenarios" [22]. Finally, why SOC is favoured over the Ramsey approach is the fact that when seeking the most efficient use of funds, dragged away from private investments, the Ramsey formula does not always secure the Pareto improvement in the consumption level for the society [23]. The choice between SOC and Ramsey should reflect the source of policy funding, distinguishing between consumption or public spending and private investments crowded out at present. It should also take into consideration mixed cases, i.e., when the project displaces private investments today to provide consumption benefits in the future [16,96].

5. Conclusions

The discrepancy between prescriptive and descriptive approaches to SDR has reverberated for a long time in academic discourse. The paper aims at estimating SDR for Poland which could be used for long-term energy sector transition policies. It provides a wide range of values, depending on the estimation method as well as the period analysed. Our recommendation is based on the Ramsey–Gollier SRTP approach for longest available dataset, giving the value of 4.39%.

Considering the choice of the most appropriate proxy for the Social Discount Rate, we have "to avoid the trap of modelling what is easily quantifiable rather than what really matters" [46]. The value obtained in the study, although only slightly lower than the EU recommendations applied at present (5%), may have a substantial impact on the weight of delayed effects, as it increases the present value of EUR 1 spent in 30 years time from 0.23 to 0.28 of its future worth and from 0.09 to 0.12 for a 50-year delay. Considering the long-term perspective and substantial outlays anticipated in the area of energy investments (approx. EUR 50 billion until 2030), a careful estimation of the discount rate is needed more than ever.

Although the Ramsey–SRTP formula, we argue for, is far from being flawless, it offers several advantages over competing approaches. The most vital arguments in favour of choosing this approach are given below.

First, it offers a relatively stable-in-time estimate, not affected by the volatility of financial market rates, which is particularly important for the energy sector with long-time planning horizons and a weak correlation with market returns. Second, as Nesticò and Maselli [33] point out, "the SRTP provides a lower SDR value than that obtained with the SOC method. The first is therefore more advantageous for projects with long-term effects." The implications well suit energy policies, as their impacts reach decades rather than years. Third, while the CRI-SRTP approach provides even lower estimates, its applicability is dubious, as the saving offer has relatively short maturity dates. Since the Ramsey formula rests on growth predictions, it is not limited by a repayment perspective. Fourth, as observed by Feldstein [53] "the political process may be invoked because the market cannot express the 'collective' demand for investment to benefit the future." The additional argument, based on the longevity of energy policy impacts, is provided by their intergenerational character, where aggregated market preferences obviously omit not-born-yet individuals. The point made here applies to both SOC and CRI, supporting the leading role of the prescriptive method, designed to capture public (instead of private) choices.

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References

1. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. In *The European Green Deal*; European Commission: Brussels, Belgium, 2019.
2. IPCC Reports. Available online: https://www.ipcc.ch/reports/ (accessed on 7 December 2020).
3. *Polityka Energetyczna Polski Do Roku 2040*; Ministry of Climate and Environment: Warsaw, Poland, 2018.
4. *Krajowy Plan Na Rzecz Energii i Klimatu Na Lata 2021–2030*; Ministry of State Assets: Warsaw, Poland, 2019.
5. Global Carbon Atlas. Available online: http://www.globalcarbonatlas.org/en/content/welcome-carbon-atlas (accessed on 8 December 2020).
6. Renewable Energy: Twelve EU States Are Already Exceeding Their Targets for 2020. Available online: https://www.en-former.com/en/eurostat-renewable-energy-figures-goals/ (accessed on 8 December 2020).
7. European Statistical Office. Available online: https://ec.europa.eu/eurostat (accessed on 20 January 2021).
8. *Projekt Nowelizacji Ustawy o Efektywności Energetycznej z Dnia 20 Maja 2016*; Ministry of Climate and Environment: Warsaw, Poland, 2020.
9. Widuto, A.; Pernilla, J. *Just Transition Fund*; European Parliament: Brussels, Belgium, 2020.
10. Gawlikowska-Fyk, A.; Borkowski, M. *Jak Polska Może Osiągnąć Zwiększone Cele Redukcji Emisji Gazów Cieplarnianych Do 2030 Roku*; Forum Energii: Warsaw, Poland, 2020.

11. Lachowicz, M.; Gacki, M.; Moskwik, K. *Paliwa i Motory Wzrostu Gospodarczego. Wpływ Cen Surowców i Produkcji Energii Na Polskę*; Jagiellonian Institute: Warsaw, Poland, 2020.
12. *Wkład Polskiego Sektora Energetycznego w Realizację Globalnej Polityki Klimatycznej*; Polish Electricity Association: Warsaw, Poland, 2018.
13. Moore, M.A.; Boardman, A.E.; Vining, A.R.; Weimer, D.L.; Greenberg, D.H. "Just Give Me a Number!" Practical Values for the Social Discount Rate. *J. Policy Anal. Manag.* **2004**, *23*, 789–812. [CrossRef]
14. Lind, R.C.; Arrow, K.J.; Corey, G.R.; Dasgupta, P.; Sen, A.K.; Stauffer, T.; Stiglitz, J.E.; Stockfisch, J.A. *Discounting for Time and Risk in Energy Policy*; Routledge: New York, NY, USA, 2013; ISBN 1135985189.
15. Arrow, K.J. Discounting and Public Investment Criteria. In *Water Research*; Johns Hopkins Press: Baltimore, MA, USA, 1966; pp. 13–32.
16. Spackman, M. Social Discounting and the Cost of Public Funds: A Practitioner's Perspective. *J. Benefit-Cost Anal.* **2020**, *11*, 244–271. [CrossRef]
17. Zhuang, J.; Liang, Z.; Lin, T.; Guzman, F.D. *Theory and Practice in the Choice of Social Discount Rate for Cost-Benefit Analysis: A Survey*; Asian Development Bank (ADB): Manila, Philippines, 2007.
18. Florio, M. *Applied Welfare Economics: Cost-Benefit Analysis of Projects and Policies*; Routledge: New York, NY, USA, 2014; ISBN 1317814258.
19. Dasgupta, A.K.; Pearce, D.W. *Cost-Benefit Analysis: Theory and Practice*; Macmillan International Higher Education: New York, NY, USA, 1972; ISBN 1349154709.
20. Boardman, A.; Greenberg, D.; Vining, A.; Weimer, D.L. *Cost-Benefit Analysis*; Cambridge University Press: Cambridge, UK, 2018; ISBN 9781108401296.
21. Ramsey, F.P. A Mathematical Theory of Saving. *Econ. J.* **1928**, *38*, 543–559. [CrossRef]
22. Groom, B.; Maddison, D. New Estimates of the Elasticity of Marginal Utility for the UK. *Environ. Res. Econ.* **2019**, *72*, 1155–1182. [CrossRef]
23. Burgess, D.F.; Zerbe, R.O. Appropriate Discounting for Benefit-Cost Analysis. *J. Benefit-Cost Anal.* **2011**, *2*, 1–20. [CrossRef]
24. Poterba, J. *The Rate of Return to Corporate Capital and Factor Shares: New Estimates Using Revised National Income Accounts and Capital Stock Data*; National Bureau of Economic Research, Inc.: Cambridge, MA, USA, 1999.
25. Kuo, C.-Y.; Jenkins, G.P.; Mphahlele, M.B. The Economic Opportunity Cost of Capital in South Africa. *S. Afr. J. Econ.* **2003**, *71*, 523–543. [CrossRef]
26. Gollier, C. Time Horizon and the Discount Rate. *J. Econ. Theory* **2002**, *107*, 463–473. [CrossRef]
27. Weitzman, M.L. Why the Far-Distant Future Should Be Discounted at Its Lowest Possible Rate. *J. Environ. Econ. Manag.* **1998**, *36*, 201–208. [CrossRef]
28. Almansa, C.; Martínez-Paz, J.M. What Weight Should Be Assigned to Future Environmental Impacts? A Probabilistic Cost Benefit Analysis Using Recent Advances on Discounting. *Sci. Total Environ.* **2011**, *409*, 1305–1314. [CrossRef]
29. Drupp, M.A.; Freeman, M.C.; Groom, B.; Nesje, F. Discounting Disentangled. *Am. Econ. J. Econ. Policy* **2018**, *10*, 109–134. [CrossRef]
30. Cropper, M.L.; Aydede, S.K.; Portney, P.R. Preferences for Life Saving Programs: How the Public Discounts Time and Age. *J. Risk Uncertain.* **1994**, *8*, 243–265. [CrossRef]
31. Foltyn-Zarychta, M. *Ocena Inwestycji Międzypokoleniowych—Kryteria Etyczne w Ekonomicznej Ocenie Efektywności Projektów Inwestycyjnych*; C.H. Beck: Warsaw, Poland, 2018.
32. Evans, D.J. The Elasticity of Marginal Utility of Consumption: Estimates for 20 OECD Countries. *Fisc. Stud.* **2005**, *26*, 197–224. [CrossRef]
33. Nesticò, A.; Maselli, G. A Protocol for the Estimate of the Social Rate of Time Preference: The Case Studies of Italy and the USA. *J. Econ. Stud.* **2020**, *47*, 527–545. [CrossRef]
34. Evans, D.J.; Sezer, H. Social Discount Rates for Member Countries of the European Union. *J. Econ. Stud.* **2005**, *32*, 47–59. [CrossRef]
35. Cropper, M.L.; Freeman, M.C.; Groom, B.; Pizer, W.A. Declining Discount Rates. *Am. Econ. Rev.* **2014**, *104*, 538–543. [CrossRef]
36. Arrow, K.J.; Cropper, M.L.; Gollier, C.; Groom, B.; Heal, G.M.; Newell, R.G.; Nordhaus, W.D.; Pindyck, R.S.; Pizer, W.A.; Portney, P.R.; et al. Should Governments Use a Declining Discount Rate in Project Analysis? *Rev. Environ. Econ. Policy* **2014**, *8*, 145–163. [CrossRef]
37. Gollier, C.; Koundouri, P.; Pantelidis, T. Declining Discount Rates: Economic Justifications and Implications for Long-Run Policy. *Econ. Policy* **2008**, *23*, 758–795. [CrossRef]
38. European Commission. *Guide to Cost-Benefit Analysis of Investment Projects. Economic Appraisal Tool for Cohesion Policy 2014-2020*; European Commission: Brussels, Belgium, 2015.
39. *The Green Book Central Government Guidance on Appraisal and Evaluation 2020*; HM Treasury: London, UK, 2020.
40. *Guidelines for Preparing Economic Analyses*; U.S. Environmental Protection Agency: Washington, DC, USA, 2010.
41. Florio, M.; Sirtori, E. *The Social Cost of Capital: Recent Estimates for the EU Countries*; CSIL Centre for Industrial Studies: Milano, Italy, 2013.
42. Seçilmiş, E.; Akbulut, H. Social Discount Rates for Six Transition Countries. *Ekon. Cãsopis* **2019**, *67*, 629–646.
43. Saługa, P.W. Discount Rate Selection for Long-Term Sequential Mineral Projects. *Gospod. Surowcami Miner.* **2017**, *33*, 49–70. [CrossRef]

44. Peñalver, D.; Poudineh, R. Social Discount Rate and the Energy Transition Policy. *Energy Insights* **2020**, *75*, 1–13.
45. Steinbach, J.; Staniaszek, D. *Discount Rates in Energy System Analysis*; Buildings Performance Institute Europe: Brussels, Belgium, 2015.
46. Hermelink, A.H.; de Jager, D. *Evaluating Our Future. The Crucial Role of Discount Rates in European Commission Energy System Modelling*; The European Council for an Energy Efficient Economy & Ecofys: Stockholm, Sweden, 2015.
47. Stern, N. Welfare weights and the elasticity of the marginal valuation of income. In *Studies in Modern Economic Analysis: The proceedings of the Association of University Teachers of Economics, Edinburgh, 1976*; Basil Blackwell: Oxford, UK, 1977; ISBN 9780631179702.
48. Gollier, C. *Pricing the Planet's Future: The Economics of Discounting in an Uncertain World*; Princeton University Press: Princeton, NJ, USA, 2012; ISBN 9781400845408.
49. Burgess, D. *The Appropriate Measure of the Social Discount Rate and Its Role in the Analysis of Policies with Long-Run Consequences*; Mercatus Symposium; Mercatus Center at George Mason University: Arlington, TX, USA, 2018.
50. Harberger, A.C.; Jenkins, G.P. Musings on the Social Discount Rate. *J. Benefit-Cost Anal.* **2015**, *6*, 6–32. [CrossRef]
51. Baumol, W.J. On the Social Rate of Discount. *Am. Econ. Rev.* **1968**, *58*, 788–802.
52. Spackman, M. *Discount Rates and Rates of Return in the Public Sector: Economic Issues*; Government Economic Service Working Paper; HM Treasury: London, UK, 1991; Volume 113.
53. Feldstein, M.S. The Social Time Preference Discount Rate in Cost Benefit Analysis. *Econ. J.* **1964**, *74*, 360–379. [CrossRef]
54. Eckstein, O. A Survey of the Theory of Public Expenditure Criteria. In *Public Finances: Needs, Sources, and Utilization*; National Bureau of Economic Research, Inc.: Cambridge, MA, USA, 1961; pp. 439–504. ISBN 0870143034.
55. Parfit, D. *Reasons and Persons*; Oxford University Press: Oxford, UK; New York, NY, USA, 1986; ISBN 9780198249085.
56. Percoco, M. A Social Discount Rate for Italy. *Appl. Econ. Lett.* **2008**, *15*, 73–77. [CrossRef]
57. Kula, E. Estimation of a Social Rate of Interest for India. *J. Agric. Econ.* **2004**, *55*, 91–99. [CrossRef]
58. Kula, E. Derivation of Social Time Preference Rates for the United States and Canada. *Q. J. Econ.* **1984**, *99*, 873–882. [CrossRef]
59. Kula, E. Social Interest Rate for Public Sector Appraisal in the United Kingdom, the United States and Canada. *Proj. Apprais.* **1987**, *2*, 169–174. [CrossRef]
60. Helgeson, J.; Dietz, S.; Atkinson, G.; Hepburn, C.; Sælen, H. Siblings, Not Triplets: Social Preferences for Risk, Inequality and Time in Discounting Climate Change. *Economics* **2009**, *3*, 1–28. [CrossRef]
61. Cowell, F.A.; Gardiner, K. *Welfare Weights*; Office of Fair Trading: London, UK, 2000.
62. Pearce, D.; Atkinson, G.; Mourato, S. *Cost-Benefit Analysis and the Environment: Recent Developments*; OECD: Paris, France, 2006; ISBN 9264010041.
63. Public Debt—Ministry of Finance—Gov.Pl Website. Available online: https://www.gov.pl/web/finance/public-debt (accessed on 7 December 2020).
64. Federal Reserve Economic Data FRED St. Louis Fed. Available online: https://fred.stlouisfed.org/ (accessed on 7 December 2020).
65. Narodowy Bank Polski—Internet Information Service. Available online: https://www.nbp.pl/homen.aspx?f=/en/statystyka/monetary-and-financial-statistics.html (accessed on 7 December 2020).
66. Rzepińska, A. Opodatkowanie Dochodów z Kapitałów Pieniężnych w Polsce Jako Jedna z Istotnych Determinant Decyzji Gospodarczych Przedsiębiorcy. *Kryt. Prawa* **2013**, *5*, 243–264. [CrossRef]
67. Ustawa z Dnia 21 Listopada 2001 r. o Zmianie Ustawy o Podatku Dochodowym Od Osób Fizycznych Oraz Ustawy o Zryczałtowanym Podatku Dochodowym Od Niektórych Przychodów Osiąganych Przez Osoby Fizyczne (Dz.U. 2001 Nr 134 Poz. 1509). Available online: http://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20011341509/O/D20011509.pdf (accessed on 20 October 2020).
68. Ustawa z Dnia 12 Listopada 2003 r. o Zmianie Ustawy o Podatku Dochodowym Od Osób Fizycznych Oraz Niektórych Innych Ustaw (Dz.U. 2003 Nr 202 Poz. 1956). Available online: https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20032021956/O/D20031956.pdf (accessed on 20 October 2020).
69. Główny Rynek GPW—Rynek Główny. Available online: https://www.gpw.pl/ (accessed on 7 December 2020).
70. Główny Urząd Statystyczny. Available online: https://stat.gov.pl/ (accessed on 7 December 2020).
71. World Population Prospects—Population Division—United Nations. Available online: https://population.un.org/wpp/Download/Standard/Population/ (accessed on 7 December 2020).
72. OECD Tax Statistics. Available online: https://www.oecd-ilibrary.org/taxation/data/oecd-tax-statistics_tax-data-en (accessed on 7 December 2020).
73. Reed, H.; Dixon, M. National Insurance: Does It Have a Future? *Public Policy Res.* **2005**, *12*, 102–110. [CrossRef]
74. Sawulski, J. Kogo Obciążają Podatki w Polsce? *IBS Policy Pap.* **2019**, *1*, 1–11.
75. Kłos, B. Emerytury z Funduszu Ubezpieczeń Społecznych Przyznane w Latach 2009–2013. *Anal. BAS* **2015**, *3*, 1–12.
76. Akbulut, H.; Seçilmiş, E. Estimation of a Social Discount Rate for Turkey. *Socio-Econ. Plan. Sci.* **2019**, *67*, 78–85. [CrossRef]
77. Kelleher, J.P. Energy Policy and the Social Discount Rate. *Ethics Policy Environ.* **2012**, *15*, 45–50. [CrossRef]
78. Feldstein, M. Opportunity Cost Calculations in Cost-Benefit Analysis. *Public Financ.* **1964**, *19*, 117–139.
79. Rogowski, W.; Lipski, M. Oszczędności i Kredyty Polskich Gospodarstw Domowych. *Nauk. Ekon.* **2019**, *30*, 157–168. [CrossRef]
80. Newell, R.; Pizer, W. *Discounting the Benefits of Future Climate Change Mitigation*; EW Center on Global Climate Change: Washington, DC, USA, 2001.

81. Orr, S.W. Values, Preferences, and the Citizen-Consumer Distinction in Cost-Benefit Analysis. *Politics Philos. Econ.* **2007**, *6*, 107–130. [CrossRef]
82. Foltyn-Zarychta, M.; Zerbe, R. The Economics of CSR: The role of citizen-consumer mix in the social responsible investing. In *La Responsabilità Sociale D'impresa tra Diritto Societario e Diritto Internazionale*; Università degli Studi di Bari Aldo Moro: Bari, Italy, 2019; Volume 175, pp. 81–113. ISBN 9788849541052.
83. Nyborg, K. Homo Economicus and Homo Politicus: Interpretation and Aggregation of Environmental Values. *J. Econ. Behav. Organ.* **2000**, *42*, 305–322. [CrossRef]
84. Burgess, D.F.; Zerbe, R.O. The Most Appropriate Discount Rate. *J. Benefit-Cost Anal.* **2013**, *4*, 391–400. [CrossRef]
85. Jorgenson, D.W.; Vickrey, W.; Koopmans, T.C.; Samuelson, P.A. Discussion. *Am. Econ. Rev.* **1964**, *54*, 86–96.
86. *Metoda Określania Wskaźnika Zwrotu Kosztu Zaangażowanego Kapitału Dla Operatorów Systemów Elektroenergetycznych Na Lata 2016-2020*; Energy Regulatory Office: Warsaw, Poland, 2015.
87. *Koszt Kapitału Dla Operatorów Systemów Elektroenergetycznych Na Lata 2011–2015*; Energy Regulatory Office: Warsaw, Poland, 2010.
88. Harberger, A.C. *Project Evaluation. Collected Papers*; Macmillan: London, UK, 1972; ISBN 9781349016532.
89. Creedy, J.; Passi, H. Public Sector Discount Rates: A Comparison of Alternative Approaches. *Aust. Econ. Rev.* **2018**, *51*, 139–157. [CrossRef]
90. A Formula for Success: Reviewing the Social Discount Rate. Available online: https://www.oxera.com/agenda/a-formula-for-success-reviewing-the-social-discount-rate/ (accessed on 7 December 2020).
91. Addicott, E.T.; Fenichel, E.P.; Kotchen, M.J. Even the Representative Agent Must Die: Using Demographics to Inform Long-Term Social Discount Rates. *J. Assoc. Environ. Resour. Econ.* **2019**, *7*, 379–415. [CrossRef]
92. Gollier, C.; Mahul, O. Term Structure of Discount Rates: An International Perspective. Available online: https://www.ethz.ch/content/dam/ethz/special-interest/mtec/cer-eth/cer-eth-dam/documents/research/seminar/2017/Gollier.pdf (accessed on 7 December 2020).
93. He, X.; Wang, F.; Wallington, T.J.; Shen, W.; Melaina, M.W.; Kim, H.C.; Kleine, R.D.; Lin, T.; Zhang, S.; Keoleian, G.A.; et al. Well-to-Wheels Emissions, Costs, and Feedstock Potentials for Light-Duty Hydrogen Fuel Cell Vehicles in China in 2017 and 2030. *Renew. Sustain. Energy Rev.* **2021**, *137*, 110477. [CrossRef]
94. Steffen, B. Estimating the Cost of Capital for Renewable Energy Projects. *Energy Econ.* **2020**, *88*, 104783. [CrossRef]
95. *Renewable Energy Discount Rate Survey Results 2018*; Grant Thornton: London, UK, 2019.
96. Freeman, M.; Groom, B.; Spackman, M. *Social Discount Rates for Cost-Benefit Analysis: A Report for HM Treasury*; HM Treasury: London, UK, 2018.

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Article

“My Electricity” Program Effectiveness Supporting the Development of PV Installation in Poland

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Abstract: There are a lot of studies that show the legitimacy of subsidizing renewable energy; however, some mechanisms are defective, and there are problems with the appropriate allocation of funds. Therefore, this paper aims to look at the situation of allocating funds to photovoltaics (PV) micro-installations in Poland through the “My Electricity” program. The article presents the results of analyses aimed at identifying inequalities between provinces in the use of funds available under the “My Electricity” program and verifying whether these inequalities are getting worse and whether the intensity of support should not be territorially conditioned in terms of maximization an electricity production. As part of two editions of the “My Electricity” program (until 1 August 2020), over 64,000 PV micro-installations were created with an average power of approximately 5.7 kWp. The total installed PV capacity was 367.1 MWp (1st edition: 159.3 MWp, 2nd edition: 207.8 MWp). Financial resources (as a whole), in the second edition of “My Electricity” program, were distributed better than in the first edition. In the first edition, as much as 7.60% of funds were allocated inefficiently; in the second edition, it was only 3.88%. Allocation surpluses occur in provinces where the average disposable income is low and where there are a small number of households. There is a potential to introduce a territorial project selection criteria. The analysis shows that the criteria should promote provinces with higher disposable income and a larger number of households.

Keywords: photovoltaics; renewable energy sources; renewable energy; “My Electricity”; renewable energy policy; Poland; “Mój Prąd”; grant; renewable energy grants; renewable energy support

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1. Introduction

In climate policy, renewable energy has become the main contributor to mitigating climate change by reducing dependence on fossil fuels and carbon dioxide (CO_2) emissions. However, public policy aimed at supporting the production of energy from renewable sources (RES) has largely focused on encouraging investments in technologies using wind and solar resources, which has thus led to the recent increase in the capacity of installations supplied by these energy sources [1,2]. Moreover, many premises indicate that such a climate policy will be promoted in the future [3,4]. However, designing a renewable energy policy in an efficient, environmentally friendly, and socially equitable way requires an understanding of the impact of individual measures (support programs, subsidies, tax breaks, etc.) on the renewable energy market itself. Renewable energy growth in the energy mix usually has a twofold impact on the electricity market. Firstly, replacing conventional fossil technologies with generation from renewable sources leads to a reduction in CO_2 emissions in energy production (the so-called exchange effect). Secondly, there is a price effect by pushing producers with high marginal costs out of the market and a decline in the wholesale electricity price (which reduces the profits of energy producers using conventional energy technologies). Meanwhile, the consumers are in an ambivalent position—on the one hand, they can benefit from lower energy prices, and on the other hand, they face higher costs to the extent that renewable energy subsidies are refinanced by taxes. In the light of this, it seems extremely important to properly allocate aid funds in RES by specifying the criteria determining the intensity of support [2,5].

There is a lot of research about analyzing the policy support program for renewable electricity considering effective methods of promoting renewables, determining the intensity of support, and optimizing the distribution of financial support in relation to the effects they generate. For example, Nicolini and Tavoni [6], in their work, analyzed the influence of renewable energy support on promoting those technologies in France, Germany, Italy, the United Kingdom, and Spain, over the period 2000–2010. The analysis indicated that policy support positively affects the development of RES in the short and long term. However, in the short run, the feed-in tariff is more effective than the tradable green certificates mechanism in adopting renewable energy technologies. These studies are consistent with the results obtained by Dong [7], but his research focused only on the development of wind energy in Germany. Based on 92 renewable energy enterprises, Yang X. et al. [8] show that the government subsidies have a positive threshold effect on the level of investment in renewable energy in China. Their results show that Research & Development support and further technological changes are key factors in accelerating the widespread use of solar photovoltaics. The research showed that the tax incentives have a more significant impact on renewable energy investment than monetary subsidies. In addition, it has been shown that government subsidies are the main force supporting the development of medium, small, and micro renewable energy enterprises; therefore, it should focus on subsidizing these entities. Niesten et al. [9] research focuses on who uses support programs in renewable energy, based on the example of investments in onshore wind energy in the Netherlands. These analyses show the trends among people investing in wind energy as well as which mechanisms affect the size of investments and can indirectly be the starting point for activating individual groups of investors by creating financial support packages for their needs. Benalcazar et al. [10] analyzed the impact of different national support policies on renewable energy systems and hybrid micro-grid systems. The influence of weather conditions (wind speed and insolation) on the power of individual units of distributed generation was investigated. The authors showed that the final design of microgrid systems for electrifying rural areas depends on the amount of the capital subsidies as well as fuel prices variations. Lekavicius et al. [11] examine the impact of investment subsidies on the installation of renewable energy technologies that cover a large part of the investment costs in Lithuania and thus play an important role in household energy decisions. Although the analyzed support is energy-efficient, it increases social inequalities by promoting higher-income households. Thus, the subsidies spent in this way do not contribute to reducing the phenomenon of energy poverty due to the low investment capacity of the poorest households. A flat distribution of benefits could be achieved by considering the situation of households with lower income and taking into account other affordability issues. In addition, Kazak et al. [12] research shows that stimulating the energy transformation to create new and renovate existing renewable energy sources (RES) installations should be supported by allocating public financial support to achieve these goals. However, the results showed (for all sources) that there is no correlation between the high level of absorption of RES funds and the potential of energy production. The authors suggest that a similar study should be done in the context of each of the European Union member states. In contrast, the study by Bointner et al. [13] showed that the financing of renewable energy sources in the European Union takes place at the level of the Union (through the European Commission), as well as the member states themselves, with the latter spending more money on it. However, the European Commission allocates its funds more evenly between the various renewable energy sources than the member states themselves.

In light of greenhouse gas reduction, solar energy seems to be a very promising option [14,15] and (together with other renewable energy resources) has a key role in mitigation global warming by 1.5 °C [16,17]. However, the research shows numerous uncertainties and barriers connected with adopting solar technologies [18,19]. Considering only PV technologies, the most important hindrance is the financing of such installation and the uncertainty about the return on investment costs [14,20]. Vasseur and Kemp [21] showed that the perceived net cost of PV is strongly correlated with the choice to adopt (or not) of the technology that was analyzed. In addition, other studies showed that the cost is an important barrier to the adoption of PV installation and that some financial solutions provided by the government can lead to a significant increase in PV installations [22]. However, many solutions emphasize the importance of the optimal distribution of financing in relation to the effects they generate. Mundaca and Samahita [23] considered factors that influence the (non-)adoption of PV installation in the case of Sweden. The results show that both subsidies and peer effects are important factors influencing the likelihood of solar PV adoption. In addition, the work of Myojo and Ohashi [24] provided an empirical framework to assess the role of consumer subsidies in residential solar PV installations in Japan. Sue and Yoon [25] investigate how the subsidy policy influences the growth of investments in PV installations on the example of Korea. Their study shows that productivity growth is influenced by factors such as the total amount of the subsidy budget, interest rates, insolation, and land prices in each region. Interestingly, it has been shown that maximizing the installed capacity with the same subsidy budget is possible with the transition from a single subsidy for each region to a subsidized one depending on the characteristics of a given region. Balibrea-Iniesta [26] evaluated the subsidies production of electricity from photovoltaic installation with capacity greater than 100 kW installed in France. The evaluation shows that the subsidy budget should be increased to be able to develop large-scale installations. Sampedro et al. [27] show how the relocation of fossil fuel subsidies (FFS) to promote solar photovoltaics on the roof would reduce CO_2 emissions. It has been estimated that such action would reduce CO_2 emissions to 2.2% by 2030, and although this may not be the answer to all problems related to mitigating global warming, it can significantly contribute to promoting renewable energy and reducing environmental pollution without additional costs for the government (with only the transfer of funds from the FFS to RES). Torani K. et al. [28] in their work examined the prospects of solar photovoltaics (PV) in the residential and commercial sector in terms of the price of electricity and cost of solar. The developed stochastic dynamic model of adaptation solar PV showed that within 30 years, there will be a prevalent shift toward solar PV technologies both in residential and commercial sector. The result indicate that subsides and carbon price policies have little effect in accelerating adoption, and thus, an accelerating adoption may occur irrespective of these two factors.

Most of the studies discussed show the legitimacy of subsidizing renewable energy; however, some mechanisms are defective, and there are problems with the appropriate allocation of funds. Therefore, this paper aims to look at the situation of allocating funds to PV micro-installations in Poland. The article presents the results of analyses aimed at identifying inequalities between provinces in the use of funds available under the “My Electricity” program and verifying whether these inequalities are getting worse and whether the intensity of support should not be territorially conditioned, i.e., depend on the province where the project will be implemented.

Poland has average values of insolation in Europe, which in individual provinces are in the range from 900 to 1150 kWh/m^2/year (according to the Typical Meteorological Year) [29,30]. The differences in insolation occurring in individual provinces lead to a thesis that the share of projects located in southern voivodships should be greater than those located in northern Polish provinces, because the greater value of insolation makes the installation more energy-productive and economically effective. In this context, the question arises as to whether this issue should not determine the intensity of support. The economic efficiency of the installation is also influenced by its size, which is related to the effects of scale. Therefore, the power of the installation may also determine the intensity of support in addition to insolation (availability of solar energy). It is possible to estimate what the support intensity should be in individual voivodships in order to use the funds available under the "My Electricity" program most effectively. For this purpose, a mathematical model has been built, which has been used to optimize the use of subsidies financed under the "My Electricity" program. Figure 1 shows the annual insolation for each province and the total installed capacity in the "My Electricity" program until 1 August 2020 (according to the approved ranking lists).

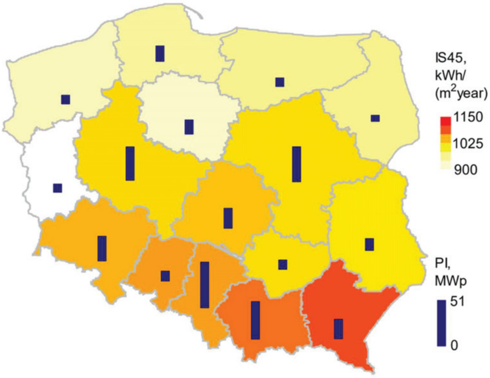


Figure 1. Insolation in Poland (for surface with tilt angle = 45° and south faced) and total photovoltaics (PV) installation power (Table 1. August 2020) [29,31].

Table 1. Average and standard deviation for PV installation power per province.

Province	Average PV Power, kWp			Standard Deviation, kWp	
	1st Edition	2nd Edition	1&2	1st Edition	2nd Edition
Lower Silesia	5.91	6.12	6.03	2.12	2.12
Kuyavian–Pomeranian	5.91	6.01	5.97	2.20	2.23
Lubelskie	5.35	5.28	5.32	2.03	2.05
Lubuskie	5.95	6.20	6.10	2.10	2.12
Łódzkie	5.96	6.08	6.02	2.18	2.21
Lesser Poland	5.40	5.60	5.52	1.84	1.89
Masowian	5.59	5.51	5.55	1.99	1.94
Opolskie	6.13	6.38	6.27	1.98	1.07
Podkarpackie	4.80	4.87	4.84	2.06	2.17
Podlaskie	5.32	5.39	5.35	1.62	1.63
Pomeranian	5.64	5.75	5.71	1.95	2.07
Silesian	5.66	5.75	5.71	2.05	2.17
Świętokrzyskie	5.08	5.15	5.11	2.01	2.06
Warmian–Masurian	5.63	5.90	5.79	1.91	2.04
Greater Poland	5.53	5.67	5.62	2.09	2.20
West Pomeranian	5.82	5.82	5.82	1.94	2.06

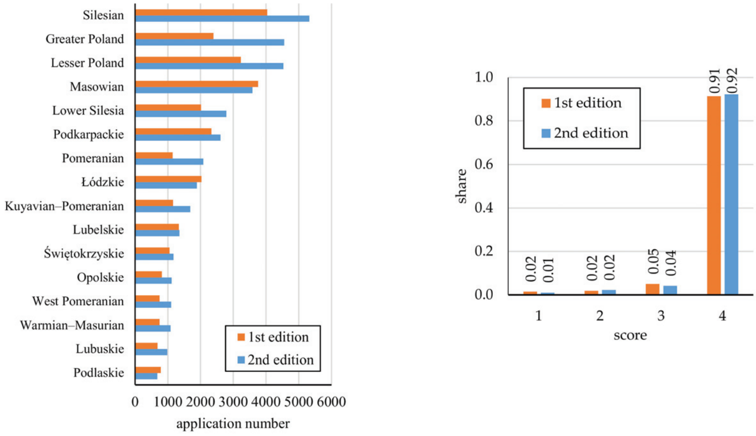
Color agenda: green—the highest value, red—the lower value. Source: own study.

The paper is structured as follows. In Section 2, the data about the subsidiary program "My Electricity" for co-financing photovoltaic micro-installation in households in Poland is presented. The data are collected for two editions of the "My Electricity" program and are given for different provinces in Poland. In addition, the data about the average yearly insolation for a 45° tilted surface south faced, average income in a household and the number of households in each of the voivodships is shown. Section 3 focuses on analysis and calculations, including the average power of PV installations and the average value of subsidies in each of the analysed provinces. In Section 4, an analysis of the subsidy program effectiveness is carried out in order to assess whether the funds transferred under the subsidy are optimally distributed in relation to the effects generated by the "My Electricity" program. For this purpose, data analyses have been carried out and a mathematical model has been built, using the statistical method of multiple regression allowing describing the covariance of several variables by fitting functions to them. The total power of PV installations (which received co-financing) in individual provinces has been assumed as the dependent variable. The explanatory variables have been the total number of households, the value of subsidies in the first edition of the "My Electricity" program, the average insolation, and the average disposable income in a household (analyzed at the province level). Additionally, the results of the analysis have been discussed. Finally, Section 5 discusses the economic and ecological implications of the "My Electricity" program on provinces in Poland, and conclusions are raised.

2. Data

The data available on the website of the PV micro-installations co-financing program "My Electricity" have been used for the purpose of this research (https://mojprad.gov.pl). The available data included the following information: name, surname, province, installation capacity (kWp), subsidy (PLN), rate (on a scale of 1 to 4 points).

In the first edition of the "My Electricity" program, there were 28,437 submitted and approved applications, and in the second edition, there were 35,914 applications (as of 1 August 2020). The summary of applications numbers divided into provinces and program editions is presented in Figure 2a.



(**a**) (**b**)

Figure 2. (**a**) Number of applications accepted in two editions of the "My Electricity" program (applications accepted until 1 August 2020) [31]; (**b**) Share of PV installations with a certain number of points among installations supported by both editions of the "My Electricity" program (applications accepted until 1 August 2020).

In both editions, the largest number of accepted applications came from the Silesian province. The lowest number of applications in the first edition was submitted in the Lubuskie province, and in the second edition, the lowest number of applications was submitted in the Podlasie province.

The information published as part of the ranking lists includes the number of points awarded depending on the installation unit price, which is expressed in PLN/kWp. When this price is lower than PLN 6000/kWp (1333 EUR/kWp, 1 EUR = 4.5 PLN), the evaluated application received 4 points. When the unit price was higher, a correspondingly smaller number of points were awarded (minimum 1). The vast majority (over 91%) of applications received 4 points—see Figure 2b.

The province with the highest score in the first edition was Opolskie: 3.91 (the average number of points awarded), and the province with the lowest province was Pomeranian: 3.79. In turn, in the second edition, the province with the highest average number of points awarded was Lubelskie with 3.92, and that with the lowest average number of points was Świętokrzyskie Province with 3.78. For both editions of the program, the Lubelskie province achieved the highest average number of points awarded: 3.91, and Pomeranian Province had the lowest: 3.80. Due to the over 90% share of applications with four points awarded, this issue was not analyzed in the following chapters. Some disproportions can be justified by the differences in the contracting price typical for each province [32], the size of the competition among assembly companies, as well as the size of installations expressed in kWp (Table 1).

The analysis is also based on the following data (for each province):

- Number of households, published by the Central Statistical Office [32].
- Average insolation as statistical climatic data for the area of Poland available on the archival website of the Ministry of Investment and Development [29].
- Value of disposable income published by the Central Statistical Office [33].

The numerical values for the above-mentioned data are presented in Table 2.

Table 2. The number of applications submitted in the second edition of the "My Electricity" program, the number of households (including in rural areas), the average insolation, and the value of disposable income in individual provinces.

Province	**No. of Households, Thousand**		**Number of Applications**	**IS45**	**DR**
	Total	**Rural**		**kWh/m^2/year**	**PLN/month**
Lower Silesia	1100	275	4804	1086.1	5311
Kuyavian–Pomeranian	729	239	2842	930.3	4641
Lubelskie	742	356	2694	1049.8	4602
Lubuskie	365	115	1655	891.9	4605
Łódzkie	944	282	3919	1074.2	4864
Lesser Poland	1080	454	7758	1130.5	5156
Masowian	1943	557	7346	1055.3	6159
Opolskie	354	147	1931	1101.4	4788
Podkarpackie	649	336	4941	1151.6	4463
Podlaskie	417	145	1455	974.8	4645
Pomeranian	806	224	3231	962.8	5290
Silesian	1728	315	9353	1098.4	5200
Świętokrzyskie	429	208	2223	1054.8	4529
Warmian–Masurian	516	182	1827	973.6	4376
Greater Poland	1129	418	6946	1057.3	4756
West Pomeranian	639	170	1852	942.8	4872
Poland	13,568	4421	64,777		

IS45—average yearly insolation for 45° tilted surface south faced. DR—average disposable income in a household in 2018. Source: own study based on [29,31–33].

3. Analysis and Calculations

The total installed PV capacity for both editions of the program was 367.1 MWp (1st edition: 159.3 MWp, 2nd edition: 207.8 MWp).

In both editions, the average PV installation power of 5.69 kWp was achieved (5.57 kWp in the first edition and 5.79 kWp in the second edition). The standard deviation for the data from the first edition has a value of 2.01 kWp, and that for the second edition has a value of 2.07 kWp. The curves presenting the occurrence of specific installations sizes for both editions and also the maximum unit grant amount are presented in Figure 3.

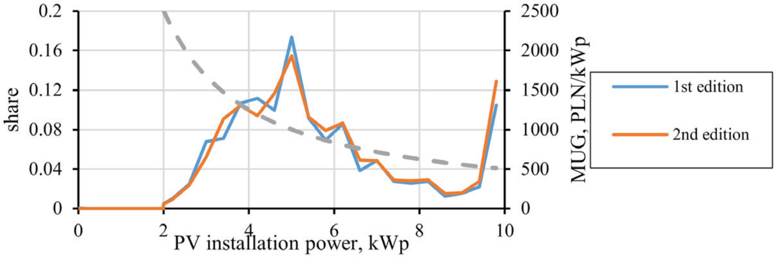


Figure 3. Share of PV installations of a certain capacity among installations installed in both editions of "My Electricity" program (applications accepted until 1 August 2020). MUG—maximum unit grant amount per kWp.

The average capacity for installations in the provinces scale are presented in Table 1. In total, PLN 323.45 million was spent under the program, which is 32% of the entire program budget, amounting to PLN 1 billion. The average subsidy to the kWp amounted to PLN 881. The results for individual provinces are presented in Table 3.

Table 3. The average value of the subsidy and standard deviations within the subsidy to kWp.

Province	Average Unit Value of the Subsidy PLN/kWp			Standard Deviation, PLN/kWp	
	1st Edition	2nd Edition	1&2	1st Edition	2nd Edition
Lower Silesia	839.4	816.6	826.0	334.8	347.4
Kuyavian–Pomeranian	836.6	830.4	832.9	361.5	382.7
Lubelskie	924.4	945.4	934.9	387.8	381.0
Lubuskie	834.4	805.3	816.9	321.8	345.1
Łódzkie	831.5	820.3	826.0	351.9	361.2
Lesser Poland	922.3	891.8	904.2	324.5	333.6
Masowian	887.7	906.6	896.9	344.6	355.5
Opolskie	810.3	783.6	794.7	318.4	315.4
Podkarpackie	1 032.5	1 023.6	1 027.7	340.1	362.2
Podlaskie	927.0	928.3	927.6	377.1	377.3
Pomeranian	873.3	867.7	869.6	370.0	353.9
Silesian	878.5	869.1	873.2	351.5	347.3
Świętokrzyskie	974.8	970.0	972.3	388.5	391.0
Warmian–Masurian	876.8	845.8	858.1	362.4	378.8
Greater Poland	893.6	880.0	884.6	354.1	346.8
West Pomeranian	847.4	858.9	854.2	356.1	340.7

Color agenda: green—the highest value, red—the lower value. Source: own study.

As shown in Table 3, the highest average subsidies to power (expressed in kWp) were in Podkarpackie province and the lowest were in the Opolskie province. The difference in values of the unit subsidy between these provinces is over PLN 200/kWp, which is more than 20% of the average subsidy in the whole country. These differences are mainly due to the average installed capacity under the program in provinces (Table 1) and the maximum amount of the subsidy, which is PLN 5000 (Figure 3—MUG).

Similarly to the presented conclusions from the work of Olczak et al. [34], the relationship between the installed capacity and the number of provinces residents has been presented—see Figure 4.

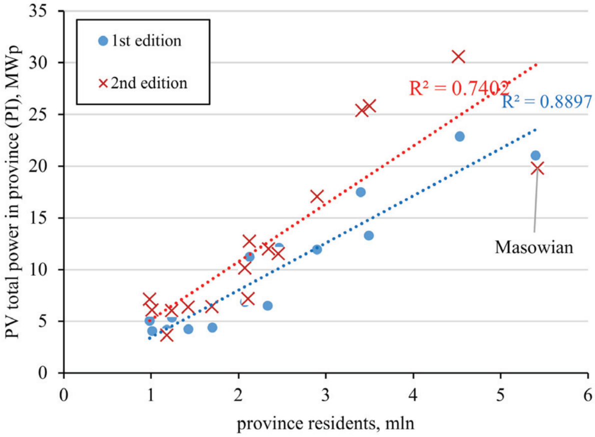


Figure 4. Dependence of installed capacity in the province on the number of residents in the province in both editions of the "My Electricity" program (applications accepted until 1 August 2020) [31].

The value of the R^2 coefficient (Figure 4) for second edition is much higher, without taking into account the Masowian province (point 5.42 million; 19.77 MWp in Figure 4), which is 0.91. In case of the first edition, eliminating from the calculation of the R^2 coefficient the above-mentioned province practically does not change the result. Due to the high correlation shown in Figure 4, the power index expressed in *Wp* per resident (*PPI*) [7] was calculated according to the formula below. The results are listed in Table 4.

$$PPI(prov.) = \frac{PI(prov.)}{LM(prov.)}, \ \frac{Wp}{inhab.} \tag{1}$$

where

PI—power of installations installed in the province;
L—number of residents in the province.

Table 4. Results of calculations of the PPI index (PV power per resident) for each province.

Province	**PPI, Wp/inhab.**		
	1st Edition	**2nd Edition**	**1&2**
Lower Silesia	4.11	5.88	9.99
Kuyavian–Pomeranian	3.29	4.89	8.18
Lubelskie	3.38	3.40	6.78
Lubuskie	4.06	5.99	10.05
Łódzkie	4.91	4.69	9.60
Lesser Poland	5.40	7.44	12.84
Masowian	3.89	3.65	7.53
Opolskie	5.08	7.22	12.30
Podkarpackie	5.26	5.98	11.24
Podlaskie	3.52	3.08	6.60
Pomeranian	2.77	5.12	7.89
Silesian	5.04	6.77	11.81
Świętokrzyskie	4.30	4.89	9.19
Warmian–Masurian	2.95	4.47	7.42
Greater Poland	3.79	7.38	11.17
West Pomeranian	2.56	3.78	6.35
Poland	4.12	5.41	9.54

Color agenda: green—the highest value, red—the lower value. Source: own study.

Then, the number of applications (PV installations created under the "My Electricity" program) per 1000 households (Table 5) was calculated, as well as the installed capacity per household (*PPH*) and per one rural household (*PPHC*):

$$PPH(prov.) = \frac{PI(prov.)}{LG(prov.)}, \frac{Wp}{household} \tag{2}$$

where

LG—the number of households in the province.

$$PPHC(prov.) = \frac{PI(prov.)}{LGW(prov.)}, \frac{Wp}{rural\ household\ .} \tag{3}$$

where

LGW—number of rural households in the province.

Table 5. Comparison of the number of applications with the number of households in the province.

Province	No. Applications/1000 Households	No. Applications/1000 Rural Households	PPH	PPHC
			Wp/Households.	Wp/Rural Households
Lower Silesia	4.4	17.5	26.4	105.3
Kuyavian–Pomeranian	3.9	11.9	23.3	71.0
Lubelskie	3.6	7.6	19.3	40.2
Lubuskie	4.5	14.4	27.9	88.6
Łódzkie	4.2	13.9	25.0	83.8
Lesser Poland	7.2	17.1	40.5	96.4
Masowian	3.8	13.2	21.0	73.2
Opolskie	5.5	13.2	34.2	82.6
Podkarpackie	7.6	14.7	36.9	71.3
Podlaskie	3.5	10.0	18.7	53.7
Pomeranian	4.0	14.5	22.9	82.6
Silesian	5.4	29.7	30.9	169.7
Świętokrzyskie	5.2	10.7	26.5	54.6
Warmian–Masurian	3.5	10.1	20.5	58.2
Greater Poland	6.2	16.6	34.6	93.4
West Pomeranian	2.9	10.9	16.9	63.6
Poland	4.8	14.7	27.0	82.8

Color agenda: green—the highest value, red—the lower value. Source: own study.

The lowest ratio of the installations number per 1000 households (PPH) has been achieved in the West Pomeranian province, which is 2.9, and the highest was in the Podkarpackie province, which is 7.6; nationwide, it is 4.8. Taking into account rural households, the lowest rate was achieved in the Lublin province, which is 7.6, and the highest was in the Silesian province, which is 29.7. The highest PPH index was achieved for the Lesser Poland province and the lowest was achieved for the West Pomeranian province. In turn, in the case of the PPHC indicator: the maximum was in the Silesian province, 169.7, and the lowest was in the Lublin province: 40.2.

4. Analysis of the Effectiveness of the Subsidy Program

4.1. Analysis

In order to assess whether the funds transferred as part of the subsidy are optimally distributed in relation to the effects generated by the "My Electricity" program, data analysis was carried out, and a mathematical model was built. For this purpose, the statistical method of multiple regression was used, allowing describing the covariance of several variables by fitting functions to them. The dependent variable was the sum of the capacity of PV installations (which received co-financing) in individual provinces. The explanatory variables were: the sum of the subsidies value in the first edition of the "My Electricity" program, the average value of a subsidy per household, the average insolation, and the average disposable income in a household. Values for the explanatory variables and the dependent variable were registered at the province level.

The collinearity of explanatory variables was examined. The results are shown in Figure 5. The collinearity of the variables was not found. The values of the Variance Inflation Factor (VIF) indicators for all analyzed variables are below 6. Due to the transformations of the variables used to build the model, structural multicollinearity was observed, but it does not affect the quality of forecasting the value of the explained variable, which is crucial for this work. Structural multicollinearity is important for the interpretation of model parameters; however, this issue has no significance for the research problem being solved.

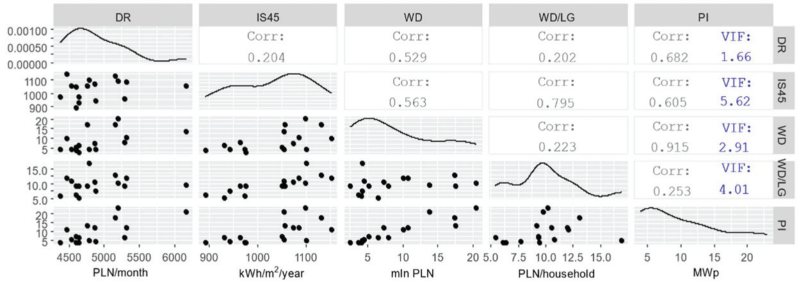


Figure 5. Correlation and collinearity of explanatory variables. VIF—Variance Inflation Factor.

Backward stepwise regression technique was used. The parameters for the model meeting the conditions of linear regression analysis are presented in Table 6. Table 7 presents the expected values of the dependent variable (installed capacity in individual provinces) and the values of the residual component.

Table 6. Regression model statistics.

Variable	Coefficient	Standard Error	t Stat	p-Value	Lower 95%	Upper 95%
Intercept	8255.22	1783.39	4.63	0.001238	4220.92	12,289.52
DR IS45	−0.002091	0.000538	−3.887968	0.003686	−0.003307	−0.000874
WD IS45	1.963×10^{-6}	2.171×10^{-7}	9.045	8.195×10^{-6}	1.472×10^{-6}	2.455×10^{-6}
WD WD/LG	-4.030×10^{-8}	1033×10^{-8}	−3.902	3.610×10^{-3}	-6.366×10^{-8}	-1.693×10^{-8}
IS45 WD/LG	−0.001691	0.000305	−5.537807	0.000362	−0.002382	−0.001000
DR IS45 WD	-1.086×10^{-10}	3.164×10^{-11}	−3.432	7.487×10^{-3}	-1.802×10^{-10}	-3.701×10^{-11}
DR IS45 WD/LG	4.031×10^{-7}	7.869×10^{-8}	5.122	6.261×10^{-4}	2.251×10^{-7}	5.811×10^{-7}
	df	SS	MS	F	F materiality level	
Regression	6	586,011,923	97,668,654	1233.42	1.3534×10^{-12}	
Residual	9	712,670	79,186			
Total	15	586,724,592				
Regression Statistics						
R multiples	0.9994					
R square	0.9988					
Adjusted R-squared	0.9980					
Standard error	281.40					
Trials	16					

Where: *LG*—total number of households (in thousands); *WD*—the sum of the subsidies in the first edition of "My Electricity" program (PLN); *IS45*—average insolation calculated on a plane inclined to the horizontal at an angle of 45° to the south (kWh/m^2/year); *DR*—average disposable income in a household in 2018 (PLN/month). Source: own study.

Table 7. Predicted and residual values.

Observation	Province	Predicted Power of PV Installation, kWp	Residual Values
1	Lower Silesia	12,035.86	−120.56
2	Kuyavian–Pomeranian	6496.75	340.33
3	Lubelskie	7486.66	−319.94
4	Lubuskie	4168.02	−52.06
5	Łódzkie	11,589.85	509.02
6	Lesser Poland	18,457.67	−87.28
7	Masowian	20,940.80	58.89
8	Opolskie	4826.05	184.31
9	Podkarpackie	11,105.44	86.00
10	Podlaskie	4464.94	−309.10
11	Pomeranian	6541.13	−73.42
12	Silesian	22,910.45	−80.00
13	Świętokrzyskie	5520.53	−183.52
14	Warmian–Masurian	4140.21	71.45
15	Greater Poland	13,352.24	−110.21
16	West Pomeranian	4275.45	86.10
Sum		158,312.04	0.00

Color agenda: green—the highest value, red—the lower value. Source: own study.

The obtained results indicate that the constructed linear regression equation for the sum of installed PV power is correct because of the following:

(1) All explanatory variables were correctly captured in the linear regression model because the *p*-value of the Student’s *t*-test for these variables was less than the significance level of 0.05.

(2) The *p*-value of the F test calculated for the linear regression model was 1.3534×10^{-12}, and it is less than the significance level of 0.05.

(3) The alignment factor R^2 was 0.9994, which is very high, and it can be interpreted as follows: the exploitation factor a was almost 100% as explained by the explanatory variables.

In addition, all formal requirements for classical linear regression analysis have been met:

(1) Explanatory variables are exogenous, which means that the values of the random term are not a function of the explanatory variables of the linear regression equation.

(2) There is a linear relationship between the explanatory variables and the dependent variable.

(3) The number of observations n is greater than the number of structural parameters of the regression equation.

(4) Explanatory variables are non-random.

(5) The expected value of the random component is zero (Table 7).

(6) Values of the random component have a distribution close to the normal distribution N (0, σ), which has been confirmed by the Shapiro–Wilk statistical test, for residuals W = 0.94051, *p*-value = 0.3553.

Knowing the power of PV installations in the province and the average annual insolation, it is possible to determine the theoretical annual electricity production.

The model has been used to determine the value of the subsidy for each province, which with a given value of subsidy (the sum of subsidies for the first edition of “My Electricity” program equal to 140 million PLN) will maximize the total value of the theoretical annual electricity production. In this way, it was determined how optimally the subsidy should be distributed to individual provinces, which thus provides grounds for determining the territorial criteria for selecting projects for co-financing under the “My Electricity” program.

4.2. Discussion of the Analysis Results

The results of the analysis indicate that it is possible to improve the efficiency of using funds under the "My Electricity" program. The optimal distribution of subsidies allows increasing the theoretical (average annual) electricity production by 1.68% (first edition) and 3.26% (second edition).

Table 8 presents the value of subsidies for each province under the first and second editions of the "My Electricity" program. Table 9 presents the amount of subsidies for optimal variants (while maintaining the theoretical electricity production at the same level).

Table 8. The amount of the subsidy (WD), PLN.

Province	1st Edition	2nd Edition
Lower Silesia	10,001,972	13,933,500
Kuyavian–Pomeranian	5,719,621	8,413,577
Lubelskie	6,624,871	6,769,633
Lubuskie	3,365,275	4,879,917
Łódzkie	10,043,978	9,447,032
Lesser Poland	16,086,613	22,621,446
Masowian	18,640,837	17,930,030
Opolskie	4,060,058	5,561,416
Podkarpackie	11,555,170	13,021,064
Podlaskie	3,852,511	3,369,764
Pomeranian	5,647,971	10,403,653
Silesian	20,057,216	26,580,026
Świętokrzyskie	5,202,406	5,849,303
Warmian–Masurian	3,692,589	5,383,188
Greater Poland	11,833,316	22,712,726
West Pomeranian	3,696,053	5,509,597
Sum	140,080,457	182,385,872

Color agenda: green—the highest value, red—the lower value. Source: own study.

Table 9. The size of the subsidy calculated for optimal variants, PLN.

Province	Optimal Variant for 1st Edition	Optimal Variant for 2nd Edition
Lower Silesia	13,402,642	17,138,203
Kuyavian–Pomeranian	4,118,127	5,132,281
Lubelskie	7,088,612	9,003,611
Lubuskie	2,389,345	3,025,548
Łódzkie	10,144,416	12,942,433
Lesser Poland	14,156,216	18,323,371
Masowian	19,200,057	24,564,138
Opolskie	6,090,087	7,785,982
Podkarpackie	7,857,514	10,156,430
Podlaskie	3,929,561	5,088,344
Pomeranian	7,737,720	9,779,434
Silesian	17,850,917	22,858,816
Świętokrzyskie	4,682,165	6,024,782
Warmian–Masurian	3,249,478	4,091,223
Greater Poland	10,413,316	13,400,508
West Pomeranian	5,063,593	6,391,132
Sum	137,373,767	175,706,238

Color agenda: green—the highest value, red—the lower value. Source: own study.

The analysis proved that it is possible to maintain the theoretical electricity production at the same level with a lower total value of the subsidy. In case of the first edition of the "My Electricity" program, it was possible to achieve the same theoretical electricity production with the subsidy value lower by 1.93%, and in the second edition, it was possible with the value lower by 3.66%. So, the funds in the second edition of the "My Electricity" program were distributed less effectively than those in the first edition.

When analyzing individual provinces in terms of the optimal level of subsidies, it was found that in case of first edition, the subsidy deficit (at the level of 7.20% of the total value of subsidies for edition 1) occurred in eight provinces. However, in the case of the second edition, the deficit of subsidies (at the level of 11.28% of the total value of subsidies for second edition) occurred in eight provinces. The surplus and deficits of subsidies in individual provinces are presented in Tables 10 and 11.

Table 10. Surpluses (positive value) and deficits (negative value) in subsidizing individual provinces, percentage. Value calculated in relation to the value of subsidies for individual provinces.

Province	1st Edition	2nd Edition
Lower Silesia	34	23
Kuyavian–Pomeranian	−28	−39
Lubelskie	7	33
Lubuskie	−29	−38
Łódzkie	1	37
Lesser Poland	−12	−19
Masowian	3	37
Opolskie	50	40
Podkarpackie	−32	−22
Podlaskie	2	51
Pomeranian	37	−6
Silesian	−11	−14
Świętokrzyskie	−10	3
Warmian–Masurian	−12	−24
Greater Poland	−12	−41
West Pomeranian	37	16

Color agenda: green—the highest value, red—the lower value. Source: own study.

Table 11. Surpluses (positive value) and deficits (negative value) in subsidizing individual provinces, percentage. The value is calculated in relation to the total value of the subsidy (total for Poland).

Province	1st Edition	2nd Edition
Lower Silesia	−2.43	−1.76
Kuyavian–Pomeranian	1.14	1.8
Lubelskie	−0.33	−1.22
Lubuskie	0.7	1.02
Łódzkie	−0.07	−1.92
Lesser Poland	1.38	2.36
Masowian	−0.4	−3.64
Opolskie	−1.45	−1.22
Podkarpackie	2.64	1.57
Podlaskie	−0.06	−0.94
Pomeranian	−1.49	0.34
Silesian	1.58	2.04
Świętokrzyskie	0.37	−0.1
Warmian–Masurian	0.32	0.71
Greater Poland	1.01	5.11
West Pomeranian	−0.98	−0.48

Color agenda: green—the highest value, red—the lower value. Source: own study.

The total value of the surplus subsidies in the first edition was 9.13% of the total value of the subsidy allocated in the first edition. In the case of the second edition, this surplus was 14.94%. These values can be equated with monetary value, which were incorrectly/ineffectively distributed. In case of the second edition, the inequality in the distribution of funds between provinces slightly increased compared to the first edition, as measured by the Herfindahl–Hirschman index (HHI). For the data from the first edition, the HHI index amounted 0.0861, and for the second edition, it was 0.0870. The HHI value for the optimal cash distribution in the first edition amounts 0.0839, and in the second one, it was 0.0842. Therefore, the optimal distribution of subsidies between provinces should be more uneven than it was in both editions.

Correlation analysis showed that the values of surpluses and deficits correlate with the value of the average disposable (DR) income in individual provinces and subsidies value (WD) and average value of a subsidy per household (WD/LG) (Table 12).

Table 12. Values of correlation coefficients of subsidies surpluses/deficits in individual provinces and disposable income, the number of households and insolation, average value of a subsidy per household.

Parameter	1st Edition	2nd Edition
DR—average disposable income in a household	−0.35	−0.40
IS45—Insolation	0.20	0.01
WD—Subsidies value	0.36	0.43
LG—Number of households	0.08	−0.06
WD/LG—Average value of a subsidy per household	−0.19	−0.20

Source: own study.

Allocation surpluses occur in provinces where the average disposable income is low, and deficits where the average income value is high. The situation is similar in the case of an average value of a subsidy per household: allocation surpluses occur in provinces with a low-value subsidy per household, and deficits occur with a large-value subsidy per household. The value of insolation (IS45) and number of households (LG) is very slightly correlated with surpluses/deficits of subsidies. It is also worth noting that allocation surpluses occur in voivodships where the amount of the subsidy granted was high. It is characteristic that in the second edition of the "My Electricity" program, the above-mentioned correlations increased. This may indicate the saturation of the household sector with photovoltaic installations (an increase in the correlation coefficient for subsidies value (WD)), which means that less and less effective investments are undertaken (perhaps smaller and worse located). Thus, the importance of parameters such as average disposable income in a household is growing. Conclusions that can be drawn on this basis indicate that it would be reasonable to introduce a territorial project selection criterion that would allow increasing the allocation level in provinces with higher disposable income and in voivodships where the average value of a subsidy per household is high. Households with a higher value of disposable income invest in installations with a greater capacity, thanks to which the subsidy is better used due to the positive economies of scale, which is decreasing unit costs of purchasing PV installations along with the increase in the capacity of PV installations. Although the average value of subsidies per household (WD/LG) is poorly correlated with subsidies surpluses/deficits in individual provinces (the value of the correlation coefficient is around −0.2), the nature of this relationship is surprising and difficult to explain. It most probably results from social conditions (education, imitation, territorial, and social segmentation), which cause the "snowball effect". This issue requires in-depth research.

5. Summary

As part of two editions of the "My Electricity" program (until 1 August 2020), over 64,000 PV micro-installations were created, with an average power of approximately 5.7 kWp. The total installed PV capacity was 367.1 MWp (1st edition: 159.3 MWp. 2nd edition: 207.8 MWp).

The highest subsidies to the kWp were achieved in the Podkarpackie province with practically the highest productivity (which brings additional benefits for the household). On the one hand, every PLN spent in the Podkarpackie province contributes to higher ecological and economic effects than, for example, in the northern provinces. This work has shown that a different way of distributing the subsidy (other criteria) would contribute to the same effects in terms of energy productivity, generating savings in the form of PLN 2.7 million in the case of the first edition and PLN 6.7 million in the case of the second edition of the program.

Financial resources (as a whole) in the second edition of the "My Electricity" program were distributed worse than in the first edition. In the first edition, as much as 1.93% of funds were allocated inefficiently; in the second edition, it was only 3.66%. However, if we analyze and compare each province, the inequality in the allocation of funds in the second edition increased in comparison to the first edition.

Allocation surpluses occur in provinces where the average disposable income is low and where there is a high value of subsidies per household.

There is a potential to introduce a territorial project selection criteria. The analysis shows that the criteria should promote provinces with higher disposable income and high-value household subsidies. However, the significance of the latter parameter should be clearly explained. The "My Electricity" program is coming to an end. In the future, research should be planned to take into account of the complete data for both editions of the program. Moreover, the research should be extended to the analysis of the optimal allocation of subsidies from the point of view of various parties, i.e., applicants, the state, and the society. The research results may be helpful in designing a new PV technology support program (in 2021).

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Abbreviations

DR	average disposable income in a household in 2018, PLN/month
HHI	Herfindahl–Hirschman index
IS45	average yearly insolation for 45° tilted surface south faced, kWh/m^2/year
LG	number of households in the province
LGW	number of rural households in the province
LM	number of residents in the province
MUG	maximum unit grant amount per kWp, PLN/kWp
PI	total sum of PV power in province, MWp
PLN	Polish monetary unit
PPH	installed capacity per household, Wp/household
PPHC	installed capacity per rural household, Wp/rural household
PPI	the power index expressed in Wp per resident, Wp/inhab.
Prov.	province
PV	photovoltaic
VIF	Variance Inflation Factor
WD	sum of the subsidies in the first edition of "My Electricity" program, PLN

References

1. REN21 Renewables 2018 Global Status Report (Paris: REN21 Secretariat). Available online: http://www.ren21.net/gsr-2018/ (accessed on 12 November 2020).
2. Abrell, J.; Kosch, M.; Rausch, S. Carbon abatement with renewables: Evaluating wind and solar subsidies in Germany and Spain. *J. Public Econ.* **2019**, *169*, 172–202. [CrossRef]
3. Fischer, C.; Newell, R.G. Environmental and technology policies for climate mitigation. *J. Environ. Econ. Manag.* **2008**, *55*, 142–162. [CrossRef]
4. Meckling, J.; Sterner, T.; Wagner, G. Policy sequencing toward decarbonization. *Nat. Energy* **2017**, *2*, 918–922. [CrossRef]
5. Abrell, J.; Rausch, S.; Streitberger, C. The economics of renewable energy support. *J. Public Econ.* **2019**, *176*, 94–117. [CrossRef]
6. Nicolini, M.; Tavoni, M. Are renewable energy subsidies effective? Evidence from Europe. *Renew. Sustain. Energy Rev.* **2017**, *74*, 412–423. [CrossRef]

7. Dong, C.G. Feed-in tariff vs. renewable portfolio standard: An empirical test of their relative effectiveness in promoting wind capacity development. *Energy Policy* **2012**, *42*, 476–485. [CrossRef]
8. Yang, X.; He, L.; Xia, Y.; Chen, Y. Effect of government subsidies on renewable energy investments: The threshold effect. *Energy Policy* **2019**, *132*, 156–166. [CrossRef]
9. Niesten, E.; Jolink, A.; Chappin, M. Investments in the Dutch onshore wind energy industry: A review of investor profiles and the impact of renewable energy subsidies. *Renew. Sustain. Energy Rev.* **2018**, *81*, 2519–2525. [CrossRef]
10. Benalcazar, P.; Suski, A.; Kamiński, J. The Effects of Capital and Energy Subsidies on the Optimal Design of Microgrid Systems. *Energies* **2020**, *13*, 955. [CrossRef]
11. Lekavičius, V.; Bobinaitė, V.; Galinis, A.; Pažėraitė, A. Distributional impacts of investment subsidies for residential energy technologies. *Renew. Sustain. Energy Rev.* **2020**, *130*, 109961. [CrossRef]
12. Kazak, J.K.; Kamińska, J.A.; Madej, R.; Bochenkiewicz, M. Where renewable energy sources funds are invested? spatial analysis of energy production potential and public support. *Energies* **2020**, *13*, 5551. [CrossRef]
13. Bointner, R.; Pezzutto, S.; Grilli, G.; Sparber, W. Financing innovations for the renewable energy transition in Europe. *Energies* **2016**, *9*, 990. [CrossRef]
14. Mitchell, C.; Sawin, J.L.; Pokharel, G.R.; Kammen, D.; Wang, Z.; Fifita, S.; Jaccard, M.; Langniss, O.; Lucas, H.; Nadai, A.; et al. Policy, Financing and Implementation. In *Renewable Energy Sources and Climate Change Mitigation*; Cambridge University Press: Cambridge, UK, 2011.
15. Jacobson, M.Z.; Delucchi, M.A.; Bauer, Z.A.F.; Goodman, S.C.; Chapman, W.E.; Cameron, M.A.; Bozonnat, C.; Chobadi, L.; Clonts, H.A.; Enevoldsen, P.; et al. 100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World. *Joule* **2017**, *1*, 108–121. [CrossRef]
16. Arvizu, D.; Bruckner, T.; Chum, H.; Edenhofer, O.; Pichs-Madruga, R.; Sokona, Y.; Seyboth, K.; Eickemeier, P.; Matschoss, P.; Hansen, G.; et al. IPCC, 2011: Summary for Policymakers. In *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*; IPCC: Geneva, Switzerland, 2011; ISBN 9789291691319.
17. Canales, F.A.; Jadwiszczak, P.; Jurasz, J.; Wdowikowski, M.; Ciapała, B.; Kaźmierczak, B. The impact of long-term changes in air temperature on renewable energy in Poland. *Sci. Total Environ.* **2020**, *729*, 138965. [CrossRef]
18. Rai, V.; Reeves, D.C.; Margolis, R. Overcoming barriers and uncertainties in the adoption of residential solar PV. *Renew. Energy* **2016**, *89*, 498–505. [CrossRef]
19. Sahu, B.K. A study on global solar PV energy developments and policies with special focus on the top ten solar PV power producing countries. *Renew. Sustain. Energy Rev.* **2015**, *43*, 621–634. [CrossRef]
20. Zelazna, A.; Gołębiowska, J.; Zdyb, A.; Pawłowski, A. A hybrid vs. on-grid photovoltaic system: Multicriteria analysis of environmental, economic, and technical aspects in life cycle perspective. *Energies* **2020**, *15*, 3978. [CrossRef]
21. Vasseur, V.; Kemp, R. The adoption of PV in the Netherlands: A statistical analysis of adoption factors. *Renew. Sustain. Energy Rev.* **2015**, *41*, 483–494. [CrossRef]
22. Faiers, A.; Neame, C. Consumer attitudes towards domestic solar power systems. *Energy Policy* **2006**, *34*, 1797–1806. [CrossRef]
23. Mundaca, L.; Samahita, M. What drives home solar PV uptake? Subsidies, peer effects and visibility in Sweden. *Energy Res. Soc. Sci.* **2020**, *60*, 101319. [CrossRef]
24. Myojo, S.; Ohashi, H. Effects of consumer subsidies for renewable energy on industry growth and social welfare: The case of solar photovoltaic systems in Japan. *J. Jpn. Int. Econ.* **2018**, *48*, 55–67. [CrossRef]
25. Suh, J.; Yoon, S.G. Maximizing solar PV dissemination under differential subsidy policy across regions. *Energies* **2020**, *13*, 2763. [CrossRef]
26. Balibrea-Iniesta, J. Economic analysis of renewable energy regulation in France: A case study for photovoltaic plants based on real options. *Energies* **2020**, *13*, 2760. [CrossRef]
27. Sampedro, J.; Arto, I.; González-Eguino, M. Implications of switching fossil fuel subsidies to solar: A case study for the European Union. *Sustainability* **2017**, *10*, 50. [CrossRef]
28. Torani, K.; Rausser, G.; Zilberman, D. Innovation subsidies versus consumer subsidies: A real options analysis of solar energy. *Energy Policy* **2016**, *92*, 255–269. [CrossRef]
29. Ministry of Development Typical Reference Year. Available online: https://www.gov.pl/web/fundusze-regiony/dane-do-obliczen-energetycznych-budynkow (accessed on 18 December 2019).
30. Olczak, P.; Matuszewska, D.; Zabagło, J. The Comparison of Solar Energy Gaining Effectiveness between Flat Plate Collectors and Evacuated Tube Collectors with Heat Pipe: Case Study. *Energies* **2020**, *13*, 1829. [CrossRef]
31. NFOŚiGW Mój Prąd. Available online: https://mojprad.gov.pl/wyniki-1-naboru-2019/ (accessed on 7 April 2020).
32. CSO. *National Census*; Central Statistical Office: Warsaw, Poland, 2014.
33. CSO. *Household Budget Survey in 2018*; Central Statistical Office: Warsaw, Poland, 2019.
34. Olczak, P.; Matuszewska, D.; Kryzia, D. "Mój Prąd" as an example of the photovoltaic one off grant program in Poland. *Energy Policy J.* **2020**, *23*, 123–138. [CrossRef]

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Impact of Trade and Financial Globalization on Renewable Energy in EU Transition Economies: A Bootstrap Panel Granger Causality Test

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Abstract: The globalized world has experienced significant environmental degradation together with raising global production and population. In this context, the employment of renewable energy use has become crucial for a sustainable environment and development. In the research, the mutual causality among renewable energy, trade and financial globalization, real GDP per capita, and CO_2 emissions in EU transition economies experiencing the integration with global economy was explored through bootstrap panel Granger causality test for the period of 1995–2015. The causality analysis revealed a unilateral causality from trade globalization to renewable energy in Estonia, Latvia, and Slovenia, and from renewable energy to trade globalization in Croatia and Lithuania. However, no significant causality between financial globalization and renewable energy was revealed. On the other side, a unilateral causality from CO_2 emissions to renewable energy in Lithuania and Slovenia, and from renewable energy to CO_2 emissions in Czechia, Hungary, and Latvia and a reciprocal causality between renewable energy to CO_2 emissions in Romania and Slovakia and a unilateral causality from real GDP per capita to renewable energy in Czechia, Romania, and Slovenia was discovered in the causality analysis.

Keywords: trade globalization; financial globalization; CO_2 emissions; real GDP per capita; renewable energy; bootstrap panel Granger causality; EU transition economies

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1. Introduction

Global production has increased considerably as of the Industrial Revolution. In turn, energy requirements have also increased considerably. The considerable increases in fossil fuel consumption have been experienced due to global production and population growth. However, sustainable economic development, environmental sustainability and health problems have accompanied the rising consumption of fossil fuels [1–3]. The aforementioned developments have directed countries towards renewable energy production regarding its sustainability and clean energy properties.

Renewable energy is a sustainable, replenishable and less carbon-intensive energy type derived from sources like wind, solar, hydropower, geothermal, bioenergy, and the ocean [4]. Although renewable energy production requires a high amount of investment and technology, countries have turned to renewable energy production. Thus the global renewable power production raised to 25.01 exajoules in 2019 from 0.18 exajoules in 1965 [5]. In this context, scholars and policy-makers have tended to explore the factors underlying renewable energy production. The studies have revealed real GDP per capita, financial openness, foreign direct investment inflows, trade openness, energy prices, stock market returns, energy dependence, human development, democracy, population, CO_2 emissions as the institutional, demographic and economic factors underlying the renewable energy [6–11].

The related empirical literature reveals that a few scholars had studied the influence of trade and financial globalization on renewable energy. However, both trade and financial globalization can contribute to renewable energy production and consumption through increases in production, technological transfer and financing provision. The study aims to contribute to the limited literature considering the gap in the relevant literature. In this regard, the paper aims to analyze the causality among trade and financial globalization, renewable energy, CO_2 emissions, real GDP per capita in the sample of eleven EU transition states during the period 1995–2015 through Kónya [12] causality test. The EU transition economies have begun to integrate with the global economy through an institutional and economic transformation as of the late 1980s. Furthermore, the EU transition economies experienced significant increases in share of energy from renewable sources in total energy as seen in Table 1. Therefore, we explore the causality between economic globalization indicators and renewable energy in sample of EU transition economies.

Table 1. Share of energy from renewable sources in total energy (%).

Country	1990 (World Bank, 2020a)	2009 (Eurostat, 2020)	2018 (Eurostat, 2020)
Bulgaria	1.91684851	12.005	20.528
Croatia	21.9231797	23.597	28.024
Czechia	3.57150703	9.978	15.15
Estonia	3.35607862	22.931	29.996
Hungary	3.85666956	11.674	12.489
Latvia	17.5696905	34.318	40.292
Lithuania	3.09677851	19.798	24.448
Poland	2.50148484	8.661	11.284
Romania	3.35576588	22.157	23.875
Slovakia	2.22533593	9.368	11.896
Slovenia	12.3519506	20.147	21.149

Source: Eurostat [13] and World Bank [14].

The paper's remaining sections are structured as follows: the next part briefly summarizes the related literature, the third part introduces the dataset and the methodological approach, and the fourth section conducts the applied analysis and the study ends up with the conclusions.

2. Literature Review

Renewable energy has become a significant energy source for a sustainable environment and development. Therefore, the determinants of renewable energy production have been widely explored in energy and environment economics. The related empirical literature has generally remained inconclusive, in other words, have reached mixed findings about the impact of institutional and economic variables on renewable energy for different country groups. We evaluate that this can mainly result from the use of samples with different characteristics and methods. Furthermore, the world experienced a considerable improvement in the globalization process. Most of the countries have integrated with global markets and can benefit from the positive aspects of globalization. However, a few researchers have centered on the interaction between globalization, economic globalization, and renewable energy. The scholars have generally used the globalization index in the limited relevant empirical literature, although globalization is a multifaceted process. This research focuses on trade and financial globalization on CO_2 emissions, considering the aforementioned issues.

In the literature about the impact of globalization on CO_2 emissions, Leitão [15] and Yazdi and Shakouri [16] found a reciprocal causality between globalization and renewable energy. However, Padhan et al. [17] revealed a negative influence of economic globalization on renewable energy consumption, but Gozgor et al. [18] discovered a positive influence of economic globalization on renewable energy.

In this context, Leitão [15] analyzed the causality among globalization, CO_2 emissions, economic growth, and renewable energy in Portugal during the period 1970–2010 and discovered a reciprocal causality between globalization and renewable energy. On the other hand, Yazdi and Shakouri [16] researched the causality among globalization, trade openness, economic growth, and renewable energy consumption in Iran for the period of 1992–2014 through ARDL cointegration test and revealed a reciprocal causality between globalization, renewable energy consumption, and economic growth.

Padhan et al. [17] researched the effect economic globalization and economic growth on renewable energy consumption in OECD member states through quantile regression for the period of 1970–2015 and revealed a negative influence of economic globalization on renewable energy consumption, but a positive influence of real GDP per capita on renewable energy consumption. However, Gozgor et al. [18] reached the opposite conclusion for the nexus of economic globalization and renewable energy in the same sample through cointegration analysis.

In the empirical literature, the relationship between trade liberalization/trade and renewable energy has been explored and different causality directions between two variables have been revealed for the different countries. In this context, Sebri et al. [19] explored the interaction among trade openness, CO_2 emissions, economic growth, and renewable energy consumption in BRICS countries for the duration of 1971–2010 through VECM and a mutual causality between economic growth and renewable energy was discovered. On the other side, Rasoulinezhad and Saboori [9] explored the relationship among financial and trade openness, CO_2 emissions, economic growth, and renewable energy consumption in Commonwealth of Independent States over the 1992–2015 period through causality analysis and no significant causality between trade liberalization and renewable energy consumption, but a unilateral causality from financial openness to renewable energy consumption and a bilateral causality between renewable energy and economic growth was discovered.

Jebli et al. [20] explored the causality among trade openness, CO_2 emissions, economic growth, and renewable energy consumption in 22 Central and Southern American economies throughout 1995–2010 through panel VECM Granger causality and a unilateral causality from renewable energy to trade openness, CO_2 emissions, and economic growth was revealed in the short run, but a bilateral causality among renewable energy, trade openness, and CO_2 emissions in the long run. Zeren and Akkuş [21] examined the causality between trade openness, renewable energy consumption in top Bloomberg emerging economies over 1980–2015 period through the Dumitrescu and Hurlin [22] panel causality test and a mutual causality between trade liberalization and renewable energy was discovered.

On the other side, Murshed [23] researched the influence of trade openness on renewable energy consumption in South Asian Economies for 2000–2017 through causality and regression analyses and discovered that trade openness enhanced renewable energy consumption. Akar [24] reached a similar finding for Balkan countries. Alam and Murad [25] explored the influence of trade openness, economic growth on renewable energy consumption in 25 OECD states over 1970–2012 period through panel ARDL. They discovered a positive influence of trade liberalization and economic growth on renewable energy consumption. However, Lau et al. [26], Kumaran et al. [27], and Zhao et al. [28] reached conclusions suggesting a negative impact of trade openness on renewable energy.

Furthermore, some researchers have explored the influence of total trade or foreign trade volume on renewable energy. In this context, Aïssa et al. [29] researched the interaction among renewable energy consumption, trade, and output in eleven African countries through panel cointegration analysis. They revealed a positive long-run effect of trade on renewable energy, but no causality between renewable energy consumption and trade or output. Kim and Kim [30] also explored the relationship between renewable energy and international trade and discovered a positive effect of international trade on renewable energy. Jebli and Youssef [31] also conducted research on the mutual interaction among foreign trade, CO_2 emissions, economic growth, and renewable energy consumption in Tunisia over 1980–2009 period through causality analysis and a unilateral causality from trade, GDP, CO_2 emissions, to renewable energy has been discovered.

Jebli et al. [32] researched the interaction between trade and renewable energy in OECD member states over the duration of 1980–2010 and a unilateral causality from trade to renewable energy was discovered. Tiba et al. [33] also analyzed the interaction among foreign trade, renewable energy, environment, and economic growth in 24 middle and high income countries and a unilateral causality from foreign trade to renewable energy, a mutual causality between CO_2 emissions and economic growth, between CO_2 emissions and renewable energy was discovered in high income countries. Furthermore, a mutual causality between trade/economic growth and renewable energy was discovered in middle-income countries.

Amri [34] explored the relationship among trade, economic growth, and renewable energy in 72 developed and developing countries for the duration of 1990–2012 through dynamic regression analysis and found a mutual causality between trade/income and renewable energy consumption. Liu et al. [35] analyzed the interaction among renewable energy, trade, and output in 15 Asia-Pacific countries over 1994–2014 period through cointegration and causality analyses and a unilateral short run causality from import to renewable energy and output and a mutual causality between renewable energy and output and a unilateral causality from international trade to renewable energy was discovered. Nathaniel and Khan [36] explored the interaction among trade, renewable energy, and ecological footprint in ASEAN countries for the period of 1990–2016 through cointegration and causality analyses, and no significant causality between trade and renewable energy was discovered.

The studies on the impact of GDP per capita and economic growth on renewable energy have reached mixed findings.

Alabi et al. [37] explored the causal interaction between economic growth and renewable energy consumption in Angola, Algeria, and Nigeria over the 1971–2011 period and disclosed a bi-lateral causality between two variables. Caruso et al. [38] reached similar findings for selected EU countries. However, Menyah et al. [39], Ocal and Aslan [40], and Bakirtas et al. [41] reached a significant causality from economic growth to renewable energy.

On the other side, Lin et al. [42] researched the determinants of the renewable electricity share in total electricity consumption in China for the 1980–2011 period and revealed a positive influence of economic growth on renewable electricity consumption. Lau et al. [26] researched the determinants of renewable energy consumption in Malaysia over the 1980–2015 period through ARDL approach and disclosed a positive influence of economic growth on renewable energy. Przychodzen and Przychodzen [43] explored the determinants of renewable energy consumption in 27 transition economies for the period of 1990–2014 and economic growth positively affected renewable energy production.

However, Mehrara et al. [44] explored the factors underlying renewable energy use in Economic Cooperation Organization countries during the period 1992–2011 and revealed a negative impact of economic growth on renewable energy use. Omoju [45] reached the same findings for China. Akar [24] explored the determinants of renewable energy in Balkan countries over the 1998–2011 period through regression analysis and disclosed a negative effect of economic growth on renewable energy consumption. Ergun et al. [10] researched the determinants of renewable energy consumption in Africa from 1990 to 2013 through regression analysis and revealed a negative impact of gross domestic product per capita on renewable energy production.

Some scholars explored the interaction between CO_2 emissions and renewable energy consumption and mainly revealed a positive impact of CO_2 emissions on renewable energy. In this context, Omri and Nguyen [46] researched the impact of CO_2 emissions on renewable energy consumption in 64 countries during the 1990–2011 period through regression analysis and reached a positive impact of CO_2 emissions on renewable energy consumption. On the other side, Dogan and Seker [47] explored the determinants of CO_2 emissions in the EU and revealed a bilateral causality between CO_2 emissions and renewable energy.

Omri et al. [48] analyzed the determinants of renewable energy consumption in 64 countries through regression analysis and revealed the CO_2 emissions as a significant driver of renewable energy consumption. However, Paweenawat and Plyngam [49] researched the causality among CO_2 emissions, energy consumption, income, and renewable energy in Thailand over the 1986–2012 period through ARDL approach. They revealed no significant causality between CO_2 emissions and renewable energy in the short run.

3. Data and Econometric Methodology

The study explores the causal interaction among renewable energy, trade globalization, financial globalization, CO_2 emission, and real GDP per capita in EU transition economies for the duration of 1995–2015. Renewable energy is proxied by share of energy from renewable sources, trade globalization and financial globalization are respectively represented by indexes of trade globalization and financial globalization calculated on an annual basis by [50]. Trade globalization index is calculated based on exports and imports of goods and services, trade regulations, trade partner diversity, trade agreements, trade taxes, and tariffs. On the other side, the financial globalization index is calculated based on international investments in foreign direct investments, portfolio investments, international debt, international income payments, international reserves, international investment agreements, investment restrictions, and capital account openness [51]. Real GDP per capita is proxied by GDP per capita (constant 2010 US$) and CO_2 emissions are represented by CO_2 emissions (metric tons per capita) as seen in Table 2. The renewable energy data existed for the period of 1990–2015 in the database of World Bank and the period of 2009–2018 in Eurostat database. Therefore, the study period was specified as 1995–2015 regarding World Bank data [14] and all the variables were annual.

Table 2. Dataset definition.

Variables	Definition	Source
RNW	Share of energy from renewable sources (%)	World Bank [14]
TRGI	Trade globalization index	KOF Swiss Economic Institute [50]
FINGI	Financial globalization index	KOF Swiss Economic Institute [50]
GDP	GDP per capita (constant 2010 US$)	World Bank [52]
CO	CO_2 emissions (metric tons per capita)	World Bank [53]

The study sample consists of eleven transition states of EU. The programs Gauss 10.0 (APTECH Systems, Higley, Arizona, USA), EViews 10.0 (HIS Global, Irvine, California, USA), and Stata 14.0 (StataCorp LLC, TA, USA) were used for the empirical analysis. The average share of energy from renewable sources of the sample in the study duration was 16.35%. The average of trade and financial globalization indexes in the sample were 73.76 and 65.63, but three variables considerably varied among the cross-sections. On the other side, the average of real GDP per capita was 12,097 USD, but it varied very considerably among the countries. Lastly, the average CO_2 emissions were about 6.75 metric tons per capita as seen in Table 3.

Table 3. Main characteristics of the series.

Variables	Mean	Std. Dev.	Min	Max
RNW	16.34636	9.542929	3.106707	40.36562
TRGI	73.76266	10.54052	42.95188	91.06991
FINGI	65.6343	12.83061	33.496	87.16071
GDP	12097.59	4950.488	3784.204	25430.35
CO	6.755519	2.850889	2.682623	14.66803

In a selection of the panel causality tests, the presence of cross-sectional dependency and heterogeneity in the panel exhibits importance to obtain relatively more reliable results. In this context, disregarding the cross-sectional dependence would probably produce size and bias distortions in the analyses [54,55]. Furthermore, seemingly unrelated regression (SUR) would exceed ordinary least squares (OLS) by estimating the equation sets one by one [56] and in turn transforms the model in a way that the error terms become uncorrelated [56]. On the other side, the slope coefficients' heterogeneity is essential for causality analysis. The causality between two series by putting the panel's joint constraint is a robust null hypothesis [57]. Homogeneity presumption for panel parameters cannot include heterogeneity among the countries because of country-specific features [58].

In the pretests, the presence of cross-sectional dependency and heterogeneity for the series was discovered. Therefore, we investigated the causal interaction among the series through Kónya [12] bootstrap panel Granger causality test regarding cross-sectional dependency and heterogeneity. Konya [12] bootstrap causality test rests on SUR and critical values are calculated for each cross-section through bootstrapping. Therefore, stationarity of the series is not required and Granger causality test can be employed for each country in the panel through Konya [12] causality test. The test rests on the following SUR estimation of two equation sets:

$$\begin{aligned}
y_{i,t} &= \alpha_{1,1} + \sum_{i=1}^{ty_1} \beta_{1,1,i} y_{1,t-i} + \sum_{i=1}^{lx_1} \gamma_{1,1,i} \chi_{1,t-i} + \varepsilon_{1,1,t} \\
y_{2,t} &= \alpha_{1,2} + \sum_{i=1}^{ly_1} \beta_{1,2,i} y_{2,t-i} + \sum_{i=1}^{lx_1} \gamma_{1,2,i} \chi_{2,t-i} + \varepsilon_{1,2,t} \\
y_{N,t} &= \alpha_{1,N} + \sum_{i=1}^{ly_1} \beta_{1,N,i} y_{N,t-i} + \sum_{i=1}^{lx_1} \gamma_{1,N,i} \chi_{N,t-i} + \varepsilon_{1,N,t}
\end{aligned} \tag{1}$$

and:

$$\begin{aligned}
\chi_{1,t} &= \alpha_{2,1} + \sum_{i=1}^{ly_2} \beta_{2,1,i} y_{1,t-i} + \sum_{i=1}^{lx_2} \gamma_{2,1,i} \chi_{1,t-i} + \varepsilon_{2,1,t} \\
\chi_{2,t} &= \alpha_{2,2} + \sum_{i=1}^{ly_2} \beta_{2,2,i} y_{2,t-i} + \sum_{i=1}^{lx_2} \gamma_{2,2,i} \chi_{2,t-i} + \varepsilon_{2,2,t} \\
\chi_{N,t} &= \alpha_{2,N} + \sum_{i=1}^{ly_2} \beta_{2,N,i} y_{N,t-i} + \sum_{i=1}^{lx_2} \gamma_{2,N,i} \chi_{N,t-i} + \varepsilon_{2,N,t}
\end{aligned} \tag{2}$$

where the renewable energy is proxied y, trade globalization index is proxied by x in system 1; y denotes the renewable energy, x denotes the financial globalization index in system 2; y denotes the renewable energy, x denotes the CO_2 emissions in system 3; y denotes the renewable energy, x denotes the real GDP per capita in system 4. l is the length. In this context, a unilateral significant causality from x to y is revealed if not all the $\gamma_{1,j,i}$s are zero, but all $\beta_{2,j,i}$s are zero. On the other side, a significant unilateral causality from y to x is revealed if all $\gamma_{1,j,i}$s are zero, but not all $\beta_{2,j,i}$s are zero. Furthermore, a reciprocal significant causality between x and y is revealed if neither $\gamma_{1,j,i}$s nor $\beta_{2,j,i}$s are zero. Lastly, no significant causality between x and y is revealed if all $\gamma_{1,j,i}$s and $\beta_{2,j,i}$s are zero.

4. Empirical Analysis

In the empirical analysis part of the study, first presence of cross-sectional dependency and heterogeneity were explored through relevant econometric tests. For this reason, the cross-sectional dependency test of LM, LM CD, and $LM_{adj.}$), which are respectively developed by [59–61] were conducted to question the cross-section independence, and the test results were introduced in Table 4. The null hypothesis (H_0 = cross-sectional independence) declined at a 5% significance level, and cross-sectional dependency among the series was discovered.

Table 4. Cross-sectional dependence tests' results.

Test	Test Statistic	Prob.
LM	76.23	0.0306
LM adj *	2.381	0.0173
LM CD *	4.248	0.0000

* two-sided test.

The homogeneity presence was explored through [62] homogeneity tests, and the results were introduced in Table 5. The null hypothesis asserting the presence of homogeneity was declined at 1% significance level, and the existence of heterogeneity was discovered. The results of both tests directed us to employ a causality test regarding cross-sectional dependency and heterogeneity.

Table 5. Homogeneity tests' results.

Test	Test Statistic	Prob.
$\widetilde{\Delta}$	9.015	0.000
$\widetilde{\Delta}_{adj.}$	10.571	0.000

The causal interaction among renewable energy, trade globalization, financial globalization, CO_2 emissions, and real GDP per capita in eleven EU transition economies for 1995–2015 was explored through bootstrap causality test and test results reported in Tables 6–9. The causality analysis between trade globalization and renewable energy presented in Table 6 and a unilateral causality from trade globalization to renewable energy in Estonia, Latvia, and Slovenia, and unilateral causality from renewable energy to trade globalization in Croatia and Lithuania was discovered. In theoretical terms, a significant causality between trade globalization and renewable energy is expected, considering the increases in the output and technological transfer resulting from trade globalization. Still, the causality direction can be changed depending on the countries' potential and approach towards renewable energy. In this context, Aïssa et al. [29], Rasoulinezhad and Saboori [9], and Nathaniel and Khan [36] revealed no significant causality between trade and renewable energy, but Sebri et al. [19], Amri [34], and Zeren and Akkuş [21] discovered a two-way causality between two variables. On the other side, Jebli and Youssef [31], Jebli et al. [32], Tiba et al. [33], and Liu et al. [35] revealed a unilateral causality from trade to renewable energy. Still, Jebli et al. [20] showed a unilateral causality from renewable energy to trade. Our findings revealed that trade globalization had a significant effect on the renewable energy in Estonia, Latvia, and Slovenia incompatible with Jebli and Youssef [31], Jebli et al. [32], Tiba et al. [33], and Liu et al. [35]. On the other side, a significant causality from renewable energy to trade globalization was revealed in Croatia and Lithuania incompatible with Jebli et al. [20].

Table 6. Causality analysis between renewable energy and trade globalization.

Countries	**H_0: TRGI Is Not the Cause of RNW**				**H_0: RNW Is Not the Cause of TRGI**			
	Wald St.	**Bootstrap Critic Value**			**Wald St.**	**Bootstrap Critic Values**		
		1%	**5%**	**10%**		**1%**	**5%**	**10%**
Bulgaria	8.8464	44.7627	24.2052	17.1286	7.3971	32.0311	16.2259	10.7983
Croatia	0.4123	32.8062	15.8140	10.7433	34.8960 **	37.9527	19.3220	12.9013
Czechia	0.7446	42.9621	20.6403	14.3989	5.4331	44.3254	23.2376	15.5162
Estonia	12.9861 *	35.4443	17.5990	11.6910	0.1451	30.4781	15.2729	10.5094
Hungary	7.8702	6.9005	26.1133	18.9257	0.1856	44.7453	22.4945	15.2530
Latvia	16.3657 **	22.5088	12.3336	8.2503	0.1588	35.5174	18.4655	12.3581
Lithuania	1.8563	40.3328	20.7102	14.1074	27.2157 **	30.5951	16.2497	11.0971
Poland	7.0130	55.5188	30.9381	22.0181	9.2569	47.9452	24.0374	16.7736
Romania	4.8904	32.9063	17.7028	12.0731	4.3656	42.0022	20.0110	13.4153
Slovakia	7.4813	45.3693	23.6163	16.0807	0.2603	40.0041	21.8501	15.0193
Slovenia	13.3336 *	36.0687	17.6316	12.1915	3.9083	39.0535	19.7149	13.3175

**, * indicates that it is respectively significant at 5%, 10%.

Table 7. Causality analysis between renewable energy and financial globalization.

Countries	**H_0: FINGI Is Not the Cause of RNW**				**H_0: RNW Is Not the Cause of FINGI**			
	Wald St.	**Bootstrap Critic Value**			**Wald St.**	**Bootstrap Critic Value**		
		1%	**5%**	**10%**		**1%**	**5%**	**10%**
Bulgaria	2.4116	41.7844	22.5821	5.4261	1.6362	32.3546	16.4587	11.0447
Croatia	0.3166	29.4784	15.6118	10.7328	0.3302	41.3339	21.2784	14.4160
Czechia	6.0159	30.6188	15.7428	10.8004	4.3581	34.3406	18.8492	12.7182
Estonia	0.4498	27.8959	13.8942	9.5116	0.9312	39.6911	20.1473	13.6960
Hungary	7.8604	37.6044	20.2577	14.3526	7.7433	36.3349	18.9620	12.7462
Latvia	3.2370	23.7755	12.1965	8.1950	0.5179	37.1669	18.8811	12.3706
Lithuania	0.1824	30.5119	15.4894	10.4238	2.3816	29.6871	15.8014	10.7737
Poland	4.9238	48.5862	25.8412	17.9884	1.4323	40.4925	22.3914	15.3243
Romania	2.2956	29.4947	16.6234	11.4730	0.2762	47.2754	24.9916	17.5495
Slovakia	3.4114	48.2462	24.2063	16.9555	0.4606	44.7273	23.7293	16.2438
Slovenia	4.6394	31.7152	16.2565	11.3121	0.5743	33.5498	17.9570	12.3690

Table 8. Causality analysis between renewable energy and CO_2 emissions.

Countries	H_0: CO_2 Emission Is Not the Cause of RNW				H_0: RNW Is Not the Cause of CO_2 Emission			
	Wald St.	Bootstrap Critic Value			Wald St.	Bootstrap Critic Value		
		1%	5%	10%		1%	5%	10%
Bulgaria	4.2209	28.3144	14.5398	9.6870	4.1849	27.78286	14.6908	0.1074
Croatia	2.3197	38.3059	20.2272	13.7559	0.5236	42.24757	20.1602	13.2400
Czechia	5.6996	34.8510	17.9577	12.1791	78.5323 ***	37.90574	21.2318	14.4659
Estonia	2.9785	30.7269	16.0333	10.4784	4.7461	30.11468	14.8927	9.8172
Hungary	1.5115	51.1984	26.7677	18.3740	16.4136 *	44.07672	23.8917	16.3845
Latvia	0.6672	29.4360	14.8573	9.6784	12.9507 *	36.25140	19.0939	12.5903
Lithuania	14.4073 **	26.7428	13.3773	8.7281	2.7378	28.31456	15.3157	10.0500
Poland	0.33374	28.9642	15.0131	10.1679	3.6145	43.67226	22.8993	15.7815
Romania	17.2924 **	27.7321	14.0219	9.7921	33.5551 **	38.07972	20.0294	13.6791
Slovakia	22.0571 *	43.8053	22.5734	15.8978	19.4469 *	39.57048	23.2065	16.4650
Slovenia	12.2983 *	32.5947	17.6888	11.5974	10.4034	44.19843	22.9981	16.2071

***, **, * indicates that it is respectively significant at 1%, 5%, 10%.

Table 9. Causality analysis between real GDP per capita and renewable energy.

Countries	H_0: GDP Is Not the Cause of RNW				H_0: RNW Is Not the Cause of GDP			
	Wald St.	Bootstrap Critic Value			Wald St.	Bootstrap Critic Value		
		1%	5%	10%		1%	5%	10%
Bulgaria	2.0464	50.8993	29.1946	20.1993	7.1154	53.3875	29.44463	20.8589
Croatia	0.4233	35.0795	18.5855	12.2062	0.4570	45.3903	22.44310	14.7866
Czechia	16.2285 *	37.6513	22.2228	15.8881	6.3666	51.3260	26.75393	18.8187
Estonia	3.4169	28.8198	14.9741	9.97130	10.5094	53.1987	28.49377	19.3129
Hungary	5.9984	57.1728	32.3425	22.8146	5.3495	31.1988	17.01013	11.6173
Latvia	4.6993	20.6217	10.4578	7.1282	0.8446	50.9055	25.71107	17.2067
Lithuania	1.8078	52.7100	30.2212	21.8787	6.9219	62.2689	35.59382	25.7880
Poland	24.0955	74.0902	43.6008	33.4240	2.8522	31.0150	15.81786	10.4976
Romania	23.5227 **	34.1308	18.6578	12.8874	3.9612	49.2939	7.18408	18.5251
Slovakia	16.0550	61.6467	35.6302	26.1593	10.8854	72.1978	39.51884	28.4645
Slovenia	14.2667 *	38.4524	19.4535	13.4619	0.4506	47.6993	24.63181	17.3053

**, * indicates that it is respectively significant at 1%, 5%, 10%.

The causality analysis between financial globalization and renewable energy presented in Table 7 revealed no significant causality between financial globalization and renewable energy. A significant causality from financial globalization to renewable energy is expected because it facilitates the countries to provide the funds in the international markets. Furthermore, Leitão [15] and Yazdi and Shakouri [16] revealed a reciprocal interaction between globalization and renewable energy.

The causality analysis between CO_2 emissions and renewable energy presented in Table 8 a unilateral causality from CO_2 emissions to renewable energy in Lithuania and Slovenia, and unilateral causality from renewable energy to CO_2 emissions in Czechia, Hungary, and Latvia and a reciprocal causality between renewable energy to CO_2 emissions in Romania and Slovakia. Theoretically, rising CO_2 emissions is one of the countries' motivations to make renewable energy investments because renewable energy is a relatively more environmentally friendly energy type. Therefore, the use of renewable energy is expected to decrease CO_2 emissions. In this context, a significant causality between renewable energy and CO_2 emissions in Czechia, Hungary, Latvia, Romania, and Slovakia was compatible with the theoretical considerations and Jebli and Youssef [31], Tiba et al. [33], and Jebli et al. [20].

Lastly, the causality analysis between real GDP per capita and renewable energy introduced in Table 9 denoted a unilateral causality from real GDP per capita to renewable energy in Czechia, Romania, and Slovenia. A significant causality between real GDP per capita and renewable energy is expected because renewable energy development requires substantial investments, and increasing GDP raises the countries' energy requirement. However, significant causality from real GDP per capita to renewable energy was revealed for Czechia, Romania, and Slovenia incompatible with Jebli and Youssef [31], and Padhan et al. [17]. However, Sebri et al. [19], Jebli et al. [32], Yazdi and Shakouri [16], Amri [34], Rasoulinezhad and Saboori [9] revealed a mutual causality between economic growth and renewable energy consumption.

5. Conclusions

The serious environmental degradation and decreasing fossil fuel supplies have led policy-makers and scholars to seek alternative solutions for sustainable economic growth and the environment. In this context, renewable energy resources have become a critical option for decarbonization, together with the technological developments in renewable energy production and the countries head for renewable energy production. For example, the EU aims to meet 32% of energy requirements from renewable energy by 2030 to achieve the first climate-neutral continent by 2050. Therefore, the specification of the factors underlying renewable energy production has become crucial. In turn, determinants of renewable energy production/consumption have been extensively researched in the related literature. The scholars have generally reached conflicting findings of institutional and economic determinants of renewable energy production or consumption. However, the impact of economic globalization indicators on renewable energy has been explored by a limited number of scholars. Therefore, we researched the causality among economic globalization indicators, real GDP per capita, CO_2 emissions, and renewable energy in a sample of EU transition economies through bootstrap panel Granger causality test of Kónya [12] taking notice of heterogeneity and cross-section independence among the series.

The causality analysis revealed that trade globalization significantly influenced renewable energy in Estonia, Latvia, and Slovenia, which experienced significant renewable energy production progress. Still, no significant causality between financial globalization and renewable energy was revealed. The relevant theoretical considerations and empirical findings indicated that both trade and financial globalization significantly influence renewable energy and, in turn, renewable energy has a significant influence on trade. On the other side, a unilateral causality from CO_2 emissions to renewable energy was revealed in Lithuania and Slovenia, and unilateral causality from renewable energy to CO_2 emissions was discovered in Czechia, Hungary, and Latvia and a mutual causality between renewable energy and CO_2 emissions in Romania and Slovakia in compatible with relevant theoretical and empirical literature. Lastly, a unilateral causality from real GDP per capita to renewable energy in Czechia, Romania, and Slovenia was discovered.

The EU aims to meet 32% of energy requirements from renewable energy by 2030. The Czechia, Hungary, Poland, and Slovakia in EU transition economies especially should make a significant improvement to catch the target. However, renewable energy production needs relatively high investments. Therefore, all the EU countries, especially the countries in the question above, should benefit from trade and financial globalization to improve renewable energy production through technology and financing transfer. Future studies can focus on the mechanisms through which trade and financial globalization affect renewable energy production.

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References

1. Omer, A.M. Energy use and environmental impacts: A general review. *J. Renew. Sustain. Energy* **2009**, *1*, 53101. [CrossRef]
2. Bologna, S. Energy and Sustainable Economic Development. In *Renewable Energy for Unleashing Sustainable Development*; Colombo, E., Bologna, S., Masera, D., Eds.; Springer: Cham, Switzerland, 2013. [CrossRef]
3. Manisalidis, I.; Stavropoulou, E.; Stavropoulos, A.; Bezirtzoglou, E. Environmental and Health Impacts of Air Pollution: A Review. *Front. Public Health* **2020**, *8*, 14. [CrossRef] [PubMed]
4. IEA. Renewables. 2020. Available online: https://www.iea.org/fuels-and-technologies/renewables (accessed on 15 September 2020).
5. BP. Statistical Review of World Energy 2020 (69th Edition). 2020. Available online: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf (accessed on 15 September 2020).
6. Sadorsky, P. Renewable energy consumption, CO_2 emissions and oil prices in the G7 countries. *Energy Econ.* **2009**, *31*, 456–462. [CrossRef]
7. Apergis, N.; Payne, J.E. The causal dynamics between renewable energy, real GDP, emissions and oil prices: Evidence from OECD countries. *Appl. Econ.* **2014**, *46*, 4519–4525. [CrossRef]
8. Ackah, I.; Kizys, R. Green growth in oil producing African countries: A panel data analysis of renewable energy demand. *Renew. Sustain. Energy Rev.* **2015**, *50*, 1157–1166. [CrossRef]
9. Rasoulinezhad, E.; Saboori, B. Panel estimation for renewable and non-renewable energy consumption, economic growth, CO_2 emissions, the composite trade intensity, and financial openness of the commonwealth of independent states. *Environ. Sci. Pollut. Res.* **2018**, *25*, 17354–17370. [CrossRef]
10. Ergun, S.J.; Owusu, P.A.; Rivas, M.F. Determinants of renewable energy consumption in Africa. *Environ. Sci. Pollut. Res.* **2019**, *26*, 15390–15405. [CrossRef]
11. Chang, C.-L.; Ilomäki, J.; Laurila, H.; McAleer, M. Causality between CO_2 Emissions and Stock Markets. *Energies* **2020**, *13*, 2893. [CrossRef]
12. Kónya, L. Exports and growth: Granger causality analysis on OECD countries with a panel data approach. *Econ. Model.* **2006**, *23*, 978–992. [CrossRef]
13. Eurostat. Share of Energy from Renewable Sources. 2020. Available online: https://ec.europa.eu/eurostat/databrowser/view/nrg_ind_ren/default/table?lang=en (accessed on 12 August 2020).
14. World Bank. Renewable Energy Consumption (% of Total Final Energy Consumption). 2020. Available online: https://data.worldbank.org/indicator/eg.fec.rnew.zs (accessed on 15 June 2020).
15. Leitão, N.C. Economic growth, carbon dioxide emissions, renewable energy and globalization. *Int. J. Energy Econ. Policy* **2014**, *3*, 391–399.
16. Yazdi, S.K.; Shakouri, B. The globalization, financial development, renewable energy, and economic growth. *Energy Sources Part B Econ. Plan. Policy* **2017**, *12*, 707–714. [CrossRef]
17. Padhan, H.; Padhang, P.C.; Tiwari, A.K.; Ahmed, R.; Hammoudeh, S. Renewable energy consumption and robust globalization(s) in OECD countries: Do oil, carbon emissions and economic activity matter? *Energy Strat. Rev.* **2020**, *32*, 100535. [CrossRef]
18. Gozgor, G.; Mahalik, M.K.; Demir, E.; Padhan, H. The impact of economic globalization on renewable energy in the OECD countries. *Energy Policy* **2020**, *139*, 111365. [CrossRef]
19. Sebri, M.; Ben-Salha, O. On the causal dynamics between economic growth, renewable energy consumption, CO_2 emissions and trade openness: Fresh evidence from BRICS countries. *Renew. Sustain. Energy Rev.* **2014**, *39*, 14–23. [CrossRef]
20. Jebli, M.B.; Youssef, S.B.; Apergis, N. The dynamic linkage between renewable energy, tourism, CO_2 emissions, economic growth, foreign direct investment, and trade. *Latin Am. Econ. Rev.* **2019**, *28*, 2–19. [CrossRef]
21. Zeren, F.; Akkuş, H.T. The relationship between renewable energy consumption and trade openness: New evidence from emerging economies. *Renew. Energy* **2020**, *147*, 322–329. [CrossRef]
22. Dumitrescu, E.; Hurlin, C. Testing for Granger non-causality in heterogeneous panels. *Econ. Model.* **2012**, *29*, 1450–1460. [CrossRef]
23. Murshed, M. Does Improvement in Trade Openness Facilitate Renewable Energy Transition? Evidence from Selected South Asian Economies. *South Asia Econ. J.* **2018**, *19*, 151–170. [CrossRef]
24. Akar, B.G. The Determinants of Renewable Energy Consumption: An Empirical Analysis for the Balkans. *Eur. Sci. J. ESJ* **2016**, *12*, 594. [CrossRef]
25. Alam, M.; Murad, W. The impacts of economic growth, trade openness and technological progress on renewable energy use in organization for economic co-operation and development countries. *Renew. Energy* **2020**, *145*, 382–390. [CrossRef]

26. Lau, L.S.; Yii, K.J.; Lee, C.Y.; Chong, Y.L.; Lee, E.H. Investigating the determinants of renewable energy consumption in Malaysia: An ARDL approach. *Int. J. Bus. Soc.* **2018**, *19*, 886–903.
27. Kumaran, V.V.; Ridzuan, A.R.; Khan, F.U.; Abdullah, H.; Mohamad, Z.Z. An empirical analysis of factors affecting renewable energy consumption in association of Southeast Asian Nations-4 countries. *Int. J. Energy Econ. Policy* **2020**, *10*, 48–56. [CrossRef]
28. Zhao, P.; Lu, Z.; Fang, J.; Paramati, S.R.; Jiang, K. Determinants of renewable and non-renewable energy demand in China. *Struct. Chang. Econ. Dyn.* **2020**, *54*, 202–209. [CrossRef]
29. Aïssa, M.S.B.; Jebli, M.B.; Youssef, S.B. Output, renewable energy consumption and trade in Africa. *Energy Policy* **2014**, *66*, 11–18. [CrossRef]
30. Kim, K.; Kim, Y. Role of policy in innovation and international trade of renewable energy technology: Empirical study of solar PV and wind power technology. *Renew. Sustain. Energy Rev.* **2015**, *44*, 717–727. [CrossRef]
31. Jebli, M.B.; Youssef, S.B. The environmental Kuznets curve, economic growth, renewable and non-renewable energy, and trade in Tunisia. *Renew. Sustain. Energy Rev.* **2015**, *47*, 173–185. [CrossRef]
32. Jebli, M.B.; Youssef, S.B.; Ozturk, I. Testing environmental Kuznets curve hypothesis: The role of renewable and non-renewable energy consumption and trade in OECD countries. *Ecol. Indic.* **2016**, *60*, 824–831. [CrossRef]
33. Tiba, S.; Omri, A.; Frikha, M. The four-way linkages between renewable energy, environmental quality, trade and economic growth: A comparative analysis between high and middle-income countries. *Energy Syst.* **2016**, *7*, 103–144. [CrossRef]
34. Amri, F. Intercourse across economic growth, trade and renewable energy consumption in developing and developed countries. *Renew. Sustain. Energy Rev.* **2017**, *69*, 527–534. [CrossRef]
35. Liu, X.; Zhang, S.; Bae, J. Renewable energy, trade, and economic growth in the Asia-Pacific region. *Energy Sources Part B Econ. Plan. Policy* **2018**, *13*, 1–7. [CrossRef]
36. Nathaniel, S.; Khan, S.A.R. The nexus between urbanization, renewable energy, trade, and ecological footprint in ASEAN countries. *J. Clean. Prod.* **2020**, *272*, 122709. [CrossRef]
37. Alabi, O.; Ackah, I.; Lartey, A. Re-visiting the renewable energy-economic growth nexus: Empirical evidence from African OPEC countries. *Int. J. Energy Sect. Manag.* **2017**, *11*, 387–403. [CrossRef]
38. Caruso, G.; Colantonio, E.; Gattone, S.A. Relationships between Renewable Energy Consumption, Social Factors, and Health: A Panel Vector Auto Regression Analysis of a Cluster of 12 EU Countries. *Sustainability* **2020**, *12*, 2915. [CrossRef]
39. Menyah, K.; Wolde-Rufael, Y. CO_2 emissions, nuclear energy, renewable energy and economic growth in the US. *Energy Policy* **2010**, *38*, 2911–2915. [CrossRef]
40. Ocal, O.; Aslan, A. Renewable energy consumption–economic growth nexus in Turkey. *Renew. Sustain. Energy Rev.* **2013**, *28*, 494–499. [CrossRef]
41. Bakirtaş, I.; Çetin, M.A. Yenilenebilir Enerji Tüketimi İle Ekonomik Büyüme Arasındaki İlişkisi: G-20 Ülkeleri. *Sosyoekonomi* **2016**, *24*, 131–145. [CrossRef]
42. Lin, B.; Omoju, O.E.; Okonkwo, J.U. Factors influencing renewable electricity consumption in China. *Renew. Sustain. Energy Rev.* **2016**, *55*, 687–696. [CrossRef]
43. Przychodzen, W.; Przychodzen, J. Determinants of renewable energy production in transition economies: A panel data approach. *Energy* **2020**, *191*, 116583. [CrossRef]
44. Mehrara, M.; Rezaei, S.; Razi, D.H. Determinants of Renewable Energy Consumption among ECO Countries; Based on Bayesian Model Averaging and Weighted-Average Least Square. *Int. Lett. Soc. Humanist. Sci.* **2015**, *54*, 96–109. [CrossRef]
45. Omoju, O. Determinants of renewable energy development in China. In Proceedings of the 38th IAEE International Conference Energy Security, Technology and Sustainability Challenges Across the Globe, Antalya, Turkey, 25–27 May 2015.
46. Omri, A.; Nguyen, D.K. On the determinants of renewable energy consumption: International evidence. *Energy* **2014**, *72*, 554–560. [CrossRef]
47. Dogan, E.; Seker, F. Determinants of CO_2 emissions in the European Union: The role of renewable and non-renewable energy. *Renew. Energy* **2016**, *94*, 429–439. [CrossRef]
48. Omri, A.; Daly, S.; Nguyen, D.K. A robust analysis of the relationship between renewable energy consumption and its main drivers. *Appl. Econ.* **2015**, *47*, 2913–2923. [CrossRef]
49. Paweenawat, S.W.; Plyngam, S. Does the causal relationship between renewable energy consumption, CO_2 emissions, and economic growth exist in Thailand? An ARDL approach. *Econ. Bull.* **2017**, *37*, 697–711.
50. KOF Swiss Economic Institute. KOF Globalisation Index. 2020. Available online: https://kof.ethz.ch/en/forecasts-and-indicators/indicators/kof-globalisation-index.html (accessed on 15 June 2020).
51. Gygli, S.; Haelg, F.; Potrafke, N.; Sturm, J.-E. The KOF Globalisation Index—Revisited. *Rev. Int. Organ.* **2019**, *14*, 543–574. [CrossRef]
52. World Bank. GDP Per Capita (Constant 2010 US$). 2020. Available online: https://data.worldbank.org/indicator/NY.GDP.PCAP.KD (accessed on 15 June 2020).
53. World Bank. CO2 Emissions (Metric Tons Per Capita). 2020. Available online: https://data.worldbank.org/indicator/EN.ATM.CO2E.PC (accessed on 15 June 2020).
54. O'Connell, P.G. The overvaluation of purchasing power parity. *J. Int. Econ.* **1998**, *44*, 1–19. [CrossRef]
55. Pesaran, M.H. Estimation and Inference in Large Heterogeneous Panels with a Multifactor Error Structure. *Econometrica* **2006**, *74*, 967–1012. [CrossRef]

56. Zellner, A. An efficient method of estimating seemingly unrelated regressions and tests for aggregation bias. *J. Am. Stat. Assoc.* **1962**, *57*, 348–368. [CrossRef]
57. Granger, C.W.J. Some aspects of causal relationships. *J. Econ.* **2003**, *112*, 69–71. [CrossRef]
58. Breitung, J. A Parametric approach to the Estimation of Cointegration Vectors in Panel Data. *Econ. Rev.* **2005**, *24*, 151–173. [CrossRef]
59. Breusch, T.; Pagan, A. The Lagrange Multiplier Test and its Applications to Model Specification in Econometrics. *Rev. Econ. Stud.* **1980**, *47*, 239–253. [CrossRef]
60. Pesaran, M.H. General Diagnostic Tests for Cross-Sectional Dependence in Panels. *CESinfo Work. Pap.* **2004**, *1229*. Available online: https://ideas.repec.org/p/ces/ceswps/_1229.html (accessed on 10 April 2020). [CrossRef]
61. Pesaran, M.H.; Ullah, A.; Yamagata, T. A bias-adjusted LM test of error cross-section independence. *Econ. J.* **2008**, *11*, 105–127. [CrossRef]
62. Pesaran, M.H.; Yamagata, T. Testing slope homogeneity in large panels. *J. Econ.* **2008**, *142*, 50–93. [CrossRef]

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An Analysis of Support Mechanisms for New CHPs: The Case of Poland

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Abstract: The increasing demand for energy on a global scale, as well as the social pressure related to counteracting the effects of climate change, has created favourable conditions for the transformation of energy sectors towards the possession of low-emission generation sources. This situation, however, requires investment actions in order to modernise the existing power and CHP (Combined Heat and Power) plants and construct new units. These issues, together with the climate and energy policy pursued by the European Union, are the main reasons for the emergence of various governmental mechanisms supporting the replacement of old coal power units with highly efficient cogeneration units based on gas turbines and other units. The support may take different forms. This article discusses two examples of mechanisms available on the Polish market, i.e., (**i**) the capacity market and (**ii**) promoting electricity from high-efficiency cogeneration in the form of individual cogeneration premium. The purpose and novelty of the analysis was to identify the pros and cons and the key parameters which determine the advantage of a given mechanism. Both these mechanisms have been characterised and then compared via the example of a planned cogeneration gas unit (an open cycle gas turbine—OCGT). This assessment was made using discount methods based on the FCFF (free cashflow to company) approach. The analysis did not bring forward an unequivocal answer as to the absolute advantage of any of the solutions, but it was able to point out significant problems related to their practical use.

Keywords: support systems; energy policy; cogeneration; capacity market; individual cogeneration premium

1. Introduction

The systematic increase in energy demand observable at the global level [1–3], combined with more and more widespread discussion and initiatives to counteract the negative effects of climate change, has created favourable conditions for a transformation towards sustainable, low-emission energy systems.

Over the last few years, several studies have been developed to deal with changes in the energy industry. One of the most interesting that increases the awareness of the inevitability of these changes is the works of Falcon et al. [4] describing the most effective mix for energy transition in the biofuel industry. Another important work is the one by Owen et al. [5], taking up the subject of the finance gap for the energy sector transition. In turn, Tombs [6] in his work presents a discussion concerning the vision of the energy sector in the future.

This challenge is particularly important in countries like Poland, whose economy—and, in particular, the fuel-energy sector—is based on solid, fossil primary energy carriers such as coal and lignite. The European context seems particularly important due to the European Commission's consequent and active decarbonisation policy. One of the solutions that can help in the transformation of the electricity and heat generation sectors in particular countries is the cogeneration systems based on gas turbines [7,8]. They are an alternative to both conventional power plants and coal-fired CHP plants. In Poland, the development of and increase in the use of cogeneration has been mentioned as one of the strategic directions of the energy policy [9]. The support of combined electricity and heat generation is also a priority of the European Union [10,11], which, in addition to actions aimed at eliminating the generation units that do not meet certain emission standards (Directive on industrial emissions and BAT conclusions), works indirectly through directives supporting the increase in electric efficiency (Directive 2012/27/EU [12]) and promotion of high-efficiency cogeneration (Directive 2004/8/EC [13]).

The development of highly efficient cogeneration by replacing the currently operating systems using relatively cheap coal fuels requires appropriate support from individual member-state governments, who are obliged to implement both the European Union's policies and directives. However, for the aforementioned changes to take place, the proposed solutions must take a tangible, financial form [14].

The support might take various forms, one of them being the so-called feed-in tariffs, often used for renewable technologies and described in more detail by Couture et al. [15,16] and Kemausuor et al. [17]. The capacity market has the ability to support both new and already existing units [18–20]. Tax exemptions in both the investment period and operating period are described by Galinato and Yoder [21]—the authors focus on the impact of such actions on the reduction of the volume of greenhouse gases. Tax incentives have also been described by Pablo-Romero [22] in a work researching the influence of support on the development of the solar energy market in Spain. By analysing both literature and legislation of individual countries, one is able to encounter numerous mechanisms of direct support paid to producers on both national and local levels. Such solutions are based on, i.e., the trade in property rights (certificates) attesting to the production of energy by means of a supported technology—in units using renewable energy sources, in cogeneration units—or attesting to the achieved energy savings. On the one hand, this allows the owners of these units to generate additional income; on the other hand, if the existing regulations require the energy companies to present a certain volume of energy produced by means of supported technologies, additional costs may be generated, resulting from the need to purchase certain property rights in the event of non-compliance with the imposed limits. These and previously mentioned solutions have been described extensively in the works of Abolhosseini and Heshmati [23], Sousa and Martins [24] and Yang et al. [25].

The influence of various support mechanisms on the planned development of modern power-generation technologies has been analysed in the works of Jung and Feng [26]. The subject has also been taken up by Erdogdu [27], who analysed the relationship between governmental support and energy market reforms in 27 countries.

The abovementioned works show how much potential there is in improving the implemented policy and applying certain support instruments. This potential, when it comes to promoting modern energy generation technologies, was well presented in the works of Huijben et al. [28]. They described the governmental mechanisms of supporting photovoltaic energy. Thanks to their implementation, Belgium has become one of the European leaders in terms of the use of this type of energy source. This example shows that, thanks to the appropriately selected support mechanisms, it is possible to achieve the country's strategic goals. However, none of the encountered works dealt with the subject of comparison and choice between different support systems.

The main goal and, at the same time, an important contribution of this article to the discourse and its novelty is the analysis and comparison of the two governmental support mechanisms that can potentially be used by the owners of large cogeneration gas units in Poland: (**i**) the capacity market (a market mechanism enabling payment reception for new and existing generating units, including RES (Renewable Energy Sources), as well as DSR (Demand Side Response), in exchange for the readiness to provide power services) [29] and (**ii**) promoting high-efficiency cogeneration electricity in the form of an individual cogeneration premium. These mechanisms, allowing to gain additional income—outside the electricity, heat and system services market–have been analysed in terms of both implementing the goal of maximising possible profits as well as the risk factors related to the implementation of obligations resulting from each of the mechanisms. The support system analysis was carried out on the example of a company considering the construction of a cogeneration gas-fired unit. The planned investment actions include constructing a new generation unit that would include a gas turbine with the power of 90 MWe and a heat recovery steam boiler with the total capacity of 200 MWt. The described cogeneration, natural-gas-powered unit will produce useful heat supplied to the public heating network, while the unit CO_2 emission performance standard will be below the threshold of 450 kg/MWh.

The contribution of this publication to the ongoing discussions about the support mechanisms is not only to choose the best solutions for current conditions but also to compare the functioning and mutual interaction of the mechanisms in question. Such analyses allow us to identify the disadvantages of particular solutions, which, at the end of the day, helps to create a better and more coherent support policy. In this context, our work also contributes to the ongoing discussion on green financing [30]. Supporting investments in low- or zero-emission high-efficiency cogeneration technologies (natural gas can be considered as a transition fuel) can help transform the energy sector and decarbonise the whole economy, contributing to the achievement of the EU environmental policy objectives, including climate neutrality. However, the existing regulatory barriers (as shown in our work) may reduce the effectiveness of the support system and cause the advantages of one solution over others. In addition, the conclusions of such an analysis can be applied in other countries and regions that are currently considering the choice of a support system for CHP units.

The article is structured as follows. The first part describes both support systems and their legal conditions (Section 1) as well as the methodology adopted for their evaluation (Section 2). The assessment results are then presented for the basic assumptions and for different market scenarios. Then, the borderline levels of economic factors determining the advantage of a given support system are analyzed and discussed (Section 4). The work is completed with a short summary and conclusions (Section 5).

2. Materials and Methods

This section presents the characteristics of the analysed support mechanisms, as well as technical and economic assumptions for the cogeneration system under consideration, together with the description of the methodology and comparative analysis of the abovementioned mechanisms.

2.1. Capacity Market

As a result of many years of debate on the selection of the optimal solution to counteract the long-term threats related to the adequacy of generation capacity in the National Power System, in 2017, Poland introduced a centralised capacity market, being one of a number of Capacity Remuneration Mechanisms. The mechanism to secure the required level of available capacity, while providing support for the existing and planned units, is the so-called Dutch auction with a uniform clearing price [31].

The detailed rules of mechanism participation have been specified in the following regulations:

- the Act of 8 December 2017 on the capacity market (hereinafter "CMA") [32];
- four resolutions on the performance of capacity obligation, security and parameters of particular auctions [33–36];
- capacity market regulations approved by the decision of the President of the Energy Regulatory Office [37].

In addition to national regulations, the manner in which units based on fossil fuels function within the capacity mechanisms is regulated by the resolution of the European Parliament and EU Council (EU) 2019/943 dated 5 June 2019 on the internal electricity market (hereinafter "resolution 2019/943") [38].

In an auction of this kind, the starting price is gradually reduced to the level wherein the demand and supply lines intersect. The participants may (**i**) remain in the auction until it is closed or (**ii**) submit one of the declarations concerning their further participation, one of them being the submission of the so-called exit bid—a participant determines the price level, below which they will not wish to become a party to the capacity agreement. There are two types of offeror in every auction [39]:

- price-makers—entities allowed to quit an auction at any moment (new and modernised units and the DSR demand-reduction units);
- price-takers—entities allowed to quit an auction upon submission of an exit bid, and only with the price below the price set for the price-takers (existing units).

Functioning of generation units on the two-commodity market (electricity and capacity) through granting the producers extra support imposes new obligations on producers, the implementation of which guarantees the achievement of specific revenues and additional costs (financial penalties). According to CMA, the Capacity Provider, being the owner of a physical unit or authorized to dispose of it in the capacity market, and in the case of being certified for a capacity market unit (further "CMU") auction, which is then subject to capacity obligation, shall be obliged:

1. for the capacity market unit to be ready to provide to the system the capacity referred to in the capacity agreement;
2. to provide electrical capacity to the system during stress events and in the amount of an adjusted capacity obligation.

Performance of the capacity obligation, understood as ensuring the security of supplies to the system, is carried out in the so-called stress events, specified in the current regulations as working days between 7:00 a.m. and 10:00 p.m. Thus, in the extreme case of power shortages in the system, it is possible that a situation will emerge, wherein the Capacity Provider shall be obliged to provide continuous capacity supplies for 15 h for several consecutive days. During the stress event, the Operator may call upon the Capacity Provider to carry out its capacity obligation at the maximum level specified in the capacity agreement.

High-efficiency cogeneration units may participate in the capacity market mechanism on the same terms as power plants, subject to additional rights arising from the nature of the work and environmental benefits of such units. The legislator has foreseen the possibility of concluding a long-term capacity agreement by a new unit (a planned capacity market unit) for 15 yearly supply periods, if the Capacity Supplier incurs a minimum level of net unit investment expenditure related to the available net capacity (hereinafter "CAPEX level").

Moreover, the Capacity Provider possessing the CMU, being a unit of high-efficiency cogeneration, may prolong the duration of a capacity agreement concluded during an auction by 2 additional years (so-called green bonus), in case the generation unit: (**i**) keeps the specific carbon dioxide emission factor at the level below or equal 450 kg CO_2/MWh of generated electricity, and (**ii**) at least half of the heat generated in such a unit is transferred to the heat distribution system, with its carrier being hot water.

Since the introduction of CMA up until today (March 2020), four capacity auctions have been carried out for the supply years of 2021–2024. The most important results of these auctions have been presented in Table 1.

Table 1. Results of the carried out capacity auctions.

Capacity Auctions	Unit	2021	2022	2023	2024
Clearing Price	€/kW/year	55.88	46.05	47.19	60.42
Volume of the Capacity Obligations	GW	22.4	10.5	10.6	8.6
Number of Units	pcs.	160	120	94	103
New Units Share	%	18.4%	0.0%	8.0%	16.6%

2.2. Individual Cogeneration Premium

In order to create a stable regulatory and economic environment for cogeneration in Poland, on 14 December 2018, by force of the Act on promoting electricity from high-efficiency cogeneration [40] (hereinafter "uCHP"), a package of support mechanisms diversified depending on the type and unit size which was adopted—replacing the hitherto system of energy certificates. One of the forms of support provided for in the Act is the individual cogeneration premium (hereinafter "ICP"), which may be applied for by the entities planning to invest in new high-efficiency cogeneration units with installed net electric capacity of no less than 50 MWe.

The basic requirements concerning conditions to be fulfilled by a new unit to apply for the above support include:

- the need to obtain a promise of concession (or a promise of a concession change) to generate electricity, along with positive verification of a financial gap (the so-called "incentive effect")—such an analysis is carried out using the assumptions made by Energy Regulatory Office (ERO), which will be presented in the course of this article;
- the need to introduce the generated useful heat to the public heating network—the volume of energy covered by support in a given accounting period shall depend on the percentage share of the produced heat introduced to the network;
- CO_2 emission at the level not higher than 450 kg CO_2/MWh of generated energy (electricity and heat);
- installation, in the unit, of devices manufactured within 60 months before the onset of electricity generation;
- construction of the unit within 48 months from the enrolment decision;
- compliance with technical requirements enabling the electricity generated by the unit to be qualified as high-efficiency cogeneration;
- inability to make an investment decision (understood as commencing construction works or making binding commitments, causing the investment to become irreversible) on the construction of a unit before the enrolment decision.

In order to obtain support in the form of ICP, it is necessary to submit a given unit to participate in the selection process, wherein the President of the Energy Regulatory Office (hereinafter "PERO") determines the level of acceptable support individually for each unit. Due to the fact that an auction is not the form of determining the level of support for the construction of a new unit with an electric capacity over 50 MWe (as on the capacity market), PERO is, each time, required to examine the so-called "incentive effect" in the course of the previous procedure to grant the concession promise. This examination is performed by means of filling in the ERO-made form of technical and economic description of a planned investment and allows us to resolve the fundamental—taking into consideration granting public support—issue of the dependence of an investment implementation on the potentially granted support mechanism. In practice, what is assessed is the existence of the so-called "financial gap" of the planned investment—if the net present value (NPV) of the enterprise calculated in the form is higher than zero, it means that the investment does not require support to be carried out. Only obtaining a negative NPV in the course of the assessment procedure for the incentive effect carried out by PERO allows participation in the subsequent stages of the ICP selection process.

After submitting a filled-out form, PERO determines the level of support for each new unit in the amount required for their proper operation and reimbursement of investment costs. According to the resolution issued by uCHP, the individual cogeneration premium expressed in Polish Zlotys per 1 MWh of electricity is "(. . .) calculated for a 15-year period of support and corresponds to the average discounted cost of electricity and heat generation in the entire life cycle of a given unit, decreased by the projected discounted revenue of this unit" [41].

$$\mathrm{ICP} = \frac{\sum_{t=1}^{n} (\mathrm{NI_t} + \mathrm{KO_t} + \mathrm{KP_t} + \mathrm{P_t})(1 + r)^{-t}}{\sum_{t=1}^{k} \mathrm{E_t}(1 + r)^{-t}} \tag{1}$$

where

k—support period of 15 years;
n—cost averaging period (economic lifetime of the project);
$\mathrm{NI_t}$—investment outlays in year t;
$\mathrm{KO_t}$—operating costs (excl. fuel) in year t;
$\mathrm{KP_t}$—fuel costs in year t;
$\mathrm{P_t}$—revenue in year t;
$\mathrm{E_t}$—electricity production in year t;
r—discount rate assumed by ERO;
t—year.

The obtained ICP (1) is available to cogeneration units (for electricity produced and sold) in the subsequent 15 years after the selection process decision, with its maximum level being approximately 34.88 €/MWh (which results from the resolution of the Minister competent for energy). Thus, in order to get support in the scope projected at the investment stage, it is required to actually produce and sell the assumed volume of electricity. The constant ICP value obtained in the selection process is annually indexed by means of the consumer price index (CPI).

2.3. Assumptions of Comparative Analysis

In this section, we present in detail the methodology used to assess the economic efficiency with the use of the analysis of discounted cash flows. Moreover, we will also present the key data and assumptions made for the calculations.

In the following analyses, the key methods of assessing economic effectiveness were used [42]. The net present value approach, although very popular, has also disadvantages. We can mention, among others [43]:

- difficulty with choosing a discount rate;
- problems with estimating cash flow;
- NPV mostly ignores future tax breaks;
- problems with the inflation forecast.

Moreover, the net present value method is a static method, which is inflexible, so it is difficult to adapt to changes in the environment [44].

The authors are aware of these shortcomings, but the aim of the analysis is not to evaluate this methodology but to use it comprehensively to analyse the mentioned support systems. The basic rule for the analysis of discounted cash flow (DCF) is to correlate the amount of expected future profits with the amount of initial cash investment required to purchase the tangible assets or to start commercial production. Its aim is to simulate all cash flows anticipated for the full period of project implementation [45].

In the subject analysis, a method was used based on the construction of a model of discounted cash flows FCFF (free cash-flow to firm)—cash flows attributable to equity capital owners and creditors:

$$\text{FCFF} = \text{operating profit less tax} - \text{capital expenditure} + \text{depreciation} - \text{change in working capital} \tag{2}$$

$$\text{NPV} = \sum_{t=0}^{T} \frac{\text{FCF}_t}{(1+r)^t} = \left[\sum_{t=0}^{T} \frac{\text{CF}_t}{(1+r)^t}\right] - \left[\sum_{t=0}^{T} \frac{I_t}{(1+r)^t}\right] + \frac{A_T}{(1+r)^T} \tag{3}$$

where

FCF_t—free cash flow in year t;
CF_t—cash flow in year t (excl. capital expenditure and residual values);
I_t—investment outlays in year t;
A_T—residual value in year T;
r—weighted average cost of capital (discount rate);
T—total number of years, required for the implementation of project.

In this model (3), the cash flows attributable to all parties financing the enterprise are discounted with a discount rate which is the weighted average cost of capital (WACC).

For the sake of analysis, two types of weighted average cost of capital were adopted (Table 2). The first one represents the market value and was delivered by the investor, while the other one was established by the Energy Regulatory Office (ERO) and is used to assess the "incentive effect" at the stage of application for a concession promise. It is worth mentioning that the individual cogeneration premium (ICP) is calculated for the abovementioned minimum return level, i.e., in accordance with ERO's assumptions—4.96%. So, in the assessed case, the difference between these capital costs works to the investors' disadvantage.

Table 2. Assumptions concerning the cost of capital.

Assumptions	Unit	Source	Value
WACC real (pre-tax)	%	Investor	5.56
WACC real (pre-tax) ERO	%	ERO	4.96

The basic indicator, with regard to the presented analysis, has been the levelized cost of electricity (LCOE):

$$\text{LCOE} = \frac{\sum_{t=1}^{n} (\text{NI}_t + \text{KO}_t + \text{KP}_t)(1+r)^{-t}}{\sum_{t=1}^{n} E_t (1+r)^{-t}} \tag{4}$$

where

LCOE—levelized unit cost of electricity;
n—period of cost averaging (economic lifetime of the project);
NI_t—investment outlays (capex) in year t;
KO_t—cost of operation (excluding fuel cost) in year t;
KP_t—cost of fuel in year t;
E—Energy production in year t;
r—discount rate;
t—year.

Currently, LCOE is the standard when it comes to the assessment and comparability of power technologies, expressing the cost of produced electricity as the value of electricity, which, throughout the entire operating period of a given technology (investment and operating phases), guarantees covering the costs of operating activities, investment outlays, costs of debt management and the required return for the investors [46–49].

The price assumptions for which the comparative analysis of the support systems was carried out were adopted in accordance with the current ERO form, which had been drawn up for the sake of the "incentive effect" assessment at the stage of submitting the application for a concession promise. The prices are presented in Table 3 and, according to ERO's assumptions, are fixed throughout the entire analysis period.

Table 3. Price assumptions adopted by the Energy Regulatory Office.

ERO Price Projections—Real	Unit	Source	Fixed Prices throughout the Period of 25 Years
Electricity selling price	€/MWh	ERO	58.76
Heat selling price	€/GJ	ERO	11.80
Price of CO_2 emission allowances	€/Mg	ERO	24.71
Price of natural gas	€/GJ	ERO	7.58
Price of capacity	€/MW	Authors' assumption	55.88

Regarding the aim of the analysis—the comparison of two support mechanisms—such an assumption seems the best solution, because ICP is calculated with the aforementioned assumptions; on the other hand, however, their use for the sake of the capacity market analyses creates a mutual point of reference.

For the sake of comparison of the two analyzed support mechanisms, a number of assumptions have been adopted concerning reconstruction of a coal CHP plant with the use of a gas turbine with a power of 90 MWe together with a heat recovery steam boiler with a total power of 200 MWt. Detailed data for the planned installation, as well as the values of investment costs and their distribution in time, are presented in Table 4.

Table 4. Basic parameters and assumptions for a new gas-fired CHP plant.

Basic Parameters/Assumptions	Unit	Value
Gross electric capacity	MWe	90
Net electric capacity	MWe	88.5
Gross heating capacity	MWt	200
Net heating capacity	MWt	200
CO_2 emission ratio	kg/MWh	244.5
Total investment costs, incl.	M€	81.42
Distribution of investment costs:		
in the 1st year of construction	%	12%
in the 2nd year of construction	%	36%
in the 3rd year of construction	%	49%
in the 4th year of construction	%	3%

The revenue side of the investment projects in question includes two main revenue positions, the revenue from the sale of electricity and the revenue from the sale of heat.

The cost side includes positions comprising yearly costs of functioning of the analysed enterprises, including costs of operation and maintenance—basic elements of these costs being the costs of fuel and energy, costs of emission, maintenance and repairs. The assumptions adopted to determine the above items are presented in Table 5.

Table 5. Basic parameters and assumptions for a new gas-fired CHP plant—the first year of operation.

Basic Parameters/Assumptions	Unit	Value
Volume of electricity sales	MWh	606,819.0
Volume of heat sales	GJ	3,126,303.1
Capacity volume offered on the capacity market	MWe	75.49
Carbon dioxide emission volume (CO_2)	Mg	364,194.89
Natural gas consumption volume	TJ	6491.89
Other variable costs (excl. fuel and environmental costs)	M€	1.38
Fixed operation and maintenance (O&M) costs	M€	2.07

Moreover, Figure 1 presents the production and sales volumes of electricity and heat, in accordance with the long-term production plans/projections. As can be seen, in the analysed period, an approximate 6.5% decrease in electricity and gas production volumes was assumed, which also had an impact on the reduction of the amount of natural gas consumption and in the level of carbon dioxide emission, to a similar extent. Attention should be paid to the differences between the actual energy sales volumes and the fixed levels of those parameters assumed by ERO—in accordance with the discussed assumptions—at the stage of assessment of the existing financial gap (the incentive effect).

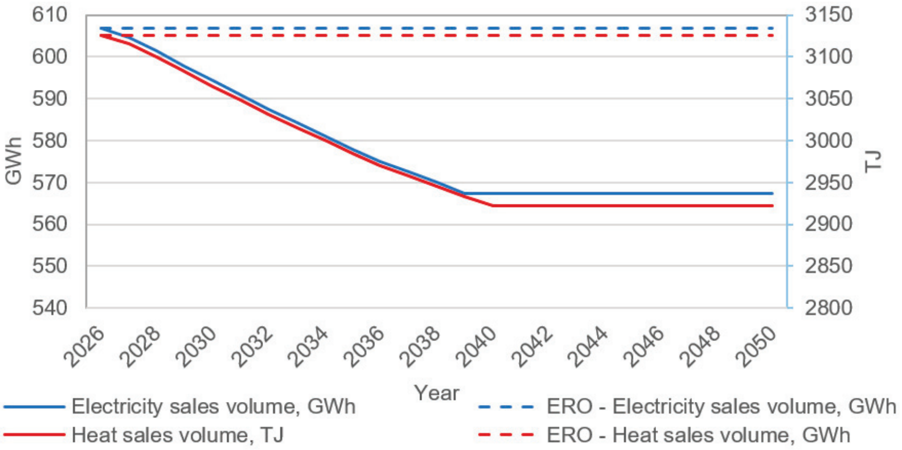


Figure 1. Heat and electricity sales plan and ERO assumptions.

3. Results

This section is divided into two parts. The first one presents the results of comparison of the two aforementioned support mechanisms, taking into account the technical and economic assumptions presented above. The second part presents the results of the scenario analysis for the fluctuating electricity price assumed by the regulator to establish the ICP and the future changes in electricity market prices.

3.1. Results for the Basic Assumptions

The calculation results for the key economic efficiency ratios for the scenario, including revenues from participation in the capacity market, as well as the individual cogeneration premium, are presented in Table 6.

Table 6. Analysis results for ERO's price assumptions.

Parameters/Results	Unit	No Support	No Support—ERO "Incentive Effect"	Ind. Cogen. Premium [2]	Capacity Market [1]
WACC (real, pre-tax)	%	5.56	4.96	5.56	5.56
NPV	M€	23.33	57.81	23.33	63.42
Internal rate of return (IRR)	%	9.14	11.74	9.14	14.70
LCOE	€/MWh	55.22	50.58	55.22	49.15

[1] For the assumed capacity price equal to 55.82 €/kW; [2] No support resulting from the positive NPV.

In the analysed option without support, the internal rate of return on investment is IRR (FCFF) = 9.14%, while the discounted value of cashflows—with a discount rate of 5.56—NPV (FCFF) = €23 million. The variant taking into account the capacity market support at the level of 55.82 €/kW presents the more favourable results. In this case, the internal return rate on investment is IRR (FCFF) = 14.70, and the discounted value of cashflows—with a discount rate of 5.56%—NPV (FCFF) = €63.24 million.

The LCOE (formula 4) value at the level of 49.15 €/MWh means that the average market prices in the investigated period would have to fall below this level in order for the project in question to cease to be profitable. The value is as much as 6 €/MWh lower than the bottom price for the no-support option.

Due to the positive NPV calculated for the sake of ERO's assessment of the "incentive effect" (at the level of €58 million), the analysed project is not entitled to the individual cogeneration premium (ICP). It should be noted that the NPV is calculated with the "minimum capital cost" assumed by ERO, with a fixed level of production, and importantly, without taking into account the replacement expenditure, thus the differences between the abovementioned ratio and the NPV value without support. The border level of an average market price below which, according to ERO's assumptions (used at the stage of assessment of the "incentive effect"), should reduce the electricity prices in order for the entity to apply for support in the form of ICP for the analysed project equals the estimated LCOE and is 50.58 €/MWh. The LCOE ratio, estimated for the same pricing assumptions, but of the cost of capital assumed by the investor and the real production and sales energy volumes, is higher and amounts to 55.22 €/MWh.

Detailed relation between the analysed support systems and the lack of thereof, and the ERO-assumed, fixed electricity price at the level of 58.75 €/MWh, are presented in Figure 2.

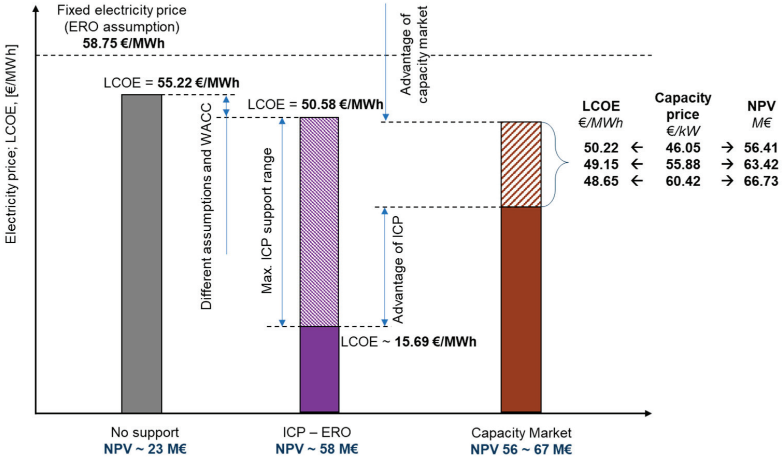


Figure 2. Results according to ERO assumptions.

In the case of the variant without any support (grey bar), the determined LCOE rate is 55.22 €/MWh, which means that the assumed electricity price—the dashed line—would have to fall below this level for the project to cease to be profitable. Due to the inability to apply for ICP, the revenues in this mechanism would be zero, and thus the results should be the same as in the no-support scenario. However, during the previous analysis it was decided to include the calculations (purple bar) made for the cost of capital and the fixed volumes of energy production and sales, assumed by ERO in the assessment of the financial gap. According to these assumptions, the electricity price would have to be below 50.58 €/MWh (estimated LCOE level) for the investment to cease to be profitable (which would mean the possibility to participate in the ICP selection process). In this situation, the ICP would be tenable up to the price level of approximately 15.69 €/MWh (which results from the maximum allowable support at the level of 34.88 €/MWh)—the dashed area of the chart.

An important issue with this support mechanism is also the fact that the aim of granting the ICP is to zero the NPV established under ERO assumptions. This means that the ICP may "increase" the too low electricity price, but only to the level of 50.58 €/MWh and not to the required amount of 55.22 €/MWh.

In the case of receiving support from the capacity market (brown bar), calculations were made for three historical price levels in the capacity market. It should be noted that the calculated LCOE falls between 50.22 and 48.65 €/MWh in the scope of prices corresponding to the minimum (46.05 €/MWh) and maximum (60.42 €/MWh) capacity auction clearing prices in the already carried out capacity auctions.

As may be noted, the LCOE values for the capacity market constitute limits for the absolute advantage of this form of support over ICP. At the same time, market prices below this level (from the perspective of cost analysis) make up for the advantage of ICP. Yet, as it will be presented further on in this work, this advantage carries a high risk within itself.

3.2. Results of the Scenario Analysis

One of the key high-risk factors in the case of cogeneration support in the form of individual cogeneration premium is the discrepancy in the scope of prices assumed to establish the ICP and the real prices of electricity in the future. To assess this relation, the following assumptions were made:

- The price of electricity taken by ERO to calculate the ICP amounts to 48.84 €/MWh—it is a level below the one determined by LCOE (50.58 €/MWh) for ERO assumptions, which entitles it to be granted ICP (one must bear in mind that the prices adopted by ERO stem from the market situation; hence, assuming such a low price would have to be purposeful or otherwise mean significant price drops in the market in the years to come).
- Based on the above assumption, an ICP (formula 1) is calculated, which amounts to 2.37 €/MWh.

In such conditions, the changes in market electricity prices have been assumed as:

- ○ +15% compared to ERO assumptions—the price rises to 56.16 €/MWh;
- ○ −15% compared to ERO assumptions—the price falls to 41.51 €/MWh.

The analysis results are presented accordingly in Figure 3 (for the 15% price increase) and in Figure 4 (for the 15% price reduction).

The analysis of the obtained results shows that the 15% increase compared to the ICP calculation allows for achieving a positive NPV at the level of €18 million (the purple bar in Figure 3), which constitutes a much better result when compared with the no-support scenario (NPV= €6 million—the grey bar). It comes from the fact that the market electricity prices allow for charging "double margins" on each kWh of sold energy, i.e., both from the capacity market and the ICP. Despite such a privileged situation, it is not the best solution, because in the same conditions, with revenue drawn from the capacity market (the brown bar in Figure 3), it is possible to reach the NPV value amounting to €50 million (for the price of € 60.42/kW).

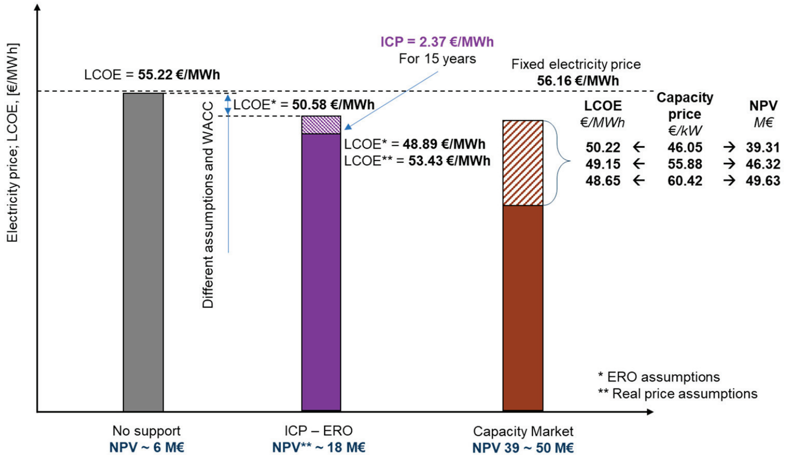


Figure 3. Results: 15% increase in electricity prices compared to the base price 48.84 €/MWh.

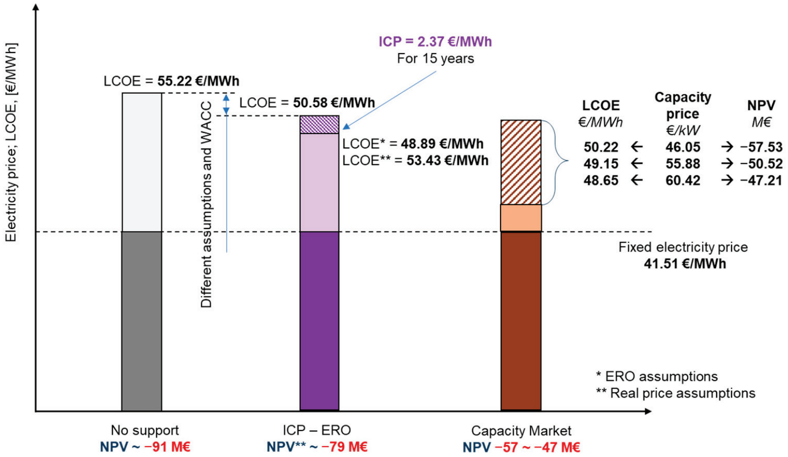


Figure 4. Results: 15% decrease in electricity prices compared to the base price 48.84 €/MWh.

On the other hand, the reduction of electricity price by 15% compared to the level assumed for ICP calculation generates the NPV of €−79 million (the purple bar in Figure 4), which means a much better result compared to the no-support scenario (NPV = €−91 million—the grey bar). However, it is still a value far from zero, because the real market prices remain at a level below those adopted by ERO for establishing the ICP; hence, the premium is insufficient to cover the emerging difference. At the same time, to achieve the ICP, one must constantly produce electricity, which, in the analysed circumstances, seems to lack the economic justification. The bright-coloured area of the bars, above the electricity price levels, depicts the losses incurred for the adopted conditions. In the case of ICP, these losses are partially levelled by the granted premium; its amount, however, as mentioned before, was calculated for different, more favourable market conditions.

The situation of the analysed enterprise in the case of support from the capacity market is presented by the brown bar; the NPV value is also negative and amounts to approximately €-47 million for the maximum analysed capacity price (60.42 €/kW). The value was estimated with regard to an assumption that energy production at such unfavourable prices will take place. It is worth noting that the capacity market (unlike ICP) is a more flexible mechanism in this respect, especially in the case of the analysed cogeneration systems, where the electricity production is but one of many revenue sources.

4. Discussion

Receiving support as part of the considered mechanisms (i.e., capacity market and individual cogeneration premium), as well as the application procedures, is associated with a number of possible risk factors.

The basic difference between the considered support mechanisms is their aim. The capacity market is a mechanism based on the rules of demand and supply. The value of "support" determined in this way is a price for the provision of a particular service—the capacity obligation. More importantly, the impact of capacity market revenue on the financial result of a unit is subject to no restriction, unlike the ICP, where the aim is the support itself—in the form of public aid—of the newly constructed cogeneration units. The support is only provided to an extent required to start the investment at a level (NPV = 0) understood as a bonus to each sold MWh. At the same time, the analysis and establishing an ICP is a one-time action carried out in accordance with the regulator's assumptions, which, in the case of a price change, may generate additional revenues—as was shown in the previous section—resulting from the difference between the price assumed by the regulator and the market reality later on.

Thus, in terms of future cashflows, both mechanisms at the very start determine the level of support, which—providing that all formal requirements are met and, in the case of ICP, the volumes of sold electricity are maintained—remains unchanged. Therefore, the difference between the two mechanisms comes down to the following:

- making the support dependent on the level of sold electricity (ICP) or the lack of such dependence (CM);
- the differences in formal requirements, including the necessity to prove the financial gap, in the case of ICP;
- the assumptions adopted by ERO when establishing the ICP;
- the level of declared capacity obligation;
- the auction clearing price reached in the capacity market.

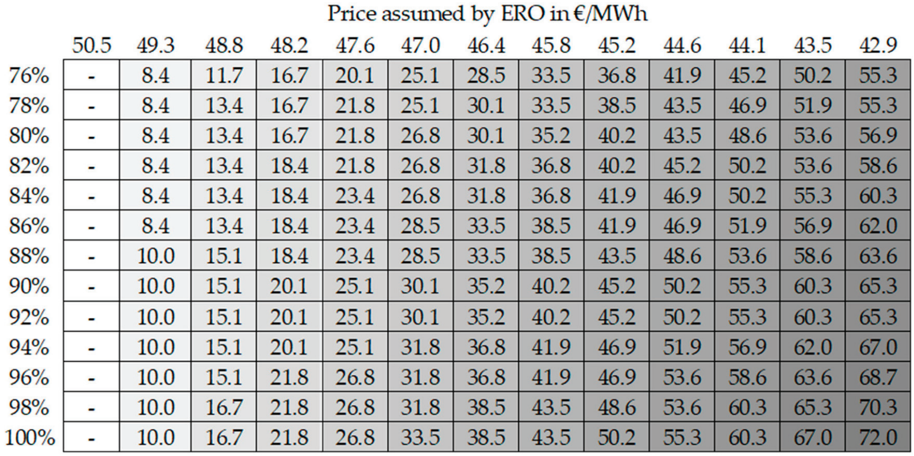
It should be noted that the future energy prices do not influence the difference between the considered support mechanisms. On the other hand, they determine the absolute economic efficiency of an investment.

From the above considerations and calculations, three main decision factors emerge, delimiting the choice between the described support mechanisms for which detailed analysis has been carried out. For the capacity market, it is most of all the auction-based price of capacity, while for the ICP, it is the assumed electricity price as of the moment of designating the support level and the future electricity sales volume.

Based on the example of these factors, a sensitivity analysis was carried out, its aim being to establish the border levels of the considered parameters in order to decide which of the support mechanisms would be more adequate (Figure 5).

As can be noted in Figure 5, for example, for the price of 47.0 €/MWh assumed by ERO to establish the ICP and with the planned electricity production of 80% of the available production potential, the minimum capacity price deciding on the capacity market's advantage as a support mechanism is 26.8 €/kW.

As may be easily noted, an ICP established with the price assumed by the regulator at 50.5 €/MWh and more gives the capacity market full advantage, regardless of the granted support price and planned electricity production volume. On the other hand, setting an ICP with a regulator-assumed price of 42.9 €/MWh and energy sales of 96% gives advantage to this mechanism—the price required on the capacity market of 68.7 €/kW exceeds the hitherto historical prices and equals itself with the capacity market auction entry price (approx. 69 €/kW).



	Price assumed by ERO in €/MWh												
	50.5	49.3	48.8	48.2	47.6	47.0	46.4	45.8	45.2	44.6	44.1	43.5	42.9
76%	-	8.4	11.7	16.7	20.1	25.1	28.5	33.5	36.8	41.9	45.2	50.2	55.3
78%	-	8.4	13.4	16.7	21.8	25.1	30.1	33.5	38.5	43.5	46.9	51.9	55.3
80%	-	8.4	13.4	16.7	21.8	26.8	30.1	35.2	40.2	43.5	48.6	53.6	56.9
82%	-	8.4	13.4	18.4	21.8	26.8	31.8	36.8	40.2	45.2	50.2	53.6	58.6
84%	-	8.4	13.4	18.4	23.4	26.8	31.8	36.8	41.9	46.9	50.2	55.3	60.3
86%	-	8.4	13.4	18.4	23.4	28.5	33.5	38.5	41.9	46.9	51.9	56.9	62.0
88%	-	10.0	15.1	18.4	23.4	28.5	33.5	38.5	43.5	48.6	53.6	58.6	63.6
90%	-	10.0	15.1	20.1	25.1	30.1	35.2	40.2	45.2	50.2	55.3	60.3	65.3
92%	-	10.0	15.1	20.1	25.1	30.1	35.2	40.2	45.2	50.2	55.3	60.3	65.3
94%	-	10.0	15.1	20.1	25.1	31.8	36.8	41.9	46.9	51.9	56.9	62.0	67.0
96%	-	10.0	15.1	21.8	26.8	31.8	36.8	41.9	46.9	53.6	58.6	63.6	68.7
98%	-	10.0	16.7	21.8	26.8	31.8	38.5	43.5	48.6	53.6	60.3	65.3	70.3
100%	-	10.0	16.7	21.8	26.8	33.5	38.5	43.5	50.2	55.3	60.3	67.0	72.0

Figure 5. Border price on the capacity market (€/kW) determining its advantage over ICP with the assumed energy price used to determine the ICP and real sales level.

If, however, the above results are juxtaposed with the real capacity market prices (55.88–60.42 €/kW), then for the ICP to gain advantage, ERO would have to lower the projected energy price by 25% (58.76 to 44.1 €/MWh) which, even in the current situation, seems very unlikely.

Another group of factors determining the relations between each of the analysed support mechanisms are the formal and legal requirements connected with each of them, and so—with respect to the aim of introduction of the capacity market (that being providing electricity supplies at every hour of the year by ensuring an appropriate level of disposal capacity in the system)—materialisation of each of the risk factors related to both the investment process and carrying out of the capacity obligation may result not only in the reduction or lack of expected revenues but also in the need to incur financial penalties.

On the other hand, in terms of risks related to commercial production, an important issue is the lack of regular revenues from ICP due to its dependence on the level of actually produced electricity. Thus, depending on the heating requirements in the years to come and both planned and unplanned periods of unavailability, the volume of produced electricity may deviate—within the anticipated return on investment horizon—from the projections at the stage of planning.

Nonetheless, the main issue in the case of ICP in the current formal and legal reality is the stage of assessment of the "incentive effect" or, more precisely, the technical end economic description form. It is not as much about the necessity to present the financial gap as it is about the adopted assumptions, which, in the current form, deviate from the market reality. Naturally, the differences between the anticipated prices and the capital cost will always emerge and constitute an element that brings about the potential of a higher revenue from a given support mechanism, as was shown above. The issue, however, is the differences related to the assumed production volumes, or replacement investments, whose amount should, at this stage, reflect the reality, and it does not. These differences result in the support mechanism entry threshold being artificially inflated, which seems illogical with regard to its preliminary aim.

5. Conclusions

Based on the analyses of the economic efficiency of a planned investment in a new gas-fired cogeneration unit, taking into account the potential support mechanisms in the form of capacity market and the individual cogeneration premium, as well as on the basis of the concluded sensitivity analyses of the risk factors with the largest impact, the following conclusions may be formulated. The mechanism of cogeneration support in the form of an individual cogeneration premium is burdened with a high risk for a unit of this type to participate in the selection process carried out by the President of ERO. The investment does not meet the preliminary qualification criteria verified at the stage of applicating for the concession promise, entitling the user to apply for this form of support.

The scenario analysis allowed us to assess the mutual relations between the two support mechanisms. The situation of the analysed enterprise in the case of granting support from the capacity market in all scenarios proved better than in the case of the ICP support. The next step was to analyse the sensitivity and thus determine the market conditions for which it would be possible to ascertain an absolute advantage of one of the mechanisms. This analysis proved that for the price assumed by ERO to determine the ICP at the level of 50.5 €/MWh and more, we can speak of the capacity market's advantage. While setting the ICP with a price assumed by the regulator at 42.9 €/MWh and with energy sales of at least 96%, the latter of the mechanisms proves more advantageous.

The goal of an individual cogeneration premium is to provide support aimed at NPV = 0, although, as was shown, the unfavourable differences in ERO's assumptions as to the market conditions may cause actual negative NPV values for the investors. Importantly, the differences may also prove advantageous for the investor. The basic feature of the ICP as a support mechanism, as well as the highest-risk factor for the considered cogeneration units operating in the fluctuating market environment, is the dependence of the real support on the volumes of produced and sold electricity. Each deviation from the volumes declared at the selection process causes the decrease in revenues and negatively influences the investment's economic efficiency.

Unlike ICP, the support from participating in the capacity market may generate a positive and unlimited NPV. It should be emphasized that also new production units, according to the capacity auction regulations, have the status of price-makers, which means that they may withdraw from a capacity auction at any time, whenever they feel that the capacity price in the next round of auction proceedings might fall below the designated level which guarantees a satisfactory revenue return on investment. Moreover, the revenues from the capacity market are independent of the electricity production and sales volume. Thus, the generation units are granted a large degree of operational flexibility, required especially in the dynamically changing market conditions. This mechanism also allows a better use of the economic potential of heat accumulators in the planned units. Therefore, from the financial implications point of view—presented in this paper as production costs, LCOE—the capacity market seems to be more adapted to market realities than ICP. The CHP unit presented in this paper could obtain NPV by EUR 33–44 million higher than in the case of ICP.

The use of the generally known methods described in our work to solve the research problem and the calculations carried out allowed for the analysis and comparison of the two governmental support mechanisms (the capacity market and individual cogeneration premium) that can potentially be used by the owners of large cogeneration gas units in Poland. Based on our results, we were also able to compare the functioning and mutual interaction of these mechanisms. The contribution of the presented research also includes the identification of existing regulatory barriers which may reduce the effectiveness of the support system. This will be helpful in developing a better and more coherent support policy in CEE (Central and Eastern Europe) countries with a significant share of cogeneration capacities.

The main limitation of this research is the engineering nature of the empirical analyses that focus on the comparison of support mechanisms in the context of market realities. There is no qualitative assessment focusing on the direction of the introduced changes and their impact on the economy as a whole. Nevertheless, the applied approach, although very limited, is—to the best of our knowledge—necessary, and, at the same time, is thus the novelty of this paper. As it was presented in the Introduction, the subject of support systems is still widely discussed. However, most of the papers focus on the qualitative aspects of designing support policy. These analyses should be enriched or assessed in the context of policy engineering and this is the goal of this publication.

The insights and relationships presented in this paper may provide information for support policy-makers as well as for researchers of this topic. Of course, this work does not in any way exhaust the issues related to the assessment of support systems. Further research should, on the one hand, enrich the analysis with qualitative aspects and, on the other hand, aim to create a multidimensional sensitivity analysis taking into account the remaining market factors such as gas prices, heat prices, etc. What is more, such analyses should be performed for the support systems available in other countries. Such a comparison would become an invaluable tool for developing a coherent energy policy.

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Nomenclature

CMU	capacity market unit
CMA	the Act on the capacity market
uCHP	the Act on promoting electricity from high-efficiency cogeneration
ERO	Energy Regulatory Office
ICP	individual cogeneration premium
PERO	President of the Energy Regulatory Office
NPV	net present value
IRR	internal rate of return
LCOE	levelized cost of energy
FCFF	free cash flow to firm
DCF	discounted cash flow

References

1. Equinor. *Equinor Energy Perspectives 2019: Long-Term Macro and Market Outlook*; Equinor ASA: Stavanger, Norway, 2019; p. 64.
2. BP p.l.c. *BP Energy Outlook 2019 Edition*; BP plc: London, UK; Available online: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2019.pdf (accessed on 21 May 2020).
3. IEA. *World Energy Outlook 2019—Analysis—IEA*; IEA: Paris, France, 2019; ISBN 978-92-64-97300-8.
4. Falcone, P.M.; Lopolito, A.; Sica, E. Instrument mix for energy transition: A method for policy formulation. *Technol. Forecast. Soc. Chang.* **2019**, *148*, 119706. [CrossRef]
5. Owen, R.; Brennan, G.; Lyon, F. Enabling investment for the transition to a low carbon economy: Government policy to finance early stage green innovation. *Curr. Opin. Environ. Sustain.* **2018**, *31*, 137–145. [CrossRef]
6. Thombs, R.P. When democracy meets energy transitions: A typology of social power and energy system scale. *Energy Res. Soc. Sci.* **2019**, *52*, 159–168. [CrossRef]
7. Pilavachi, P. Power generation with gas turbine systems and combined heat and power. *Appl. Therm. Eng.* **2000**, *20*, 1421–1429. [CrossRef]
8. Papadimitriou, A.; Vassiliou, V.; Tataraki, K.; Giannini, E.; Maroulis, Z. Economic Assessment of Cogeneration Systems in Operation. *Energies* **2020**, *13*, 2206. [CrossRef]
9. Ministerstwo Energii. *Polityka Energetyczna Polski do 2040 r.—Strategia Rozwoju Sektora Paliwowo-Energetycznego*; Ministerstwo Energii: Warszawa, Poland, 2019.
10. Parmar, A.A.; Darji, B.P.B. Capacity market functioning with renewable capacity integration and global practices. *Electr. J.* **2020**, *33*, 106708. [CrossRef]

11. European Commission. *European Commission Green Paper—A 2030 Framework for Climate and Energy Policies*; COM(2013) 169 Final; European Commission: Brussels, Belgium, 2013; pp. 1–16.
12. European Parliament Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on Energy Efficiency. *Off. J. Eur. Union* **2012**, *315*, 1–56.
13. European Parliament Directive 2004/8/EC of the European Parliament and of the Council of 11 February 2004 on the Promotion of Cogeneration Based on A Useful Heat Demand in the Internal Energy Market and Amending Directive 92/42/EEC. *Off. J. Eur. Union* **2004**, *52*, 50–60.
14. Atănăsoae, P. The Operating Strategies of Small-Scale Combined Heat and Power Plants in Liberalized Power Markets. *Energies* **2018**. [CrossRef]
15. Couture, T.D.; Cory, K.; Williams, E. *A Policymaker 's Guide to Feed-in Tariff Policy Design*; National Renewable Energy Laboratory: Golden, CO, USA, 2010.
16. Couture, T.; Gagnon, Y. An analysis of feed-in tariff remuneration models: Implications for renewable energy investment. *Energy Policy* **2010**, *38*, 955–965. [CrossRef]
17. Kemausuor, F.; Adaramola, M.S.; Morken, J. A Review of Commercial Biogas Systems and Lessons for Africa. *Energies* **2018**, *11*, 2984. [CrossRef]
18. Cramton, P.; Ockenfels, A.; Stoft, S. Capacity Market Fundamentals. *Econ. Energy Environ. Policy* **2013**, *2*. [CrossRef]
19. Komorowska, A.; Kamiński, J. A review of the 2018 Polish capacity market auctions. *Polityka Energ.* **2019**, *22*, 75–88. [CrossRef]
20. Stamtsis, G.; Doukas, H. Cooperation or Localization in European Capacity Markets? A Coalitional Game over Graph Approach. *Energies* **2018**. [CrossRef]
21. Galinato, G.I.; Yoder, J.K. An integrated tax-subsidy policy for carbon emission reduction. *Resour. Energy Econ.* **2010**, *32*, 310–326. [CrossRef]
22. Pablo-Romero, M.D.P.; Sánchez-Braza, A.; Perez, M. Incentives to promote solar thermal energy in Spain. *Renew. Sustain. Energy Rev.* **2013**, *22*, 198–208. [CrossRef]
23. Abolhosseini, S.; Heshmati, A. The main support mechanisms to finance renewable energy development. *Renew. Sustain. Energy Rev.* **2014**, *40*, 876–885. [CrossRef]
24. Sousa, J.L.; Martins, A.G. Portuguese Plan for Promoting Efficiency of Electricity End-Use: Policy, Methodology and Consumer Participation. *Energies* **2018**, *11*, 1137. [CrossRef]
25. Yang, X.; He, L.; Xia, Y.; Chen, Y. Effect of government subsidies on renewable energy investments: The threshold effect. *Energy Policy* **2019**, *132*, 156–166. [CrossRef]
26. Jung, S.H.; Feng, T. Government subsidies for green technology development under uncertainty. *Eur. J. Oper. Res.* **2020**, *286*, 726–739. [CrossRef]
27. Erdogdu, E. Implications of liberalization policies on government support to R&D: Lessons from electricity markets. *Renew. Sustain. Energy Rev.* **2013**, *17*, 110–118. [CrossRef]
28. Huijben, J.; Podoynitsyna, K.; Van Rijn, M.; Verbong, G. A review of governmental support instruments channeling PV market growth in the Flanders region of Belgium (2006–2013). *Renew. Sustain. Energy Rev.* **2016**, *62*, 1282–1290. [CrossRef]
29. Benalcazar, P.; Kamiński, J. Capacity markets and cogeneration facilities: Recommendations for Poland. *Polityka Energ. Energy Policy J.* **2016**, *19*, 61–76.
30. Falcone, P.M. Environmental regulation and green investments: The role of green finance. *Int. J. Green Econ.* **2020**, *14*, 159. [CrossRef]
31. Tucki, K.; Orynycz, O.; Wasiak, A.; Świć, A.; Dybaś, W. Capacity Market Implementation in Poland: Analysis of a Survey on Consequences for the Electricity Market and for Energy Management. *Energies* **2019**, *12*, 839. [CrossRef]
32. Sejm Rzeczypospolitej Polskiej. USTAWA z dnia 8 grudnia 2017 r. o Rynku Mocy; Dz. U. 2018 poz. 9. Warszawa, Poland, 2020; pp. 1–82. Available online: https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20180000009 (accessed on 28 October 2020).
33. Rząd Rzeczypospolitej Polskiej. Rozporządzenie Ministra Energii z dnia 18 lipca 2018 r. w Sprawie Wykonania Obowiązku Mocowego, Jego Rozliczania i Demonstrowania Oraz Zawierania Transakcji na Rynku Wtórnym; Dz.U. 2018 poz. 1455. Warszawa, Poland, 2013; pp. 1–10. Available online: https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20180001455 (accessed on 28 October 2020).

34. Rząd Rzeczypospolitej Polskiej. Rozporządzenie Ministra Energii z dnia 3 września 2018 r. w Sprawie Zabezpieczenia Finansowego Wnoszonego przez Dostawców Mocy Oraz Uczestników Aukcji Wstępnych; Dz.U. 2018 poz. 1730. Warszawa, Poland, 2013; pp. 1–10. Available online: https://www.pse.pl/rynek-mocy-dokumenty-powiazane (accessed on 28 October 2020).
35. Rząd Rzeczypospolitej Polskiej. Rozporządzenie Ministra Energii z dnia 22 sierpnia 2018 r. w Sprawie Parametrów Aukcji Głównych dla Okresów Dostaw Przypadających na Lata 2021–2023; Dz.U. 2018 poz. 1632. Warszawa, Poland, 2013; pp. 1–10. Available online: https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20180001632 (accessed on 28 October 2020).
36. Rząd Rzeczypospolitej Polskiej. Rozporządzenie Ministra Energii z dnia 2 sierpnia 2019 r. w Sprawie Parametrów Aukcji Głównej dla Roku Dostaw 2024 Oraz Parametrów Aukcji Dodatkowych dla Roku Dostaw 2021; Dz.U. 2019 poz. 1457. Warszawa, Poland, 2013; pp. 1–10. Available online: https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20190001457 (accessed on 28 October 2020).
37. Polskie Sieci Elektroenergetyczne-Polish Transmission System Operator. *Capacity Market Regulations*; Polskie Sieci Elektroenergetyczne S.A.: Konstancin-Jeziorna, Poland, 2018; Available online: https://www.pse.pl/web/pse-eng (accessed on 28 October 2020).
38. The European Commission. *Comission Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the Internal Market for Electricity*; European Commission: Brussels, Belgium, 2018; Volume 2019, pp. 54–124.
39. Benalcazar, P.; Nalepka, P. The Polish capacity market proposal vs the British model. *Polityka Energ.* **2017**, *20*, 59–72.
40. Sejm Rzeczypospolitej Polskiej. USTAWA z dnia 14 grudnia 2018 r. o Promowaniu Energii Elektrycznej z Wysokosprawnej Kogeneracji; Dz. U. 2019 poz. 42. Warszawa, Poland, 2020; pp. 1–113. Available online: https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20190000042 (accessed on 28 October 2020).
41. Rząd Rzeczypospolitej Polskiej. Rozporządzenie Ministra Energii z dnia 22 września 2019 r. w Sprawie Zakresu Danych do Wyliczenia Premii Gwarantowanej Indywidualnej i Premii Kogeneracyjnej Indywidualnej Oraz Sposobu ich wyliczania, w tym Sposobu Uwzględniania Wartości Otrzymanej Pomocy; Dz.U. 2019 poz. 1858. Warszawa, Poland, 2019; pp. 1–10. Available online: https://www.infor.pl/akt-prawny/DZU.2019.189.0001858,rozporzadzenie-ministra-energii-w-sprawie-zakresu-danych-do-wyliczenia-premii-gwarantowanej-indywidualnej-i-premii-kogeneracyjnej-indywidualnej-oraz-sposobu-ich-wyliczania-w-tym-sposobu-uwzgledniania.html (accessed on 28 October 2020).
42. Jory, S.; Benamraoui, A.; Roshan Boojihawon, D.; Madichie, N. Net present value analysis and the wealth creation process: A case illustration. *Account. Educ. J.* **2016**, *26*, 85–99.
43. Smith, L.D. Discounted cash flow analysis—Methodology and discount rates. *CIM Bull.* **2002**, *95*, 101–108.
44. Gallo, A. A Refresher on Net Present Value. *Harv. Bus. Rev.* Available online: https://hbr.org/2014/11/a-refresher-on-net-present-value (accessed on 26 October 2020).
45. Murillo-Zamorano, L.R. Economic Efficiency and Frontier Techniques. *J. Econ. Surv.* **2004**, *18*, 33–77. [CrossRef]
46. Gerdes, K.; Summers, W.M.; Wimer, J. *Cost Estimation Methodology for NETL Assessments of Power Plant Performance*; DOE/NETL-2011/1455; National Energy Technology Laboratory: Pittsburgh, PA, USA, 2011; Volume 26.
47. Kopacz, M.; Kapłan, R.; Kwaśniewski, K. Evaluation of the economic efficiency of hydrogen production by lignite gasification. *Polityka Energ.* **2019**, *22*, 21–36. [CrossRef]
48. Kost, C.; Schlegl, T.; Thomsen, J.; Nold, S.; Mayer, J. Levelized Cost of Electricity—Renewable Energies. *Fraunhofer ISE* **2012**, *2*, 79110.
49. Zhuang, X.; Xu, X.; Liu, W.; Xu, W. LCOE Analysis of Tower Concentrating Solar Power Plants Using Different Molten-Salts for Thermal Energy Storage in China. *Energies* **2019**, *12*, 1394. [CrossRef]

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Article

Grand Challenges in Central Europe: The Relationship of Food Security, Climate Change, and Energy Use

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Abstract: Pursuing various sustainable development goals is posing new challenges for societies, policymakers, and researchers alike. This study implements an exploratory approach to address the complexity of food security and nuance its relationship with other grand challenges, such as energy use and climate change, in Central European countries. A multiple factor analysis (MFA) suggests that the three pillars of food security relate differently to climate change: food affordability and food accessibility positively correlate with climate change, while food quality has a negative association with temperature rise. However, if countries switched to renewable energy resources, all three pillars of food security could be achieved simultaneously. The study also underlines regional inequalities regarding grand challenges and emphasizes the need for innovative local solutions, i.e., advances in agriculture systems, educational programs, and the development of environmental technologies that consider social and economic issues.

Keywords: climate change; food security; grand challenges; multiple factor analysis; regional studies; renewable energy; sustainable development goals

1. Introduction

The National Academies of Science, Engineering and Medicine (NASEM) have raised pressing global and grand challenges that environmental scientists and engineers have uniquely put together for advanced support [1]. The report highlights issues regarding the sustainability of food, fossil energy, and renewable (solar, water, biomass) resources; climate change control; pollution and waste; efficient, healthy and resilient cities; as well as informed decisions and policies. However, future goals of sustainable development face several hindrances due to the interaction of complex socio-economic issues.

Several studies attempt to explore the interactions and find the optimal balance among crucial social, economic, and environmental areas influencing the future of humanity [2–4]. Academics have long been analyzing new scenarios to explore how the world may change in the rest of the 21st century. In the 2000s, a promising effort was made to predict the trajectories of population change, economic growth, and greenhouse gas emissions (GHGs) by the Special Report on Emissions Scenarios

(SRES) [2]. Moss et al. [3] described a 'parallel process' of representative concentration pathways (RCPs) that may occur on a warming planet [4]. Meanwhile, various pathways have been identified to predict the future of global society, including demographic and economic features as well [5]. Shared socio-economic pathways (SSPs) are used as inputs for the climate change projections, assessed in the Intergovernmental Panel on Climate Change (IPCC) 6th Assessment Report in 2020 [6]. The new framework combines RCPs and other climate predictions in a scenario matrix architecture to support countries' ratified policies, such as those of the Paris Agreement 2025 and 2030 [7].

Scenarios for SSPs are designed to enable researchers to explore climate impacts and adaptation requirements within baseline and mitigation narratives [8] that may address broad socio-economic trends to cover futures [9]. For instance, SSP3 as the "Rocky Road", which faces enormous challenges in mitigating climate change, predicts the fragmented world of resurgent nationalism. The low priority given to tackling climate change seems to lead to extensive deprivation in some regions [10]. Inequalities worsen over time between industrialized and growth-intensive developing countries; thus, countries are focusing on achieving regional energy, and only SSP3 emphasizes the importance of food security related to development goals [11].

Long-term energy security, i.e., the continuous access to clean, reliable, and affordable energy in a variety of forms and services [12] and the scarcity of non-renewable energy resources worldwide, is a crucial issue of sustainable economic development [13]. As one of the critical inputs to agriculture, sustainable energy should also allow for long-term food security. Food security maintenance is a challenging concept as it deals extensively with food production, distribution, and consumption. The Rome Declaration on World Food Security (1996) reiterated the right of everyone to have access to safe and nutritious food, under the right to adequate food and the fundamental right of everyone to be free from hunger [14].

Attempts at improving food security may be supported by using renewable energy sources, which may mitigate the effects of climate change [15]. However, the impact of climate change on food security has been controversial in the literature. Alcamoa et al. [16] analyzed the effects of climate scenarios in Russia using the Global Assessment of Security (GLASS) model and argued that extreme climate events pose an increasing threat to the security of food systems and water resources. Climate change is affecting food quality due to rising temperatures and declining plant growth periods [17]. Global warming affects precipitation, which has a direct negative effect on soil moisture content and groundwater balance [18]. There are other important consequences of climate change besides water balance changes. Vișinescu and Bularda (2008) claimed the need to maintain and use river meadows as an anti-drought solution [19]. Thus, the impact of certain functions of drainage ditches on hydrological conditions, i.e., regulating water flow and nutrient retention, are likely to depend on the composition and structure of the biological communities in the ditches [20].

The link between energy use and climate change has been underestimated with the various dimensions of food security to addressing global challenges, such as eradicating hunger and developing sustainable food, agriculture, and renewable energy systems. As an exception, Hasegawa et al. [21] noted that the implementation of a stringent climate (change) mitigation policy has a more significant and adverse impact on global hunger and food consumption than the direct effects of climate change. In addition, the energy–climate–food security nexus has been examined mostly in case studies [22,23] or based on the food supply chain related to food security issues [24]. To our knowledge, no prior studies have examined regional differences taking the complexity of food security, energy use, and climate change into account.

In this paper, we propose that by examining the interrelations of the different dimensions of global challenges, we can gain novel insights into whether and how Sustainable Development Goals (SDGs) could be achieved simultaneously. The paper studies the relationship between climate change and energy use with the three different pillars of food security (affordability, accessibility, and quality). The novelty of this approach is to treat food security as a multidimensional construct, which may lead to more nuanced findings on how key SDGs could be solved at both a regional and global level. We rely on data collected in Central European (CE) countries between 2012 and 2018. A multiple factor analysis (MFA) is applied to compute the relationship among blocks of variables. The advantage of MFA is calculating correlations between the indices in each pillar while also taking regional disparities within CE into account.

2. Materials and Method

2.1. Data and Variables

Several systematically collected groups of indicators attempt to measure the effects of human activity on the state of the planet. In this paper, groups of variables related to climate change, energy use, and food security, including food affordability (FAF), food accessibility (FAC), and food quality (FQ), were carefully selected. Table 1 presents the variables and their descriptions for CE countries. CE covers territories based on collective historical, social, and cultural identity [25]. However, it is often divided into West-Central Europe and East-Central Europe [26]. The latter contains the Visegrád Group (V4), countries that are strategic alliance partners and strongly integrated economic counterparts. The following countries were analyzed: Austria, Belgium, Germany, the Netherlands, Switzerland, and the V4 ones (the Czech Republic, Hungary, Poland, and Slovakia).

Table 1. Descriptions of indicators.

Pillar	Period	Indicator	Source *	Abbreviation	Measurement
Climate Change	2012–2017	Air pollution	W.B.	air_pollution	Micrograms per cubic meter
	2012–2018	CO_2 emission (Cropland)	W.B., FAO	co2_crop	Gigagrams
	2012–2018	CO_2 emission (Grassland)	W.B., FAO	co2_grass	Gigagrams
	2017–2018	Soil erosion	HWSD	soil_erosion	Score (1–4) 1 = best
	2017–2018	Forest area	W.B.	forest_change	% of the total land
	2012–2018	Temperature rise	EIU	temperature_rise	Score 0 = least vulnerable
Energy Use	2012–2015	Energy intensity level	W.B.	energy_int_level	Megajoule at PPP ** GDP
	2012–2018	Renewable electricity output	EUROSTAT	ren_electric_output	% of total output
	2012–2018	Renewable energy consumption	EUROSTAT	ren_energy_cons	% of the final energy
	2012–2018	Final energy consumption from biomass and renewable waste	EUROSTAT	final_energy_cons	Thousand tons of oil equivalent
Food Affordability (FAF)	2012–2018	Food consumption as a share of household expenditure	W.B.	food_consump	% of total household expenditure
	2012–2018	Gross Domestic Product (GDP) per capita	EIU	gdp_per_capita	USD at PPP ** per capita
	2012–2018	Agricultural import tariffs	WTO	agr_imp_tarif	% (Percent)
	2012–2018	Food import dependency	FAO	food_imp_depend	% (Percent)
Food Accessibility (FAC)	2012–2018	Average food supply	FAO	food_supply	Kcal/person/day
	2012–2018	Volatility of agricultural production	EIU	agr_prod_vol	Standard Deviation (0–1)
	2012–2018	Urban absorption capacity	EIU	urban_absorb	GDP (% of real change)-period of urban growth
	2012–2018	Population growth	W.B., EIU	population_growth	% (Percent)
	2012–2018	Road infrastructure	EIU	road_infra	Score (0–4) 4 = best
	2012–2018	Port infrastructure	EIU	port_infra	Score (0–4) 4 = best
	2012–2018	Political stability	EIU	pol_stab	Score (0–100) 100 = best
	2012–2018	Public expenditure on agricultural R&D	EIU	pub_exp_agrrd	Score (1–9) 9 = highest
	2012–2018	Food loss	FAO	food_loss	Waste/supply (ton)
Food Quality (FQ)	2012–2018	Diet diversification	FAO, EIU	diet_divers	% (Percent)
	2012–2018	Dietary availability of vegetal iron	FAO	diet_veg_iron	Mg/person/day
	2012–2018	Dietary availability of animal iron	FAO	diet_anim_iron	Mg/person/day
	2012–2018	Protein quality	EIU	protein_qual	Score (0–100) 100 = best

[1] Notes: * EIU: Economist Intelligence Units; EUROSTAT: Statistical Office of the European Union; FAO: Food and Agricultural Organization; HWSD: Harmonized World Soil Database; W.B.: World Bank; WTO: World Trade Organization. **: Purchasing Power Parity.

The climate change pillar contains various World Development Indicators (WDI) from the World Bank Dataset [27] and the Harmonized World Soil Database (HWSD) [28], collected by the Food and Agricultural Organization (FAO). The pillar includes measures of air pollution (PM2.5 mean annual exposure), greenhouse gas emissions (CO_2 grass- and cropland), environment-related loss of forest area and soil erosion. Temperature rise, which is also essential to measure a country's vulnerability to climate change, was added here from the Global Food Security Index (GFSI) of the Economist Intelligence Units (EIU) Database [29] and standardized to the extent possible to facilitate cross-country comparisons.

The energy usage pillar involves the energy intensity level of primary (fossil) energy, which is the ratio between energy supply and Gross Domestic Product (GDP) measured at purchasing power parity (PPP) [27]. The energy output and consumption before transformation to similar end-user fuels (renewable electricity and refined petroleum products) and other energy indices were included in this pillar from the Eurostat Energy Database [30]—namely, final energy from combustible renewables and waste, such as solid biomass and animal products, gas and liquid from biomass, and municipal waste.

Data for food security indicators were drawn mainly from the European Intelligence Unit [29] and the Food and Agricultural Organization (FAO) [31]. Food security is defined here as the state in which people at all times have physical, social, and economic access to sufficient and nutritious food that meets their dietary needs for a healthy and active life [32]. This paper uses GFSI and FAO indicators, which are the most widely used measurements of food security at the national level. To improve the transparency and validity of the pillars, insecurity indicators are added from the World Bank Global Consumption Dataset [33] and the Tariff Online Facility of World Trade Organization (WTO) [34].

FAF measures the capacity and costs of a country's people to pay for food under normal circumstances and at times of food-related shocks. For instance, GDP per capita and food consumption expenditures of consumers to purchase food. Thus, FAF contains the agricultural import tariffs and food dependence control vulnerability to external price shocks. FAC influences the supply and the ease of access to food. FAC denotes the sufficiency of the national food supply, the risk of supply disruption, the agricultural infrastructure to expand agricultural output, the local and innovation capacity to reduce food loss as well as political stability. Finally, FQ contains the variety, nutritional quality, and availability of average diets. This category is sometimes referred to as 'utilization' because it explores the energy and nutrient intake by individuals and the diversity of the diet [31].

The selected pillars also reveal the progress of the environmental targets set by the 2030 Agenda for Sustainable Development [35]. SDGs require efforts to promote renewed policies and approaches regarding the great challenges. For example, SDG 2 relates to 'End hunger, achieve food security and improved nutrition and promote sustainable agriculture' [36]. The zero-hunger challenge supports the prevention of children's stunted growth (under the age of two), full access to adequate food all year round, sustainable food production systems, increase in smallholder productivity and income, and calling for zero loss or a waste of foods. SDG 7.1 promotes ensuring access to affordable, reliable, and renewable energy resources and services, SDG 11.6 contributes to reducing the adverse environmental effect of urban development, SDG 14.5 supports to conserving coastal and maritime areas, and SDG 15.5 aims to protect and prevent the extinction of threatened species.

2.2. Statistical Analysis

MFA was first introduced by Thurstone [37] and later described as well by Escoffier and Pagès [38]. The method is useful for analyzing a group of inter-correlating variables divided into blocks. In the first stage, a traditional principal component analysis (PCA) was performed on each variable block, and in the second stage, the blocks were made comparable through normalization by using the square root of the first eigenvalue obtained from the separate PCAs [39]. In the final stage of the analysis, a global PCA was performed on the normalized blocks of variables. Observations are represented in a lower (usually two) dimensional map; the coordinates are called factor scores. MFA provides a unique concept of partial factor scores which make it possible to position each observation by taking different groups of variables into account.

Besides balancing variable groups, MFA provides results specific to the group structure of the set of variables. For instance, the detailed groups of variables can give synthetic images and factors from separate analyses. MFA is also suitable for graphically displaying observations and their relations and hence building diverse clusters [40]. MFA is helpful to analyze different types of observations described by various groups of variables, and the method is even more valuable when the data set is large and complex [41]. It derives an integrated representation of the remarks and the relationships among groups of examined variables. The analysis was performed by FactoMiner, an R software package [42] for multivariate analysis [43].

3. Results

An MFA was conducted using the variables in Table 1. MFA first computes a series of PCAs. The relationship of the components with the global analysis was explored by computing loadings (correlations) between the components of each pillar (climate change, energy resources, and food security) and the global analysis. In this study, the analysis consists of five (T) datasets called blocks. Each block is a (I × J[t]) rectangular data matrix denoted by Y[t], where I is the number of observations and J[t] is the number of variables of the t-th block. Each data matrix is pre-processed (centered and normalized) and denoted by X[t]. Each observation is assigned a 'mass' which reflects its importance and is stored in an I × I diagonal matrix (M). The normalized blocks are concatenated into an I × T matrix called the global data matrix (Z) [38].

A standard PCA was used to estimate the singular value decomposition of the global data Z matrix:

$$Z = U\Delta V^T \text{ with } U^TU = V^TV = I, \tag{1}$$

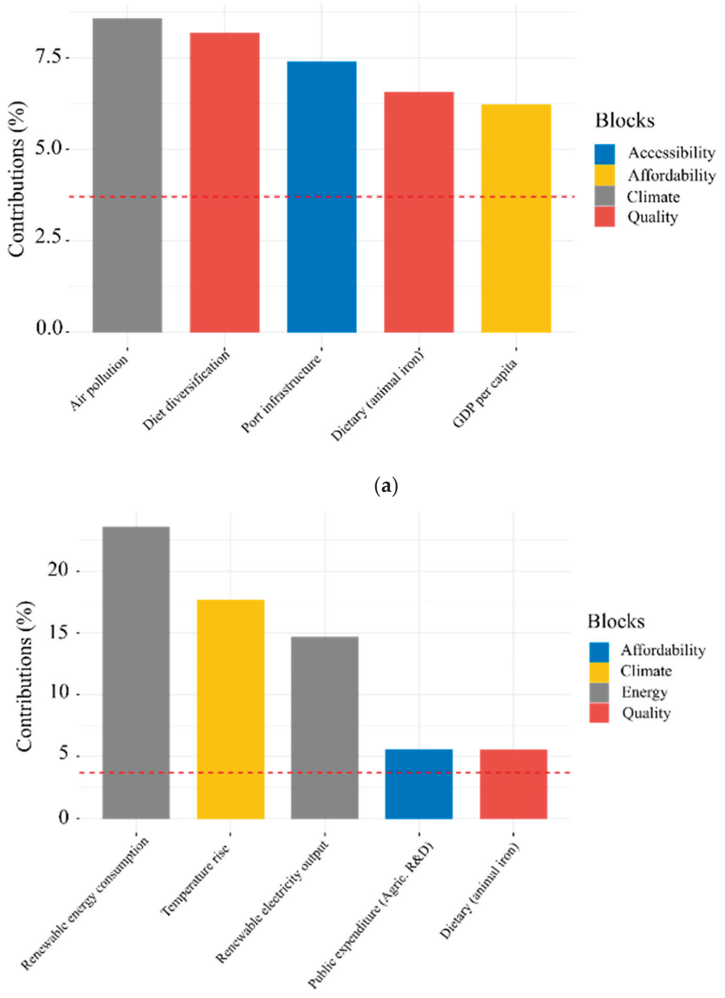
where U and V are the left and right singular vectors of Z, respectively, and Δ is the diagonal matrix of the singular values. The global (F) factor scores are obtained as:

$$F = M^{-1/2}U\Delta, \tag{2}$$

where each row represents an observation, and each column is a component (dimension). The eigenvalue of the first dimension (DIM1) corresponds to 37.8% of the inertia (Figure 1a). DIM1 is associated with air pollution, dietary diversity, port infrastructure, and GDP per capita (productivity). The second dimension (DIM2) corresponds to 13.9% of the inertia. DIM2 relatively strongly correlates with renewable energy resources, temperature rise, dietary diversity, and expenditures on agricultural R&D (Figure 1b).

3.1. Validation of Results

The validation of MFA components was carried out using several methods (Table 2): random sampling with replacement (bootstrapping), a permutation test within each block to preserve exchangeability, and exhaustive (leave-one-out) [44] and non-exhaustive (split-half) estimation [45]. These cross-validation (rotation estimation) techniques are crucial for assessing the accuracy of any predictive model in practice [46].



(**a**)

(**b**)

Figure 1. Contributions (%) of indicators and blocks to the dimensions: (**a**) the first dimension (DIM1) corresponds to 37.8% of inertia; (**b**) the second dimension (DIM2) explains 14.0% of inertia. Notes: estimation based on multiple factor analysis (MFA).

Table 2. Validation results of MFA components' explanatory power.

Component	Explained Variance (%)	Bootstrap Simulation * (*p*-value)	Permutation Test Within Each Block * (*p*-value)	Split-Half Test * (*p*-value)	LOO ** Validation (% of Variation)
1	37.8%	0.794	<0.001	0.320	6.9
2	14.0%	0.132	0.056	0.802	14.7
3	13.5%	0.502	<0.001	0.173	8.3

Notes: * N = 1000 iterations. ** Leave-one-out (LOO).

First, a bootstrap simulation was performed (N = 1000) with repetition for all indicators within each iteration. In the case of permutation tests, the permutation of the objects was applied within each block separately, resulting in a random dataset. The critical values were evaluated by the distribution of the explained variances of the MFA components. The two-sided p-values were calculated from the distributions. The null hypothesis of the test concerns to the initially explained variances are not different from the simulated ones. Both results show that the first and second components (DIM1 and DIM2) explain the largest proportion of the variance and are stable.

Regarding the split-half test, the dataset was halved into equal parts and a separate MFA was performed on each part. This process was repeated N times; the explained variance of MFA components was recorded and compared with one another by a Wilcoxon signed-rank sample test [47]. The lack of significance indicates no statistical difference between the two splits, and the second component is the most stable. In the leave-one-out cross-validation test, the MFA was executed nine times (there are nine countries in the dataset, and one country was left out each time from the analysis) to estimate the variation coefficients, i.e., the standard deviation divided by the mean. The value of the coefficient did not exceed the critical 20% in any case. Based on the results, the selected first two components were proved to be stable during validation tests and also explain a sufficient amount of variance.

3.2. Global Space and Partial Analysis

The global analysis reveals the common structure of the examined space regarding the pillars (groups of variables) in the model. It shows the relationship between the variables projecting the data set for global analysis. The projection matrix (Figure 2) contains the contributions of global factor scores (percentages).

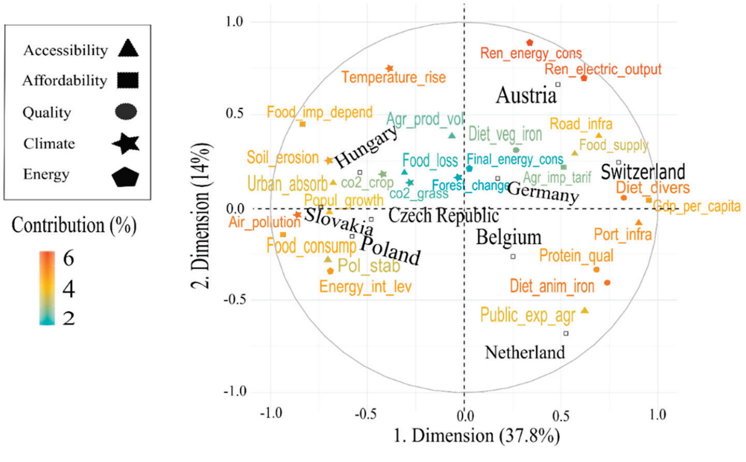


Figure 2. Individual blocks (grand challenges) and the contributions (%) of each indicator in the Central European (CE) countries to the first two dimensions (principal components). DIM1 corresponds to 37.8%, DIM2 explains 14% of inertia. Notes: estimations are based on MFA.

The global space map can be divided into four quadrants based on the two dimensions specified by the MFA. Each quadrant contains countries with different food security, climate, and energy profiles. The first quadrant (i.e., Austria, Germany, and Switzerland) can be characterized by a high level of renewable energy output and consumption, GDP per capita, food supply, and diet diversity. Germany, loading closer to the centroid, is associated with a high percentage of forest area and final energy consumption. The V4-country group forms a cluster on the other pole of the first dimension, i.e., in the second and third quadrants. The second quadrant contains Hungary, which is more strongly associated with soil erosion and temperature rise than the other CE countries. Hungary is dominated by agricultural landscapes in the plains and intensive agricultural, especially maize production, which can be damaged by high temperatures and low rainfall. Slovakia is on the border of the second and third quadrants, described by relatively high urban absorption compared to Poland and the Czech Republic due to its topography. In Slovakia, as mountain forests cover most of the country, the agricultural production is limited by the availability of arable land. The third quadrant (Poland and the Czech Republic) is characterized by relatively high food consumption, improved energy intensity level, and political stability. Finally, the fourth quadrant (the Netherlands and Belgium) can be described by more intense public expenditure in agricultural R&D, and better food (protein) quality.

Figure 2 suggests a link between the consumption of energy resources, climate change, and food security issues. For instance, the energy intensity level of primary resources (e.g., energy supply per GDP) is associated with the climate change pillar (high air pollution, soil erosion, and temperature rise), high FAF (i.e., food consumption and import dependency), and high FAC (i.e., population growth, political stability, and urban absorption). At the other pole of DIM1, GDP per capita, as a FAF indicator, is also related to better food accessibility (i.e., higher expenditure in agriculture R&D, food supply, and port infrastructure) and improved food quality (FQ) (i.e., protein quality and dietary diversity). Regarding the second dimension (DIM2), temperature rise seems to correlate with renewable energy consumption and electricity output negatively. Thus, the final energy consumption from biomass and renewables is negatively associated with GHG emissions and forest land changes.

Figure 3 shows each CE country as a single point based on the first two principal components of the global analysis. The partial points position each country from the perspective of the five different pillars. Hence, the individual and regional differences, as well as the overall status of CE countries, can be evaluated.

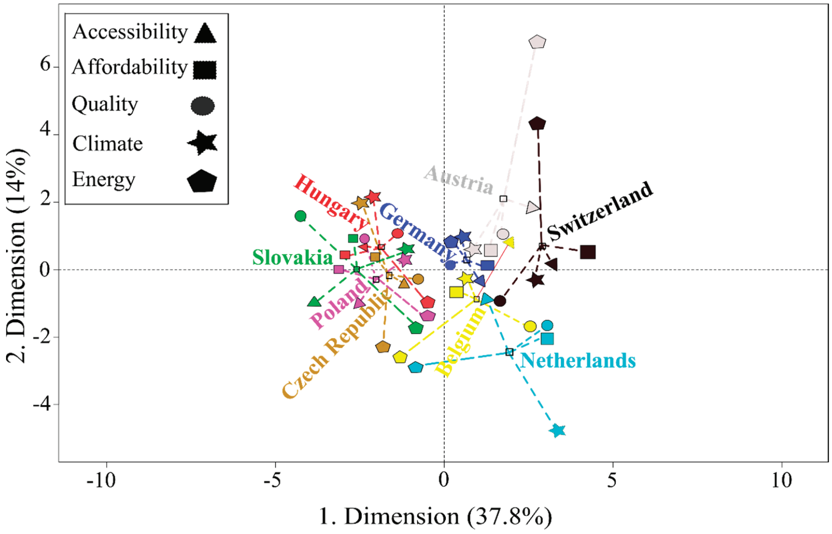


Figure 3. The contributions of each block (grand challenges) to the position of CE countries. DIM1 corresponds to 37.8%, DIM2 explains 14% of the inertia. Notes: estimations are based on MFA.

The V4 group seems to be more strongly affected by energy usage and climate change than by food security issues. Lower levels of renewable energy consumption and electricity generation can also be observed in all V4 countries. According to the partial findings, Hungary is the most exposed to the effects of climate change (especially rising temperatures). In Slovakia and Poland, on the other hand, food accessibility (urban absorption) is more distinctive. In terms of FAF, Hungary is in the worst situation, while the Czech Republic is facing major FQ issues (dietary diversity and protein quality).

In the second dimension, Austria, Germany, and Switzerland are described by high renewable energy consumption and electricity output. The Netherlands, one of the drivers of environmental protection and sustainable food policy in the EU [48], stands out for its lower risk of climate change and higher food protein quality and dietary diversity.

4. Discussion

A key finding of the MFA is that food security can be sustained if policy measures support a stable macro-environment [49], including improved food supply, better infrastructure, and less import dependency as a precursor to higher productivity. The sustainable food economy can contribute to economic growth by increasing investments (physical and human capital) and reducing macro (price and political) instability [50]. On the other hand, stability supports poverty alleviation by reducing vulnerability to sudden shocks of food prices or food availability [51]. A crucial outcome of a rural-focused regional growth policy is to achieve food security when economic growth has raised the poor above the direct poverty line and to stabilize food prices and stocks and prevent exogenous shocks [52].

Besides, food intake plays a crucial role in productivity growth, supported by better protein quality, dietary diversity, and health in the human body [53]. The findings of the current study are consistent with those of Deolalikar [54], who found that adequate childhood nutrition can also improve educational attainment and economic growth per capita. Population growth as a socio-economic indicator is positively associated with food consumption, which supports the idea that an increased and healthier food consumption reduces mortality rates [55] and may upsurge life expectancy [56]. However, in developed countries, increased food consumption is a major cause of obesity and can reduce the expected lifetime [57].

The global MFA revealed that climate change is negatively related to dietary availability and protein quality. Interestingly, the results suggest that global warming may adversely affect water availability, crop yields, and reduce food and environmental quality in the future [58]. However, better FAC is driven by population growth, urbanization, and industrialization, and increased food consumption is a challenge to sustain the required level of food quality. The findings of the present study are consistent with Khan et al. [59], who reviewed water management and crop production in China and pointed to the need to integrate climate, energy, food, environment, and population considerations. Hepperly [60] argued that increased agricultural production leads to higher energy consumption, especially fossil fuels, and thus to higher levels of greenhouse gas emissions, pollution, deforestation, and deteriorating water and food quality.

The extent of deliberate hydrological changes in Central Europe has been enormous, from small streams and ditches to the largest rivers. However, the current droughts are not only due to climate change. The long-term frequency of extreme droughts has been stable and severe in the last two or three centuries, which were also typical in the coastal part of Poland and Silesia [61]. Another important aspect is the change in plant water conditions due to the partial closure of the stomata. The impact of transient water scarcity and shortage with increasing CO_2 concentration leads to improved water-use efficiency (WUE) and less water consumption of plants due to limited transpiration [62]. In addition, the complex effect of climate change (not just rainfall) significantly limits the growth of timber (oak and pine tree stands) in Central Europe [63]. Other trees are sensitive to extreme weather events and environmental conditions, such as heatwaves [64] and late spring frost [65]. The effect of long-term climate change, extreme frosts, and sub-optimal temperatures on the earlier occurrence of flushing and flowering fruit (wine) stages [66] and on the phenology of vegetables, for instance, potato production [67], is transforming the distribution of food supply and waste in Central Europe undesirably.

The Global Target for Sustainable Energy 2030 (Development Goal 7) is to increase the share of renewable energy sources in global energy production [68] and double the global rate of energy efficiency improvement [69]. Eco-efficiency leads to sustainability, which is closely linked to the separation of energy and material intensity, the prevention and management of food waste and air pollution, recycling, the widespread use of renewable energy, as well as the enhancement of the product life cycle and consolidation [70]. The findings of our study confirm the inverse relationship between (a) renewable energy consumption and electricity generation and (b) vulnerability to temperature rise and CO_2 emissions. Mouratiadou [71] also examined the effects of irrigation of bioenergy crops based on shared socioeconomic pathways (SSPs) and found it to be the most critical factor leading to significantly higher water demand due to climate change mitigation.

Climate change and local air pollution seem to be crucial to address regional energy policy issues in the case of CE countries. Our findings confirm that energy transformation could significantly reduce greenhouse gas emissions while ensuring sufficient energy is available through greater energy efficiency and a gradually increasing share of renewable energy sources [72]. Improving decarbonization in energy-intensive industries introduces efficiency (electrification) measures and savings from renewable energy technologies [73]. Agroforestry systems provide carbon sequestration and essential wood products against the greenhouse effect [74]. Furthermore, modern biomass heating applications and liquid biofuels are expected to double from the current energy supply level by 2050 [75]. Liu et al. [76] advocate the positive effects of biofuels on final total greenhouse gas emissions and show their advantages over fossil fuels. The production of biofuel-cellulosic biomass can also reduce crude oil consumption and pollution from fossil fuels [62].

However, air pollution is not limited to energy production and is closely linked to the food system. Along the food supply chain, agricultural production, processing, and distribution generate significant pollutants [77]. The excessive use of chemical fertilizers and animal husbandry are the primary sources of agricultural emissions [78]. In addition, the exhaust fumes from industrial waste and vehicles (aircraft, trucks) related to the food system contribute expressively to air pollution [79]. Air pollution not only reduces the supply of raw ingredients but can affect consumer demand and choice [80], and food supply will eventually change food prices [81].

5. Conclusions

The main objective of this study was to examine the interrelations of climate change, energy use, and food security, i.e., food affordability, accessibility, and quality, to shed light on novel research perspectives on grand challenges and Sustainable Development Goals (SDGs). A multiple factor analysis (MFA) was used to calculate correlations between the aforementioned pillars while also taking regional disparities within CE countries into account. The advantage of MFA is that it analyzes different types of observations described by various groups of variables, and the method is even more valuable when the data set is large and complex.

Contrary to previous approaches, we consider the complexity of food security, which is necessary for exploring the subtle interconnections of socio-economic and environmental issues. We found that the different pillars of food security are likely to have different impact on other sustainable development goals, namely: (a) higher FAF and FAC are associated with climate change and higher energy intensity level of primary resources; (b) better FQ couples with lower temperature rise and higher output per capita; (c) temperature rise is adversely related to renewable energy consumption and electricity output. At the regional level, we also found that (d) the V4 group seems to be relatively more affected by energy usage and climate change than by food security issues; (e) Austria, Germany, and Switzerland make better use of renewable energy; (f) the Netherlands stands out for its lower risk of climate change and higher food protein quality and dietary diversity.

The methodological implication is that researchers need to consider the various dimensions of complex sustainable development phenomena when they endeavor to measure and examine the impacts of grand challenges. The findings are also important for policymakers in Central Europe and globally, since the demand for safe and clean food and sustainable energy grows with a rising population worldwide.

Creative solutions are needed to maximize energy, food, and water supplies while reducing adverse climate impacts. For example, a unique concept of solar spectrum unbundling in food, energy, and water systems (SUFEWS) proposes to maximize crop production while simultaneously producing energy and managing waste supply by separating the solar spectrum on a plot of land. Gençer et al. [82] suggested that reflective parabolic troughs can be located above the field to accumulate solar energy from near-infrared and far-infrared light waves, while the desired solar spectrum for food production is passed to plants on the ground. Near-infrared light can be used to generate energy, and near-far and far-infrared power supply distillation or reverse osmosis is supported by hydropower treatment processes. Besides, electricity generated by solar panels can contribute to sustainable agricultural production or be exported to nearby residents.

Progress in agriculture systems is desirable, including crop and alternative food production methods, reduction of food waste, and changes in dietary diversity [83]. Optimizing productivity by managing irrigation is essential in, for example, paddy areas and can considerably reduce global methane and nitrous oxide emissions [84]. In addition, the usage of efficient agrochemicals, improved pest and disease forecasting, the adoption of modern wastewater treatment, the optimization of animal feed, and the improvement of the livestock environment should be assessed in order to improve the impact of agricultural and energy policies on food security and climate change mitigation [85–87].

Changing the diet can also be an effective tool to reduce air pollution due to the shift from animal husbandry to crop production, as raising ruminants has a greater impact on air pollution [88]. Meanwhile, meat-free protein products are diversifying, including innovative plant-based products that can be grown from animal and plant tissue cells in culture. Such products significantly increase the affordability of food and, if accepted by consumers, can reduce the constant demand for animals [89], thereby reducing the soil, energy, and water needs of animal proteins [90] and the associated adverse effects of environmental and climate change, while increasing the availability of nutrients [91].

This study calls for the improvement of educational outcomes related to sustainable food, climate change, and energy challenges in practice. Environmental education programs should rely on the integration of strict energy-saving system maintenance, big data science, and decision analysis, and redesign them into sustainable engineering projects. Therefore, the cooperation of scholars and social science experts is essential to understand the social, cultural, economic, regional, and political contexts of environmental challenges [1]. The curricula of engineering programs could be enriched with topics related to grand challenges and their interrelations, in addition to traditional focus areas, such as climate, energy, and air pollution.

There are some limitations to this study related to the method and variables chosen. The most important is omitted-variable bias, as the studied pillar variables reflect the authors' partly subjective choice. In general, sampling error may have a stronger bias on PCA results than on the correlations among observations [92]. Another potential problem is that the scope of the study appears to be broad; however, the inclusion of several indices is required to map the subtle interactions of seemingly unrelated development goals.

To conclude, exploring the effects and linkages of grand challenges should not rely on simplistic research questions [93]. Goals related to sustainable development are difficult to delineate and implement simultaneously due to their complexity and interdependence. Hence, future research has to be carried out across different disciplines and theories (e.g., economic growth, circular economy, sustainability, resource management, and climate theories) to retrace and develop indicators that reflect the status quo of our planet and potential trajectories. For example, researchers may consider the impacts of government incentives, community development, and environmental activities. The integration of sustainable economic growth, population growth, crop production, climate change, energy use, and water supply analyses is essential for a more comprehensive and reliable assessment of the food security pillars.

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References

1. NASEM. *Environmental Engineering for the 21st Century: Addressing Grand Challenges*; The National Academies Press: Washington, DC, USA, 2019; ISBN 978-0-309-47652-2.
2. Nakicenovic, N.; Alcamo, J.; Grubler, A.; Riahi, K.; Roehrl, R.; Rogner, H.; Victor, N. *Special Report on Emissions Scenarios*; Cambridge University Press: Cambridge, UK, 2000; ISBN 0 521 80081 1.
3. Moss, R.H.; Edmonds, J.A.; Hibbard, K.A.; Manning, M.R.; Rose, S.K.; Van Vuuren, D.P.; Carter, T.R.; Emori, S.; Kainuma, M.; Kram, T.; et al. The next generation of scenarios for climate change research and assessment. *Nature* **2010**, *463*, 747–756. [CrossRef] [PubMed]
4. van Vuuren, D.P.; Riahi, K.; Moss, R.; Edmonds, J.; Thomson, A.; Nakicenovic, N.; Kram, T.; Berkhout, F.; Swart, R.; Janetos, A.; et al. A proposal for a new scenario framework to support research and assessment in different climate research communities. *Glob. Environ. Chang.* **2012**, *22*, 21–35. [CrossRef]
5. Ebi, K.L.; Hallegatte, S.; Kram, T.; Arnell, N.W.; Carter, T.R.; Edmonds, J.; Kriegler, E.; Mathur, R.; O'Neill, B.C.; Riahi, K.; et al. A new scenario framework for climate change research: Background, process and future directions. *Clim. Chang.* **2014**, *122*, 363–372. [CrossRef]
6. Kriegler, E.; Edmonds, J.; Hallegatte, S.; Ebi, K.L.; Kram, T.; Riahi, K.; Winkler, H.; van Vuuren, D.P. A new scenario framework for climate change research: The concept of shared climate policy assumptions. *Clim. Chang.* **2014**, *122*, 401–414. [CrossRef]
7. Paris Agreement. *United Nations Treaty Collection*; Paris Agreement: Paris, France, 8 July 2016.
8. Riahi, K.; van Vuuren, D.P.; Kriegler, E.; Edmonds, J.; O'Neill, B.C.; Fujimori, S.; Bauer, N.; Calvin, K.; Dellink, R.; Fricko, O.; et al. The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Glob. Environ. Chang.* **2017**, *42*, 153–168. [CrossRef]
9. van Vuuren, D.P.; Stehfest, E.; Gernaat, D.E.H.J.; Doelman, J.C.; van den Berg, M.; Harmsen, M.; de Boer, H.S.; Bouwman, L.F.; Daioglou, V.; Edelenbosch, O.Y.; et al. Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. *Glob. Environ. Chang.* **2017**, *42*, 237–250. [CrossRef]
10. Dearing, J.A.; Wang, R.; Zhang, K.; Dyke, J.G.; Haberl, H.; Hossain, M.S.; Langdon, P.G.; Lenton, T.M.; Raworth, K.; Brown, S.; et al. Safe and just operating spaces for regional social-ecological systems. *Glob. Environ. Chang.* **2014**, *28*, 227–238. [CrossRef]
11. Fujimori, S.; Hasegawa, T.; Masui, T.; Takahashi, K.; Herran, D.S.; Dai, H.; Hijioka, Y.; Kainuma, M. SSP3: AIM implementation of shared socioeconomic pathways. *Glob. Environ. Chang.* **2017**, *42*, 268–283. [CrossRef]
12. The United Nations. *The Secretary-General's Advisory Group on the Energy and Climate Change (AGECC) Energy for a Sustainable Future. Report and Recommendations*; United Nations: New York, NY, USA, 2010.
13. Popp, J.; Oláh, J.; Fekete, M.F.; Lakner, Z.; Máté, D. The relationship between prices of various metals, oil and scarcity. *Energies* **2018**, *11*, 2392. [CrossRef]
14. 14. Food and Agriculture Organization of the United Nations. In *World Food Summit-Final Report*; FAO: Rome, Italy, 13–17 November 1996.
15. Calvin, K.; Bond-Lamberty, B.; Clarke, L.; Edmonds, J.; Eom, J.; Hartin, C.; Kim, S.; Kyle, P.; Link, R.; Moss, R.; et al. The SSP4: A world of deepening inequality. *Glob. Environ. Chang.* **2017**, *42*, 284–296. [CrossRef]
16. Alcamo, J.; Dronin, N.; Endejan, M.; Golubev, G.; Kirilenko, A. A new assessment of climate change impacts on food production shortfalls and water availability in Russia. *Glob. Environ. Chang.* **2007**, *17*, 429–444. [CrossRef]

17. Fricko, O.; Havlik, P.; Rogelj, J.; Klimont, Z.; Gusti, M.; Johnson, N.; Kolp, P.; Strubegger, M.; Valin, H.; Amann, M.; et al. The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. *Glob. Environ. Chang.* **2017**, *42*, 251–267. [CrossRef]
18. Kriegler, E.; Bauer, N.; Popp, A.; Humpenöder, F.; Leimbach, M.; Strefler, J.; Baumstark, L.; Bodirsky, B.L.; Hilaire, J.; Klein, D.; et al. Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century. *Glob. Environ. Chang.* **2017**, *42*, 297–315. [CrossRef]
19. Vișinescu, I.; Bularda, M. Hard changes of Danube hydrological regime and its impact on agriculture in dammed territories. *An. Inst. Natl. Cercet. Agric. Fundulea* **2008**, *76*, 101–112.
20. Herzon, I.; Helenius, J. Agricultural drainage ditches, their biological importance and functioning. *Biol. Conserv.* **2008**, *141*, 1171–1183. [CrossRef]
21. Hasegawa, T.; Fujimori, S.; Havlík, P.; Valin, H.; Bodirsky, B.L.; Doelman, J.C.; Fellmann, T.; Kyle, P.; Koopman, J.F.L.; Lotze-Campen, H.; et al. Risk of increased food insecurity under stringent global climate change mitigation policy. *Nat. Clim. Chang.* **2018**, *8*, 699–703. [CrossRef]
22. Benites-Lazaro, L.L.; Giatti, L.; Giarolla, A. Topic modeling method for analyzing social actor discourses on climate change, energy and food security. *Energy Res. Soc. Sci.* **2018**, *45*, 318–330. [CrossRef]
23. García Kerdan, I.; Giarola, S.; Hawkes, A. A novel energy systems model to explore the role of land use and reforestation in achieving carbon mitigation targets: A Brazil case study. *J. Clean. Prod.* **2019**, *232*, 796–821. [CrossRef]
24. Bhat, R.; Jõudu, I. Emerging issues and challenges in agri-food supply chain. In *Sustainable Food Supply Chains*; Elsevier: Philadelphia, PS, USA, 2019; pp. 23–37. ISBN 9780128134115.
25. Tötösy, S. *Comparative Central European Culture*; Tötösy de Zepetnek, S., Ed.; Purdue University Press: West Lafayette, IN, USA, 2002; ISBN 1557532885.
26. Kłoczowski, J. Actualité des grandes traditions de la cohabitation et du dialogue des cultures en Europe du Centre-Est. In *L'heritage Historique de la Res Publica de Plusieurs Nations*; KUL: Lublin, Poland, 2004; pp. 29–30. ISBN 83-85854-82-7.
27. The World Bank. World Development Indicators | DataBank. Available online: https://databank.worldbank.org/data/source/world-development-indicators (accessed on 11 May 2020).
28. Food and Agriculture Organization of the United Nations. Harmonized World Soil Database v 1.2. Available online: http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/ (accessed on 11 May 2020).
29. European Intelligence Units Global Food Security Index (GFSI). Available online: https://foodsecurityindex.eiu.com/Country (accessed on 11 May 2020).
30. Eurostat Energy Database. Available online: https://ec.europa.eu/eurostat/web/energy/data/database (accessed on 11 May 2020).
31. FAOSTAT. Available online: http://www.fao.org/faostat/en/#data/GC (accessed on 5 March 2020).
32. Clay, E. Food security: Concepts and measurement. In *Trade Reforms and Food Security*; Food and Agriculture Organization of the United Nations, Ed.; FAO: Rome, Italy, 2003.
33. The World Bank, Global Consumption Database. Available online: http://datatopics.worldbank.org/consumption/ (accessed on 11 May 2020).
34. WTO Tariff Download Facility: WTO Tariff Database. Available online: http://tariffdata.wto.org/Default.aspx?culture=en-US (accessed on 11 May 2020).
35. United Nations Development Group (UNDG). *Mainstreaming the 2030 Agenda for Sustainable Development Reference Guide to UN Country Teams*; United Nations Development Group (UNDG): New York, NY, USA, March 2017.
36. Love, P. *Debate the Issues: New Approaches to Economic Challenges*; OECD Insights, OECD Publishing: Paris, France, 2016; ISBN 9789264262119.
37. Thurstone, L.L. Multiple factor analysis. *Psychol. Rev.* **1931**, *38*, 406–427. [CrossRef]
38. Escofier, B.; Pages, J. Multiple factor analysis (AFMULT package). *Comput. Stat. Data Anal.* **1994**, *18*, 121–140. [CrossRef]
39. Abdi, H.; Williams, L.J.; Valentin, D. Multiple factor analysis: Principal component analysis for multitable and multiblock data sets. *Wiley Interdiscip. Rev. Comput. Stat.* **2013**, *5*, 149–179. [CrossRef]
40. Pagés, J.; Husson, F. Multiple factor analysis with confidence ellipses: A methodology to study the relationships between sensory and instrumental data. *J. Chemom.* **2005**, *19*, 138–144. [CrossRef]

41. Pagès, J. Multiple factor analysis. In *Multiple Factor Analysis by Example Using R.*; Chapman and Hall, CRC Press: London, UK, 2014; ISBN 9781482205473.
42. European Environmental Agency R Core Team (2020). Available online: http://www.eea.europa.eu/data-and-maps/indicators/oxygen-consuming-substances-in-rivers/r-development-core-team-2006 (accessed on 26 September 2020).
43. Husson, F.; Josse, J.; Lê, S. FactoMineR: An R package for multivariate analysis. *J. Stat. Softw.* **2008**, *25*. [CrossRef]
44. Stone, M. An asymptotic equivalence of choice of model by cross-validation and Akaike's criterion. *J. R. Stat. Soc. Ser. B.* **1977**, *39*, 44–47. [CrossRef]
45. Kohavi, R. A study of cross-validation and bootstrap for accuracy estimation and model selection. *Proc. Fourteenth Int. Jt. Conf. Artif. Intell.* **1995**, *2*, 1137–1143.
46. Allen, D.M. The relationship between variable selection and data augmentation and a method for prediction. *Technometrics* **1974**, *16*, 125–127. [CrossRef]
47. Wilcoxon, F. Individual comparisons by ranking methods. *Biom. Bull.* **1945**, *1*, 80–83. [CrossRef]
48. Solorio, I. Bridging the gap between environmental policy integration and the EU's energy policy: Mapping out the "Green Europeanisation" of energy governance. *J. Contemp. Eur. Res.* **2011**, *7*, 396–416.
49. Birdsall, N.; Ross, D.; Sabot, R. Inequality and growth reconsidered: Lessons from East Asia. *World Bank Econ. Rev.* **1995**, *9*, 477–508. [CrossRef]
50. Ramey, G.; Ramey, V.A. Cross-Country evidence on the link between volatility and growth. *Am. Econ. Rev.* **1995**, *85*, 1138–1151.
51. Timmer, C.P. The macro dimensions of food security: Economic growth, equitable distribution, and food price stability. *Food Policy* **2000**, *25*, 283–295. [CrossRef]
52. Timmer, C.P. Food security and economic growth: An Asian perspective. *Asia. Pac. Econ. Lit.* **2005**, *19*, 1–17. [CrossRef]
53. Strauss, J. *The Impact of Improved Nutrition on Labor Productivity and Human Resource Development: An. Economic Perspective*; Yale University, Economic Growth Center: New Haven, CT, USA, 1985.
54. Deolalikar, A.B. Nutrition and labor productivity in agriculture: Estimates for rural South India. *Rev. Econ. Stat.* **1988**, *70*, 406–413. [CrossRef]
55. Miyamoto, K.; Kawase, F.; Imai, T.; Sezaki, A.; Shimokata, H. Dietary diversity and healthy life expectancy—An international comparative study. *Eur. J. Clin. Nutr.* **2019**, *73*, 395–400. [CrossRef]
56. Haseeb, M.; Kot, S.; Hussain, H.I.; Jermsittiparsert, K. Impact of economic growth, environmental pollution, and energy consumption on health expenditure and R&D expenditure of ASEAN countries. *Energies* **2019**, *12*, 3598. [CrossRef]
57. Walls, H.L.; Backholer, K.; Proietto, J.; McNeil, J.J. Obesity and trends in life expectancy. *J. Obes.* **2012**, *2012*, 107989. [CrossRef]
58. Kang, Y.; Khan, S.; Ma, X. Climate change impacts on crop yield, crop water productivity and food security—A review. *Prog. Nat. Sci.* **2009**, *19*, 1665–1674. [CrossRef]
59. Khan, S.; Hanjra, M.; Mu, J. Water management and crop production for food security in China: A review. *Agric. Water Manag.* **2009**, *96*, 349–360. [CrossRef]
60. Hepperly, P. Environmental, energetic and economic comparisons of organic and conventional farming systems. *Bioscience* **2009**, *55*, 573–582. [CrossRef]
61. Przybylak, R.; Oliński, P.; Koprowski, M.; Filipiak, J.; Pospieszyńska, A.; Chorążyczewski, W.; Puchałka, R.; Dąbrowski, H.P. Droughts in the area of Poland in recent centuries in the light of multi-proxy data. *Clim. Past* **2020**, *16*, 627–661. [CrossRef]
62. Van De Geijn, S.C.; Dijkstra, P. Physiological Effects of Changes. In *Atmospheric Carbon Dioxide Concentration and Temperature on Growth and Water Relations of Crop Plants*; Springer: Dordrecht, The Netherlands, 1995; pp. 89–99.
63. Misi, D.; Puchałka, R.; Pearson, C.; Robertson, I.; Koprowski, M. Differences in the climate-growth relationship of scots pine: A case study from Poland and Hungary. *Forests* **2019**, *10*, 243. [CrossRef]
64. Bauweraerts, I.; Wertin, T.M.; Ameye, M.; Mcguire, M.A.; Teskey, R.O.; Steppe, K. The effect of heat waves, elevated [CO2] and low soil water availability on northern red oak (*Quercus rubra* L.) seedlings. *Glob. Chang. Biol.* **2013**, *19*, 517–528. [CrossRef] [PubMed]

65. Puchałka, R.; Koprowski, M.; Przybylak, J.; Przybylak, R.; Dąbrowski, H.P. Did the late spring frost in 2007 and 2011 affect tree-ring width and earlywood vessel size in Pedunculate oak (Quercus robur) in northern Poland? *Int. J. Biometeorol.* **2016**, *60*, 1143–1150. [CrossRef]
66. Leolini, L.; Moriondo, M.; Fila, G.; Costafreda-Aumedes, S.; Ferrise, R.; Bindi, M. Late spring frost impacts on future grapevine distribution in Europe. *F. Crop. Res.* **2018**, *222*, 197–208. [CrossRef]
67. Pulatov, B.; Linderson, M.L.; Hall, K.; Jönsson, A.M. Modeling climate change impact on potato crop phenology, and risk of frost damage and heat stress in northern Europe. *Agric. For. Meteorol.* **2015**, *214–215*, 281–292. [CrossRef]
68. Boulanger, P.-M. Sustainable development indicators: A scientific challenge, a democratic issue. *Surv. Perspect. Integr. Environ. Soc.* **2008**, *1*, 59–73. [CrossRef]
69. Allen, C.; Metternicht, G.; Wiedmann, T. National pathways to the Sustainable Development Goals (SDGs): A comparative review of scenario modelling tools. *Environ. Sci. Policy* **2016**, *66*, 199–207. [CrossRef]
70. Shah, I.H.; Dong, L.; Park, H.S. Tracking urban sustainability transition: An eco-efficiency analysis on eco-industrial development in Ulsan, Korea. *J. Clean. Prod.* **2020**, *262*, 121286. [CrossRef]
71. Mouratiadou, I.; Biewald, A.; Pehl, M.; Bonsch, M.; Baumstark, L.; Klein, D.; Popp, A.; Luderer, G.; Kriegler, E. The impact of climate change mitigation on water demand for energy and food: An integrated analysis based on the Shared Socioeconomic Pathways. *Environ. Sci. Policy* **2016**, *64*, 48–58. [CrossRef]
72. Gielen, D.; Boshell, F.; Saygin, D.; Bazilian, M.D.; Wagner, N.; Gorini, R. The role of renewable energy in the global energy transformation. *Energy Strateg. Rev.* **2019**, *24*, 38–50. [CrossRef]
73. Lechtenböhmer, S.; Nilsson, L.J.; Åhman, M.; Schneider, C. Decarbonising the energy intensive basic materials industry through electrification–Implications for future EU electricity demand. *Energy* **2016**, *115*, 1623–1631. [CrossRef]
74. Ramachandran Nair, P.K.; Nair, V.D.; Mohan Kumar, B.; Showalter, J.M. *Carbon Sequestration in Agroforestry Systems*; Elsevier: Philadelphia, PS, USA, 2010; Volume 108, ISBN 978-94-007-1630-8.
75. Saygin, D.; Gielen, D.J.; Draeck, M.; Worrell, E.; Patel, M.K. Assessment of the technical and economic potentials of biomass use for the production of steam, chemicals and polymers. *Renew. Sustain. Energy Rev.* **2014**, *40*, 1153–1167. [CrossRef]
76. Liu, W.; Xu, J.; Xie, X.; Yan, Y.; Zhou, X.; Peng, C. A new integrated framework to estimate the climate change impacts of biomass utilization for biofuel in life cycle assessment. *J. Clean. Prod.* **2020**, *267*, 122061. [CrossRef]
77. Sun, F.; Dai, Y.; Yu, X. Air pollution, food production and food security: A review from the perspective of food system. *J. Integr. Agric.* **2017**, *16*, 2945–2962. [CrossRef]
78. Wang, H.; Zhang, X.; Ma, Y.; Hou, Y. Mitigation potential for carbon and nitrogen emissions in pig production systems: Lessons from the North China Plain. *Sci. Total Environ.* **2020**, *725*, 138482. [CrossRef]
79. Masiol, M.; Harrison, R.M. Aircraft engine exhaust emissions and other airport-related contributions to ambient air pollution: A review. *Atmos. Environ.* **2014**, *95*, 409–455. [CrossRef]
80. Ul Haque, A.; Yamoah, F.A.; Sroka, W. Willingness to reduce food choice in favour of sustainable alternatives: The role of government and consumer behaviour. *Contrib. Manag. Sci.* **2020**, 31–51. [CrossRef]
81. Palacios-Argüello, L.; Gondran, N.; Nouira, I.; Girard, M.A.; Gonzalez-Feliu, J. Which is the relationship between the product's environmental criteria and the product demand? Evidence from the French food sector. *J. Clean. Prod.* **2020**, *244*, 118588. [CrossRef]
82. Gençer, E.; Miskin, C.; Sun, X.; Khan, M.; Bermel, P.; Alam, M.; Agrawal, R. Directing solar photons to sustainably meet food, energy, and water needs. *Sci. Rep.* **2017**, *7*, 3133. [CrossRef]
83. Weidner, T.; Yang, A.; Hamm, M.W. Consolidating the current knowledge on urban agriculture in productive urban food systems: Learnings, gaps and outlook. *J. Clean. Prod.* **2019**, *209*, 1637–1655. [CrossRef]
84. Nishimura, S.; Sawamoto, T.; Akiyama, H.; Sudo, S.; Yagi, K. Methane and nitrous oxide emissions from a paddy field with Japanese conventional water management and fertilizer application. *Glob. Biogeochem. Cycles* **2004**, *18*. [CrossRef]
85. Sheriff, G. Efficient waste? Why farmers over-apply nutrients and the implications for policy design. *Rev. Agric. Econ.* **2005**, *27*, 542–557. [CrossRef]
86. Dorward, L.J. Where are the best opportunities for reducing greenhouse gas emissions in the food system (including the food chain)? A comment. *Food Policy* **2012**, *37*, 463–466. [CrossRef]

87. Tuomisto, H.L.; Hodge, I.D.; Riordan, P.; Macdonald, D.W. Does organic farming reduce environmental impacts?—A meta-analysis of European research. *J. Environ. Manage.* **2012**, *112*, 309–320. [CrossRef] [PubMed]
88. Friel, S.; Dangour, A.D.; Garnett, T.; Lock, K.; Chalabi, Z.; Roberts, I.; Butler, A.; Butler, C.D.; Waage, J.; McMichael, A.J.; et al. Public health benefits of strategies to reduce greenhouse-gas emissions: Food and agriculture. *Lancet* **2009**, *374*, 2016–2025. [CrossRef]
89. Burton, R.J.F. The potential impact of synthetic animal protein on livestock production: The new "war against agriculture"? *J. Rural Stud.* **2019**, *68*, 33–45. [CrossRef]
90. Popp, J.; Lakner, Z.; Harangi-Rákos, M.; Fári, M. The effect of bioenergy expansion: Food, energy, and environment. *Renew. Sustain. Energy Rev.* **2014**, *32*, 559–578. [CrossRef]
91. Leisner, C.P. Review: Climate change impacts on food security-focus on perennial cropping systems and nutritional value. *Plant. Sci.* **2020**, *293*, 110412. [CrossRef]
92. Hotelling, H. Relations between two sets of variates. *Biometrika* **1936**, *28*, 321–377. [CrossRef]
93. Barnes, D.; Wilkerson, T.; Stephan, M. Contributing to the development of grand challenges in maths education. In Proceedings of the 13th International Congress on Mathematical Education, Hamburg, Germany, 24–31 July 2016; Kaiser, G., Ed.; Springer International Publishing: Cham, Switzerland, 2017; pp. 703–704.

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