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Economic and Social Consequences of the COVID-19 Pandemic in Energy Sector

Edited by
Tomasz Rokicki, Piotr Bórawski and Sebastian Saniuk

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Preface to "Economic and Social Consequences of the COVID-19 Pandemic in Energy Sector"

Accepting the proposal to join the editorial process of this Special Edition was inspired by the COVID-19 pandemic and its impact on many sectors and areas of economic activity. One such area is the energy sector and the entire energy market. Here, you can see the concrete economic and social effects of the COVID-19 pandemic. They can be observed and carefully evaluated. The effects of a pandemic can be both positive and negative. On the one hand, there have been changes in the energy companies themselves, including adaptation to the needs of consumers. On the other hand, the energy market is also undergoing changes on the demand side. Models of energy consumption and distribution have changed. This involved, e.g., people being forced to spend time at home or to work remotely. The nature of work in enterprises and trade has also changed. As a result, the energy balance has changed. All of these changes can also affect energy prices and how energy is distributed. The new situation could also contribute to faster development of work on alternative energy sources or the use of renewable energy. As a result of the pandemic, innovations were introduced in many industries, which also indirectly influenced the directions of changes in the energy market and in the energy sector. The attitude of society towards energy issues has also changed. In lockdown conditions, this resource has become crucial for people. In such difficult times, society appreciates innovations and changes that should be introduced with care for the natural environment, including saving energy resources.

The purpose of the Special Issue was to collect the results of research and experience on the consequences of the COVID-19 pandemic in the energy sector and the energy market, broadly understood, that were visible after a year. In particular, the impact of COVID-19 on the energy sector in the EU, including Poland, and the US was examined. The topics concerned various issues, e.g., the situation of energy companies, including those listed on the stock exchange, mining companies, and those dealing with renewable energy. Topics related to the development of electromobility, managerial competences, energy expenditure of local government units, sustainable development of energy, and energy poverty during a pandemic were also discussed.

As guest editors of this Special Issue, we would like to extend our sincere thanks to MDPI and the *Energies* team for providing this extraordinary learning and development opportunity, and to the editorial team, especially Ms. Vicky Chen, for the continued support and attention. Such interactions are an excellent platform for scientific development, especially for young scientists, and we hope that readers will enjoy this research.

Tomasz Rokicki, Piotr Bórawski, and Sebastian Saniuk
Editors

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Article

Changes in Energy Consumption and Energy Intensity in EU Countries as a Result of the COVID-19 Pandemic by Sector and Area Economy

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Abstract: Energy is vital for the proper functioning of the various sectors of the economy and social life. During the pandemic, there have been some changes in these aspects that need to be investigated. The main objective of this article is to identify the direction of change caused by the COVID-19 pandemic in energy consumption and energy intensity in sectors and economic areas in EU countries. The specific objectives are to identify the importance of energy consumption in sectors and areas of the economy in individual EU countries; to determine the dynamics of change and variability during the pandemic in energy consumption in individual sectors and areas of the economy in EU countries, especially during the COVID-19 pandemic; to determine the changes in energy intensity of individual economic sectors and the differences in energy intensity between individual EU countries, including during the COVID-19 pandemic. Using a purposive selection method, all 27 EU Member States were selected for the study on 31 December 2020. The analysed period covered the years 2005–2020. The sources of material were literature and data from Eurostat. Descriptive, tabular and graphical methods, dynamic indicators with a fixed base and variable base, Gini coefficient, coefficient of variation, Pearson's linear correlation coefficient, and multi-criteria analysis were used for analysis and presentation. It was found that the structure of energy consumption had remained unchanged for several years, with transport, industry and households dominating. There were no significant differences between countries. The COVID-19 pandemic reduced energy consumption in all sectors of the economy, the largest in transport and services and the smaller in industry. At the same time, household energy consumption increased. As a result of the pandemic, there was an increase in energy intensity in all sectors of the economy, the largest in industry. Western European countries had a lower energy intensity of the economy than Central and Eastern European countries. There was little change over several years. Countries generally maintained their ranking. The pandemic did not change anything in this respect, meaning that it had a similar impact on individual EU countries.

Keywords: energy efficiency; reducing energy intensity; ranking of countries' energy intensity; multi-criteria analysis; sectors of the economy; households; economic effects of the pandemic; social effects of the pandemic; countries of Western Europe; countries of Central and Eastern Europe

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1. Introduction

1.1. Energy Consumption in the Economic Sectors and the Household Area

One of the most critical factors determining countries' and regions' economic and social development is access to energy. Ideally, energy sources should be readily available and cheap [1,2]. Unfortunately, this is not always the case. Therefore, countries need to reduce their energy demand, i.e., be less energy-intensive [3]. A second reason is also environmental issues [4]. Economic activity and energy consumption are closely linked;

hence the economy is called energy-dependent [5]. In the long term, economic growth and urbanisation are key factors leading to increased energy demand [6]. It is also important to remember that there is a national energy transition, meaning that both energy sources are changing (renewable energy is being developed), and production technologies are changing to more energy-efficient ones [7]. Technology transfer is promoted by globalisation [8], as is renewable energy development [9]. Such activities affect many areas of business and society. Examples include the promotion of electromobility [10], investment in renewable energy [11,12], and education toward a more environmentally responsible society [13,14].

There are differences in energy demand between the various sectors of the economy. The highest demand is reported by industry [15]. In contrast, the transport sector has the highest growth rate [16]. It all depends on the phase of economic development of a country. On the other hand, energy demand for transport grows steadily and takes up most of the total energy use in the later stages of development [17]. Innovations are needed in this sector to lower energy absorption and reduce air pollution. For example, advances in vehicle technology can reduce the energy intensity of the transport sector and improve the energy efficiency of transport operations [18]. The service sector is one of the fastest growing. Barriers can be found in this sector due to the high fragmentation of companies. The most important of these are insufficient knowledge, the low priority given to energy and financial difficulties [19,20]. In agriculture, the increase in energy demand is due to the increase in mechanisation, which leads to another issue—for example, replacing human labour with machine labour requires energy [21]. There are differences between countries. These are due to human capital characteristics, environmental conditions and the technical efficiency of crop and livestock production [22]. Interestingly, agriculture is a sector that produces more renewable energy than it consumes. By all means, progress is being made, but change is relatively slow [23]. Energy intensity may decrease with economic growth because of the technical changes that accompany this growth [24].

Household energy consumption is steadily increasing. The reason for this is the increasing share of various types of electricity-powered devices, such as computers and smartphones [25]. There are a great many factors that can influence household energy consumption. Among the most important are climate and urbanisation [26], housing characteristics, appliance use, household demographics [27,28], and population income [29]. One of the limiting factors for household energy consumption is energy prices [30]. Households seem to have the most variables determining the level of energy consumption. One of the most important is the economic factor.

1.2. Energy Policy Developments and Trends in Energy Consumption

EU energy policy is built on three pillars: competition, security of supply and sustainability. Targets such as reducing greenhouse gas emissions, increasing energy generated from renewable sources and increasing energy efficiency are also important [31–33]. Energy policy focuses on the liberalisation of the whole sector and, on the other hand, on developing a more sustainable energy sector [34–36]. All objectives have been progressively pursued and evolved. Important energy policy documents of recent years include Strategy 2010. It focuses on achieving energy efficiency targets and implementing low-carbon technologies [37]. The 2016 document on renewable energy should also be mentioned [38]. The energy policy, announced in 2015 in the 'Energy Union Strategy', is based on five closely related areas, namely: security, solidarity and trust among EU countries; full integration of the internal energy market; energy efficiency with reduced dependence on energy imports; decarbonisation of the economy; research, innovation and competitiveness towards low-carbon energy technologies [39]. In fact, energy integration within the EU has been an important objective since 2015.

In 2019, the Clean Energy for All Europeans package introduced a new comprehensive EU strategy. The aim was to achieve carbon neutrality by 2050 by facilitating a shift away from fossil fuels and replacing them with cleaner energy. One of the five targets is improving energy efficiency by saving and reducing greenhouse gas emissions. This aim assumes a 32.5% increase in energy efficiency by 2030 compared to the base year. The national targets are based on the country's relative wealth (in GDP per capita). Less wealthy countries have less ambitious targets [40].

An action plan known as the European Green Deal has been created to address the challenges of climate change and environmental degradation. It aims to help transform the EU into a modern, resource-efficient and competitive economy that achieves zero net greenhouse gas emissions by 2050 and decouples economic growth from resource consumption. The aim is to reduce net greenhouse gas emissions by at least 55% by 2030 compared to the 1990 emission levels measured. Actions must be taken in this regard to address several areas. In terms of energy policy, one objective is to prioritise energy efficiency, improve the energy performance of buildings and develop an energy sector based mainly on renewable sources. In addition, changes are envisaged in the industrial, agricultural and transport sectors [41].

1.3. The Impact of COVID-19 on Business and Social Life

The COVID-19 pandemic generally had a negative impact on the economy. However, some activities benefited from it. Gourinchas [42] pointed to the very high degree of interconnectedness and specialisation of manufacturing activities. In such a situation, the collapse of supply chains will have cascading effects on many activities. Baldwin [43] identified circular flows that arose during the pandemic. COVID-19 decreased demand for face-to-face interaction services, such as hotels, restaurants and retail. On the other hand, there has been an increase in demand for services that can be provided remotely without the need for face-to-face contact. Information and communication technology (ICT) services can be cited as an example. Differences between countries were also due to the scale of the pandemic and the restrictions put in place by governments [44]. Using Canada as an example, Slade [45] singled out activities that were restricted during COVID-19, such as short-run production of furniture, automobiles, printing, petroleum, chemicals and plastics, non-metallic minerals, and computers, electronics and electricals. However, the increase in demand in the short term was in food and beverage and paper production. In the long term, production stabilised. In wholesale trade, sales of agricultural products, motor vehicles and construction parts and materials declined. Reductions in physical goods affected virtually all industries. Retail sales fell, except for food and beverages. Lebedeva and Moskalenko [46], using Ukraine as an example and 2020 data, found that industries such as car manufacturing, leather production, light industry, furniture manufacturing, coal mining, and oil and gas extraction were most affected. De Vet et al. [47] examined industrial production in the EU27. They found a sharp decline in this production in March and April 2020 (−11.1 and −20%, respectively, compared to the previous period), coinciding with the first wave of coronavirus spread. A rebound followed this in May and June 2020 (up 13% and 10.4% change from the previous period, respectively). Changes in production value were correlated with the disease situation and the restrictions put in place. Using Korea as an example, He and Wang [48] found that there were declines in all sectors, including food sales. In this country, restrictions and limitations were not extensive, but the country's orientation towards importing and exporting goods and services was vital. Therefore, the impact of the pandemic was significant. The impact of COVID-19 on the economy may therefore be mixed. Arellana et al. [49], using Colombia as an example, found that in the first months of the pandemic, only the transport of goods increased, while the reduction was in the transport of people. Nonetheless, in the early stages of the pandemic, revenue declines were recorded in all transport sectors. Passenger transport was particularly negatively affected. Li et al. [50] found a correlation between the situation of passenger air transport worldwide and the rate of disease growth. The more morbidity there was, the more restrictions and a considerable reduction in the number of journeys. Similar results were obtained by Sun et al. [51,52] for the world and by Linka et al. [53,54] for European countries. Rahman and Thill [55] confirmed the patterns occurring based on studies in 86 countries.

The impact of COVID-19 on society is extensive and has far-reaching consequences. The economic aspects have already been presented. Social and health aspects can be mentioned next [56]. The first group can include the inability to use many services, cancellation or postponement of large-scale sporting events, avoidance of national and international travel and cancellation of services, disruption of the celebration of cultural, religious and festive events [57], stress and depression among the population, the need to maintain social distance with peers and family members [58], inability to use hotels, restaurants and places of worship [59], closure of entertainment venues such as cinemas and theatres, sports clubs, gymnasiums, swimming pools [60], postponement of examinations and remote learning [61]. In the EU countries, the pandemic had a very big impact on the tourism sector. Three countries are in the top five global travel destinations, ie Spain, France and Italy [59]. As for the health consequences for the public, the main ones mentioned are high health risks from contracting coronavirus, lack of access to medical services, and postponement of surgeries and procedures. All these restrictions meant that people had to spend a lot of time at home, only with their immediate family members. As a result, household expenses increased, including those for energy consumed.

1.4. Justification, Aims and Structure of the Article

The topics of this article are important and topical. The issues of energy consumption and energy intensity of individual sectors are essential for sustainable development and improving energy use efficiency. Ambitious targets have been set in the EU for significant energy consumption reductions and efficiency improvements. In addition, no country wants to sacrifice energy consumption for production and growth. These objectives appear to be somewhat contradictory. One possibility is to improve energy use by introducing new technologies, which should be appropriately performed in every sector. Reducing the energy consumption of households is also not insignificant. In this case, in addition to introducing energy-efficient appliances and solutions, education and a change in public habits are necessary. The background outlined in this way shows the direction of energy policy changes in the EU. The subject is important for future generations and the possibility of living in an unspoilt environment and benefiting from as yet inexhaustible energy resources. Therefore, this makes it all the more important to find out whether there have been changes in energy consumption patterns across sectors and areas of the economy during the COVID-19 epidemic. Did the pandemic significantly reduce energy consumption in particular sectors and areas? Or did it cause an increase in some? What were the differences in this respect? For aspects related to energy intensity, differences between sectors can also be identified. In addition, it would be important to identify differences between countries, whether these were exacerbated by the pandemic or reduced. In the first weeks, the pandemic certainly caused a surprise and a reduction in energy consumption, and this was an effect not anticipated in any of the forecasts. The occurrence of the pandemic worldwide was a particular problem. Of course, the impact varied from country to country and geographic region to geographic region. However, no one was immune from the effects of a pandemic. The scale and unpredictability of the phenomenon certainly had a major impact on the functioning of individual sectors and areas. The EU is reasonably coherent regarding policy objectives, including climate and energy. However, this grouping is made up of very diverse countries. It is also possible to distinguish groups of countries that are quite similar on energy issues. The conjuncture before the pandemic was very good. The changing playing field may also have caused energy consumption and intensity changes. What is new in this paper is the presentation of a comprehensive analysis of the impact of COVID-19 on energy consumption in different sectors of the economy and households. We believe that these two segments are interconnected. Remote working, for example, has somehow shifted some energy consumption from offices to employees' homes. In the case of energy intensity, it is novel to present the changes that have taken place in this respect in EU countries and to identify whether there were countries that lost during the pandemic and those that gained. A problem and limitation is the lack of comprehensive data available. Individual sectors are assessed as a whole, which somewhat limits the inference about the development of individual industries. Based on the literature review, it is known that there were differences between individual industries within the industry sector, or services within the service sector, as well as transport modes within the entire transport sector. The authors of this article have not yet encountered such a comprehensive study of the energy consumption of individual sectors and areas of the economy, as well as their energy intensity, during the COVID-19 pandemic. It will be interesting to determine whether energy consumption and intensity changes were halted during the COVID-19 pandemic and how they proceeded in individual sectors and areas. The above aspects make the research necessary and unique. The article presented here can fill a research gap.

The article's main objective is to identify the direction of change caused by the COVID-19 pandemic in energy consumption and energy intensity in sectors and areas of the economy in EU countries.

The specific objectives are:

1. Identifying the importance of energy consumption in sectors and areas of the economy in each EU country;
2. To determine the dynamics of change and variability during the pandemic in energy consumption by sector and economic area in EU countries, particularly during the COVID-19 pandemic;
3. To determine changes in the energy intensity of individual economic sectors and how this varies between EU countries, including during the COVID-19 pandemic.

The article seeks the answers to three research hypotheses:

Hypothesis 1. *The COVID-19 pandemic affected the decrease in energy consumption in EU countries in the material (industry) and customer contact (services) sectors, while it caused an increase in households.*

Hypothesis 2. *The occurrence of the COVID-19 pandemic has hampered the favourable development of energy intensity reductions in individual economic sectors in EU countries.*

Hypothesis 3. *Western European countries were characterised by lower energy intensity than Central and Eastern European countries, but these differences have decreased steadily.*

The organisation of the work is as follows: Chapter 1 provides an introduction to the topic. The importance of energy consumption in sectors and areas of the economy is presented, as well as EU energy policy trends and objectives. The impact of COVID-19 on various economic and social activities is also shown. This section also includes the rationale and objectives of the article. Section 2 proposes methods to identify energy consumption and energy intensity changes in EU countries. In Section 3, the research findings were presented. In Section 4, the reference is made to other research results that dealt with the relationships tested. Furthermore, the main conclusions of this paper can be found in Section 5.

2. Materials and Methods

2.1. Data Collection, Processing, and Limitations

Using a purposive sampling method, all 27 EU Member States were selected for the study as of 31 December 2020. The UK was a member of the EU until 31 January 2020. In addition, in 2020, detailed statistical data on this country were no longer collected by Eurostat. It was, therefore, decided not to include this country in the analyses.

The study period covered 2005–2020, particularly 2019 and 2020. The adoption of such a period is justified on the merits. In May 2004, there was an extensive enlargement of the EU with ten new countries. The year 2005 was the first full year in the enlarged membership. Bulgaria and Romania joined in 2007, and Croatia in 2013. By 2019, changes in energy consumption and energy intensity due to the normal functioning of the economy can be observed. In 2020, there was an economic crisis caused by the COVID-19 pandemic. The European continent was quite severely affected by the pandemic.

The literature on the subject and statistical data available in the Eurostat database were used for research purposes. Some limitations were the datasets available and their detail. We could not analyse individual industries in detail, so we focused on sectors and areas of activity. Additionally, the 2021 data had not yet been published; the most recent data were for 2020, which was the first year of the pandemic, and, according to various analyses, this was when the most significant changes in energy consumption occurred. By 2021, businesses and society had already adapted to some extent to the new reality and were able to react accordingly. Therefore, the lack of data from 2021 will not distort the analysis results.

2.2. Applied Methods

The research was divided into stages. Figure 1 shows a diagram of the conducted research.

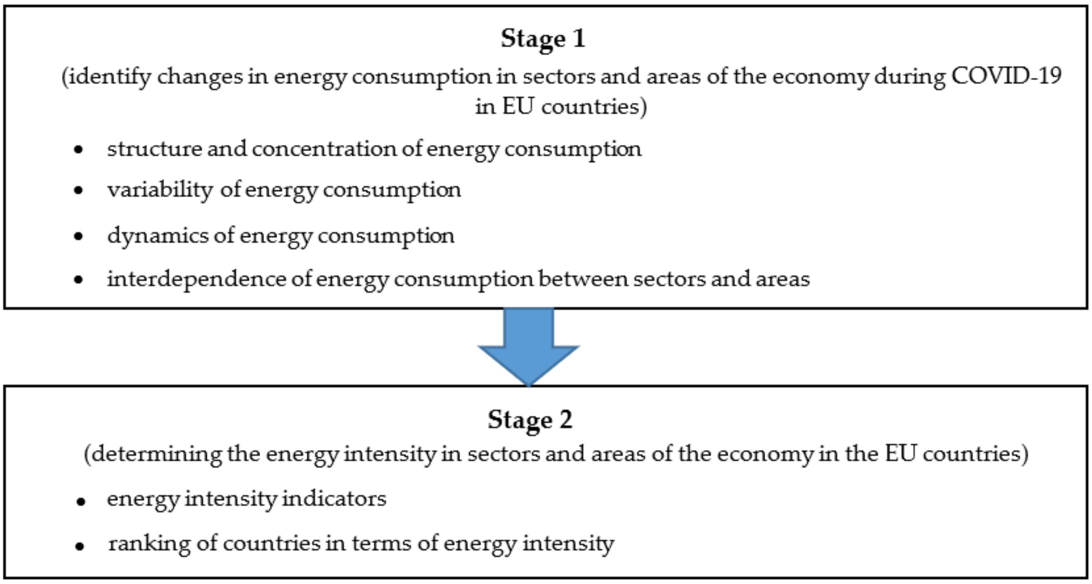


Figure 1. Diagram of the conducted research.

The research conducted was divided into two stages. In the first stage, the collected data were statistically analysed using selected indicators of structure, measures of location and variability, as well as selected measures of dynamics and correlation. Descriptive methods (tabular and graphical) were also used in this stage.

The complete picture of the structure of the surveyed community is provided by the absolute number of a given part of the community. The easiest way to present the structure of a community is the structure indicators (frequency, relative numbers) expressing the share of a part of the community (n_i) in the whole community ($\sum n_i$). This measure assumes values from 0 to 1, and the sum of all indicators for the whole population is 1. Sometimes it is useful to know how many statistical units have a value that does not exceed the assumed level of the indicator, e.g., 50%. Then we determine the cumulative structure indicators by summing up the indicators for the following parts of the community. For some variables, information on the degree of concentration and the evenness of the variable distribution among the individuals making up the collective may be equally valuable. One widely accepted measure of this kind is the Gini coefficient, which can be calculated using the following formula [62]:

$$G = \frac{\sum_{i=1}^{n}(2i - n - 1)x_i}{n^2\overline{x}} \quad (1)$$

where: n—the size of the population; x_i—the value of the variable for the *i-th* statistical unit; $\overline{x}$—arithmetic mean of the variable in the whole population.

Statistical data analysis aims to obtain a synthetic representation of the results of a study using appropriate numerical characteristics (statistical parameters). The following groups of parameters are most commonly used in the analysis of community structure:

- Measures of position;
- Measures of dispersion (variability, dispersion);
- Measures of asymmetry.

The classic measures of the position include the arithmetic mean. For a detailed series, it is defined as the sum of the elements of the series divided by its size. The arithmetic mean is a good measure of the average characteristic level in the studied population only concerning a population with a low degree of variation. It is also sensitive to extreme observations. The lower the variation of a series, the higher the cognitive value of the average. Therefore, when interpreting it, it is necessary to know the level of variation in the data. Of the several measures available, the best is the variance and the root of the variance, i.e., the standard deviation. The variance for a detailed series is calculated from the formula [63]:

$$\sigma^2 = \frac{1}{n}\sum_{i=1}^{n}(x_i - \overline{x})^2 \tag{2}$$

It is convenient to assess the degree of variation, especially when comparing two or more communities, using the coefficient of variation, which is the quotient of the arithmetic mean and the standard deviation. Coefficients of variation are useful when comparing several communities from the point of view of one characteristic or one community from the point of view of several characteristics. Large values of the coefficient of variation indicate a high degree of variation in the population concerning the characteristic under study.

Another type of analysis is the search for relationships between characteristics. Most often, we are interested in examining a community for two characteristics. If both are measurable, then the recommended way to assess the relationship is Pearson's linear correlation coefficient. For two detailed series, x and y, this coefficient is given by the formula [64]:

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{x})^2 \sum_{i=1}^{n}(y_i - \overline{y})^2}} \tag{3}$$

Values of Pearson's linear correlation coefficient range from $\langle -1{,}1 \rangle$. The greater the absolute value of r_{xy}, the stronger the relationship between the characteristics.

In the study presented in this article, we consider changes in the phenomena of interest over time. Statistics offers a group of measures used to analyse time series dynamics. The individual dynamics indices are the most popular in terms of occurrence. Like all other measures of this kind, they fall into two groups:

- Fixed base (single base) indices;
- Indexes with a movable base (chain).

Univariate dynamics measures are used to determine changes in the level of a phenomenon that has occurred in successive periods compared to the level of that phenomenon in the period adopted as the base (baseline) period. The single-basis dynamic index is calculated from the formula [65]:

$$i_{t/k} = \frac{y_t}{y_k}. \tag{4}$$

where: y_t—the magnitude of the phenomenon in the study period; y_k—the magnitude of the phenomenon in the baseline period.

Chain measures of dynamics are used to assess the changes that have occurred in the level of a phenomenon in a given period compared to the previous period. The dynamic chain index is calculated from the formula [65]:

$$i_{t/t-1} = \frac{y_t}{y_{t-1}} \tag{5}$$

Dynamics indices determine the ratio of the magnitude of the phenomenon under study in two different periods. They are unmeasured quantities. For interpretation, they are multiplied by 100 and expressed as a percentage. An index value less than 1 (100%) indicates a decrease in the level of the phenomenon, while a value greater than 1 (100%) indicates an increase.

Stage two focuses on the construction of rankings of EU Member States in terms of energy intensity in individual economic sectors based on purpose-built evaluation criteria, which have been given estimated weighting values.

In the second phase of the research conducted, a multi-criteria analysis of the EU countries was carried out based on four constructed evaluation criteria: K1–K4. These criteria expressed the ratio of final energy consumption to gross value added in a given sector: industry (K1); agriculture, forestry and fisheries (K2); services (K3); and transport (K4). The selection of the above criteria was inspired by the work of Graczyk [66], in which the author presents a set of indicators for sustainable energy development in three dimensions: social, economic and environmental, and one of the economic indicators for energy consumption is the energy intensity index.

In multi-criteria analyses, criteria are given weights to express their importance. These can be adopted arbitrarily using, for example, expert judgements or determined in a more objective way using specific numerical procedures. One method of determining objective weights is based on entropy, the so-called Shannon entropy method. Entropy determines the degree of disorder in a set. It allows the significance of individual criteria to be determined from the divergence of the values of each criterion. The Shannon method consists of several steps described in detail by Kobryn [67].

The result of the study is the construction of a ranking of EU countries based on the adopted evaluation criteria. Using the Shannon entropy method, the weights of the individual criteria were determined at the following levels: K1-40%, K2-32%, K3-18%, K4-10%. Rankings were made and then compared among themselves for the years: 2005, 2010, 2015, 2019 and 2020.

Decision support methods can be divided into single-criteria and multi-criteria. Often the very nature of the decision problem results in its multi-criteria nature. This is the case when decision-making requires the consideration of at least several decision options, each of which is influenced by a number of factors that determine its acceptability. Among the multi-criteria decision-making methods, there are mainly two basic groups of them [67]:

1. Methods based on the utility function;
2. Methods based on superiority relationships.

Utility function-based methods involve a "general to specific" approach. It consists of considering individual decision options (offers, operators etc.) separately from the point of view of each criterion and then aggregating the information thus obtained into a single whole, which may be a specific synthetic indicator (or function). The latter is based on superiority relationships. In contrast to the first, it implements a 'bottom-up' approach. We construct an overall superiority relationship between objects based on partial relationships (constructed for each criterion separately). The representative of this group of methods is the POMETHEE II algorithm (*Preference Ranking Organisation Method for Enrichment Evaluations*) [68]. The *M* objects analysed using *K* evaluation criteria can be presented in the following few steps.

Step 1

The objects must be compared in pairs for each criterion separately, which amounts to counting the following differences:

$$d^k\left(O_{[i]}, O_{[j]}\right) = O^k_{[i]} - O^k_{[j]}, \quad (6)$$

where $O^k_{[i]}, O^k_{[j]}$ denote the ratings of options *i* and *j* for criterion *k* (*i,j* = 1, . . . , *M*; *k* = 1, . . . , *K*).

Step 2

Based on the calculated differences in step 1, so-called pairwise object comparison preferences are created according to a given criterion. This boils down to applying one of the preference functions, the values of which are in the interval [0,1]. The preferences for stimulants and destimulants are given the forms respectively:

$$P^k\left(O_{[i]},O_{[j]}\right) = F^k\left\{d^k\left(O_{[i]},O_{[j]}\right)\right\}, \tag{7}$$

$$P^k\left(O_{[i]},O_{[j]}\right) = F^k\left\{-d^k\left(O_{[i]},O_{[j]}\right)\right\}, \tag{8}$$

Each preference function has the important property that if P^k $(O_{[i]}, O_{[j]}) > 0$ then P^k $(O_{[j]}, O_{[i]}) = 0$.

Step 3

When all criteria are considered, calculate aggregated preference indices for each pair of objects $O_{[i]}$ and $O_{[j]}$. This procedure is performed using the formulas:

$$\Pi\left(O_{[i]},O_{[j]}\right) = \sum_{k=1}^{K} w_k P^k\left(O_{[i]},O_{[j]}\right), \tag{9}$$

$$\Pi\left(O_{[j]},O_{[i]}\right) = \sum_{k=1}^{K} w_k P^k\left(O_{[j]},O_{[i]}\right), \tag{10}$$

This index indicates the extent to which, overall, in terms of all criteria, object $O_{[i]}$ is preferred over object $O_{[j]}$ or object $O_{[j]}$ over object $O_{[i]}$.

Step 4

Calculation of preference flows for each object. First, calculations of positive flowsΦ^+ $(O_{[i]})$ and negative flowsΦ^- $(O_{[i]})$ are made:

$$\Phi^+\left(O_{[i]}\right) = \frac{1}{m-1}\sum_{O_{[i]}\in O}\Pi\left(O_{[i]},O_{[j]}\right), \tag{11}$$

$$\Phi^-\left(O_{[i]}\right) = \frac{1}{m-1}\sum_{O_{[i]}\in O}\Pi\left(O_{[j]},O_{[i]}\right), \tag{12}$$

Positive preference flow should be interpreted as the degree to which object $O_{[i]}$ is superior to all other objects, while negative flow tells to what extent object $O_{[i]}$ is superior to all other objects.

Step 5

Calculation of net preference flows Φ $(O_{[i]})$ according to the formula:

$$\Phi\left(O_{[i]}\right) = \Phi^+\left(O_{[i]}\right) - \Phi^-\left(O_{[i]}\right), \tag{13}$$

The values of the net preference flows of the offers are in the range [−1,1], and their sum is 0. Based on the net preference values, the final ranking of the sites can be constructed by arranging them in descending order of the indicator's value.

In the PROMETHEE II algorithm presented here, step 2 is particularly noteworthy, in which a preference calculation has to be performed using appropriate top-down functions. Of the proposed functions, the Gaussian function was used, which is expressed by the formula:

$$P^k\left(O_{[i]},O_{[j]}\right) = 1 - exp\left(-\frac{d^k\left(O_{[i]},O_{[j]}\right)^2}{2\sigma^2}\right), \tag{14}$$

where σ^2 denotes the variance of the scores for the *k-th* criterion.

The Gaussian function has quite a few advantages over the other functions in the PROMETHEE II method. The preference index reacts approximately linearly for medium values of the preference function, rendering almost proportional relationships for different pairs of objects. In contrast, the preference indexes are close to each other within very large values of the preference function. The same is true for minimal differences—here, the preference indices are close to each other.

Having at our disposal a series of rankings created, for example, for successive periods, we can check whether the distributions of positions obtained by the objects can be considered similar from a statistical point of view. Two rankings are compared simultaneously. For this purpose, we used the Wilcoxon rank-sum test (also called the Wilcoxon paired rank test) [69]. This test is a non-parametric alternative to the paired observation *t*-test, but unlike it, it does not require the assumption of the normality of the distribution of observation differences to be met. It takes into account not only the sign of the paired observations but also the magnitude of the difference between them and, more precisely, the ranks of these differences. In our case, acceptance of the hypothesis being verified will mean that the rank distributions for the relevant years do not differ and that the differences in positions occupied by countries are not statistically significant. Thus, the hypothesis on the effect of changes in preferences for particular criteria on the position of countries in the ranking is also verified.

3. Results

3.1. Structure and Concentration of Energy Consumption in EU Countries by Sector and Area

A general decline can be observed when total final energy consumption between 2005 and 2020. In 2019, it was 5.2%, to reach a value of 12.9% in 2020, an increase in the rate of decline in energy consumption in one year of 7.7 percentage points. Looking at energy consumption by sector, it can be seen that only the agriculture, forestry and fisheries sectors recorded a slight increase of 3.1%, while the other sectors were characterised by a decrease in this figure (Figure 2). The industrial sector (16.0%) experienced the most significant decrease over the period under review, followed by the transport sector (10.5%), households (6.8%) and the services sector (5.1%). In addition, it should be noted that there was a clear reduction in final energy consumption in the transport sector in the last year of the period under review, which directly translated into a decrease over the entire period analysed, despite small but systematic increases between 2011 and 2019.

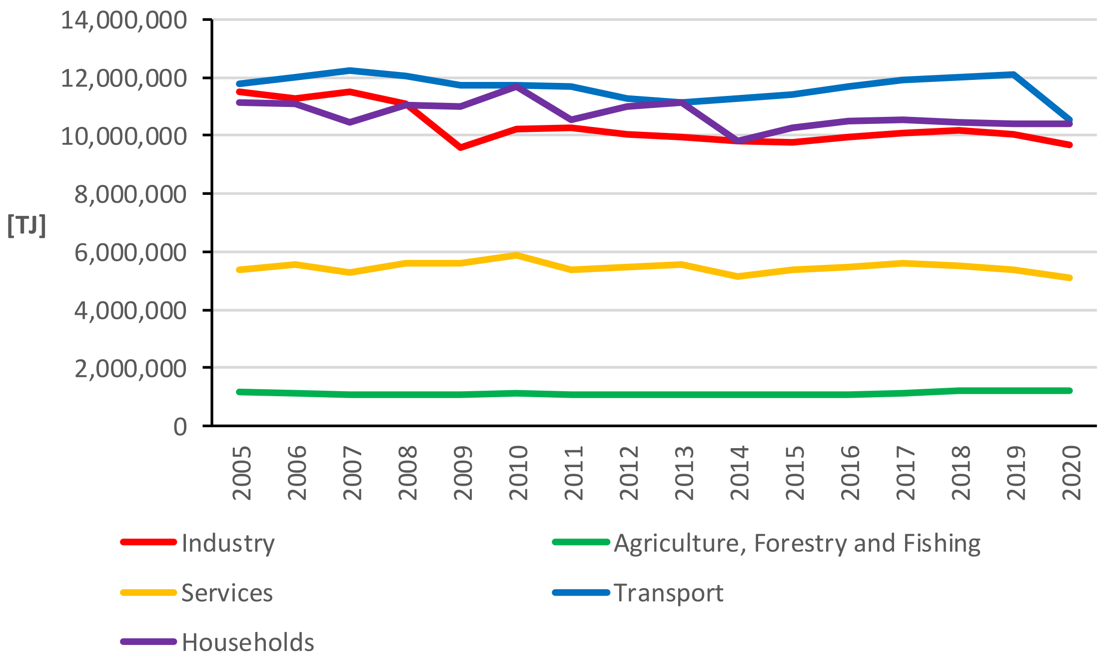


Figure 2. Final energy consumption by sector and area in EU countries from 2005 to 2020.

Figure 3 shows the structure of each EU country's final energy consumption by economic sector in 2020. The transport, industry and household sectors had the highest levels of final energy consumption in the EU countries. In contrast, the agriculture, forestry and fisheries sectors had the lowest and most stable levels.

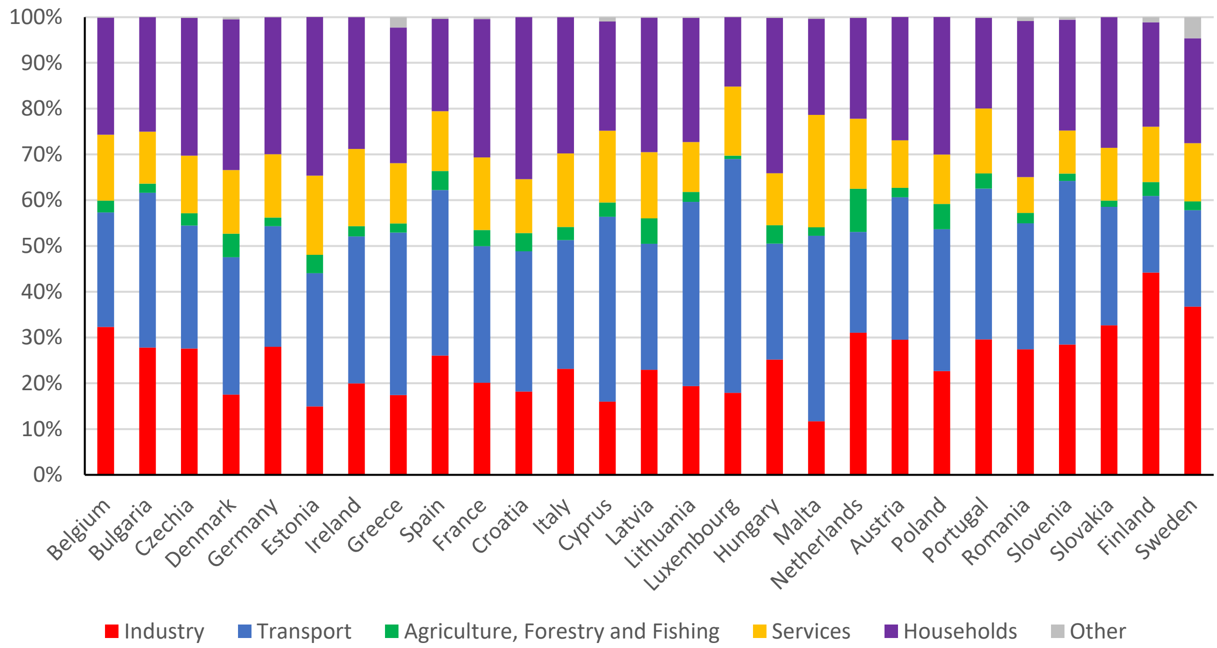


Figure 3. Structure of final energy consumption by sector and area in EU countries in 2020.

On average, the industrial, transport and household sectors accounted for around 80% of total energy consumption in the respective economies in 2020. In the industrial sector, the largest share occurred for Finland (44.2%), while the smallest share occurred for Malta (11.7%). In the transport sector, on the other hand, the highest share of energy consumption was found in Luxembourg (51.1%) and the lowest in Finland (16.7%). When analysing the household sector, the highest share of energy consumption is found in Croatia and Estonia (35.4% and 34.6%, respectively), while the lowest is in Luxembourg (15.2%).

In the next step of analysing the structure of final energy consumption in individual sectors, calculations were made relating to the degree of concentration and the evenness of its distribution among the Community countries. The results of the calculations, in the form of estimated Gini coefficients, are summarised in Table 1. The blue colour indicates the highest index results in a given sector, while the red colour indicates the lowest.

Table 1. Estimated Gini coefficient values for final energy consumption by sector and area in EU countries from 2005 to 2020. Blue indicates the best performer in a given period, and red the worst performer.

Sector	Gini Coefficient				
	2005	2010	2015	2019	2020
Industry	0.607	0.633	0.643	0.622	0.623
Agriculture, forestry and fisheries	0.614	0.617	0.646	0.611	0.625
Services	0.612	0.621	0.646	0.615	0.622
Transport	0.608	0.620	0.629	0.604	0.622
Holdings home	0.606	0.622	0.630	0.598	0.618

It should be noted that the values of the Gini coefficients for the selected years did not differ significantly across the different economic sectors. Their values exceed 0.6, which indicates a moderately high concentration of energy consumption in five of the 27 EU countries, which include: Germany, France, Italy, Spain and Poland. Moreover, the stability of this coefficient in individual sectors over the period under study is also apparent, which means that the level of concentration of final energy consumption in the EU countries has been maintained.

3.2. Variability of Energy Consumption in EU Countries by Sector and Area

Between 2005 and 2020, the final energy consumption variation coefficients were calculated for each country by selected economic sectors (Table 2). The three highest coefficient scores in each sector are marked in blue font and the three lowest in red font.

Table 2. Coefficient variation values for final energy consumption by sector and area in EU countries from 2005 to 2020. Blue indicates the three best performers in a given sector, and red the three worst performers.

Country	Coefficient of Variation				
	Industry	Agriculture, Forestry and Fishing	Services	Transport	Households
Austria	2.07%	2.30%	7.50%	4.10%	3.50%
Belgium	3.19%	8.80%	4.00%	3.70%	6.70%
Bulgaria	15.51%	19.20%	10.40%	8.80%	4.40%
Croatia	16.36%	3.40%	5.50%	5.40%	7.20%
Cyprus	16.57%	6.50%	12.30%	7.30%	5.70%
Bohemia	11.22%	7.80%	3.00%	5.20%	4.20%
Denmark	10.88%	8.70%	3.60%	4.80%	3.70%
Estonia	18.08%	12.80%	7.80%	4.60%	4.30%
Finland	6.22%	4.00%	5.20%	2.60%	5.20%
France	6.81%	1.80%	4.70%	3.90%	5.70%
Germany	3.05%	76.50%	8.00%	2.90%	5.90%
Greece	19.06%	61.20%	7.20%	15.10%	13.20%
Hungary	18.39%	15.00%	18.30%	9.40%	6.10%
Ireland	11.62%	18.70%	7.20%	9.00%	8.70%
Italy	16.21%	5.50%	7.50%	8.90%	4.50%
Latvia	8.52%	13.80%	5.20%	7.90%	10.70%
Lithuania	6.11%	4.40%	3.90%	14.50%	4.30%
Luxembourg	10.37%	8.00%	12.20%	7.90%	4.00%
Malta	10.51%	22.8%	22.10%	11.10%	15.60%
Netherlands	6.27%	4.70%	4.80%	6.40%	8.60%
Poland	6.98%	6.70%	6.40%	17.50%	4.80%
Portugal	11.01%	8.70%	9.50%	7.90%	6.70%
Romania	13.30%	25.3%	9.20%	13.00%	3.10%
Slovakia	5.78%	7.10%	19.40%	8.40%	10.40%
Slovenia	12.17%	4.00%	8.60%	8.70%	9.50%
Spain	14.11%	8.20%	6.00%	11.30%	4.40%
Sweden	3.54%	7.30%	2.80%	3.40%	4.60%
EU-27 average	10.52%	13.82%	8.23%	7.91%	6.51%

The average observed variability in the industrial sector over the period under study was 10.5%, with the highest variability recorded in Greece (19.06%), Hungary (18.39%) and Estonia (18.08%). Only Hungary experienced an increase in energy consumption over the period under review, while the other two countries had high variability due to significant decreases in energy consumption. In contrast, the lowest coefficient of variation occurred in Austria (2.07%). Significantly greater differences in the maximum values of the measure under study can be seen in the agriculture, forestry and fisheries sector. Here, the highest variability can be observed in Germany (76.5%) and Greece (61.2%), while the lowest variability is in France (1.8%). In Germany, energy consumption in agriculture increased through greater mechanisation of work and a reduction in human labour. In Greece, on the other hand, there was a decrease in energy consumption for agriculture. The other sectors: services, transport and households, are characterised by similar average variations in final energy consumption over the sixteen years studied of less than 10% and are respectively:

8.2%, 7.9%, and 6.5%. In the tertiary and household sectors, the highest variability was observed in Malta (22.1% and 15.6%, respectively), while in the transport sector, it was in Poland (17.5%). Poland is an example of a country that dominated the EU road freight transport market after accession. This country achieved a market share of around 25%, associated with increased fuel consumption. Most services were provided domestically, but there was also a significant share of international transport services. In this case, services are also provided to transport in other countries, often on their territories. In this way, Poland's transport sector carries out work previously carried out by domestic carriers, which also involves the transfer of energy consumption to other countries. This situation also occurs in other sectors, especially in industry. Production of components and even assembly are outsourced to other countries, even continents, e.g., China or India. Consequences resulted in the transfer of energy consumption to these countries. The final products are already offered in European markets. As a result, energy consumption is reduced, and energy efficiency is increased. At the same time, countries can demonstrate a reduction in environmental emissions. Assessing the energy consumption of EU countries in general by sector from 2005 to 2020, one is tempted to conclude that—except for Germany and Greece—consumption was characterised by relative stability in the sectors of agriculture, forestry and fisheries.

3.3. Energy Consumption Dynamics in EU Countries by Sector and Area before and during the COVID-19 Pandemic

The next step of the analysis was to examine the dynamics of final energy consumption by sector and area in the EU countries in 2019 and 2020. The calculated chain indices for 2019 and 2020 are shown in Table 3. The three countries with the highest energy consumption growth dynamics in a given sector and area are shown in blue, while the three countries with the lowest dynamics are shown in red. When observing the change in final energy consumption in 2020 compared to the previous year in the industrial sector, it can be seen that in 21 countries, this consumption decreased, with the most significant decreases observed for Slovakia (9.40%), Spain (8.73%) and Lithuania (8.03%). The remaining countries showed an increase, with the largest increases for Cyprus (7%) and Sweden (6.16%). In the agriculture, forestry and fisheries sectors, on the other hand, in the first year of the COVID-19 pandemic, more than half of the EU countries recorded an increase in final energy consumption, including Malta (6.07%), Portugal (5.68%) and Croatia (5.27%). Furthermore, the largest decrease compared to 2019 of 10.62% was seen in Belgium; in this case, a significant change could be experienced compared to the period from 2019 to 2018 (12.84%). In 2020, almost in all EU countries, in the case of the tertiary sector's final energy consumption, there was a decrease (except for Estonia and Ireland, where consumption was at a similar level to 2019). Bulgaria (14.83%) and Cyprus (14.77%) are the countries with the largest decreases in consumption in service activities. The transport services sector proved to be the most vulnerable to the COVID-19 pandemic. All EU countries recorded decreases in final energy consumption, with the largest decreases in Luxembourg (22.5%), Spain (21.60%), and Italy (19.20%). It is worth noting that in 16 European countries, the decrease was 10% or more. Finally, the last sector analysed, households, was also not unaffected by the COVID-19 pandemic in terms of final energy consumption. As many as 18 countries out of 27 recorded an increase in consumption, with eight countries in 2019. The most significant increases in household energy consumption were recorded in Bulgaria (10.17%), Ireland (8.49%) and Luxembourg (7.41%). However, on the other hand, similar decreases in energy consumption should also be noted in Latvia and Finland at 6.11% and 6.07%, respectively. In summary, it can be concluded that the pandemic significantly impacted changes in energy consumption, but these varied across sectors and areas. The most considerable reductions in energy consumption occurred in the transport and services sectors and smaller reductions in the industry. The pandemic caused periodic closures of particular industries, especially those requiring personal contacts, such as catering, hospitality services and many others. On the other hand, transport depended on demand for materials and products, which was reduced overall in the pandemic. There was an even greater reduction in passenger transport. Air transport was closed. It is also important to note that restrictions on social contact resulted in the introduction of remote working and remote learning, which partially caused household energy consumption to increase. In addition, it must be stated that there were differences between countries in the scale of changes in energy consumption. One of the most important reasons for this may have been the different types of restrictions introduced by individual countries. The pandemic also had its waves distributed differently from country to country. Undoubtedly, the pandemic was a factor in the changes in energy consumption in particular sectors and areas.

Table 3. Dynamics of change in final energy consumption by sector and area in EU countries from 2005 to 2020. Blue indicates the three best performers in a given sector and period, and red the three worst performers.

Country	Chained Dynamic Indexes									
	Industry		Agriculture, Forestry and Fishing		Services		Transport		Households	
	2019	2020	2019	2020	2019	2020	2019	2020	2019	2020
Austria	99.78	97.08	98.36	98.09	102.66	97.06	99.99	87.46	102.24	100.08
Belgium	96.52	96.98	112.84	89.38	98.85	97.02	99.31	87.88	97.42	100.99
Bulgaria	97.9	98.79	101.27	100.34	102.98	85.17	101.11	94.3	96.98	110.17
Croatia	100.91	99.9	101.00	105.27	100.35	90.66	104.11	88.07	97.38	101.72
Cyprus	100.42	107.00	101.78	103.98	104.19	85.23	101.1	89.17	107.54	100.52
Bohemia	98.79	99.11	102.4	100.4	102.05	93.58	101.79	94.1	98.87	102.65
Denmark	97.35	102.08	98.28	97.49	96.69	95.06	98.32	92.94	98.68	98.45
Estonia	94.15	88.83	91.00	96.74	95.26	100.95	99.98	95.29	101.09	99.3
Finland	99.07	93.48	99.98	97.09	97.95	93.19	98.5	92.92	98.94	93.93
France	97.53	93.81	99.01	103.27	98.09	92.84	99.99	84.74	99.65	97.71
Germany	97.48	97.38	107.89	101.47	95.3	97.23	101.35	90.65	103.44	100.43
Greece	94.48	97.52	104.83	99.17	102.01	89.14	102.51	85.06	105.1	104.29
Hungary	100.15	99.35	103.97	104.49	97.7	97.54	105.85	87.95	97.57	105.1
Ireland	99.52	96.37	98.04	97.86	103.04	100.58	100.66	84.36	97.18	108.49
Italy	101.07	95.72	96.57	101.1	95.74	91.01	100.79	80.8	97.6	98.45
Latvia	94.97	102.13	110.58	101.29	96.08	96.75	99.11	95.14	96.5	93.89
Lithuania	100.65	91.97	102.82	102.38	96.24	91.94	103.32	98.87	95.74	99.05
Luxembourg	97.36	92.55	91.35	96.92	112.74	94.93	102.48	77.48	92.45	107.41
Malta	103.43	102.92	115.29	106.07	105.36	96.19	106.38	82.28	107.19	101.61
Netherlands	96.87	100.57	99.9	97.64	97.91	95.5	99.31	85.5	98.07	98.43
Poland	101.01	96.54	97.32	101.44	98.48	97.08	101.94	95.59	93.07	100.51
Portugal	101.4	97.49	102.4	105.68	99.1	91.53	102.31	83.72	100.47	104.21
Romania	100.74	96.64	98.46	95.26	99.29	93.48	104.25	98.31	99.72	103.28
Slovakia	94.57	90.6	97.5	101.89	92.96	90.69	101.66	89.18	128.48	103.83
Slovenia	100.23	95.29	98.29	98.21	95.27	91.89	97.57	82.18	97.5	101.42
Spain	99.89	91.27	105.46	103.33	100.46	91.67	101.29	79.4	95.18	100.76
Sweden	98.9	106.16	103.02	93.4	97.67	99.57	98.61	94.19	98.31	97.78
EU-27 average	98.71	97.32	101.47	99.99	99.42	93.98	101.24	88.80	100.09	101.28

3.4. Interdependence of Energy Consumption in EU Countries between Sectors and Areas

The final step in the statistical analysis of final energy consumption by sector and area in the EU countries was to examine the correlation of energy consumption between the sectors and areas. What was examined was not the levels of energy consumption in a given year but the differences in energy consumption between 2019 and 2020. For this purpose, the Pearson linear correlation coefficient discussed earlier was used, and its results for individual pairs of sectors and areas are summarised in Table 4.

Table 4. Pearson's linear correlation coefficient values for individual sectors and areas in EU countries in 2019–2020.

Sector	Pearson's Linear Correlation Coefficients for Sectors and Areas				
	Industry	Agriculture, Forestry and Fishing	Services	Transport	Households
Industry	1.000				
Agriculture, forestry and fisheries	−0.708	1.000			
Services	0.815	−0.609	1.000		
Transport	0.882	−0.636	0.942	1.000	
Holdings home	0.364	−0.282	0.634	0.478	1.000

The values in Table 4 show how an increase in the difference in energy consumption in one sector is responded to by the difference in energy consumption in another. The weakest correlation is observed for the household sector. Only for the tertiary sector a clear correlation can be observed. In this case, an increase in the difference in energy consumption in households causes an increase in the difference in energy consumption in services. For the other sectors, the correlation is very weak. It is worth noting that the correlation coefficients between industry, agriculture, services and transport assumed high values, which means that changes in the energy consumption gap in one of these sectors are strongly associated with changes in the gap in the other sectors and vice versa. Therefore, this means that energy consumption in households changed differently than in the economic sectors. Mostly, it increased due to spending a lot of time at home (remote working, remote learning, isolation and quarantines). Noteworthy is the very high correlation coefficient, close to 1, between the transport and services sectors and slightly lower between the transport and industry sectors. These sectors are closely linked in terms of demand. Increases in demand in the goods and services sectors drive demand for transport. In turn, falls in demand in these sectors also reduce demand for transport.

Most of the coefficients were positive, i.e., the directions of the differences in energy consumption in the European countries are the same. Excluding the area of households—due to the low value of the coefficient, there is a negative correlation on three occasions. The highest occurred in agriculture, forestry, fishing and industry sectors. In this case, the negative sign of the coefficient means that an increase in the difference in energy consumption in one sector causes a decrease in the difference in consumption in the other. The inverse relationship is also true. As we have already shown in the case of the dynamics indices, we have generally seen decreases in energy consumption in all sectors except agriculture in 2020 compared to 2019. Hence the resulting negative linear correlation of this sector with the others.

3.5. Energy Intensity in EU Countries by Sector before and during the COVID-19 Pandemic

The second phase of the study was devoted to analysing energy intensity in the economic sector. To this end, energy intensity indices were first calculated for the industrial (K1), agricultural, forestry and fishing (K2), services (K3) and transport (K4) sectors as a ratio of final energy consumption to gross value added in the respective sector. These indicators were the criteria for a multi-criteria assessment of EU Member States. Their calculated magnitudes, which were then used to build the rankings, are presented in Table 5. The three best performers in each year and sector are shown in blue, while the three worst performers are similarly shown in red. Looking at the average energy intensity in the EU-27, it can be seen that it was systematically lower. Only in 2020 did this positive trend stop, and energy intensity slightly deteriorated in all sectors.

Table 5. Energy intensity factor values by sector in EU countries from 2005 to 2020. Blue indicates the three best performers in a given sector and period, and red the three worst performers.

Country	Energy Intensity Factor [TJ/million EUR].																			
	2005				2010				2015				2019				2020			
	K1	K2	K3	K4	K1	K2	K3	K4	K1	K2	K3	K4	K1	K2	K3	K4	K1	K2	K3	K4
Austria	5.7	6,9	1.1	27.5	5.4	6.0	0.8	23.4	4.6	5.7	0.6	20.3	4.1	5.1	0.6	18.9	4.2	5.1	0.6	18.5
Belgium	7.9	16.2	1.3	21.7	7.9	12.5	1.1	19.3	7.1	10.7	0.9	17.5	6.3	11.9	0.7	15.5	6.2	11.6	0.8	14.4
Bulgaria	33.4	7.3	4.0	75.7	15.9	5.0	2.6	53.6	12.3	4.2	2.4	56.3	10.2	4.0	2.0	48.1	10.2	3.7	1.7	49.9
Croatia	9.8	7.3	2.0	46.0	7.2	6.3	1.6	42.3	5.8	7.4	1.6	45.0	5.7	6.4	1.4	39.2	6.1	6.7	1.4	42.6
Cyprus	10.1	3.9	0.9	31.6	7.1	4.1	1.0	24.9	7.4	5.2	0.8	21.0	5.7	4.6	0.9	20.6	6.6	4.7	0.8	21.6
Bohemia	11.9	9.1	3.1	35.3	6.8	9.4	2.1	28.4	5.6	6.8	1.9	29.7	4.6	6.3	1.4	25.2	5.0	6.3	1.3	25.3
Denmark	3.2	14.8	0.9	14.9	2.7	12.5	0.7	14.8	2.1	12.1	0.6	12.6	1.9	7.4	0.5	12.3	2.0	6.7	0.5	11.1
Estonia	14.0	11.7	3.7	34.5	8.5	8.5	2.9	26.4	5.9	9.4	2.3	20.4	4.1	6.8	1.6	20.5	3.8	7.9	1.6	21.7
Finland	12.0	8.4	1.6	21.6	11.7	7.4	1.5	21.6	11.4	6.6	1.1	19.3	11.0	5.3	1.1	18.0	10.4	5.0	1.0	20.6
France	5.2	6.5	0.9	25.9	4.7	5.8	0.9	22.0	4.2	5.4	0.8	21.0	3.8	4.9	0.7	19.0	4.0	5.1	0.6	18.8
Germany	4.4	0.5	1.2	24.9	4.0	2.6	1.2	21.2	3.4	2.9	0.9	18.7	3.0	5.6	0.7	16.9	3.2	6.2	0.7	16.2
Greece	7.2	5.7	0.8	22.3	6.0	5.0	0.7	22.0	5.9	1.7	0.8	24.5	5.0	1.8	0.9	21.7	4.8	1.7	0.9	20.2
Hungary	6.4	6.9	3.8	41.2	5.0	6.8	3.0	33.7	6.3	5.7	2.1	28.4	6.4	5.8	1.4	28.5	6.8	6.4	1.4	28.6
Ireland	2.9	9.1	0.8	33.8	2.1	7.7	0.7	28.8	0.9	3.9	0.6	25.1	0.8	3.2	0.4	24.6	0.7	2.9	0.4	30.9
Italy	5.8	4.6	0.9	24.7	4.5	4.3	0.9	20.4	3.7	3.5	0.8	18.7	3.3	3.6	0.9	16.9	3.4	3.7	0.8	15.7
Latvia	15.0	12.4	4.6	28.1	11.2	9.0	3.4	27.4	9.7	7.9	2.3	21.3	8.8	7.1	1.8	20.8	9.2	7.5	1.8	23.4
Lithuania	9.3	4.9	3.5	32.1	6.8	5.5	2.6	20.6	5.5	3.3	1.9	18.6	5.1	3.1	1.5	16.6	4.7	3.0	1.4	17.3
Luxembourg	11.4	8.7	0.8	64.8	11.9	10.8	0.6	52.0	7.4	8.7	0.5	38.5	6.9	7.4	0.5	35.2	6.6	7.5	0.5	22.8
Malta	2.8	3.6	1.1	25.3	2.0	3.9	1.0	22.7	2.5	1.9	0.8	16.6	1.9	5.5	0.6	14.8	2.0	6.8	0.6	21.7
Netherlands	7.3	17.1	1.1	20.0	6.3	15.6	1.0	19.0	5.5	13.4	0.8	14.2	5.1	12.8	0.7	13.1	5.3	13.2	0.6	12.5
Poland	11.3	25.9	3.3	41.0	7.3	15.1	3.0	41.6	6.0	13.6	2.2	28.0	6.0	12.9	1.7	29.1	6.0	12.4	1.7	29.3
Portugal	10.0	6.7	1.2	48.3	8.6	5.6	0.9	36.5	6.5	4.9	1.1	30.4	6.0	4.5	0.9	26.6	6.2	5.0	0.9	31.2
Romania	18.8	1.3	2.9	30.1	7.2	2.6	1.7	26.2	6.9	2.9	1.2	21.4	5.9	2.5	0.9	20.7	6.1	2.6	0.8	20.5
Slovakia	14.5	10.9	5.1	46.3	8.7	5.2	3.1	42.9	7.4	3.6	1.7	19.2	6.5	3.5	1.3	22.5	6.6	3.4	1.1	21.5
Slovenia	9.8	4.5	1.7	45.9	7.0	4.2	1.4	42.5	5.7	3.8	1.2	35.2	4.8	3.2	1.0	30.0	4.7	3.0	0.9	27.2
Spain	8.2	5.1	0.8	43.3	5.4	3.6	0.8	32.9	4.9	3.8	0.7	26.2	4.8	3.8	0.7	26.8	4.8	3.6	0.7	27.1
Sweden	7.6	8.1	1.1	19.1	6.9	4.7	1.0	17.4	6.1	4.2	0.7	14.3	5.9	4.1	0.7	13.5	6.7	3.9	0.7	13.7
EU-27 average	9.8	8.4	2.0	34.3	7.0	7.0	1.6	29.1	6.0	6.0	1.2	24.5	5.3	5.7	1.0	22.8	5.4	5.8	1.0	23.1

With the assumptions above, for the selected years: 2005, 2010, 2015, 2019 and 2020, rankings were constructed using the PROMETHEE II method. The weights of the individual criteria, calculated according to Shannon's entropy method, were taken at levels of respectively: K1-40%, K2-32%, K3-18% and K4-10%. Each criterion is a destimulant.

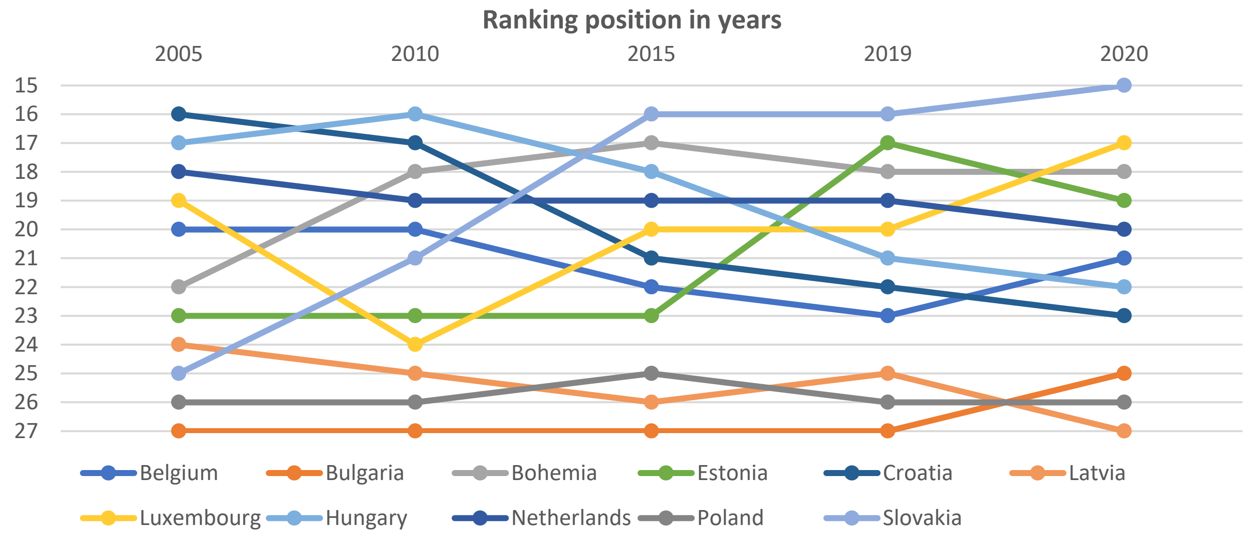
Table 6 summarises the results obtained, presenting the ranking position of a given country and the obtained value of the index of net preference flows Φ. The value of the index Φ allows not only to rank the countries (thus constructing the ranking) but also to indicate the group of dominant (positive Φ) and dominated (negative Φ, marked with grey background) countries in the constructed ranking.

From the rankings obtained for the selected years 2005–2020, it can be deduced that Ireland had the lowest energy intensity, achieving position one in 2015, 2019 and 2020. Germany and Malta also achieved position one in 2005 and 2010, respectively. The former country had low energy intensity compared to the other EU countries in 2005, 2010 and 2015. On the other hand, Malta was at the top of the surveyed countries in all years. What was also noteworthy during the period under study was Italy, which ranked highly in third or fourth place in all rankings. Furthermore, Denmark had relatively low energy intensity in 2019 and 2020.

In addition, analysing the values of the indicators Φ in the rankings presented, there are apparent differences in energy intensity between the former Eastern Bloc countries and the Western countries. Negative net preference flow indices indicate a group of 11 dominated countries. These are Belgium, Bulgaria, the Czech Republic, Estonia, Croatia, Latvia, Luxembourg, Hungary, the Netherlands, Poland and Slovakia. Among them were eight countries from the former Eastern Bloc. Only Slovenia is in the group of dominant countries, while Lithuania and Romania were initially in the group of dominant countries but later qualified. The variation in the ranking positions of individual countries from year to year is illustrated in the figures (Figure 4).

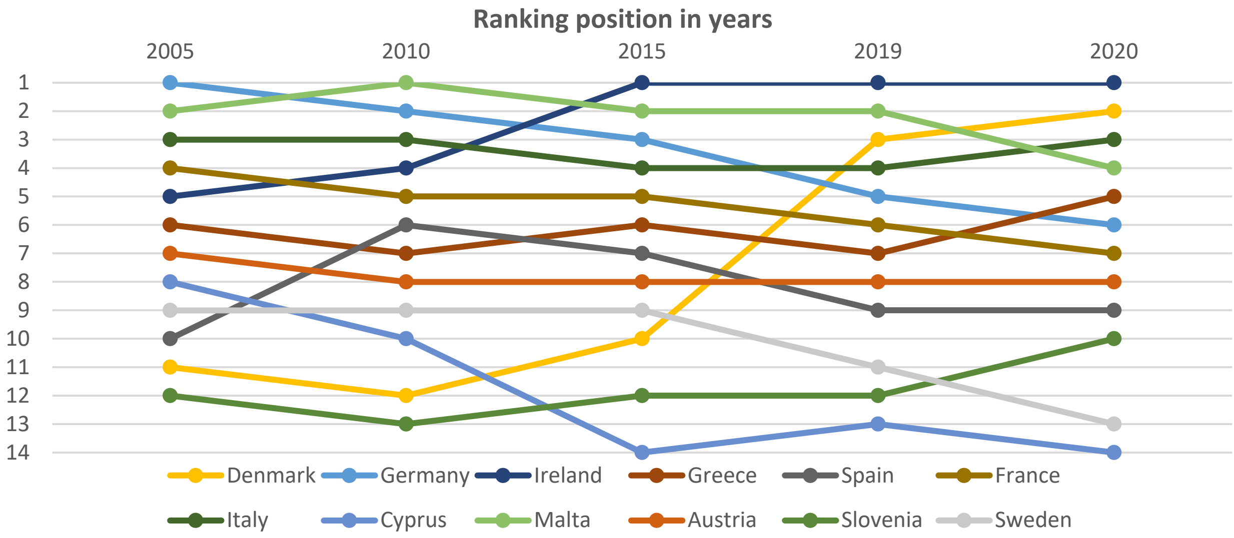
Table 6. Country rankings in energy intensity by economic sector for the years selected for the study from 2005–2020.

Country	*R's* Ranking and Net Preference Flow Rate Φ									
	2005		2010		2015		2019		2020	
	R	Φ	R	Φ	R	Φ	R	Φ	R	Φ
Austria	7	0.209	8	0.205	8	0.181	8	0.191	8	0.197
Belgium	20	−0.072	20	−0.173	22	−0.181	23	−0.241	21	−0.225
Bulgaria	27	−0.579	27	−0.486	27	−0.518	27	−0.511	25	−0.464
Croatia	16	−0.004	17	−0.030	21	−0.174	22	−0.211	23	−0.263
Cyprus	8	0.159	10	0.162	14	0.020	13	0.056	14	0.011
Bohemia	22	−0.149	18	−0.134	17	−0.125	18	−0.079	18	−0.086
Denmark	11	0.112	12	0.133	10	0.136	3	0.296	2	0.338
Estonia	23	−0.308	23	−0.237	23	−0.251	17	−0.066	19	−0.101
Finland	14	0.013	22	−0.221	24	−0.311	24	−0.329	24	−0.294
France	4	0.238	5	0.249	5	0.214	6	0.21	7	0.207
Germany	1	0.393	2	0.368	3	0.342	5	0.259	6	0.229
Greece	6	0.216	7	0.215	6	0.207	7	0.206	5	0.232
Hungary	17	−0.016	16	−0.029	18	−0.126	21	−0.176	22	−0.244
Ireland	5	0.229	4	0.304	1	0.469	1	0.494	1	0.493
Italy	3	0.268	3	0.307	4	0.313	4	0.285	3	0.291
Latvia	24	−0.373	25	−0.442	26	−0.445	25	−0.441	27	−0.493
Lithuania	15	−0.002	15	−0.004	13	0.042	14	0.041	12	0.101
Luxembourg	19	−0.068	24	−0.424	20	−0.171	20	−0.165	17	−0.072
Malta	2	0.362	1	0.437	2	0.452	2	0.361	4	0.272
Netherlands	18	−0.064	19	−0.152	19	−0.141	19	−0.164	20	−0.168
Poland	26	−0.456	26	−0.454	25	−0.404	26	−0.483	26	−0.468
Portugal	13	0.041	14	0.002	15	0.013	15	0.006	16	−0.044
Romania	21	−0.138	11	0.137	11	0.080	10	0.131	11	0.132
Slovakia	25	−0.386	21	−0.207	16	−0.039	16	−0.043	15	−0.006
Slovenia	12	0.076	13	0.060	12	0.057	12	0.100	10	0.162
Spain	10	0.144	6	0.238	7	0.197	9	0.145	9	0.171
Sweden	9	0.158	9	0.176	9	0.162	11	0.127	13	0.091

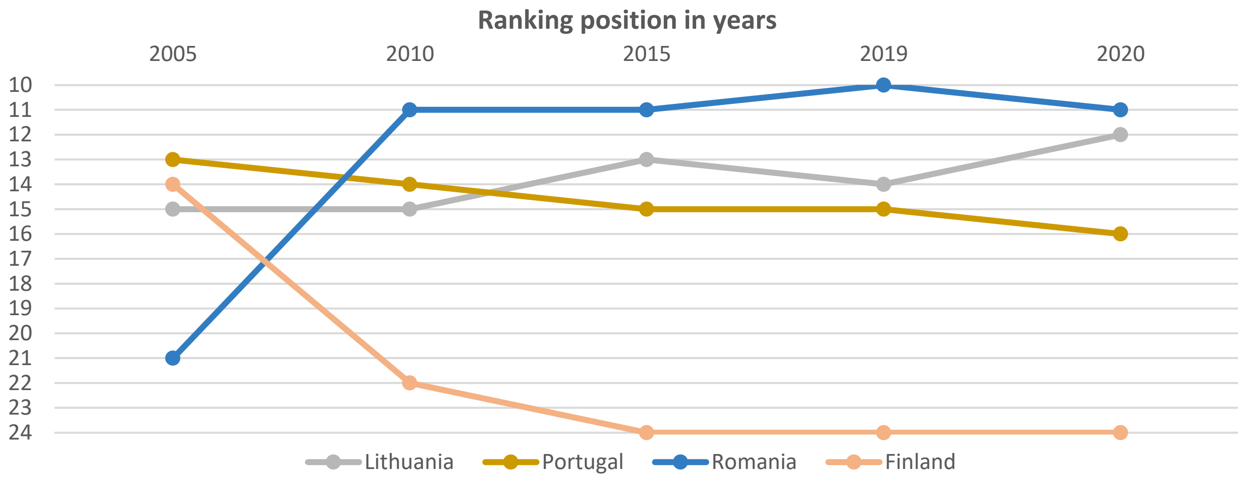


(**a**) dominated countries

Figure 4. *Cont.*



(**b**) dominant countries



(**c**) other countries

Figure 4. Positions achieved in the individual rankings for energy intensity. (**a**) dominated countries; (**b**) dominant countries; (**c**) other countries.

In addition, the stability of the obtained rankings in the individual years of the study period was also examined. For this purpose, the Wilcoxon rank-sum test was used (Table 7).

Table 7. Values of Wilcoxon rank-sum test statistics.

	Value of Test Statistic and *p*-Value			
	2010	**2015**	**2019**	**2020**
2005	174 (0.732)	199 (0.822)	208 (0.662)	199 (0.822)
2010		222 (0.441)	216 (0.530)	208 (0.662)
2015			215 (0.546)	196 (0.878)
2019				186 (0.953)

Table 7 shows the results of applying the test comparing the similarity of the distributions of the variables expressing the ranking position of the countries. Recall that rankings were compared for selected years. The upper number denotes the value of the test statistic, while the lower number determines the empirical significance level, also known as the *p*-value. The hypothesis to be verified (called the null hypothesis) assumes that the two rank distributions are not significantly different from each other. In our case, in the compared periods, there have been no significant changes in the position of the 27 ranking countries. Those changes that have occurred in it compared to the earlier period are not statistically significant.

At a standard significance level of 0.05, not once was the null hypothesis rejected. Moreover, all the *p*-values in the table are very high. Thus, in order to accept the alternative hypothesis, the significance level (the probability of making an error of the first kind—considering the true null hypothesis to be false) would have to be even higher. This way, the distributions of rankings by country for all pairs of years were not significantly different. Even if some countries did move up or down in subsequent years, it has become clear that the changes were small enough that the rankings could be considered similar.

4. Discussion

Olkuski et al. [70] note that energy consumption has been steadily increasing for many decades due to global population growth and the aspirations of developing countries to raise the standard of living of their citizens. In the EU, the opposite trend, i.e., a decrease in energy consumption, has been observed since 2007. The downward trend can be explained by relocating heavy industries outside Europe and introducing policies for efficient energy management and savings. Bertoldi et al. [71] additionally noted that these are the results of the European Union's efforts to reduce energy consumption and improve energy efficiency. In their study for the period 2000–2014, energy indicators such as energy intensity and energy consumption decreased. According to Economidou and Román-Collado [72], this makes the EU more competitive. Nevertheless, within the EU, there was a very high concentration of energy consumption in a few of the largest countries, such as Germany, France and Italy. The total energy consumption of 14 EU countries was as high as 90% in 2014 [71]. Reuter et al. [73], using a decomposition analysis for the period 2000–2015, concluded that energy consumption in the EU 28 is primarily influenced by increased energy efficiency in industry, followed by households. Bertoldi and Mosconi [74] show the effectiveness of energy efficiency policies in saving energy between 1990 and 2013 in the EU. The results show that energy reduction processes have already been initiated in the EU. According to Thomas and Rosenow [75], this process is supported by improvements in energy efficiency. In our study, we also found similar trends regarding changes in energy consumption.

Román-Collado and Economidou [76] surveyed changes in individual economic sectors in the EU between 2000 and 2018. They found that the services sector increased its share of final energy consumption by four percentage points, while the industrial and agricultural sectors decreased by four and one percentage points, respectively. The transport sector was not studied, nor was the household area. Bertoldi et al. [71] indicated that, in 2014, the largest share of final energy consumption was in the transport sector (33.22%), followed by the industrial sector (25.89%), the residential sector (24.80%), and the smallest in the services sector (13.31%). However, the analysis did not include the agricultural sector. When comparing final energy consumption by sector for five different years (i.e., 2000, 2004, 2007, 2010 and 2014), it was found that the shares changed slightly. In our study, we obtained similar results. The changes in the structure of sectors and areas of the economy were small. Borozan [77] found that the structure of sectors by final energy consumption across the EU was fairly homogeneous between 1998 and 2015. In our study, we observed similar relationships for the period 2005–2020. The study by Bertoldi et al. [78] found that the energy consumption of the transport and services sector in the EU changed more gradually between 2000 and 2015. Energy consumption increased only in the transport sector, with a downward trend in the industry and services sector and residential buildings. The rate of change in energy consumption varied considerably between EU countries. In our study, we achieved similar results. Transport had to keep up with the increase in the number of goods transported and the greater mobility of the population. Improvements in energy efficiency did not keep up with these increases. Other sectors and areas of the economy performed better in this respect. Overall, it must be said that changing energy consumption as a result of improving energy efficiency is a process that will take many years, even decades.

Grossi and Mussini [79] found in their study of EU countries between 2007 and 2012 that there were inequalities in energy intensity distribution. In addition, low-energy-intensity EU countries are more efficient in energy transition and less energy-intensive in specific economic sectors than high-energy-intensity EU countries. Similar results were obtained by Mussini [80] in a study covering the period 2003–2014. Convergence of energy intensity occurred mainly in the first years of the period studied. At that time, CEE countries with high energy intensity joined the European Union. In subsequent years, the convergence process slowed down. In our study, we found similar patterns. The differences between countries did not diminish. The most developed Western European countries continued to have the highest efficiency. On the other hand, according to Mulder [81], increasing trade and market integration should reduce differences in energy efficiency across countries. It should also be noted that less developed countries often specialise in sectors where they do not have a comparative advantage in terms of energy efficiency. Guevara et al. [82], in a study of 14 EU countries between 2000 and 2010, found that differences in industrial direct energy intensity and final energy demand mix were drivers of energy intensity differences between countries. Of course, it must be remembered that these were more developed countries than those from central and eastern Europe. Román-Collado and Colinet [83], using Spain as an example, highlighted the importance of households in reducing the energy intensity of the economy, while Trotta [84], using Finland as an example, highlighted the importance of industry and housing. In addition, Cansino et al. [85] point to the decisive role of industry, transport and service sectors in increasing energy consumption despite energy efficiency improvements. Similar conclusions were had by Miskinis et al. [86] on the example of an analysis of energy intensity in Lithuania, Latvia and Estonia from 2000 to 2018. They particularly highlighted the high share of energy-intensive industries and the rapid growth of energy consumption in the Lithuanian transport sector, which limited the reduction of consumption and energy intensity in these economies. Our research also highlights the high importance of the transport and industrial sectors for energy consumption and energy intensity of the economy.

According to Aktar et al. [87], the change in the share of production in GDP caused by the pandemic resulted in a decrease in energy demand and consumption. In the first months of the pandemic, global energy demand fell sharply. According to Broom [88], the commercial sector was also affected. Zhang et al. [89] point to a reduction in energy consumption in road transport during COVID-19. There are few studies of this type. Much more common is the theme of carbon emission reductions due to reduced urban transport, such as in the studies by Henriques [90] and Caine [91]. We did not encounter any literature on changes in agricultural energy consumption during a pandemic. Studies have generally addressed food safety during a pandemic due to the breaking of supply chains, such as in the studies by Rozaki [92] and Cardoso et al. [93]. Abulibdeh [94], on the other hand, examined the impact of the pandemic on energy consumption in the residential, industrial, commercial, public and manufacturing sectors in Qatar. The pandemic disrupted the temporal and spatial patterns of energy consumption. During the pandemic, energy consumption fell sharply in both the industrial and commercial sectors. This study was the only one that looked at a multi-sectoral analysis of energy consumption during the pandemic because the other studies primarily focused on single sectors. These studies were also limited and focused on aspects other than energy consumption and energy efficiencies, such as the effects on the environment or only the consumption of electricity by people or utilities.

Using data from Korea, Kang et al. [95] found that residential energy consumption tended to increase during COVID-19. The rate of change in building energy consumption showed a significantly positive correlation with COVID-19-related factors. Similar results were obtained by Qarnain et al. [96] for India, Abdeen et al. [97] for Canada, Farrow [98] for Australia, Krarti and Aldubyan [99] for the UK and USA, and Tleuken et al. [100] for Kazakhstan. The results confirm the relationship we observed. Of course, there was variation between countries depending on the severity of the pandemic and the constraints present. Some authors point to differences depending on the size of cities—energy consumption was higher in large and medium-sized cities.

Jiang et al. [101] pointed out spatial and temporal differences during the pandemic. In addition, energy intensity changes differently from country to country. In the USA it increased by 29%, in Japan by 8% and in China by only 3%. In the EU, the increase in energy intensity was expected to be the smallest, at around 1%. Our survey results confirmed these predictions. Only in services was the increase in energy intensity higher.

The literature review presented here shows a great deal of research on the energy consumption of entire economies or individual sectors. However, there is a lack of up-to-date research concerning recent years and relating comprehensively to all sectors and areas of the economy. In addition, there are very few studies on changes in energy consumption in individual sectors. Only one comprehensive study on energy consumption in all sectors was found. The researchers focused primarily on the increase in household energy consumption during COVID-19 and the environmental consequences resulting from reduced vehicle traffic, mainly in cities. We also found one study on energy intensity during the pandemic, but the data were estimated based on projections. In conclusion, the studies we presented are essential and can fill a research gap, as there are no studies of this kind so comprehensively showing the situation in energy consumption and energy intensity during the COVID-19 pandemic.

5. Conclusions and Recommendations

5.1. Conclusions

The conducted research allows for a few generalisations.

1. Transport, industry and households accounted for the largest share of energy consumption in the EU (about 80%), with agriculture accounting for the smallest share. The energy consumption structure in the individual EU countries was quite similar, and the deviations were insignificant. In addition, the concentration level of energy consumption in individual sectors and areas did not change over several years, indicative of an occurring stabilisation.
2. The COVID-19 pandemic reduced energy consumption in all sectors of the economy, the largest in transport and services and the smaller in industry. At the same time, energy consumption in households increased. Hypothesis 1 was verified positively.
3. The greatest variability in energy consumption was in agriculture and industry, and the least in households. In agriculture, energy consumption generally increased due to the introduction of mechanisation, which replaced human labour. In industry, there was a reduction in energy consumption, which may have been due to the introduction of less energy-intensive production technologies.
4. In general, the pandemic caused a slight increase in energy intensity in all sectors of the EU economy. This increase occurred in the case of most EU countries. The increase in energy intensity occurred particularly in industry and, to a lesser extent, in other sectors of the economy. Hypothesis 2 was verified positively for the whole EU and most EU countries.
5. Western European countries have generally been characterised by lower economic energy intensity than countries in Central and Eastern Europe. Little has changed in this respect over the past decade or so. Of course, there were some deviations, as Belgium and the Netherlands had similar energy intensity to the CEE countries, while Slovenia had similar energy intensity to the Western European countries. Hypothesis 3

was verified positively concerning the differences between the country blocks and negatively regarding the narrowing of the energy intensity gap. One of the reasons for this may still be the technological advantage of Western European economies over CEE countries.

6. Unquestionably, a general conclusion can be drawn from the study that the pandemic has inhibited the beneficial changes in the energy intensity of most EU economies. With adaptation measures in place in the next few years, EU countries can get back on track to reduce the energy intensity of their economies.

5.2. Recommendations

The study shows the changes that have taken place in the economy's energy consumption of individual sectors and areas and their energy intensity before and during the pandemic. Such a comprehensive approach is new. Research on such relationships during the COVID-19 pandemic in other European and global countries is lacking. It would be worthwhile to confront the results with each other, as the determinants and scale of constraints in a pandemic have differed from country to country. It can be clearly stated that the epidemic has created a new situation for the whole world; therefore, it requires further clarification.

A limitation of conducting such studies is the lack of available up-to-date and detailed data on individual industries within sectors. As is well known, for example, within an industry, there are more than a dozen differing industries in which conditions may vary. Another limitation may be the use of aggregated data for entire sectors. It would be interesting to research the level of companies operating in the sectors concerned. A possible direction for further research is to link the transformation of energy consumption resulting from COVID-19 in individual sectors to sustainable development, especially pollution reduction and economic development. Research could also address these linkages using examples from individual industries within sectors. The topics given may represent a research gap to be filled. The research may contribute to the construction of public policies in a post-COVID-19 scenario.

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Article

COVID-19 Impact on the Energy Sector in the United States (2020)

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Abstract: This study comprehensively examines the effects of the COVID-19 pandemic on energy consumption in the United States. The purpose of the study is to quantify the effects of lockdowns and pandemic disruptions on energy consumption trends in order to inform policymakers and utilities on how to prepare for such events in the future. The study focuses on 2020 data collected by the Federal government. The effects are quantified using descriptive statistics. State-wise and sector-wise data have been presented using plots and heat maps. Related metrics like COVID case data, GDP, emissions, and expenditures were also presented. The total energy consumption fell by 7.5% in 2020. Besides Alaska, every state saw a decrease in energy, with some as high as 26%. The residential sector had the most states that saw an increase in energy, stemming from lockdowns and working from home. Similarly, petroleum consumption saw a decrease of 11.4% as a result of a decrease in travel. Biomass-related renewable energy generation fell by 23% due to decreased demand, while all other sources increased by 7.3%. Carbon dioxide emissions fell by 10.4%, methane by 2.8%, and nitric oxide by 6.7%. The overall per capita energy expenditure for the country dropped by 18.5%. There was a stronger correlation between GDP and energy consumption than between GDP and COVID case counts. The pandemic did not affect each state or sector evenly. The statistics and correlations presented here can be used in the ongoing effort to study the global impact of the pandemic and prepare for future challenges.

Keywords: energy consumption; COVID-19 pandemic; United States; energy sector; fossil fuel; renewable energy; emissions; expenditures

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1. Introduction and Literature Review

The 2019 coronavirus disease (COVID-19) outbreak was declared a global pandemic on 11 March 2020, by the World Health Organization [1]. Since then, the entire world has faced major repercussions from which people continue to recover and adapt. In addition to public health, several other aspects of human life were affected. These included economic, social, environmental, and political aspects. Due to these combined factors, there were significant ramifications for home life, office life, leisure, global supply chain, etc. Certain areas, such as online retail, saw a huge spike in growth and traffic [2]. Certain other areas, such as hospitality and leisure, saw a huge dip [3]. Generally speaking, several countries followed national and international health guidelines and enacted "stay-at-home" orders (SAHOs) or "lockdown" on top of other containment measures. Several businesses, specifically in the service (tertiary) sector, moved to partial or fully online operation. In-person or physical operations were limited to essential employees and sectors. As mentioned, sectors such as entertainment, hospitality, leisure, sports, travel, etc. saw near-zero operation.

Towards the beginning of Summer 2020, several countries gradually started relaxing lockdown measures [4]. While people were coping with the new realities of COVID-19, the second wave of infections started proliferating in several countries. Of course, as the data [5,6] and studies like [4] show, different countries experienced successive waves of the pandemic at different times. In the United States (US), the second wave was from the end of June to the beginning of September. The third wave started towards the middle of October and peaked by the end of 2020. As a result, the death toll continued to rise, and economic disruptions continued to worsen despite government efforts to ameliorate the worst effects.

Expectedly, this drastic change in daily life had a significant impact on a multitude of socioeconomic indicators such as life expectancy, gross domestic product (GDP), commuter miles traveled, energy consumption, Internet use, consumer spending patterns, etc. Several studies over the past couple of years have attempted to quantify and record these unprecedented changes. The International Energy Agency published a comprehensive report indicating that there was a decrease in electricity consumption in several countries and regions such as the European Union, the US, China, and India [7]. In Italy, pandemic restrictions and unemployment exacerbated the poverty situation for over half a million families. Out-of-home food consumption fell by 64% in the second quarter of 2020. Food exports and imports both fell [8]. As for the global cruise tourism industry, the top three lines that account for about three-quarters of the global cruise market saw revenues drop by 59% in 2020 relative to 2019. Similarly, jobs supported by this industry were reduced by about 50.6% (590,000 jobs) [9]. In India, as a result of the 2020 lockdown and pandemic disruptions and pressure on the healthcare system, the overall mortality was about 22% higher than the same period the previous year. The hospitalization rate also increased. Females and socioeconomically disadvantaged groups faced worse outcomes in critical, life-saving, non-COVID health services [10]. One of the positive changes in 2020 relative to 2019 was a reduction in atmospheric pollutants in several countries, precipitated predominantly via a reduction in the use of fossil fuels [11].

Similarly, energy resources saw a significant change in 2020 relative to 2019. Energy production and consumption are of particular importance for a number of reasons. Energy production is by far the largest producer of greenhouse gases, which are responsible for the current climate crisis [12]. Ironically, the ability of a civilization to harness energy is considered a direct measure of its technological progress [13]. Today, the richest and most developed or rapidly developing countries use the most energy per capita. Every sector of modern economies is heavily dependent on energy. The authors in [14] list a number of studies that conclude that energy consumption correlates positively with economic growth.

While it is still early days in the COVID pandemic, several studies have attempted to understand the energy trends during the past couple of years. In [15], the general trend of a decrease in overall electricity demand for several countries most affected by COVID was studied. These included France, Germany, Italy, India, the United Kingdom (UK), and the US. It was found that, during the general lockdown period from March 2020 to June 2020, the decrease in electricity ranged from 15% to 28%. A similar reduction in electricity consumption was noted by [16] in India (23%), Spain (18%), Germany (12%), the US (5%), etc. Further, it was noted that changes in the load profiles and composition posed challenges for operators. In [17], the investigators examined the influence of pandemic waves on the business cycle by studying energy consumption in 28 European countries. They found that no country's energy consumption was immune to the pandemic's influence and that the business cycle shifted in response to reducing restrictions and non-pharmaceutical interventions. Several studies that focus on individual countries offer insight into the unique circumstances in those countries that will undoubtedly offer guidance for future scenarios. In Sharjah [18], one of the seven emirates of the United Arab Emirates (UAE), it was found that the overall variation in power demand in 2020 was only 1.04% relative to 2016–2019. Sectors such as residential and government increased, whereas commercial, industrial, and agricultural all decreased. Of all the countries examined in [18], Sharjah was found to have the lowest change. One explanation forwarded was the huge fraction of the expatriate population in the UAE, about 90%. With lockdowns forcing most of this demographic to remain at home during the early part of the hot season, the residential sector saw a 5.44% increase. In Romania, the negative impact of reduced activity on electricity consumption and

GDP in the first half of 2020 was noted [19]. For each percentage point increase/decrease in electricity consumption, the national GDP was found to increase/decrease by 1.2%.

Price fluctuations are also important considerations. The authors in [20] found that both crude oil and natural gas prices were affected by the pandemic in Japan and the US, but to different extents. In the US, oil prices were negatively impacted, whereas gas prices were positively affected. In Japan, oil prices only experienced a short-run shock, and gas prices were largely unaffected. This was explained by looking at the hundred-fold difference in case counts between the two countries. Further, Japan did not have any severe lockdown measures, with only about 27% of surveyed employers asking employees to work from home. Focusing a bit more on the US [21] looked at the energy trends in Los Angeles, California, the second-largest city and combined statistical area after New York City. Los Angeles, like the majority of the US, receives its residential heating predominantly from natural gas. Stay-at-home orders were found to have a minimal impact on natural gas consumption. However, an overall 5.1% increase in total residential energy for non-temperature-sensitive loads during the pandemic period relative to the 2018–2019 baseline was found. The Alabama Power Smart Neighborhood has energy-efficient smart devices with around 40 advanced metering data points. Analysis of pre- and post-pandemic data showed that smart devices were effective in managing residential energy consumption compared to traditional homes during lockdown periods. While overall energy use was found to be higher, the peak load in 2020 was not as sharp as in 2019. Further, it was shifted from the evening to earlier in the day. This was explained by people spreading out tasks like cooking and other household chores to the entire day during the lockdown. Weekend patterns were found to be similar to the pre-pandemic levels [22].

These recent studies serve to confirm the hypothesis that the COVID pandemic had a significant impact on human life, including energy consumption. However, these effects varied by region and over the course of the pandemic. In many cases, the effects went against expert predictions or expectations. All these observations demonstrate why it is important to study the pandemic's effects: to prepare for the future and create a more resilient society. This study focuses on energy consumption in the US during the early stages of the COVID-19 pandemic in 2020. While there are many studies analyzing pandemic energy trends, there is a dearth of studies looking at the US as a whole. This work attempts to bridge that gap. Energy consumption by the country and by individual states was analyzed. The pandemic's effect on energy prices, sectors, sources, renewable generation, etc. was examined. Related quantities like GDP and pollution have also been presented. Existing work tends to focus heavily on electricity. Here, electricity is considered individually so future studies can draw from this work. However, non-electricity (e.g., transportation) uses are given due attention. The main contributions of this work are:

- Comprehensively summarizing US energy consumption for 2020, including providing sector-wise and state-wise breakdowns using aggregate data processed from multiple sources.
- Quantifying COVID-19 impacts on US energy consumption.
- Quantifying the influence of change in energy consumption on greenhouse gas emissions and energy expenditure.

Section 2 presents the methodology and data sources. Section 3 presents the results organized by data source. A robust discussion and analysis of the results are also included. Finally, Section 4 provides some salient conclusions and scope for future work.

2. Data and Methodology

2.1. Study Area Overview

The area on which this study focused was the US. All 50 states and Washington, DC (Federal capital district) were included. The five inhabited territories in the Caribbean Sea and the Pacific Ocean were not considered. One primary reason is that data for these territories was often incomplete. The US is the fourth-largest country in the world by area, about 9.8 million km^2, the third-largest by population, and the largest by gross GDP. Due to its size, its area includes most climate types from polar in Alaska to desert in the Southwest to tropical in Hawaii and the southern tip of Florida. The US is home to people from virtually every demographic and class of society. It is one of the most developed economies in the world, with citizens enjoying a high standard of living. The economy is dominated by the tertiary sector, accounting for up to 80% of 2010 GDP [23] (the US Census Bureau terminated the collection of data for the Statistical Compendia program effective 1 October 2011). Further, to understand the energy trends, it is important to consider the distribution of people and the layout of cities. The US is roughly 80% urban, but the population is dispersed over a huge area. Cities are surrounded by large, sprawling suburbs with single-family housing. There are 317 cities with 100,000 or more people, accounting for about 85% of the population [24]. Coupled with weak public transit infrastructure, the US ends up as the second-largest consumer of energy after China. It has the second-most vehicles after China, and its citizens travel over twice as many passenger miles by air than the next country, China.

2.2. Data Sources

The data used in this study were obtained predominantly from US Federal agencies, available to the public. This allows for future work to compare and extend the present work. COVID data were obtained from Our World in Data (Oxford University) and Johns Hopkins University. Pollution and emissions data came from the US Environmental Protection Agency. Economic data were obtained from the US Bureau of Economic Analysis*. Population data came from the US Census Bureau*. Energy data came chiefly from the US Department of Energy and the US Energy Information Administration* (EIA). The three agencies with an asterisk are part of the US Federal Statistical System. Specific sources and tables have been indicated in Section 3.

The collected data were processed using commonly used spreadsheet and matrix analysis software packages, namely Excel and MATLAB. In most cases, minimal data processing was required. Specific instances of missing or incomplete data have been indicated whenever appropriate. MATLAB was used to remove non-numerical characters and create tables with properly aligned data that were easy to sum and plot. For example, state-wise petroleum data are a table with thousands of rows of data. Each state has numerous collection and reporting points. MATLAB was used to sum such data to obtain totals for each state. Excel was used to create bar graphs, heat maps, and other data visualizations. Most of the energy data are reported in “quads” or quadrillion British thermal units (QBTU) or some related unit like trillion BTU. The following conversion factor was used to convert to metric kilowatt-hours (kWh).

$$1\ \text{QBTU} = 293{,}071{,}070{,}172\ \text{kWh} \tag{1}$$

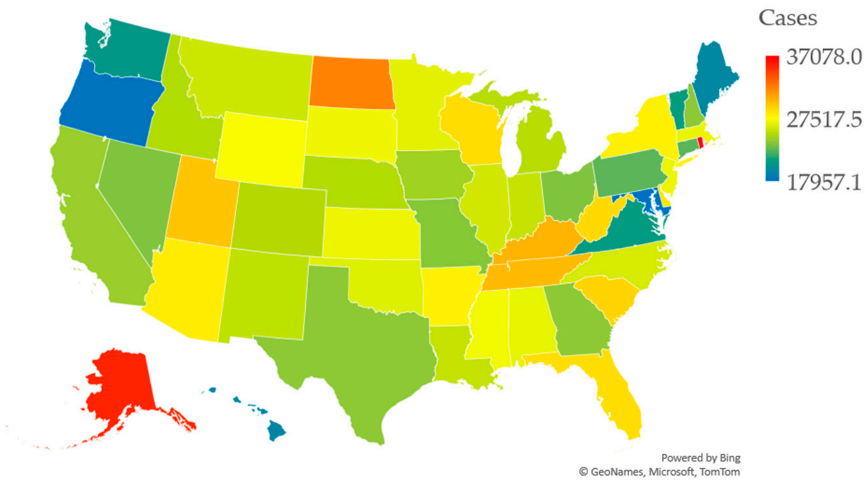
Other specific conversions have been pointed out as appropriate.

2.3. Study Design

Some of the studies cited previously have used data together with a suite of statistical analysis tools to draw powerful insights into pandemic trends. Others have applied data visualization techniques to infer geospatial and temporal patterns. This study uses a combination of data visualization and descriptive statistics to understand the effect of the pandemic on the US energy sector in 2020. First, for context, the overall energy consumption of the top few countries over 2018–2020 was compared. The US COVID case count and death toll were also presented for each state. The purpose is to establish the extent and human cost of the pandemic in each state, which happened to vary significantly for such a huge country. Next, the lockdown period was established using historical population and energy data, together with the pandemic case counts. The energy consumption for each state in 2020 was compared to 2019 to establish a basis for any change. Energy consumption was also broken down further by sector for additional insight across the country. Electricity data were then presented and analyzed. Additional data presented include energy expenditures, prices, the effect on GDP and emissions, and the state of renewable energy. The primary research question that was explored was to examine how the pandemic's effect on daily life, lockdown, and beyond, in turn, affected the US energy sector. Different US states had different responses and outcomes. States also differ in their energy mix. The energy supply of the future is slated to lean more towards renewable energy as the world aims to lower its emissions. Thus, the main contribution of this work is to capture these effects, if any, for better planning and preparedness in the future.

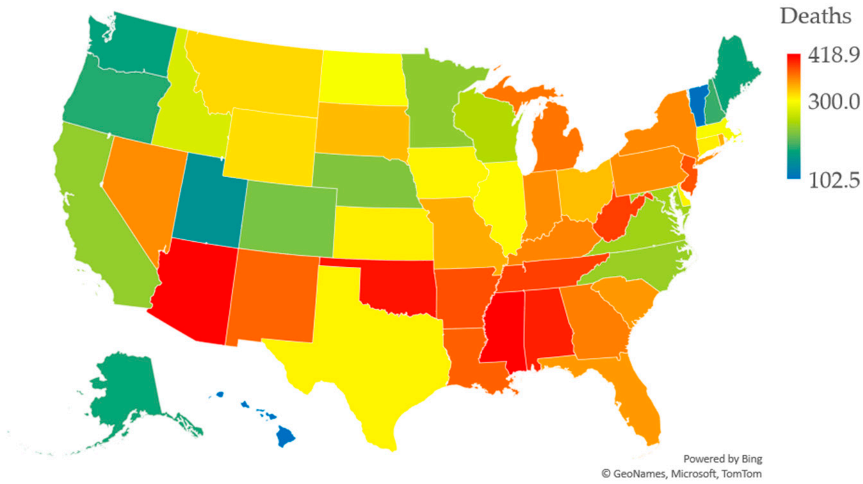
3. Results

Human beings are infinitely adaptable and innovative organisms. The COVID pandemic posed unique challenges to several aspects of human life. The most significant one was the human cost. Figure 1 shows the case count and deaths per 100,000 people for each US state as of December 2021. It also shows the population density according to the 2020 census by state in Figure 1c. For acceptable color contrast, all states above 300/km^2 are shown as red. The highest population density is Washington, DC (4361/km^2). The US has a very non-uniform distribution of people. The eastern corridor is home to the oldest and densest cities. The southernmost 'Sun Belt' states are also densely populated and rapidly growing. The west coast is also densely populated. The center or heartland, predominantly agricultural as well as home to some arid and rugged terrain (e.g., Rockies), is very sparsely populated. Looking at Figure 1a tells a different story. The normalized case count is highest in some of the most sparsely populated states, like Alaska and North Dakota. The death toll tells a grimmer story. Most of the states had a death rate on the high end of the scale. Only nine states (including Washington, DC) were below 200 deaths/100,000, whereas 32 were above 300. The US total death rate was almost twice that of Germany and about eight times that of India [25]. It is difficult to infer a strong mathematical or geographical pattern in the death rate other than to observe that it is very poorly correlated with initial population distribution and case count. This certainly defies expectations.



(**a**)

Figure 1. *Cont.*



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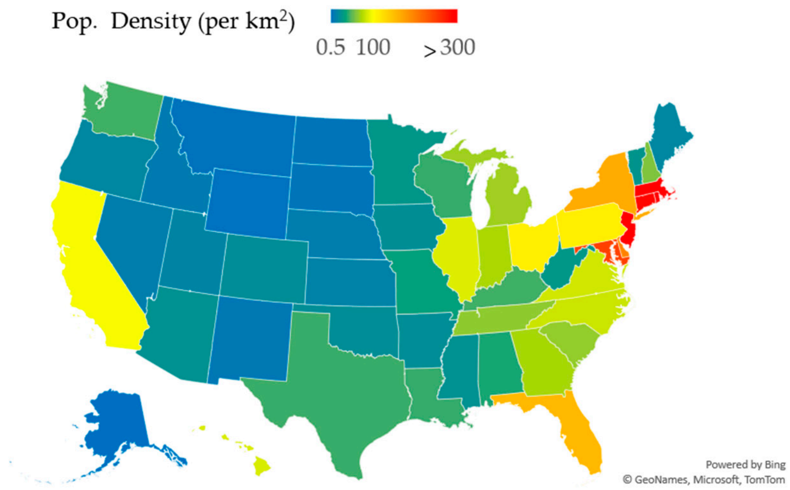


(**c**)

Figure 1. US COVID-19 statistics per 100,000 people as of December 2021 by state: (**a**) cases; (**b**) deaths; (**c**) population density [6,25,26].

The next step was to determine what was the response to the challenges of the pandemic and its effects on human life. Figure 2 shows the change in energy consumption between 2018 and 2019 and 2019 and 2020 for 10 countries, combining 51% of the global population. It also juxtaposes this with the total deaths in 2020. In general, most countries increased their energy consumption in 2019, except for the most developed economies of Germany, Japan, and the US. In 2020, however, most countries saw a reduction in energy consumption. The exceptions are China and Iran, which saw a slight increase of 0.47%, but about 10 times lower than the previous year. The drop was about 7.5% for the US. It is difficult to draw any correlation between the change in energy and the COVID deaths. However, what is clear is that, even when placed against some of the largest countries in the world in terms of population, the US clearly stands out in its death toll. This has been attributed mainly to widespread refusal to adopt safety measures like masks and vaccinations, but also the high obesity rate and aging population, two demographics that are considered vulnerable.

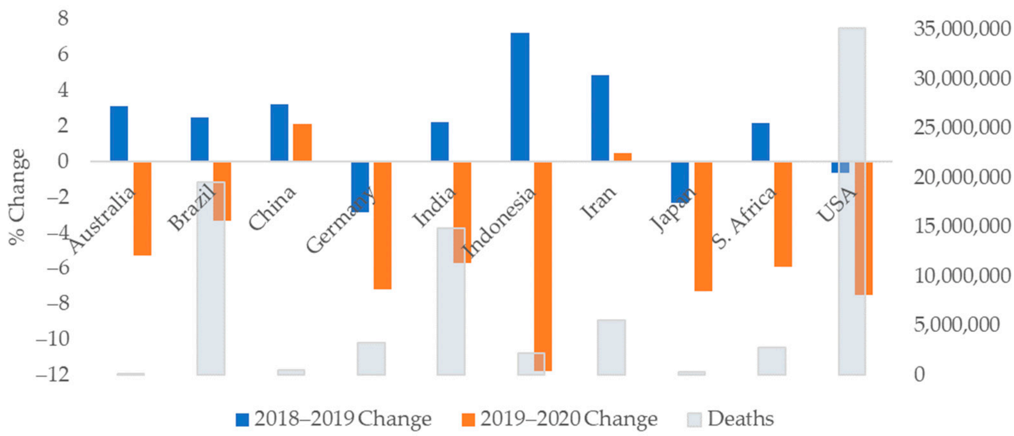


Figure 2. Change in energy consumption and 2020 COVID deaths for 10 countries [25,27].

Diving deeper into the data for the US, Figure 3 shows the historical population of the country from 1950 to 2021. It also shows the total energy consumption in terawatt-hours. Note that the listed sources have detailed methodologies about data collection and source estimates. These have been elided here for the sake of brevity. The population grew continuously, but at a gradually decreasing rate. This is because live births have fallen below the replacement level, but healthy immigration numbers drive growth. As the country continued to industrialize after World War II, energy consumption doubled within 20 years. Since then, it has increased by less than 50%, mostly leveling off from 2010 to 2020. As noted previously, the 2020 COVID drop of 7.5% is the steepest drop in at least 70 years. The only comparable drop was during the Great Recession of 2008. In 2009, the drop was 4.9%. The 2020 drop was followed by an increase of 4.7% in 2021, but the overall levels were still below the 2018 peaks. For Figure 3, there is a +0.94 correlation between the population and energy consumption, so the 2020 drop is very noteworthy and indicative of a nationwide change. The cause for this change is the COVID pandemic.

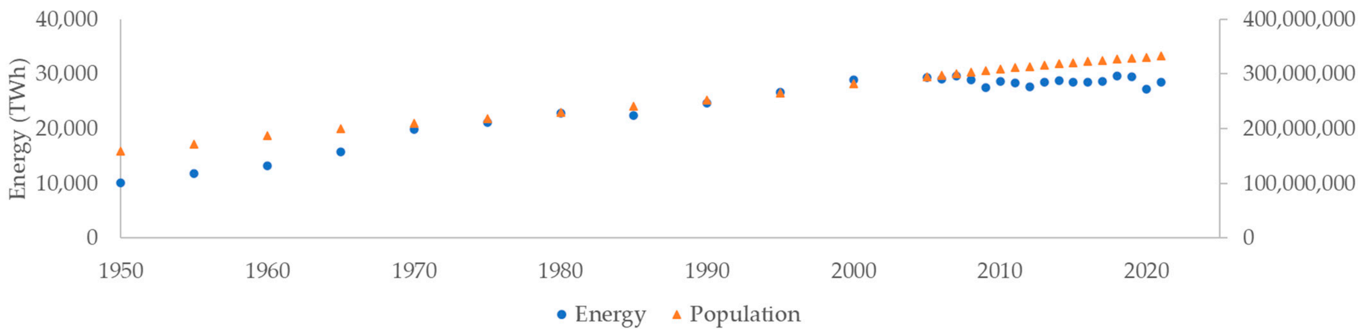
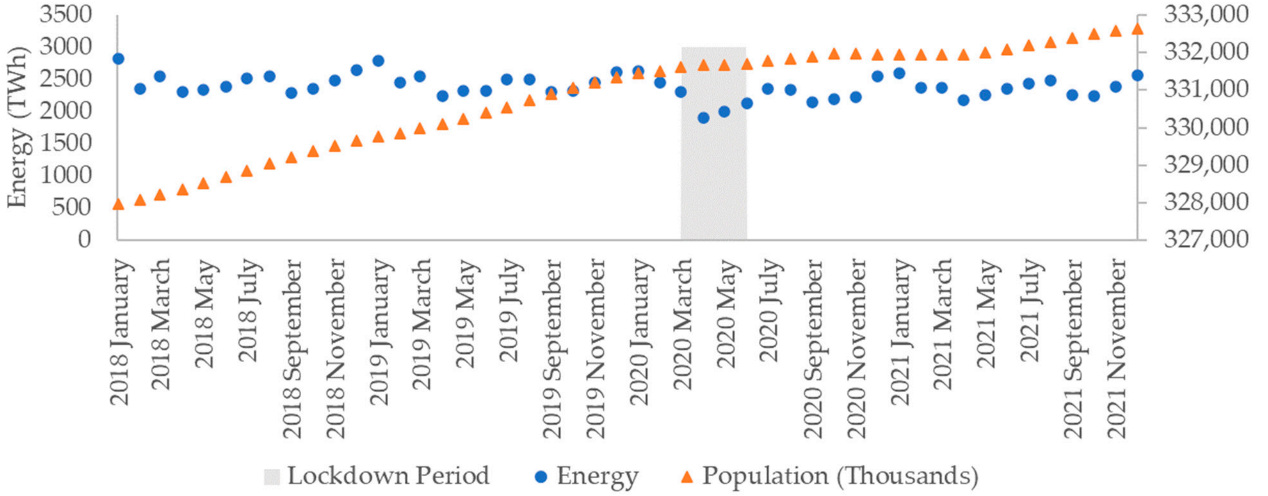


Figure 3. US historical population and total energy consumption from 1950 to 2021 [26,28].

The year 2020 had distinct phases in the US. The first couple of months were largely unaffected. Between 1 March and 6 April, 42 states and territories issued stay-at-home orders (SAHO) [29]. By early June, most of these orders had been relaxed or completely rescinded as the first wave died down. The rest of the year saw two more waves in September and leading into 2021. Figure 4 gives a snapshot of relevant statistics leading up to the pandemic, starting in 2018, and ending in December 2021. The lockdown period is highlighted in both plots. Note that no official SAHOs were issued for subsequent waves, so no further lockdown periods appear on either plot. Figure 4a gives more detail on the energy trends: the seasonal variation in energy consumption is clear from year to year. During the 2020 lockdown, there was a steep 30% drop in energy consumption as large parts of the country shut down. Interestingly, the population numbers also flatline during 2020. Besides using the SAHO dates to define the lockdown period, Figure 4b provides temporal data for the heat map in Figure 1. The first three waves, all in 2020, are clearly visible in the case count and the total deaths. The end of the first wave coincides perfectly with the final SAHOs being relaxed or rescinded. For the rest of the year, economic activity largely resumed with distancing, masking, and increased sanitization. The end of the year saw the first public vaccines administered.



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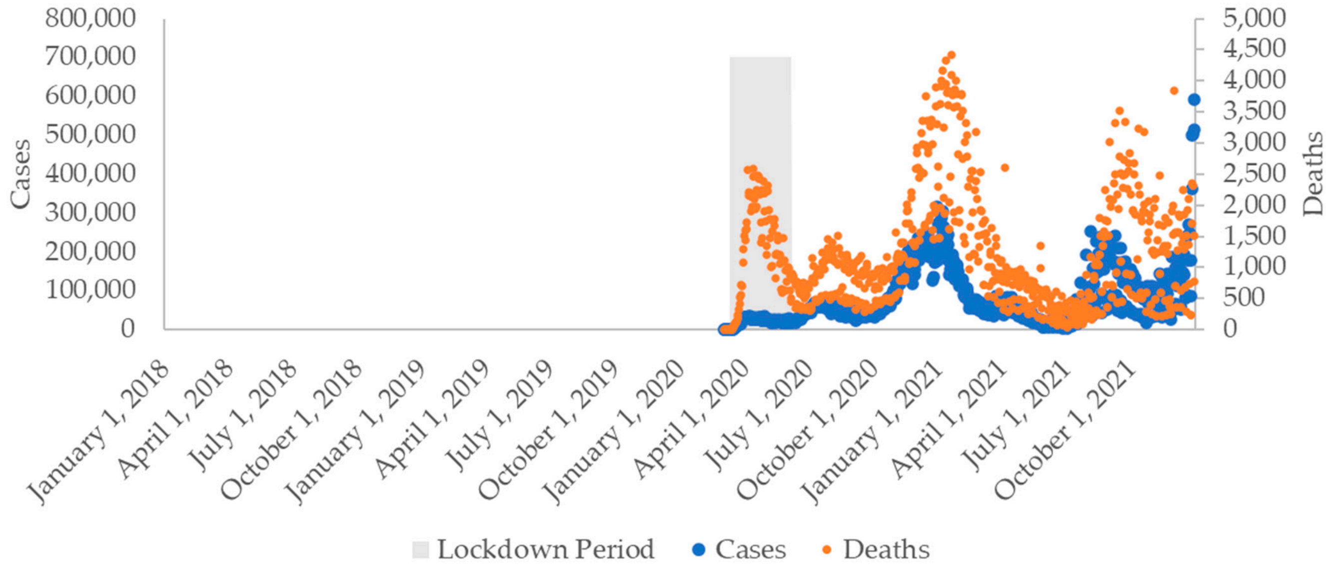


(**b**)

Figure 4. Monthly US COVID pandemic data 2018–2021: (**a**) population and total energy consumption; (**b**) cases and deaths [25,26,28,29].

Figure 5 shows the state-wise total energy consumption for the US in 2019 and 2020. Total energy and per capita energy are shown due to the wide variation in population distribution and consumption trends. The difference between 2019 and 2020 is reflected in the color bar for both years. Individually, the total energy use roughly scales with the population. Texas, despite having about 25% less population than California, uses almost twice as much energy. This is seen clearly in the per capita maps. While the distribution of consumption did not significantly vary from 2019 to 2020, it did reduce for most of the country. From state to state, there is a wide variation. Tropical states like Florida and Hawaii are on the lower end of the energy use spectrum, while Louisiana is on the higher end. North Dakota was the highest, edging out Alaska. The ratio of highest to lowest per capita consumption is over 5:1. Generally, the eastern and western portions that are more densely populated tend to be more energy efficient. The mostly rural middle of the country tends to consume more energy per capita. The COVID pandemic did not significantly alter this consumption pattern.

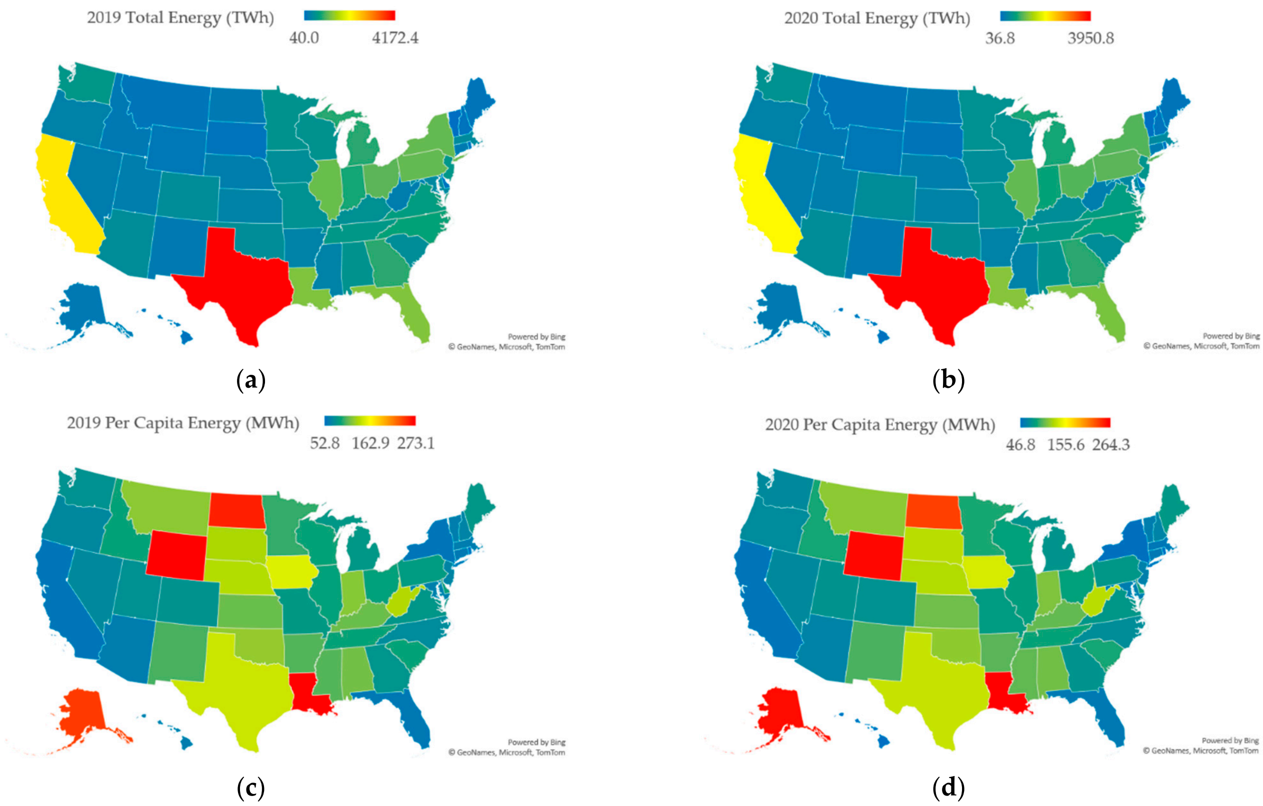


Figure 5. US state-wise energy consumption: (**a**) 2019 total energy; (**b**) 2020 total energy; (**c**) 2019 per capita energy; (**d**) 2020 per capita energy [30].

Figure 6 gives a summary of the percent change in the per capita energy consumption by state between 2019 and 2020, sorted from highest to lowest. The biggest change was for Hawaii, whose economy derives about a fifth of its GDP from tourism. This was one of the sectors that were hit the worst by the pandemic. Hawaii is isolated from the rest of the country or any other land mass, and so about 37% of its energy use comes from jet fuel. This was almost halved in 2020, contributing to the 26.4% drop in total energy. The seven states that had no statewide SAHO are marked with '**' in Figure 6. Note that in the US, there were various levels of lockdowns announced by each state with no Federal mandate ever announced. These ranged from 'mandatory for all' to 'mandatory for certain counties' to 'mandatory for persons at increased risk in certain counties'. Certain states, such as New Mexico and Texas, only issued advisory orders. The population-weighted average change for these states with SAHOs was −5.7%. For the rest of the US, it was −9.1%. All seven states are in the middle of the country, where the case count and death tolls were particularly high. The explanation is that residents in these states were less likely to follow lockdown protocols and continued with life as usual, leading to high death rates and a lower drop in energy consumption. States like New York, New Jersey, Pennsylvania, and California, which were some of the earliest to issue SAHOs, appear on the lower end of the energy drop. This implies that lockdown protocols were more likely to be followed, leading to a greater drop in energy consumption. The only state that saw an increase in energy consumption, 4%, was Alaska, whose SAHO lasted less than a month.

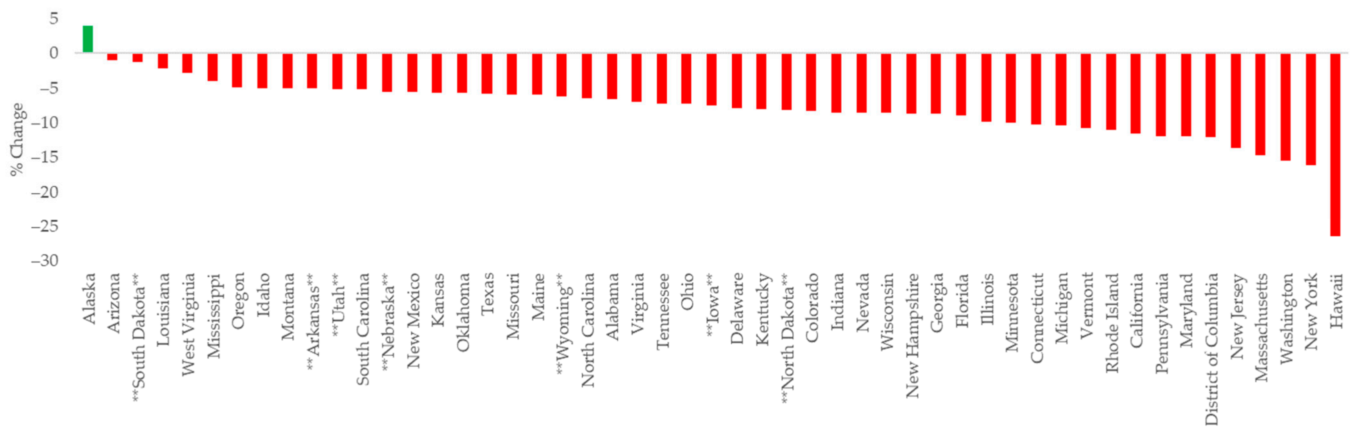
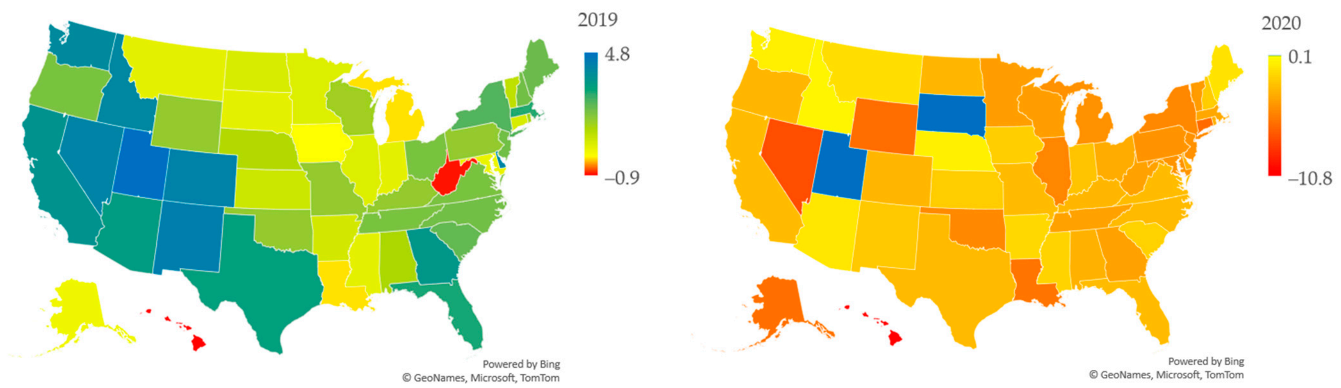


Figure 6. The 2019–2020 percent change in state-wise per capita energy consumption, sorted [30].

The effect of lockdowns on the decrease in GDP was examined next, as shown in Figure 7. For context, the US saw a 4.1% growth in GDP from 2018 to 2019. From 2019 to 2020, however, there was a 2.2% decline [31]. When comparing the decrease in energy with the decrease in GDP for each state, there is a +0.45 correlation. Comparing GDP with the normalized case count gives a +0.28 correlation, whereas GDP and normalized death rate give a +0.37 correlation. Thus, while there is a weak correlation between the health toll of the pandemic and the GDP, there is a stronger correlation between the energy drop and the GDP. Figure 7a shows that the majority of the US states experienced healthy GDP growth. In 2020, however, due to the pandemic, all but two states experienced a decrease. The exceptions were South Dakota and Utah, but the growth was about 0.1% for each. Neither state had SAHOs. Nebraska saw a 0.5% decrease and also did not have a SAHO. Once again, Hawaii experienced the maximum decrease, 10.8%. Another state heavily reliant on tourism and gambling revenue, Nevada, saw a decrease of 7.2%. Despite the increase in energy, Alaska saw a 6% decrease in GDP.



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

Figure 7. Percent change in state GDP in: (**a**) 2019; (**b**) 2020 [31].

Figure 8 shows the breakdown of total energy for each state in 2020. It gives sector-wise insight into data from Figure 5. Gulf Coast states like Alabama, Louisiana, Mississippi, and Texas, which have huge petroleum and ancillary industries, had the industrial sector as the largest consumer of energy. Pennsylvania is another heavily industrial state. Transportation is the majority in states like California and Florida. The commercial and residential sectors tend to be in the minority nationwide. When this bar graph is compared with the map in Figure 9, some patterns emerge. This figure shows the change in sector energy consumption by state in 2020 relative to 2019. Note that the color white represents no change for each map.

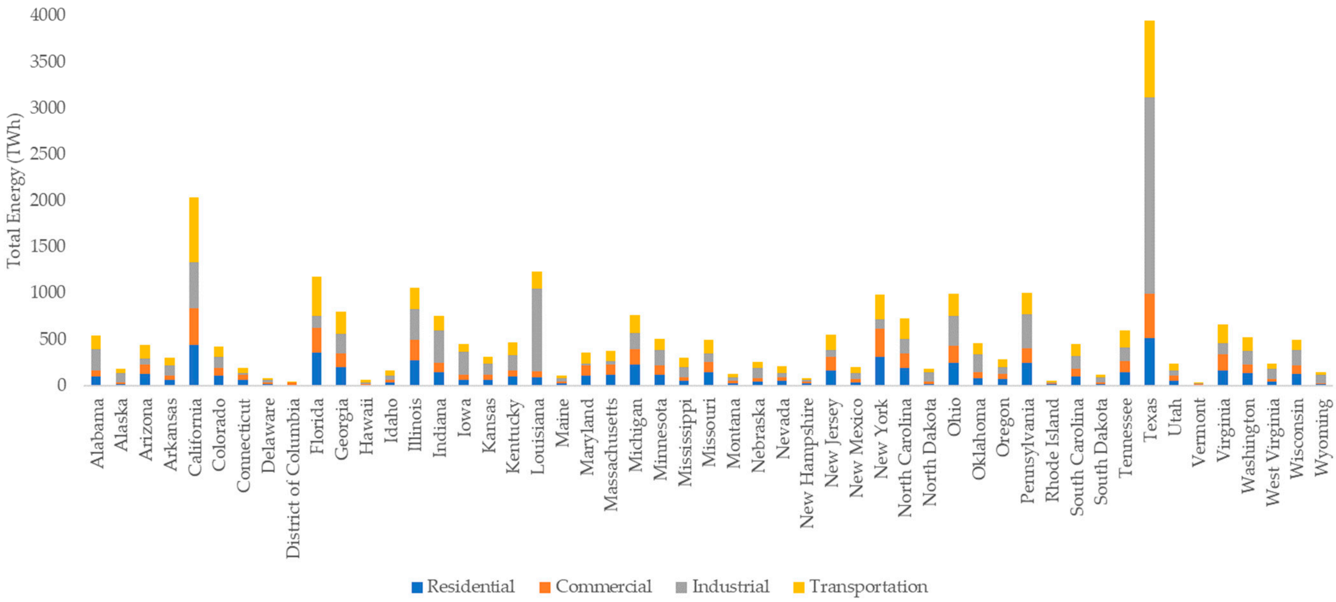


Figure 8. Total energy for each state in 2020 by sector [30].

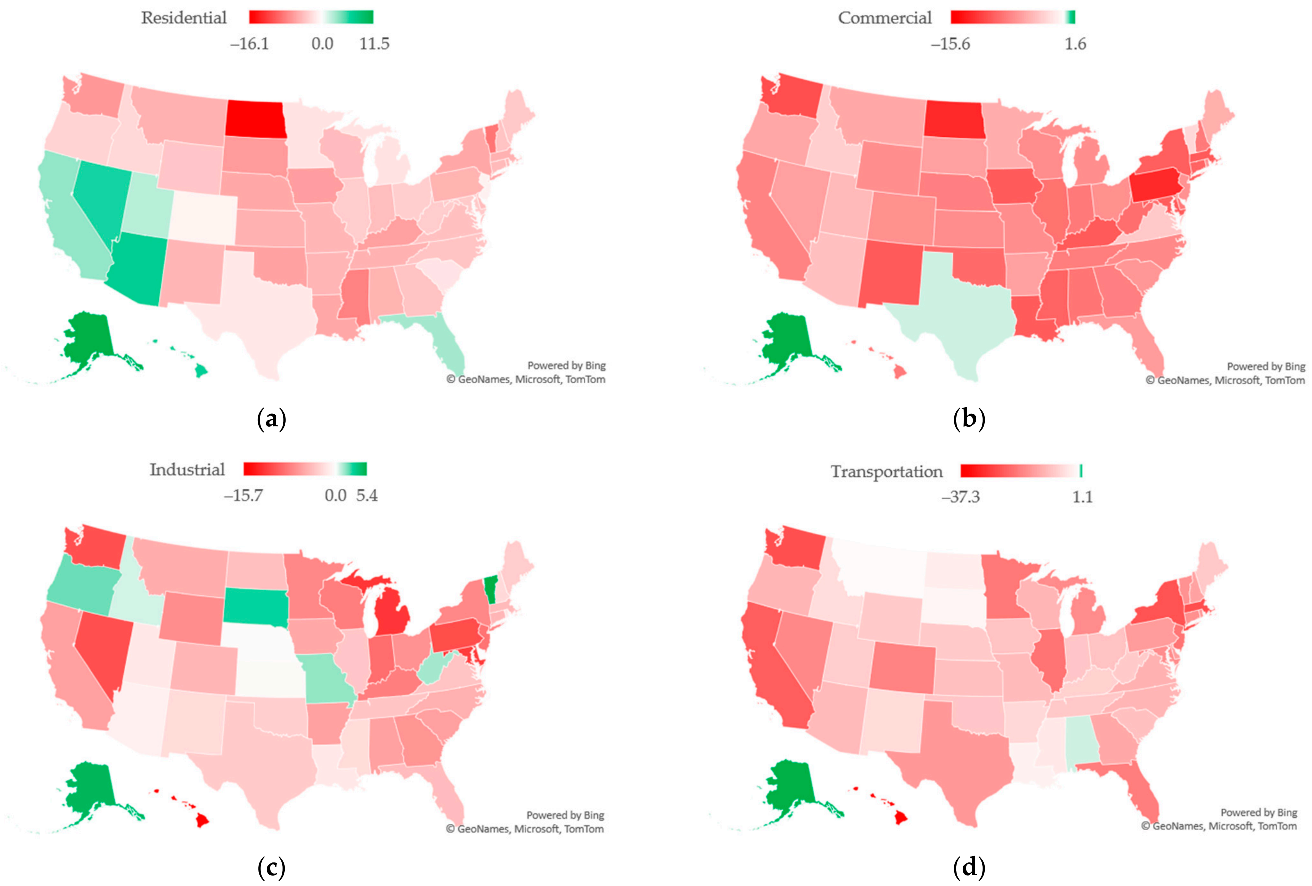


Figure 9. Change in 2020 sector energy consumption by state [30].

In the commercial sector, besides Alaska and Texas experiencing a slight increase, each state saw a decrease, as high as −15.6%. The lockdown and reduced foot traffic at millions of businesses across the nation explain this. The industrial sector appears to have been least affected. While some states saw drops as high as −15.7%, several states had an increase. This is particularly true in the middle portion of the country, including states that had no SAHO. While certain businesses completely shut down, others such as home improvement, online retail, home delivery, pandemic-related safety supplies, etc. exploded. The Great Plains dominate the geography of the middle of the country. Given the sparse population and rural landscape, the increase in energy consumption is understandable in these areas. The residential and transportation sectors are perhaps the most interesting. With monthslong lockdowns in place, several sectors of the economy switched to remote work. This continued in 2021 and 2022 with some businesses still allowing employees to work in a hybrid modality: in the office or at home. Given the car-centric, suburban city layouts in the US coupled with the fact that over 80% of the US is urban, most of the states saw a decrease in transportation energy when people stopped commuting. This, however, did not result in an increase in residential energy consumption in most states. Only seven states saw an increase, and all of these were southern states where the climate tends to be hot and dry. The exception was Alaska. Its almost 12% increase in residential energy consumption can be attributed to the winter of 2020 being colder than 2019. Note that winter conditions can vary drastically in various parts of the US, and since Alaska is located to the far northwest, it can experience significantly different conditions from the rest of the mainland. As for the states that had no SAHO, there is a +0.44 correlation between the decrease in residential energy and case count. This is a medium positive correlation, but it does suggest that as the case count increased, the residential energy tended to decrease. The following is a very plausible explanation. US hospitals were overflowing despite added capacity during the subsequent waves of the pandemic. If thousands of people were spending several days in the hospital, then they were not spending that time at home. For the country as a whole, the correlation between residential energy change and case count was lower, +0.24.

Figure 10 shows the change in 2020 electricity consumption for each state by sector. The commercial section (Figure 10b) saw a decrease in virtually every state, precipitated by the closures of most businesses. States like Nevada and Texas saw an increase, but no more than 2.5%. The industrial sector was more mixed. As mentioned previously, several industries were required to remain open and support critical societal needs like food and energy. Certain manufacturers were asked to produce pandemic safety supplies under the Defense Production Act of 1950 by order of the President of the US. The population-weighted commercial energy drop was 5.6%, whereas the industrial drop was only 3.8%. For the states without SAHOs, these were −5.3% and +1.2%, respectively. The trend is similar to the nation, with a large drop in commercial but an increase in industrial. It is interesting to note that these seven states collectively saw a rise in industrial electricity consumption while the country as a whole saw a significant decrease.

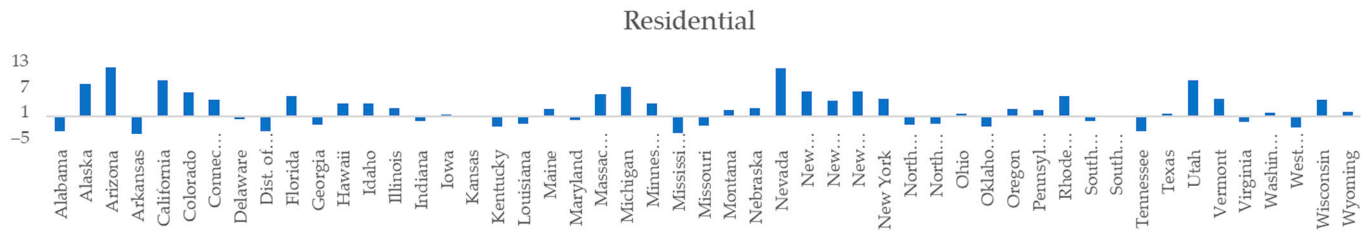


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Figure 10. *Cont.*

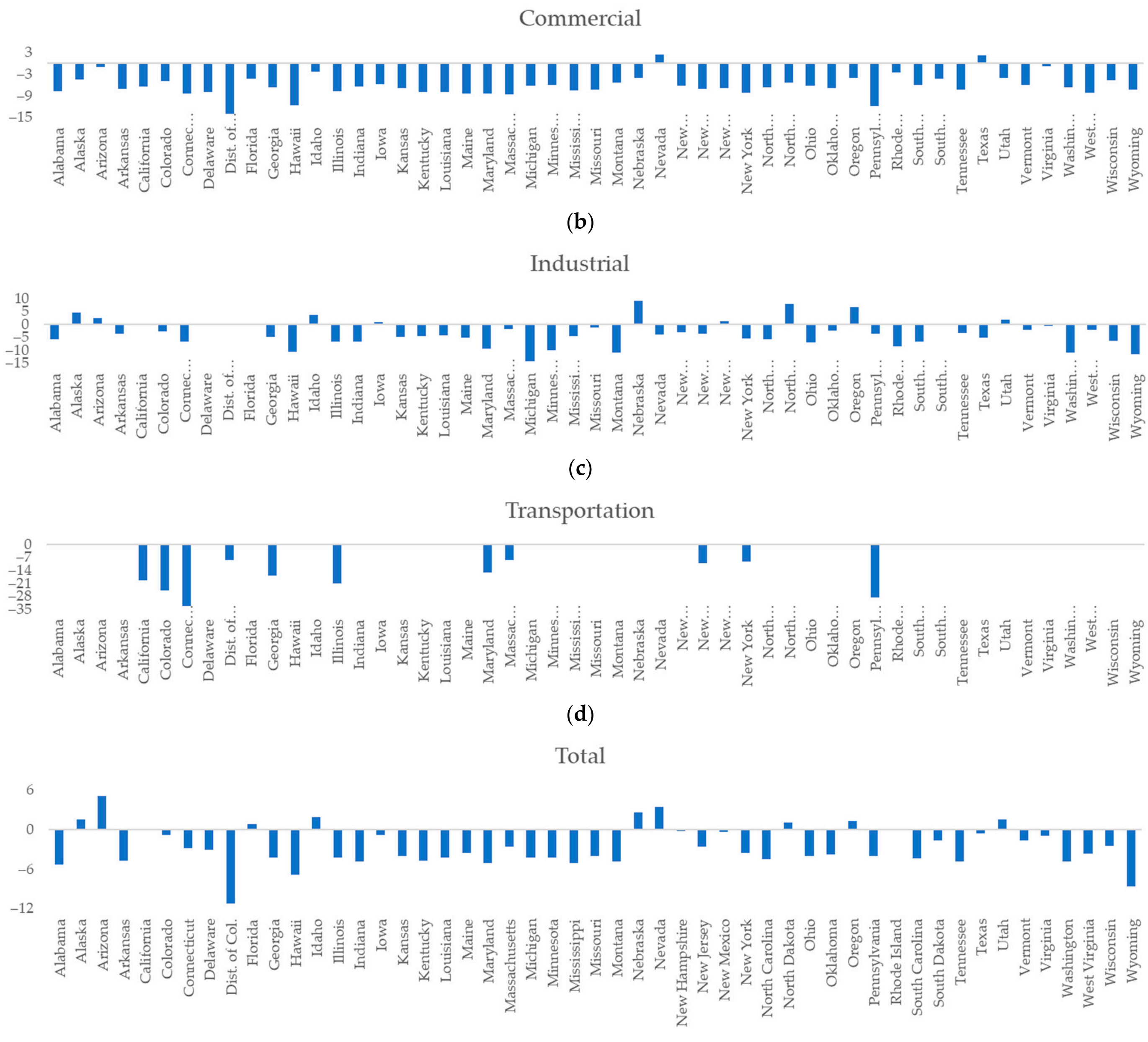

Figure 10. Change in 2020 sector electricity consumption by state [30].

In the US, electric vehicle adoption is still lacking, especially away from the coasts. Figure 10d shows the change in transportation electricity consumption and several states are at zero. The Department of Energy's database records a zero if the data are measured as zero or (s) if below a certain minimum threshold, 0.5 GWh. For the sake of plotting, both entries were treated as zero in this study. For states with data, several saw drops of over 10%. This is to be expected from the reduced travel caused by lockdowns. The most interesting sector is perhaps the residential sector, shown in Figure 10a. Southern states like Arizona and Nevada saw rises of 11.5% and 11.4%, respectively. This provides further evidence that lockdowns caused an overall 2.6% increase in residential energy consumption. However, this was not uniform, as states like Arkansas and Mississippi recorded drops in residential electricity consumption. The largest drop was in Arkansas at −4.1%. Once again, the states without SAHOs saw a much smaller increase in residential electricity, 1.4%. This supports the idea that without lockdown protocols, people did not spend as much time at home as in the states with SAHOs. A low value of 1.4% could be attributed to the natural increase in energy consumption over time. One thing to note is that the residential electricity consumption is not the same as the total residential energy consumption. There is a +0.93 correlation between the two. While several states derive more than 50% of their residential heating from electricity, natural gas and propane are also very popular. Distillate fuel (e.g., diesel, heating oil) and wood are less common but still used. The overall electricity trend in the US is similar to European countries. It was found that countries like the UK, Spain, and Italy with strict lockdowns saw a larger decrease in weekday consumption than those with less restrictive measures like the Netherlands and Sweden [32].

Figure 11 shows the historic energy consumption for the entire US by fossil fuel type. All fossil fuels are grouped into one of three categories: coal, petroleum, and natural gas. Each point represents a month between January 2010 and December 2021. Source data provide detailed methodology on heat capacity values and conversions between various fuel subtypes as well as missing or anomalous data. Figure 11a shows coal consumption in short tons (1 short ton = 0.907 metric tons). The seasonal cycle is clear, but the plot also reveals the downward trend in coal over the past 12 years. The peak value was in August 2010, and the bottom was in April 2020, about 73% lower than the peak. After the lockdown, there was a slight increase in coal consumption. The peak in 2021 was 12% higher than in 2020. It remains to be seen whether this will continue. Figure 11b shows the petroleum consumption in barrels per day (1 barrel = 158.987 L). The seasonal variation in Figure 11b can be seen, but it is not as drastic as coal. Peak consumption happens over the summer and during the holiday season towards the end of the year. Overall, there is a slight increase in consumption starting from 2010. This was because the US gradually recovered from the Great Recession. While vehicles became more efficient, consumers switched from sedans to sports utility vehicles and pickup trucks to such an extent that they account for over 50% of new vehicle sales in the latter years of the 2010s. The peak before the lockdown was in August 2018 and is about 18% higher than the bottom in September 2012. The sharp dip during the lockdown period is clear. The 2020 low was in April 2020 and was about 28% lower than in April 2019. For the year, 2020 was about 11.4% lower than 2019. However, 2021 followed the same trend as coal: 8.9% higher than in 2020, but still lower than in 2019. The natural gas consumption is shown in Figure 11c. The overall trend is that of a gradual increase since 2010, keeping in line with population growth and replacing coal. The seasonal trend is similar to that of coal. About 52% of natural gas in the US is used to produce electricity and residential heating. About 44% is used by the commercial and industrial sectors, which explains why there is a baseline of consumption regardless of the season. Lockdowns did not significantly affect consumption. The period from April to June 2020 saw a 0.3% reduction relative to 2019, but the same period saw a 1.5% increase in 2021.

Having analyzed the fossil fuel trends, Figure 12 plots show the change in renewable energy generation in 2020 relative to 2019. Figure 12a shows biomass, which includes agricultural and wood waste, biogas (including landfill gas), and bioethanol. The heart of the bioethanol industry happens to lie in the central states because these states produce the feedstock—corn. States with SAHOs like North Dakota, South Dakota, Iowa, and Nebraska saw the largest drop in production, as high as 88%. This is because of the overall decrease in demand for transportation fuel. Several production facilities halted production. Pandemic safety measures added further restrictions in those facilities. The biomass generation for the US as a whole was about 23% lower than in 2019. The vast majority of states do not have significant geothermal generation. For Hawaii, the 2019 value was reported to be zero, so the increase was technically infinite. For the sake of plotting, it was capped at 100%. For hydroelectric generation, there were huge variations from state to state. The highest change was in Kansas, 50%. The lowest change was New Jersey, −50%. For the US as a whole, it was about 2.4% lower. While this may not be a large value, given that the 2021 hydroelectric generation was 9% lower than in 2020, it continues to highlight the degree to which drought and water shortages have affected the country. On the other hand, as seen in Figure 12d, solar energy increased in almost every state as the country continues to embrace adoption. The increase was about 19.2%, with Kansas seeing a 100% increase and Rhode Island seeing a 109% increase. For wind energy, several states did not report appreciable levels, but virtually all the states that did reported an increase. The nationwide increase was about 12.5%. Midwestern states like the Dakotas, Iowa, Montana, and Nebraska saw the largest increase. The largest decrease was for Alaska, 15.4%. The total change in renewable energy was −5.8%. However, not including biomass, renewable energy increased by about 7.3% as the country continues to increase its adoption of carbon-free energy.

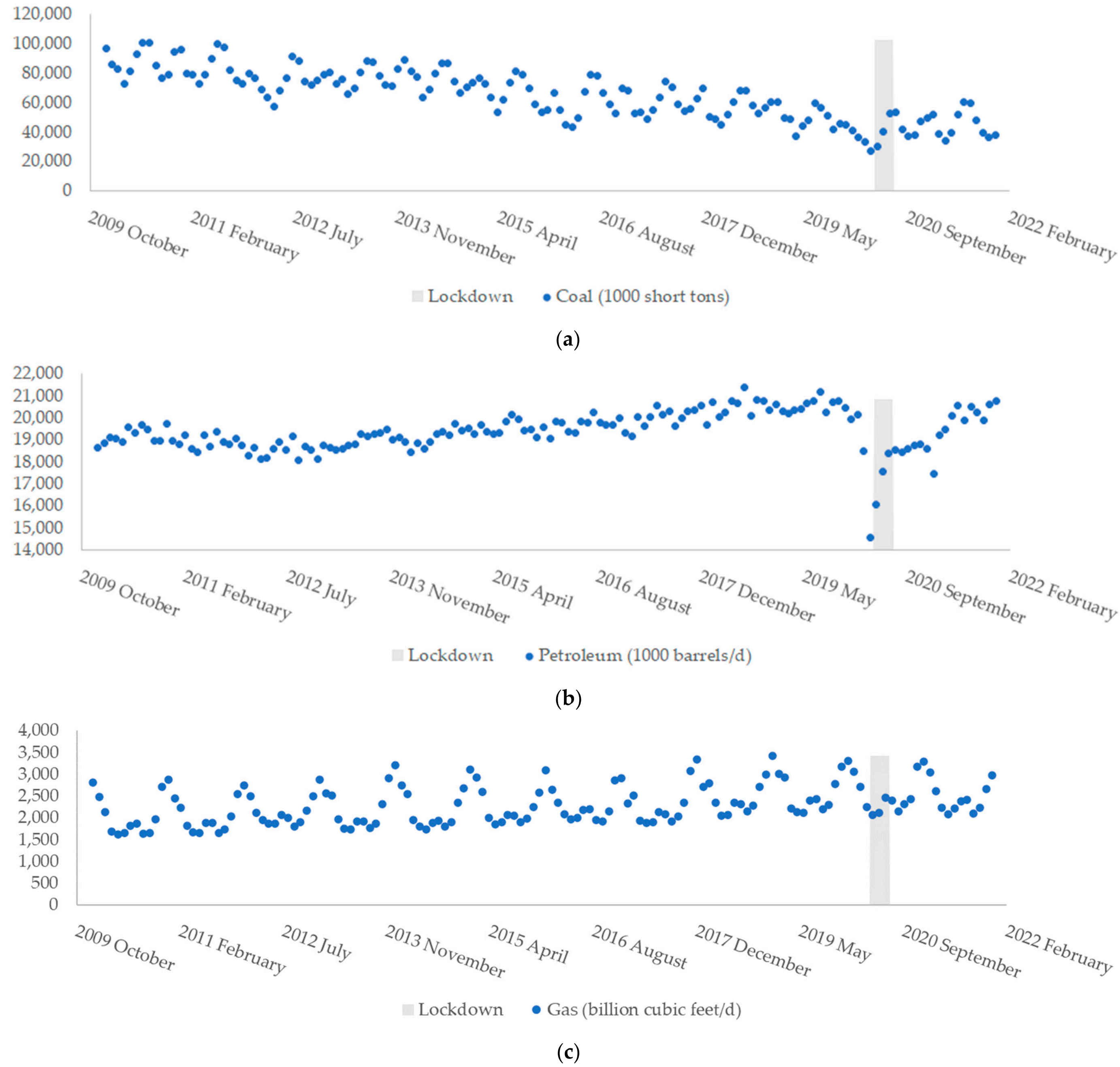

Figure 11. US historic energy consumption by fossil fuel type: (**a**) coal; (**b**) petroleum; (**c**) natural gas [33].

Figure 12. The 2019–2020 change (%) in renewable energy generation by state [30].

Figure 13 shows the final major component of US energy: total nuclear energy generation from 2018 to 2020. Not every state has nuclear power plants, so only total generation is shown. The capacity factor of the nuclear power industry averages about 90–93%. France, which is considered a world leader in nuclear power, hovers around 77%. As such, the data seen in Figure 13 are very close to the maximum generation capacity. As the capacity plot indicates, total nuclear generation has gradually fallen as the US decommissions aging nuclear plants. Correspondingly, total energy generation has fallen. The energy production in December 2020 was 4.7% lower than in January 2020. The generation plot shows some seasonal fluctuations. While nuclear plants operate as base load plants, there is some momentum on the concept of flexible nuclear operation. However, the historic data shown in Figure 13 simply show the two seasonal peaks, much like the coal and natural gas plots in Figure 11. Besides minor seasonal variations, the effect of refueling and plant maintenance outages also plays a part. The pandemic did not have any appreciable impact on the nuclear sector. Finally, it is important to note that the peak-to-trough variation in a year is about 20%, whereas it is about 50% for natural gas.

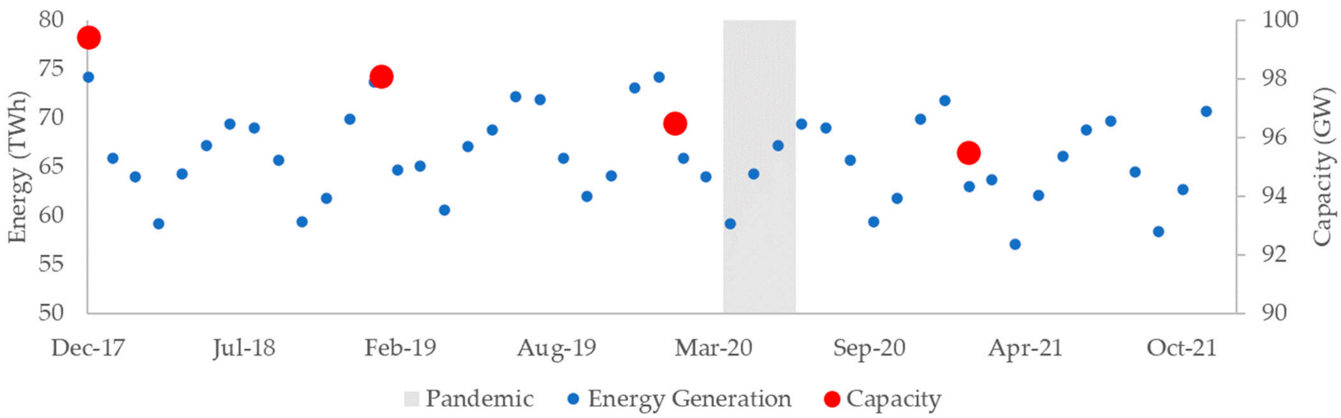

Figure 13. US nuclear energy generation 2018–2020 [30].

Figure 14 shows the historic greenhouse gas emissions for the US from 2010 to 2020. The top three pollutants are shows: carbon dioxide, methane, and nitrous oxide. From Figure 14a, the general trend that can be noted is that emissions have trended downward. Carbon dioxide emissions fell by about 7.5% between 2010 and 2019. Just the next year, they fell by 10.4%, keeping in line with the general fall in energy consumption in the country. Given that electricity and transportation account for 70% of carbon emissions, and considering that each fell by 2.5% and 7.5%, respectively, the 10.4% drop is understandable. Similarly, methane fell by 5.2% between 2010 and 2019, an average of 0.5% per year. The following year, the drop was 2.8%. The top two sources of methane emissions in the US are petroleum systems (including old or abandoned wells that leak methane) and enteric fermentation (from animal husbandry), combining for 59%. The other major sources are landfills and manure management. Since the agricultural sector is such a large methane emitter, the pandemic did not result in a decrease in methane emissions that was as drastic as carbon dioxide. Overall, between 2010 and 2020, there is a +0.78 correlation between carbon dioxide and methane. Nitrous oxide increased by 0.9% from 2010 to 2019. The largest source of nitric oxide is the agricultural section at 67%. The next two sources are fossil fuel combustion and biomass combustion, 19% in total. Between 2010 and 2019, gasoline consumption increased by 1.6% and distillate fuel (predominantly diesel) increased by 13.1%. Diesel engines typically produce ten times as much nitric oxide as gasoline engines. Similarly, biofuel production more than doubled. This explains why nitric oxide emissions increased during this period. In 2020, it fell by 6.7% due to the reduced fossil fuel consumption during the pandemic. Figure 14b shows the year-over-year change. The most severe change in any one-year period was in 2020. This demonstrates the effect the pandemic and lockdowns have on emissions. It also matches similar studies on energy and emissions trends during the pandemic.

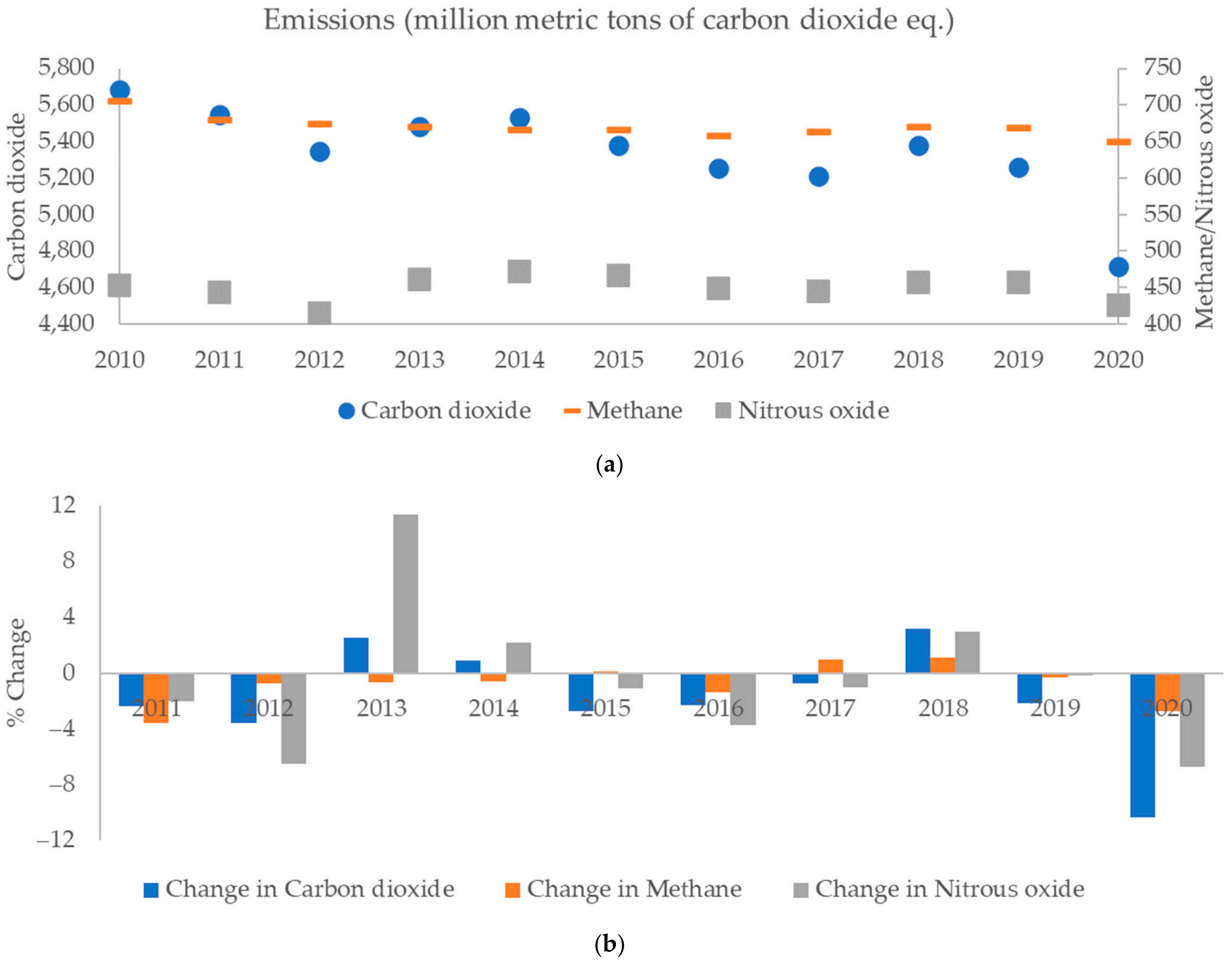

Figure 14. US greenhouse gas emissions 2010–2020: (**a**) total; (**b**) change [34].

In Figure 15, the total energy picture for 2020 can be seen in order to understand the source of the drop in energy consumption. Coal saw the largest drop at 18.8% relative to 2019, but only accounted for about 9.8% of the energy total. Given its role in heating and industrial production, natural gas decreased only by 1.8%, but accounted for 33.8% of the total. Petroleum saw a 9.3% drop while accounting for 35.8% of the total, the greatest share. Nuclear and renewable energy fell by 2.4% and 5.8%, respectively, while accounting for 8.8% and 11.4%, respectively. Finally, electricity imports from Canada and Mexico increased by +57.4%. The total energy decrease in 2020 was about −7.5%. Note that state-wise energy totals do not account for net electricity imports. As described previously, the transportation sector had the largest sector-wise drop of about 15%.

To round out the energy picture, it is instructive to consider energy expenditures [30]. On a per capita basis, the US spent USD 3040 on energy in 2020, down about 18.5% from 2019. Wyoming spent the most, USD 6707. New York spent the least, USD 2375. The largest drop was, once again, Hawaii, at 32.1%. The total state-wise electricity expenditures closely followed consumption trends, with a +0.92 correlation. There is a +0.98 correlation between electricity expenditures and total energy expenditures. Washington, DC saw the largest drop, 14%, while California saw the largest rise, 6.5%. Interestingly, California was not the state with the largest increase in consumption; its change in electricity consumption was

−0.1%. Sector-wise, expenditures fell in every sector in every state, except for a few states in the residential sector. These states were Alaska, Michigan, and southwestern states. As for energy prices, they fell in every state. The lowest drop was in Alaska, −2.6%. The largest drop was in Louisiana and Washington, DC, 19.4%. The country saw an energy-weighted overall drop in energy prices of about 8%. The state with the highest energy prices was Hawaii, USD 0.1386/kWh, while the lowest was Louisiana, USD 0.0310/kWh. This is a huge discrepancy, but it is emblematic of how these states obtain their energy. Louisiana has a massive petroleum industry. Hawaii, on the other hand, relies on importing the vast majority of its energy supply. Given its distance from the mainland, transportation costs contribute significantly to its overall energy prices. There were weak negative correlations between the average state-wise energy price and the per capita energy consumption (−0.36) and the same price and state-wise energy consumption (−0.19). However, there was a +0.997 correlation between the average state-wise energy price and state-wise energy expenditures. Note that the energy expenditure is essentially calculated by multiplying the price by the consumption.

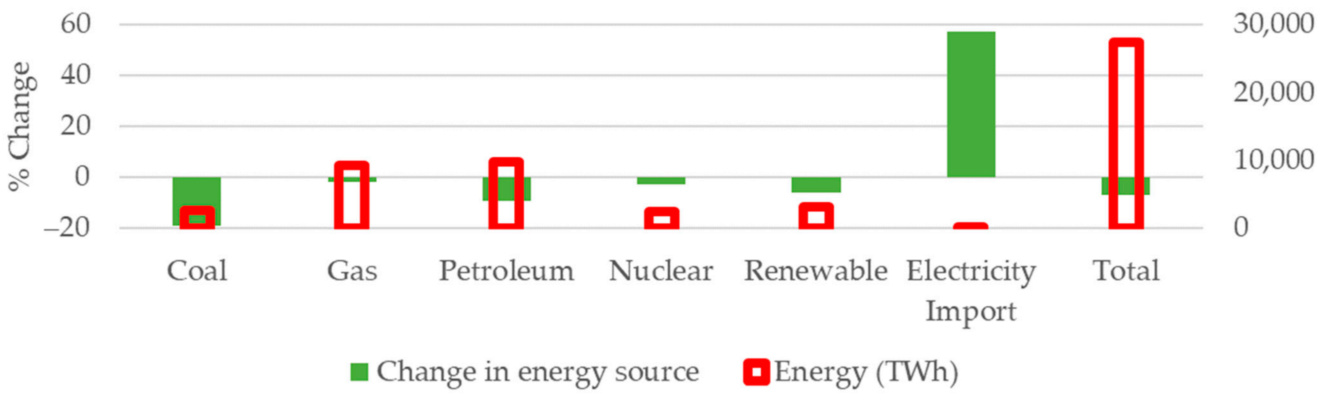

Figure 15. US 2020 energy totals by source and change relative to 2019 [30].

4. Discussion, Conclusions, and Future Work

This section provides additional discussion and key takeaways based on the results and analysis of the preceding section. This paper focuses on the impact of the COVID-19 pandemic on the energy sector in the US in 2020. The goal was to provide a comprehensive picture of the country using data gathered and processed from several sources in an easily accessible and insightful manner. As was discussed in Section 1, previous studies have focused on smaller regions or even individual cities. However, a nationwide perspective is critical for a country like the US, which is a huge energy consumer and importer. Uncovering national trends during pandemic times makes future action and preparedness easier for governments. It is hoped that future studies can draw from this work, make comparisons wherever possible, and extend its scope.

The data sources were from Federal agencies responsible for collecting state-wise data. These data, together with the associated methodology, are available for public access. However, there are significant delays in when such data are made available. The 2021 data were still not available as of Summer 2022. The 2020 data were also incomplete or required significant processing when compared to the 2019 data. Whether this was a result of the pandemic and accompanying disruptions is unclear.

- Data availability issues could delay or hinder research and policymaking during critical events like the COVID-19 pandemic. Such "black swan" events are extremely important learning experiences for society and governments, and data collection, processing, archiving, and dissemination should be treated as a priority. For example, as was described in the present work, while energy consumption as a whole fell, residential energy consumption increased in several states. Climate change, the switch to electric vehicles, etc. will severely stress the aging grid infrastructure in the US.

Utilities and planners should have access to broad data in order to prepare for such events in the future.

The fact that US case counts and death rates were some of the highest in the world has been well documented. In total, 32 out of 51 states and territories had a death rate above 300/100,000 in 2020–2021. No strong correlation between the initial population and the case count was found. Geographically speaking, the middle and southern portions of the country generally had higher rates than the east and west coasts. These human costs were juxtaposed with the change in energy consumption for some of the largest countries in the world. Virtually all countries saw a decrease in energy in 2020 relative to 2019 but saw an increase in energy in 2019 relative to 2018. Again, no strong correlation between the energy drops and the death rate was found. Out of the 10 countries, accounting for 51% of the global population, the US had the highest death rate and number of deaths and the second-highest energy drop. Historically (1950–2021), a +0.94 correlation between population and energy consumption in the US was found. A 7.5% drop in energy in 2020 was the steepest in 71 years, followed by a 4.9% drop during the 2008 Great Recession. This drop was amplified to 30% during the March–June 2020 lockdown period.

- The COVID pandemic was directly responsible for a −7.5% drop in total energy consumption in the US in 2020 due to the disruption of daily life in all sectors.

The state-wise energy consumption revealed that the rural middle of the country tended to have a higher per capita energy consumption than some of the coastal states, as high as 5:1 in some cases. The seven states without SAHOs were also centrally located, and several of the middle states imposed lockdowns as late as April. Thus, the change in energy consumption by state landed on a spectrum, from +4% (Alaska) to −26.4% (Hawaii). The population-weighted average change for the states with SAHOs was −5.7%. For the rest of the US, it was −9.1%.

- The lack of SAHOs resulted in a lower decrease in energy consumption and a higher death rate.

GDP declined by 2.2% for the US as a whole. Weak correlations between GDP and normalized case count (+0.28) and normalized death rate (+0.37) were found. A stronger correlation of +0.45 between GDP and energy drop was found.

- GDP was more heavily influenced by energy consumption than the COVID health toll.

Sector-wise energy breakdown for each state revealed a reduction in energy consumption in virtually every sector across the country. The residential sector was found to have the most states that saw an increase in energy. The industrial sector was least affected, with several states experiencing a minuscule change relative to 2019. The transportation sector was the most affected. For states without SAHOs, a +0.44 correlation between the decrease in residential energy and case count was found.

- While several states saw an increase in energy residential consumption, non-SAHO states saw a disproportionate decrease in energy as their case counts increased.

Electricity consumption followed a similar trend as the total sector-wise energy consumption. Residential electricity consumption increased by +2.6%.

- Lockdowns contributed to an increase in residential electricity consumption, but states without SAHOs experienced a lower increase, +1.4%.

Examining historical fossil fuel consumption showed that petroleum consumption was most affected by the lockdown period, dropping 28% in April 2020 and 11.4% in 2020. Coal consumption increased after the lockdown period after falling year after year for the past 12 years. Natural gas has been historically increasing as coal falls out of favor, and lockdowns did not have a significant impact on historical trends.

- As fossil fuel import economies like the US continue to reduce consumption, the influence of the pandemic and related supply chain disruptions must be accounted for. Similar events in the future can be expected to result in a decrease in petroleum consumption, but this was followed immediately by a rapid recovery.

Renewable energy generation overall decreased by 5.8%, but, excluding biomass, it increased by 7.3%. Biomass is the only renewable resource that can be said to have been seriously affected by the pandemic. The primary reason for the decrease was the precipitous decrease in biomass-based fuel production. Biomass is considered renewable and carbon neutral. However, its primary disadvantage is that it competes with food production. For countries like the US, this is not a problem. However, food security is expected to affect an increasing proportion of the global population due to supply chain disruptions, climate change, war, etc.

- Several US states still do not have appreciable levels of renewable energy. While natural resources like geothermal, solar, and wind vary dramatically across the vast nation, the lack of a unified energy policy has delayed the transition of certain state economies. This could lead to severe economic and infrastructure consequences and imbalances in the coming years.

Total nuclear energy continues to decrease as US nuclear power plants age and undergo decommissioning. US greenhouse gas emissions also expectedly decreased in 2020. Carbon dioxide emissions fell by 10.4%, methane by 2.8%, and nitric oxide by 6.7%.

- The US is still heavily dependent on fossil fuels. As such, the lockdowns provided an undesigned benefit—a decrease in energy consumption led to a decrease in emissions and cleaner air. Similar effects have been reported by other recent studies. With several companies continuing to allow employees to work from home and several business meetings and similar activities being held virtually, such enduring emissions reductions could build on the concerted effort to reduce fossil fuel consumption.

Most states saw a drop in per capita energy expenditure, about 18.5% for the country. Every sector in every state saw a drop in expenditure except for the residential sector in a handful of states. A wide disparity in spending was noted: the state that spent the most (Wyoming) spent 2.8 times more than the least (New York). A +0.92 correlation between total energy consumption and electricity expenditure was found. Similarly, a +0.98 correlation between total energy expenditure and electricity expenditure was found. Energy prices fell in every state. The overall energy-weighted average drop in price for the country was about 8%. The state with the highest price per kWh (Hawaii, USD 0.1386/kWh) was about 4.5 times higher than the state with the lowest price (Louisiana, USD 0.0310/kWh). There was a +0.997 correlation between the average state-wise energy price and state-wise energy expenditures. On the other hand, comparing price with per capita energy yields a +0.56 correlation. This is a moderate correlation and implies that states consume more energy when it is cheap. Looking at the map in Figure 5 shows that the coastal states tend to consume less energy per capita than the middle parts of the country.

Climate plays a factor as well, but one of the critical challenges facing the US today is how it manages its energy use. US citizens enjoy a relatively high standard of living, and this includes one of the highest per capita energy consumption rates in the world. Gasoline prices are less than half that of countries like the UK and Norway and lower than China, India, Indonesia, Mexico, South Korea, etc. Similarly, electricity prices are less than half that of the UK, Germany, and Denmark, and lower than Australia, Brazil, France, and Japan. Energy use is not taxed to the extent that it is in other developed countries. Fossil fuel use is still subsidized by the government, so people have very little individual impetus to rapidly switch to cleaner sources. Further, the aging grid continues to face challenges due to the climate crisis and the slow adoption of renewable sources, all of which produce electricity.

This study has the following limitations. Publicly available sources of data were used to conduct the analysis presented here. This does not represent all the pandemic-related data currently available. The focus was on data that can be easily accessed for reproducibility. In the data sources, some state-wise breakdowns were not available. For example, fossil fuel consumption by fuel type for each state. In such cases, nationwide data were presented. In order to keep the length reasonable, energy consumption by economic sector (primary, secondary, tertiary) was not presented. Similarly, the data on energy prices were also kept extremely brief. Most of the plots deal with data exclusively from 2020, since the 2021 data are incomplete. Finally, the societal impact of COVID was not considered. Rather, the focus was on energy consumption, which changed because of changes in society brought on by the pandemic. A detailed socioeconomic analysis is beyond the scope of this work.

Future work on US energy consumption and the influence of the COVID-19 pandemic should consider the 2022 data when available. Such data over the duration of the pandemic would be critical to help grid operators and utilities inform their strategies to cope with such events in the future. Over 75% of the US economy is in the tertiary sector, meaning several key businesses were able to operate remotely. However, employees in this sector tend to be the most financially flexible and spent a lower fraction of their income on food and energy. Future work could also look at the unequal impacts of the shift in the energy usage during the pandemic. Finally, future work should re-examine pandemic changes to investigate which changes, if any, have gone from short-term to long-term.

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Article

Oil and Gas Markets and COVID-19: A Critical Rumination on Drivers, Triggers, and Volatility

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Abstract: The paper endeavours to explore and analyse some critical issues in the oil and gas market that cropped up around the spread of COVID-19 and tries to identify the key drivers and triggers pertaining therewith. The spread of the first wave that began in March 2020 is crucial because of the global economic downturn that ensued due to lockdown and imposed restrictions coupled with a protracted oil price war that began between Saudi Arabia and Russia. The paper tries to address some key research questions to understand the triggers and drivers around the pandemic. These are: (1) whether the behaviour of OPEC or its key players around the pandemic could be considered uniquely different; (2) what could the triggers be for the increased volatilities that cropped up in both physical and financial markets during the pandemic; (3) what was really different about the oil market crisis around the pandemic that transformed it to an unprecedented storage crisis; (4) what really went wrong with the much-hyped U.S. shale boom during the pandemic that led to the bankruptcy of several oil and gas companies, followed by huge job losses. The paper relies on a structured review of relevant secondary literature to address these exploratory questions and builds upon a retrospective rumination on the world oil market from 1960 to 2020. This is complemented by an analysis of supporting data and evidence obtained from various sources. Considering the intertwining of oil and financial markets around the pandemic, the lessons and findings from the paper would not only be highly relevant for policymakers and stakeholders in the oil and gas sector but would be equally relevant for those in the financial markets.

Keywords: OPEC; crude price; COVID-19; volatility; storage crisis; futures; shale

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1. Introduction

As per the International Energy Agency (IEA), oil accounted for 46% of the world's energy needs as of 1971 and a decade back in 2010, the figure stood at 31%. The share has remained steady since then, and oil continues to dominate as the most important fuel, and as predicted by IEA, it will continue to be the leading component in the world's energy consumption [1].

For a commodity that is consumed so heavily worldwide, there is no second thought that any price shock and volatility that ensues therefrom would invariably have serious repercussions for global economic growth. The presence of volatility and associated price fluctuations is not new in the oil market and has existed since the discovery of oil in 1859. The historical evolution of oil markets could be divided into two phases—the phase before OPEC was formed as an entity (1859–1960) and the phase after that (1960 to present). Some of the oil shocks that shook the world in these two phases include the Suez Crisis (1956–1957), the Arab oil embargo (1973–1974), the Iranian revolution (1978–1979), the Iran–Iraq War (1980), and the Persian Gulf War (1990–1991) [2,3]. However, the more recent events in the last decade that have significantly heightened the oil price volatility include the global financial crisis of 2008, the shale gas revolution, the increase in penetration of renewable energy in the energy mix and the uptick in the growth of electric vehicles. The manifestation of this increased volatility could be observed in the form of extreme oil prices (highs and lows), often causing turmoil and stress on the budgets of major oil nations [4].

For instance, the global economy countered a phenomenal 70 per cent price drop during the period 2014 to 2016. This drop was reportedly considered one of the three biggest and longest drops in oil prices since World War II [5]. However, the unprecedented fall in prices that ensued in March 2020, triggered by a lethal double bout of COVID-19 pandemic and a protracted battle between Saudi Arabia and Russia for oil market share, was one of its kind and belied all expectations [5].

Although the key OPEC player Saudi Arabia and the non-OPEC giant Russia came to terms in April 2020 due to pressure from the U.S. and G20's intervention, the oil market had already been bruised enough by then so as not to return to normalcy very soon. This was largely caused by the crude oil market glut and a sharp drop in global fuel demand of 30% triggered by prolonged lockdowns, frequent travel bans, little or zero vehicle usage, and a downslide in the economic activity [6]. Eventually, the WTI crude oil futures price landed in the negative zone on 20 April.

To understand the movements in the oil market around pandemic time, it may not be appropriate to ignore the oil price crash as a one-off event, but one may need to take cognisance of the evolution of the World oil market, explore the dynamics of the strategy of the key players such as OPEC or its lead members such as Saudi Arabia, and the interplay of other potential drivers in determining the oil price trajectory. The volatility in oil prices usually has an adverse fallout on the real economy [7,8] but could also trigger the formation of a speculative bubble with a potential spillover on the financial markets [9].

The adverse market conditions that emerged with the rapid spread of COVID-19 only made the situation worse for the financially weak and vulnerable oil and gas companies and pushed them towards bankruptcy [10]. The business of shale emerged as the worst casualty, with their very foundation getting rattled, bringing Saudi Arabia and OPEC back as swing producers responsible for balancing the world oil market [11]. Furthermore, the unprecedented bundling of the demand and supply shocks not only roiled the oil market, but the storage capacity of surplus crude oil became completely exhausted and transformed the oil crisis into one of a kind storage crisis.

In light of the above backdrop, this paper endeavours to explore and analyse key developments in the World oil market, including the causes and triggers of the paradoxes that evolved around the pandemic, with a particular focus on the role of OPEC and the U.S. shale business. OPEC's role has been considered critical in oil's history because, since its formation in 1960, OPEC and its major producer Saudi Arabia had often exercised a balancing role in fostering stability amidst short term volatility in the world oil market.

Section 2 singles out the research problems that have been addressed in the paper and goes on to describe the approach that has been adopted to explore these research questions. The subsequent sections address the identified research questions in a sequential manner. Section 3 ruminates in detail on the evolution and variation in the behavioural psyche of OPEC in retrospect and identifies the relevant causal drivers or triggers that emerged therefrom. Section 4 goes on to delineate the volatility that cropped up in the crude and financial markets around the spread of COVID-19. Section 5 explains the price war that ensued between Saudi Arabia and Russia around the outbreak despite a deep recession that ensued in March 2020 due to the pandemic outbreak. Section 6 explores the triggers and drivers that literally transformed the oil crisis into an abnormal storage crisis around the pandemic time. Section 7 eventually moves on to elucidate the development of the shale gas market that evolved around COVID-19, given that natural gas is the next best low carbon alternative to oil. This is followed by concluding remarks.

2. Methodology/Approach

Considering the research questions, the paper tries to investigate, foremost, whether there has been any pronounced change in the OPEC's role and dominance as the oil market evolved over the years and if developments around COVID-19 made any significant dent in that. To address this research problem, the retrospective rumination has been considered essential as it may not be appropriate to judge the behaviour of OPEC and its key members based on a just one-off shock event such as the spread of COVID-19. In fact, empirical studies on oil markets carried out in the span of the last two decades raised question marks on the traditional thought process and beliefs on the drivers and fallouts of oil price shocks [12]. The author identified some key research terms, namely 'OPEC', crude price, oil price, Saudi Arabia, 'OPEC behaviour', and 'oil companies', to identify relevant research papers, books, working papers, discussion papers, policy briefs, and reports that have addressed the role of OPEC in determining world oil prices over the years. The papers that have not considered OPEC or its key players' role in any form have been excluded from the list. The authors relied on databases such as Science Direct, EBSCO, JSTOR, and Google Scholar to single out the relevant papers. Table 1, presented in the next section, provides a detailed schematic representation of the papers that the authors have found relevant and befitting. The period that has been considered for the retrospective review to reflect on variation in OPEC behaviour in World Oil Market is from 1960 to 2020. In cognisance of the retrospective analysis, the paper tries to provide an explanation of the price war that ensued in March 2020 between Saudi Arabia and Russia. The data and information to substantiate the elucidation have been collected from monthly oil markets reports of OPEC, IEA, and DoE.

A critical element that came to the fore while analysing the triggers and drivers of oil price volatility is the intermingling of the oil market, especially the crude market, and the financial markets. This link became more evident in the post financial crisis of 2008. The paper tried to explore whether this link and volatility intensified during the spread of COVID-19. The author tried to classify the select literature that focused on the interlinkage of oil and financial market around the period of spread of COVID-19 by combining the key search terms- 'oil market', 'financial market', 'speculation', 'commodity market', 'COVID-19', 'pandemic' and could identify a set of most recent literature that talks in detail about the volatility and linkage of commodity and financial markets around COVID-19. The data and information on volatility have been collected from the annual and Monthly Oil Market Report (MOMR) for March 2020 brought out by the U.S. Department of Energy (DoE), which focused on the historical values of volatility indices for both crude and financial markets since 2007.

Another startling issue that came to the fore while investigating the movements in the oil market around the spread of COVID-19 is that the oil crisis consequently took the shape of a severe storage crisis [13]. The paper takes a deep dive into the triggers and drivers behind the storage crisis. The analysis of the section relies heavily on the media reporting and illustrations from Bloomberg, Financial Times, and Wall Street Journal. This is coupled with data collected from the U.S. MOMR of DoE, IEA, and OPEC.

The paper eventually moves on to elucidate the development of the shale gas market that evolved around COVID-19. As natural gas is considered a promising and a low carbon fuel alternative to oil, and given that the U.S. has a demonstrated abundance of proven shale gas reserves and has been relying on shale for the past two decades, the nation has been in the rat race with OPEC to capture the biggest pie in the global oil and gas market. The rapid growth in the shale gas business enabled the U.S. to change its position as a net importer of oil and gas and emerge as a net exporter in 2019 [14]. However, as the pandemic broke out and the recession started nullifying all fundamentals, the U.S. shale slid into its worst patch that not only turned them into a net importer of oil and gas in 2020 but also triggered the bankruptcy of several companies in shale gas business. The outcomes were huge job losses in the oil and gas industry and bruising of the financial institutions that provided the much-needed impetus to the growth of the shale gas business in the U.S. [15]. In light of these developments, the paper tries to analyse the triggers and drivers behind the collapse of shale and gauge whether the dramatic collapse during a pandemic could be considered as just another shock impact or does this also raise moot questions on the foundation, resilience, and the sustainability of shale gas business in the U.S. The analysis of this research problem is largely based on relevant secondary literature culled out by combining search terms, namely 'shale gas', revolution, bankruptcy, COVID-19, pandemic, and complemented with data and information collected on bankruptcy compiled by Haynes and Boones.

3. OPEC and World Oil Market: A Retrospective Review

The fundamentals of the world oil market are based on demand and supply. In a simple parlance world, crude oil demand could be conceived as a function of price and income (proxied by the real GDP). The modelling of world crude oil supply, however, is not so straightforward and hence is an area of concern [16]). Several empirical studies that have been conducted to understand the functioning of the world oil market indicate that crude oil supply modelling is much more complex and does not resemble a linear form where supply is a function of the cost of production and price. This is because the oil supply can neither be considered fully competitive nor fully monopolistic. Crude oil is primarily supplied by OPEC, which is endowed with the largest pool of reserves (79.4 per cent as of 2018) while accounting for 37.1% of world production [17]. Before one takes a deep dive into the historic oil market crash that ensued at the onset of COVID-19, it would be worthwhile to briefly understand the evolution of the oil market in retrospect, and the role played by different players on the supply side in determining the world oil prices. This would also enable a better understanding of any changes in market situation or volatility that have already been building up in the oil market prior to the pandemic.

From the review of various models that have endeavoured to understand the role of OPEC (for more details, see Table 1), it becomes evident that it is not possible to explain the actions of OPEC by any single model because OPEC as an entity has rarely acted in a cohesive and deterministic manner. The wide variation in models that were constructed to explain the behavioral psyche of OPEC and its key producers after 1973, the year of the Arab oil embargo, bears ample testimony to that. The reasons for variation in OPEC or its members do include not only economic incentives but also political and geopolitical considerations [18,19]. Furthermore, there are major differences between OPEC and non-OPEC in various dimensions that could potentially have an influence on the differences in their intent. These include public vs. private ownership, extraction of crude oil reserves, the significance of oil exports as a source of (government) revenues, and the intent of amassing foreign exchange [20]. Whereas OPEC might respond differently to an increase in oil demand to sustain higher oil prices and maintain their profitability [21,22], non-OPEC producers have mostly been responding to market prices that are usually set by OPEC.

OPEC was originally established as an organisation during a meeting in Baghdad in September 1960. The five founding members were Iraq, Venezuela, Saudi Arabia, Kuwait, and Iran. Qatar, Libya, Indonesia, United Arab Emirates, Algeria, and Nigeria joined later. Gabon joined in 1975 but left in 1994. Ecuador joined in 1973 and left in 1992 (https://www.opec.org/opec_web/en/about_us/24.htm (accessed on 5 January 2022)). The main purpose of the formation of OPEC, as identified in the meeting, was to coordinate petroleum policies between member countries and to safeguard their interests. In a way, OPEC acted as a trade union to ensure that the income of member countries did not decline [23].

OPEC had the first major say or dominance in the pricing of crude oil in world markets in 1973 during the Arab–Israeli War when it successfully raised the price of crude by 70 per cent initially in October 1973 to USD 5.11 per barrel and subsequently raised it unilaterally to USD 7 per barrel in December 1973. The Arab members within OPEC imposed an 'embargo' in 1973 on the U.S. as a retaliation against their decision to support the Israeli military. The embargo was further extended to Netherlands, Portugal, and South Africa for the same reason. As part of the embargo, petroleum exports to the targeted nations were banned, and a production cut was initiated along with a price rise (https://www.csis.org/analysis/arab-oil-embargo%E2%80%9440-years-later (accessed on 6 January 2022)). The embargo was finally lifted towards the beginning of 1974 (https://www.csis.org/analysis/arab-oil-embargo%E2%80%9440-years-later (accessed on 6 January 2022)).

Between 1975 and 1978, OPEC policies were centred around stabilising demand and increasing prices in a moderate manner. Between 1979 and 1981, however, OPEC policies were largely influenced by several disruptive events that significantly enhanced crude prices volatility. These include the Iranian revolution followed by the Iran–Iraq war. Oil production stalled in the affected countries; prices climbed from USD 24/bbl. in 1979 to USD 34/bbl. in 1981; and was followed by a global transmission of shock waves [24].

After this, the crude prices started to nosedive and eventually crashed in 1986, triggered by a big oil glut and a growing pattern of shifting consumption away from oil. It was only in 1982 that OPEC started allocating formal production quotas. The group production ceiling imposed by OPEC and distributed among member countries as quotas somehow could resist the price fall. Although timely intervention by OPEC also lessened the effect of the Gulf War on the oil market in 1990–1991, excessive volatility and price weakness continued to rule the latter half of the 90s. This was largely due to the fallout of the southeast Asia currency crisis plus the economic meltdown in 1997–1998. The mild northern hemisphere winter of 1998–1999 added to that, and the price again tumbled down to the 1986 level.

In fact, in the early eighties, OPEC behaved in a noncohesive manner and was referred to as a 'clumsy cartel' [25]. The tendency of defection was more prominent among the OPEC members with relatively lower crude reserves (Qatar, Algeria, Indonesia, and Venezuela). The defection and decision to produce more than the allocated quota was triggered largely by a volatile crude market and the apprehension of these members that they might suffer heavy losses when oil prices would tumble down afterwards [26]. In other words, they wanted to make hay while the sun was shining, i.e., crude prices were on the higher side.

In contrast, producers with a large pool of reserves, such as Saudi Arabia, could manage the production of less oil even when prices were higher. However, due to the persistent defection tendency within OPEC at the beginning of the 80s, the burden of adjustment largely fell on Saudi Arabia, which ended up bearing the brunt by producing the residual amount. Given that the residual production was unplanned, it did not serve Saudi Arabia's interest in the best possible manner when it comes to profitability [21]. Finally, in the mid-eighties, Saudi Arabia refused to comply as a residual or a swing producer and started producing the amount that would help them serve their best interests by producing profitably.

The defection within OPEC raised doubts on the cohesive capability of OPEC as a combined producing entity and its ability to execute market power through adjustment in its production levels. The lost confidence was restored somehow after OPEC could manage to successfully carry out two production cuts, one after the other when the oil prices skydived to a nadir during the 1998 oil crisis. However, the unprecedented price hike of 2004, when crude price crossed USD 50 a barrel and the failure of Saudi Arabia to arrest that spike through output increase, disrupted the restored confidence once again. Some of the empirical research studies that tried to investigate the causal factors behind OPEC's failure to resist the price spiral evinced that this occurred largely due to the loss of spare capacity to produce crude [27–31]. OPEC's spare capacity is usually considered a benchmark of resilience against the impact of any crises that could potentially reduce oil supplies.

Since the early 1990s, OPEC's spare capacity was progressively exhausted [32]. Between 2003 to 2008, OPEC's total spare capacity was below 2 million barrels per day which is below 3 per cent of the global supply. This meagre spare capacity provided hardly any cushion for supply variation when the demand had been growing at a very fast pace [33]. The decline in spare capacity for both periods was due to accelerating global demand for crude coupled with low growth in non-OPEC oil supply. Although OPEC came out with an oil price band mechanism in 2000 that facilitated stabilising crude prices somehow, erosion of spare capacity and changing expectations and speculation made the situation worse, jacking up prices and increasing volatility in crude markets.

Another critical factor that usually acts as a balancing wheel between supply and demand is the stocks or inventories held by countries. During the time when production exceeds consumption, crude oil and petroleum products can be stored as inventories for future use. For instance, during the recession around 2008–2009, the significant decline in world oil demand led to stockpiles at a record level in the United States and other OECD countries. In contrast, when the demand and consumption exceed current production, supplies can be supplemented by drawing on the inventories. However, given the uncertainty of supply and demand in the oil market, limited stocks/inventories might have a serious impact on exacerbating the volatility of crude prices. (for more details see [12,34–37]).

Going by the series of developments that emerged in the world oil market at different periods historically [38], it could be aptly inferred that OPEC as an entity rarely followed a uniform strategy. After the first major oil shock in 1973, several research studies were conducted to examine the structure of the world oil market, and the role played by OPEC. As already explained in the preceding section on the methodology or approach of the paper, Table 1 tries to capture and classify this entire spectrum of studies that have focused on OPEC behaviour at a different juncture in history.

Table 1. Studies on Oil Markets and Role of OPEC.

Nature of OPEC's Behaviour over Different Time Slices	Description of the Approach/Models	Authors
OPEC as a single producing entity	Monolithic cartel model: This set of studies that evolved in the mid to late seventies considered OPEC as a single producing entity without any competition among its members. Non-OPEC suppliers were considered price-takers. 'Monolith' means the residual producer	[39–41]
Saudi Arabia's role has been recognised separately within OPEC	Two block or three block cartels: This set of studies that evolved from mid-seventies to the late eighties assumed OPEC as either a two-block cartel comprising of 'savers' and 'spenders' or a three-part cartel comprising a core, price maximiser, quantity maximiser. Saudi Arabia is considered a major part of the cartel core. This is also to account for the fact that OPEC consists of members with divergent political, economic, and social interests.	[42–48]
	Saudi Arabia as a swing producer: This set of studies that evolved around the early 80s to early 90s considered Saudi Arabia as playing the role of a balancing wheel to absorb demand and supply fluctuations to maintain a high price or Saudi Arabia is considered a leader in consonance with the well-known leader-follower model of Stackelberg.	[24,26,49–56]
OPEC's lack of effectiveness in determining world oil prices	This set of studies contended that OPEC did not have any perceptible market impact and that oil prices were the product of other market factors. These scholars have questioned OPEC's efficacy as a cartel and price maker.	[57–64]
Focus on the political reasons pertaining to OPEC behaviour	This set of scholars believes that economic analyses of OPEC preclude crucial political variables, and thus the results are largely biased. The studies contend that OPEC and its members get political mileage through international cooperation in carrying out their decisions.	[18,19,65–69]
Property Rights Model	This set of studies tried to give credence to OPEC in influencing the oil production and prices due to the transfer of ownership from international oil companies to the governments of the oil-exporting countries within OPEC towards the beginning of the 70s decade. The transfer of property rights to the governments from companies led to applying low discount rates, which was not the case earlier.	[20,57,70,71]
Target Capacity Utilisation Model and Role of Spare Capacity	This set of studies conceived of OPEC as a residual supplier of the world oil market. The set of studies presumed that OPEC's prices are influenced by the gap between its current capacity utilisation and some target level of capacity utilisation. Some of these scholars have also focused on the role of spare capacity and its link to OPEC's ability to control oil prices	[27–30,72–74]

Table 1. *Cont.*

Nature of OPEC's Behaviour over Different Time Slices	Description of the Approach/Models	Authors
Fiscal Constraint/Target Revenue Model	This set of studies accounted for different absorptive capacities of OPEC member countries. The studies contended that the conduct of OPEC member countries depended on the expectation that when oil revenues would surpass the requirement of an OPEC member country, the output level would also be restricted by the member country to make the oil revenue match its needs.	[75–80]
Target Price Model	This set of studies either assumed or inferred that OPEC aims for a certain price level or a price band and then complies with it by making necessary adjustments in the output level.	[81–83]
Signalling the Role of OPEC and coupling it with financial markets	With the growing participation of financial investors and coupling of the financial market with the commodity market, especially in and around the first decade of the millennium and especially around the period of the financial crisis of 2008, analysts tend to point towards the potential existence of signalling role of OPEC to the financial market through changes in production behaviour. The changes often also influence the shaping of expectations and provide impetus toward speculative behaviour in the financial markets, causing turmoil.	[23,84–90]
Other econometric and simulation models for investigating OPEC behaviour	This set of studies uses different types of advanced econometric models and simulations to test OPEC's behaviour in the World oil market	[21,57,91–102]

4. Volatility in Crude and Financial Markets around COVID-19

The volatility of crude oil prices has increased substantially in the past three decades. The increased volatility could be attributed to multiple factors that include the limited spare capacity of crude, limited inventory of the OECD countries, geopolitical disturbances, and complex market structure. The situation became more complex after crude oil became increasingly used as an asset class through crude oil futures, and paper barrel trading started ruling the roost. One of the serious fallouts, as one could see from these developments, was the skyrocketing crude prices to a record level of USD 147 a barrel in mid-2008, before collapsing eventually. The collapse was triggered by the financial crisis and accompanying economic recession. Some of the researchers also observed that in the long run, the volatility of the financial markets had a restraining impact on oil prices [103–105].

The oil market movements around COVID-19 did show all the vulnerabilities and volatilities that cropped up over the last three decades, and this is clearly revealed by the movements of benchmark indices of volatility. The Chicago Board Options Exchange (CBOE) Volatility Index (VIX) is considered one of the financial markets' most followed indicators with elements of credibility and reliability. The index is considered a benchmark indicator of volatility in equity markets (variation in S&P 500). OVX is usually considered a benchmark indicator of implied volatility in crude oil markets. Both the indices registered a phenomenal increase around the spread of COVID-19.

VIX climbed up to a value of 82.7 on 16 March 2020, which was significantly higher than the value that was recorded during the financial crisis of 2008–2009. OVX, on the other hand, climbed to a value of 190 on 20 March 2020, which was considered then the highest since the index started functioning in May 2007 [106]. More recent studies also demonstrated an interconnectedness and co-movements between volatility in the equity market (VIX) and crude oil markets (OVX) around the COVID-19 crisis period identified as the span from 14 February 2020 till 6 August 2020 [107].

It all started with the Declaration of Cooperation (DoC) that was signed at the OPEC ministerial meeting by OPEC plus members (OPEC and Russia) in Vienna in December 2016 to foster market stability and prevent a rapid slide in crude oil prices [108] but eventually it turned out to be futile. The crude price exceeded the USD 70 a barrel mark in 2018, triggered by the U.S. sanctions imposed on large oil producers such as Iran and Venezuela [109].

The year 2020 began with the tumbling of crude oil prices owing to compounded effect of (1) the collapse of the DoC due to the defection of Saudi Arabia and Russia in the battle for maintaining market share and (2) the deceleration in global economic growth caused by the outbreak of COVID-19. The impact could be immediately seen through a pronounced drop in the price of Brent and WTI in March 2020. The daily Brent crude price nosedived to USD 24.9/barrel on 18 March 2020, from USD 51.9/barrel on 2 March 2020, and WTI plummeted to USD 20.4/b from USD 46.8/b in the same time span, thus effectively recording more than 50 per cent drop in both the benchmark crude prices.

The drop in demand for crude oil due to the worldwide recession triggered by the pandemic made Saudi Arabia decide to cut production. However, the largest non-OPEC producer, Russia, driven by the worry of losing out on its own market share, defected, and this eventually resulted in the collapse of the DoC, rattling the oil market stability. Saudi Arabia also defected and decided to expand its crude oil production despite a falling demand exacerbating the disequilibrium further. The resulting price war led to prolonged instability in the crude oil market. Although Saudi Arabia and Russia agreed to come to the negotiating table under pressure from the U.S. and intervention by G20, the oil market had already been roiled enough by then. Under the negotiated terms of the agreement, oil-exporting countries had planned to prune an aggregate of 9.7 million barrels a day of crude supply from being released over a span of two months beginning from 1 May till the end of June [110].

However, questions began to be raised by experts and analysts on whether such a strategy would eventually turn out to be effective. The doubts in their minds were largely triggered by the glut in the crude oil market combined with a sharp drop in global fuel demand of 30 per cent due to lockdown, travel bans, grounded flights, and economic collapse [7]. Their impending fears of the lack of effectiveness in the negotiated cooperative agreement turned real with WTI crude oil futures price landing in the negative zone on 20 April. A barrel of WTI crude valued at USD18.27 a barrel on 17 April that was due for delivery in May tumbled to a nadir of USD40 a barrel on 20 April. Oil producers and traders started panicking, leading to the dumping of a large volume of futures contracts [111].

This historic drop in crude prices has also motivated researchers to examine the impact of COVID-19 on oil price volatility. Most of these studies opined that the pandemic has sucked out the global aggregate demand for oil due to the globally announced lockdown and economic downturn that ensued thereafter. The market uncertainty was exacerbated further by the adverse impact on the global supply chain [112,113] with negative repercussions on the commodity prices [114–119]. Other select studies [120–123] found a statistically significant impact of reported deaths or infections on oil price and stock market volatility.

The uncertainty is further compounded by the extensive media coverage of COVID-19. Several research studies conducted around the pandemic time delineated that media played a vital role during the crisis that resulted in a substantial impact not only on oil and stock prices but also on the environmental, social, and governance (ESG) indices [114,119,124,125]. Empirical findings by [126] further show that the media coverage of the COVID-19 pandemic had a positive impact on the dynamics of the commodity markets. Other than media coverage, high Google search volumes for COVID-19 have also been observed to influence high stock market volatility [127].

5. Price War: Calculated Move by OPEC or Unabated Quest for Market Share?

The advocates of the mean field game theory [128] tend to believe that the unabated production and subsequent price war initiated by Saudi Arabia post Russia's noncompliance with OPEC plus deal (DoC) is nothing but a battle for market shares [129]. However, there is hardly any second thought that such a retaliatory move against defection was initiated at a critical juncture when the entire world had been reeling under the severe blow that had been dealt by the pandemic. Global lockdown and related restrictions and containment measures had by then eroded substantially the effective demand for end-use petroleum products, namely gasoline, diesel, and ATF, because of abysmally low passenger travel and grounded flights. The impact of the shock was pervasive with the transmission of contagion from the oil sector to the financial sector and real economy with widespread spillovers on all associated sectors.

As already mentioned before, it would be crucial to understand whether the behaviour of bigger oil producers such as OPEC or its key player, Saudi Arabia, should be assessed in this context based on just this one-off contagion or is it equally significant to gauge whether the observed change in behaviour is fallout from increased vulnerabilities and volatilities in the oil market in the more recent years and the factors pertaining therewith. With reference to the discussion carried out in the preceding section on the volatility in the oil and financial markets, there is no second thought that the behaviour of OPEC and its key player should be analysed from an evolutionary perspective. To add to this, the retrospective review of the role of OPEC that has already been carried out in this paper clearly shows that OPEC rarely acts in a deterministic or linear fashion, and its behaviour is circumstance specific. Of course, the entire battle around COVID-19 and Saudi Arabia's unabated increase in production is to ensure that their market share does not deteriorate as it may not otherwise serve their interest in the best possible manner (in line with the thoughts of [21].

Geopolitical challenges are almost part and parcel of oil-exporting countries in the Middle East and North Africa (MENA). However, over the last two decades, several structural and deeper policy-related drivers have compounded the risk perception and volatility in oil markets. Some of these drivers are (1) stringent climate or environment-related regulations and the risk of stranded assets for the oil and gas companies (stranded assets are assets that have "suffered from unanticipated or premature write-downs, devaluations, or conversion to liabilities"); (2) increase in investors' conscience and consciousness regarding environmental, social, and governance (ESG) issues [130]; (3) improved corporate governance practices and increased accountability of board members; and (4) primacy of stakeholders' interests over those of shareholders within the corporation and in board-level decisions making [131,132].

The 2015 Paris Climate Agreement also gave a big push to climate change as a part of broader ESG issues within consideration and have increasingly been internalised as part of the board-level discussion along with other corporate agenda. With growing pressure from investors, companies have started to re-envision themselves in a climate constrained world, and even executive compensations have started to become linked with meeting climate targets. As an illustration, climate metrics now account for 8% of CEOs' incentive plans in the short run in some of the celebrated energy companies [133]. All these factors, taken together, have made the investment decisions in the fossil fuel industry a bit jittery, adding further to the volatility. The contagion of COVID-19 has only exacerbated the situation by causing a great degree of uncertainty about health and the economy with a negative impact of this changing risk perception on the oil market [134].

Given the increasing volatility in the oil market and the uncertainty involved therewith, it is not unusual for Saudi Arabia and Russia, which are low-cost producers, to change their strategic position more frequently in the quest for maintaining their market share and profitability. In line with this thought process, there is little room for a surprise if Saudi Arabia chooses the highly unlikely path of monetising its reserves faster to take advantage of the market situation, produce more, and offer more discounts to disadvantage and corner the high-cost producers. In other words, it may not be correct to think that Saudi Arabia, the dominant producer within OPEC, always acts in a stereotyped manner as a residual swing producer and responds only to the amount of oil demanded from them unless that action really serves their own best interests [31]. A parallel of this behaviour could also be observed in the current pandemic struck situation when both Saudi Arabia and Russia decided to produce more and bring down the price. The high-cost shale producers in the U.S. were eventually in a difficult situation, finding it challenging to break even and compete on a level playing field with Saudi Arabia and Russia.

Russia did not comply with the production cuts proposed by Saudi Arabia. This is because their aspirations and concerns were quite different from those of Saudi Arabia and other major oil exporters. Russia's exports cater to only a few discrete markets. The lion's share of their shipments goes to Europe, and an insignificant proportion is transmitted via pipeline to China [135]. Hence, the spillover of the pandemic could only be felt in Russia's principal export outlets. Saudi Arabia, on the contrary, has a much bigger network of global customers. A rather different justification for Russia's noncompliance with the deal comes from the sanction imposed by the U.S. on completing the Nord Stream 2 gas pipeline in the Baltic Sea and on Rosneft because of trading Venezuela's crude [129].

With Saudi Arabia clinging to the decision of producing more crude, the situation went out of control in the pandemic-afflicted world already straddling an oil slosh due to an economic downslide. Collection of oil revenues came down phenomenally because of the price crash and compounded the plight of the big oil producers. The price crash led to erosion of their economic freedom, created mounting hurdles for upstream investments, and made it challenging to sustain their production capacity [129]. Recognising the criticality of maintaining the producer–producer relation in such an uncontrollably adverse situation of free price fall that was only adding to the oil exporters' miseries, Saudi Arabia and Russia eventually decided to come to terms. A warning issued by the U.S. on imposing a tariff on Saudi and Russian crude exports to the U.S. in case of their refusal to come to the negotiating table, and intervention by other G20 members, gave a big push leading eventually to brokering a new deal. However, the unprecedented drop in demand due to containment measures had exceeded the proposed contraction in output, making the new deal ineffective in the short term and pushing down the WTI crude price further to the negative zone in April 2020 [136].

6. An Oil Crisis or a Storage Crisis?

As the contagion continued to spread and led the world to a downturn, the unabated price war compounded the glut further. With heavily oil import-dependent economies such as China and India on a staggered path of recovery [13], the entire excess oil had to be sent for reserve and storage. However, with all the onshore and offshore storage facilities becoming full to the brim with globally announced lockdown, abysmally low movement of people and grounded flights [110], a new storage crisis came to the fore. The erosion of effective demand for fuel due to lockdown and global slowdown also forced refineries to temporarily stop the process of refining crude oil into petroleum products for final use, compounding the problem further.

It deserves to be mentioned at this juncture that crude oil can be traded physically as well as in the financial markets. In physical trading, liquid oil is physically traded by different entities [114]. In the financial market, crude oil is traded through futures contracts agreed upon by buyers and sellers to take or make deliveries of barrels of crude oil at a certain designated time in the future and a pre-decided agreed price. A buyer of a crude oil futures contract shall be under obligation to buy and take delivery of crude oil when the futures contract expires. As an alternative, the buyer may choose to opt out of taking physical delivery by selling the futures contract before its expiry [114].

Speculation of crude oil prices reigns the financial market. The speculators usually enter the crude oil market when prices are lying low but are expected to look up soon. Speculators who had invested in WTI futures contracts were looking for buyers to take possession of oil barrels in May that were expiring on 21 April. However, the investors in WTI crude future were not willing to take physical delivery of WTI crude oil and were closing out of long positions in WTI May futures contracts a few days before the contracts expired on 21 April 2020 [137]. However, because of a severe glut situation coupled with a lack of effective demand for oil, there was literally no buyer because of storage challenges of excess oil. The WTI crude futures price eventually crashed to a sub-zero level on 20 April, a day before the expiry of the contract. WTI May crude futures dropped by more than 300% to USD 40 a barrel. This is also the first time in history that prices nosedived to the sub-zero level. Going by the economics of trading, this essentially means that the oil seller had to pay the buyer to offload the oil. This is almost like a pathological case in the economics of commodity trading.

Going by the commodity trading terminology, the severe blow of the pandemic and other factors made the market change its position from backwardation to contango [138]. A contango structure usually shows up when the price of commodities in futures contracts offsets their price in the spot market. The reverse situation is called backwardation. The contango structure allows traders to exercise the option of purchasing oil cheap today and then sell it off dear at an agreed point of time in future in the futures market. As for crude oil, the profitability of trading in a contango situation depends on whether the profits derived from trading are higher than the cost of storing oil. If storing cost is cheaper, the contango provides an incentive for hoarding. However, in an oversupplied market, a supplier whose stocks are accruing because of a steep dip in demand is left with no other options but to offer a discount to cajole a buyer who is otherwise not willing to buy the crude and shows up with the spot price trading at a discount to the forward. If the glut situation persists, prices will tumble further, leading to a deepening of the contango and distress in the market. This is exactly how the market looked in April 2020 [139], and the slide was primarily caused by the market stress that arose due to the timing of the May 2020 contract expiration of WTI crude futures coupled with storage concerns [140].

The financial crisis of 2008–2009 bears ample testimony to deepened contango structure and storage crisis. However, the profit that could be earned from trading crude futures during 2008–2009 was more than adequate to cover the cost of buying charter tankers for storing oil offshore. The pandemic situation was far worse than that because of a serious shortage of both onshore and offshore storage [141–143]. The excess demand for storage increased the land storage costs worldwide and hiked the cost of maritime shipping as alternate offshore storage [144]. Chartering costs for Very Large Crude Carriers (VLCC) have more than doubled since February 2020 [140].

It would also be crucial to understand the terms and conditions that were stated in the settlement procedures of the May 2020 WTI crude contract to have a clearer picture of the reasons behind the steep price slide. When the expiry date becomes closer, a contract holder could either settle the contract position by choosing an 'Exchange for Physical (EFP) contract with a counterparty transfer of the contract in exchange for cash or other futures contracts with later expiration dates' (for more details see: https://www.cmegroup.com/trading/energy/crude-oil/light-sweet-crude_quotes_settlements_futures.html (accessed on 23 October 2021)). Alternately, the contract holder may choose to take physical delivery of the crude oil and the delivery is expected to occur at a pipeline or storage facility in Cushing (for more details, see https://www.eia.gov/petroleum/weekly/includes/analysis_print.php (accessed on 20 October 2021)).

In a normal situation in Cushing, there would not be any challenges to transfer oil into the storage facility or pipeline. However, the situation became extraordinarily abnormal due to the double blow of the contagion, which left little or no option but to send all the surplus oil to the storage. On 17 April, i.e., only three days prior to the historic slide, 76% of Cushing's storage capacity was already full. Other storage facilities were either leased out or committed and left no space for uncommitted storage. With an excess demand for storage, the cost of storing oil became sky dabbing.

Given the nonavailability of uncommitted storage, deep contango and an abnormally high storage cost, it became impossible for the market participants to go for physical delivery (for more details, see: https://www.eia.gov/petroleum/weekly/archive/2020/200422/includes/analysis_print.php (accessed on 5 November 2021)). The inability to take physical delivery implied that the May 2020 WTI contract had to be settled by selling and transferring ownership of the contract to a buyer prior to the expiry date, even if that means selling at a negative price. This is exactly what has happened. As there was literally no space to store oil, supplies eventually had to be stopped to keep pace with the dramatic downturn and demand losses globally [145].

The rapid spread of the pandemic created an abnormal situation with energy contracting parties failing to respect predetermined contracts due to restrictions imposed by the government. Frequent announcements of lockdowns for a prolonged period disrupted the supply chain and affected routine operations of critical infrastructure such as ports and terminals. Soon after, energy companies began receiving force majeure notices [146]. Running factories and commercial establishments became difficult due to lockdowns, further eroding energy demand. Several refiners chose to halt their operations because of little or no demand. Apprehensions were building up that jamming of pipelines and halt to refinery operations would make it next to impossible to store excess oil because of the inadequate storage capacities. The oil market crisis got eventually transformed into an unprecedented storage crisis. With exorbitant storage costs, it appeared more profitable to build up oil storage space than to possess a futures crude contract.

7. U.S. Shale Collapse: Time to Get Back to Fundamentals

Shale fracking helped the U.S. emerge as the largest oil producer in 2019, overtaking Saudi Arabia [147]. However, soon after the bout of the pandemic started unfolding, the EIA and the U.S., in their monthly oil market report in April 2020, expressed serious doubts on whether the U.S. would be able to maintain this position, as production had been projected to tumble down by 0.5 million barrels a day in 2020 [148]. The drop was predicted in spite of the renegotiated OPEC plus agreement that was brokered after the price war.

Although the shale business was considered a boon for the U.S. and consistently registered high production levels in the initial few years, serious doubts began to be raised by noted experts and specialists on the sanctity of the business model of shale in the U.S. that eventually led the business to go bust with phenomenal adverse repercussions on their financial health [149]. What the noted energy economist, Paul Stevens, said about the shale business in the U.S. way back in 2010 in an intriguing Chatham House Report [150], even when shale was booming, came true as the shale business started showing weaknesses and vulnerabilities towards the beginning of 2020. The report, foremost, raised serious doubts on the very fulcrum of the 'shale revolution'. Concerns have also been raised about the adversity and magnitude of environmental impacts, and high depletion rates. The General Accounting Office Report on Shale Development [151] further highlighted the adverse impact of fracking on the health of the communities living in the proximity due to deterioration in the quality of water and air because of groundwater contamination and rising air pollution. In addition, seismic vulnerability increased due to an increase in the frequency of earthquakes. Other challenges that came to the fore include growing concerns for climate change through methane leakage at the sites and facilities for processing coupled with the burning of fossil fuels [152], the rising proneness of water deficit hotspots to water stress due to usage of the large volume of water in conducting fracking activity [153].

Although the investors were initially lured by the shale gas business considering it to be a good bet, all the above challenges raised questions on shale's social license to operate and compounded the uncertainty in their minds [150]. The uncertainty was further triggered by the unleashing of vulnerabilities in the U.S. shale business towards the end of the decade that began in 2010. Fracking is a resource-intensive and large cost-incurring activity in the U.S. Furthermore, there is no uniformity in performance and yields across wells. Thus, in case a cost-intensive well fails to perform and generate adequate yields, mounting losses might accrue [154]. To remain profitable, shale producers' capital and operating expenses, along with total return, should be higher than the commodity price. Furthermore, this should also be able to make up adequately for all the ongoing capital expenditure, which includes discovery and development expenses. However, weakness started to show in the shale business, with costs falling marginally short of the trading price of WTI crude in 2018 as well as in 2019 [154]. Declining yield and meagre returns deterred the investors from putting any more money into the shale gas business.

With several social and environmental disasters coupled with lapses in corporate governance being increasingly brought to the limelight, a stakeholder centric approach to business has become an imperative [155]. Over the last decade, the environmental, social and governance (ESG) criteria have become more material in the corporate as well as investment decision-making. This is coupled with a worldwide call for divestment of fossil fuels [130]. The boardrooms progressively became more vocal as more investors and shareholders started to raise concerns about whether the profits of the companies whose boards they represent were coming at the cost of primary stakeholders, namely customers, workers, and the environment. Questions started to be increasingly raised on the health and safety issues of workers as well as on the environmental and social benignity of the products besides the impact of the company on the overall health and safety of the society at large [131] and the consciousness has only increased during the pandemic time.

The adverse environmental and climate impact of shale business brought the business of fracking under scrutiny and influenced the decisions of major lenders that have been backing the shale business in the U.S. As a last resort, these big lenders even became ready to don the mantle of independent operators of oil and gas business to shield themselves from mounting losses of impending bankruptcy. This is a one of a kind event in a generation of oil and gas businesses where lenders became business operators to save their loans. Notable among these big lenders are J P Morgan Chase & Co., Wells Fargo & Co., Bank of America Corp., and Citigroup Inc., who got themselves into this new groove [7].

Plagued by mounting challenges due to erosion of effective demand and price war during the pandemic, it became next to impossible for several shale producers to break even [156]. The crisis became so deep in 2019 that even big shale producers such as Occidental had to extend a hand for government support asking the state to "provide necessary liquidity to the energy industry" as reported by Bloomberg News on 9 April 2020. (See https://oilprice.com/Latest-Energy-News/World-News/Shale-Giant-Calls-For-Federal-Help-As-Oil-Prices-Fail-To-Bounce-Back.html for more details (accessed on 2 September 2021)). Occidental Petroleum's debt rating also got downgraded by Moody's investor [157]. Another noted upstream company, Whiting Petroleum, had gone bust and went ahead with filing Chapter 11 bankruptcy, the first one to do so [158]; Callon Petroleum Company and Chesapeake Energy got into a messy soup with multibillion-dollar debts [159]. Other major players such as Noble Energy (NBL), Halliburton (HAL), and Marathon Oil (MRO) lost a substantial chunk (around 66 per cent) of their market capitalisation. Oklahoma-based noted shale driller Unit Corp. also filed for bankruptcy [160]. Losing around 40 per cent of its value in 2019–2020 [161], Exxon (XOM), which was trailing behind Chevron in market capitalisation, went ahead with deep layoffs [159].

An estimate by the University of Chicago, however, points out that drilling and fracking could only be profitable if the price hovers around USD 40 per barrel [162]. Morgan Stanley, the leading U.S. Multinational Investment Bank, estimated that USD 51 per barrel would be needed by shale business just to provide for the capital expenditure budgets in 2020 and excludes the amount that would be required for paying off debts or sending money to shareholders (https://oilprice.com/Energy/Energy-General/The-Great-US-Shale-Decline-Has-Already-Begun.html (accessed on 3 September 2021)). Yet another calculation depicts that to profitably carry out exploration and production activity, an average WTI crude price of USD 30 a barrel would be necessary to meet the opex for existing wells and USD 49 a barrel for preparing a new well for production respectively [163]. With WTI sliding to a historical low of −USD 40 a barrel, revenues tumbled down steeply, and assets experienced massive erosion of value. Several struggling oil and gas companies raised their hands in despair as they were not able to pay back their debts [7]. Going by the list maintained by Haynes and Boone from August 2015 to the end of August 2020, 244 producers went ahead with bankruptcy filing that amounted to an aggregate debt of nearly USD 172 billion. Of these, 36 companies went ahead with a bankruptcy filing in and around the pandemic period till August 2020 as they grappled with a steep drop in prices [164]. A generous support package from the government turned out to be the only option left to bail the industry out.

In sum, the oil crisis has turned the air and hype around America's shale revolution into a bubble. Some of the noted oil and gas experts, however, expressed confidence in the resilience of the U.S. shale [165]. They continued to hold the expectation that more solvent shale operators with a relatively superior grip on their finances would be able to manage themselves out of the crisis and chart a new course for the shale industry in the U.S. [166].

8. Conclusions

The volatility of oil prices in the international market, especially since the 1990s, has been a cause of worry and headache for policymakers globally. The increased volatility could be linked to several factors. These include erosion of the spare capacity of the key producer OPEC, limited inventory, especially of the OECD countries, frequent geopolitical disturbances, complex and chaotic market structure, plus disturbances or troubles inside individual member countries, political or otherwise. This is, coupled with the trading of crude oil futures, side by side with physical trading that made the situation more volatile, linking the commodity and financial markets. The oil market movements around COVID-19 revealed all these vulnerabilities and volatilities that have crept in over the last three decades and were compounded with the blow of the pandemic. This was clearly delineated by the movements of benchmark indices of volatility, namely OVX and VIX. The paper explored some of the triggers and drivers in the movement of the oil and gas market around the pandemic.

During the wild spread of COVID-19, the policymakers and businesses worldwide have countered a unique situation of the double blow. First, oil demand kept on sliding down due to a lack of passenger travel demand and grounding of flights coupled with the global downturn. Second, despite the rising volatility, Saudi Arabia and Russia were themselves entangled in an unabated quest for market share that eventually led to a price war. The increase in output volume when demand is already in free fall could not, however, be considered a right move by OPEC as it was hardly expected to yield any desirable positive outcome for itself as well as for the rest of the world. The price war only made the economics of the oil and gas industry jittery, with more stress on the financial resources of the oil exporters. From the survey of various models carried out in this paper, economic or otherwise, it becomes evident that OPEC has rarely acted in a linear and deterministic manner. The pandemic afflicted period is no exception. The retrospective rumination also underscores that there is no single model (economic as well as noneconomic) that could provide a comprehensive explanation of OPEC behaviour as the interests and behavioural psyche of OPEC and its key players kept on varying with the changing scenario of the world oil market. Although Saudi Arabia and Russia, with the aim of stabilising the bleeding crude market, eventually proposed to withhold their production, triggered further by the pressure of the U.S. or mediation of G20, the unabated drop in demand for oil could hardly offer any immediate relief. Consequently, turmoil and disruptions continued in the oil markets for the entire period of 2020–2021.

As a takeaway lesson, however, one could infer that despite the inherent vulnerabilities and volatilities that have crept up over again, including the one that arose during COVID-19, whether a stable world oil market is going to prevail or not would continue to be dependent on the fundamentals. These include, foremost, the spare capacity of the member countries in OPEC and the coalition, including those of the key players, and the cohesive capability of the coalition to respond by altering their output in volatile demand situations during disruptions caused, say, by a pandemic or due to geopolitical disturbances. The sooner the member within the coalition realises that, the better it is for the greater good of world oil markets. The stability would additionally depend on the strategic management of the inventory of crude reserves that could facilitate averting any unprecedented or unforeseen circumstances arising in world oil markets with a potential negative fallout for the financial markets and the global economy.

Another critical reason why the supply of oil could not be stopped in the immediate short run during the pandemic despite the urgent need for the same is because of the high cost involved in capping production from a high temperature, high pressure running well, which may lead to irreversible losses [167]. This essentially meant that there were no other options than to produce more oil even at a very low price leading to an unprecedented slosh in the market. Eventually, the excess oil went into reserves and storage. However, when storage was full to the brim, capping of wells and stalling production in refineries became inevitable.

By sucking out the minimum essential demand for fuels, the market situation was adversely impacted by the pandemic and followed by a steep decline in crude prices roiling all the crude benchmarks, with WTI crude becoming the worst casualty. The volatility in WTI crude was aggravated further by the speculators in the futures market. The situation was exacerbated due to inadequate storage facilities and led the WTI crude future price to an unhealthy negative zone defying all fundamentals and raising question marks on the sanctity of WTI as a benchmark. The betting behaviour of the commodity traders and speculators, massive global oil glut, unprecedented price war, and a massive storage crisis, all these factors, as explained in the paper, rattled the very foundation of the oil and gas business in a compounded manner. For the policymakers and other stakeholders of the oil and gas markets, this is great learning as the pandemic reinforced the need for shifting from a more linear predictive and deterministic modelling to modelling of chaos and uncertainty while approaching the market dynamics for the future.

The pandemic period also rumpled the American energy dominance. The sudden fall of the shale business from the acme conveys great learning for other shale players, policymakers, and stakeholders worldwide on how a hollow and shaky foundation could demonise a much-hyped boom with just a single lethal blow. The shale business could manage to have a smooth ride in the eighties and nineties only because of the reasonably high price of crude and petroleum products that enabled them to maintain the breakeven and still earn a decent supernormal profit. However, the bout of the pandemic has reversed the situation. In other words, the period of free riding was almost over as oil and gas markets became highly volatile. Unless the U.S. shale business comes to terms with this grim reality, there will be continued disruption in strategy, planning, consolidation, and the course of action as the situation keeps on changing erratically in future. Post pandemic, the expectation is that of a lean shale industry with financially solvent players who could manage to straddle through the worst pandemic period, with or without the support of the state.

Given that the entire world is now getting used to working from home, how the future policies are going to shape up would largely be contingent upon the attitude and behaviour of the commuters regarding short distance travel and long overhaul. It is obvious that people would have a second thought before travelling, and even the organisations would be conducting cost-benefit analyses to assess whether there is a scope for reducing physical travel in the post-COVID world. With many organisations already announcing permanent work from home arrangements, the impact would invariably fall on the demand of one of the major contributors to oil demand, namely the transport sector. The requirement of cooling and heating offices would also come down concomitantly. In other words, the dependence on oil is expected to come down with a potential fallout through augmented volatility and fluctuations in oil prices.

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Article

The Economic Effect of the Pandemic in the Energy Sector on the Example of Listed Energy Companies

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Abstract: The study posed a research question: did the situation caused by COVID-19 affect the economic position of energy companies? The aim of the study is to investigate the impact of the situation of the epidemic state introduced in 2020 on the activities of the efficiency of energy sector companies. The subject of the research will be the ten largest Polish power plants in terms of electricity production, including four capital groups to which they belong. Financial data from 2014 to 2020 will be used for the research. To test the effectiveness, the tools of the ratio analysis will be used. The analysis of the financial statements in terms of investments in manufacturing activities confirms the hypothesis that companies investing in new solutions and technologies will be best prepared for an exceptional situation. The results of the research show that those capital groups which in the period preceding the outbreak of the epidemic made the largest investment outlays and at the same time their financial ratios and market valuation on the Warsaw Stock Exchange were the highest, they also achieved the highest financial results during the pandemic—they had the most favorable economic situation.

Keywords: energy; energy company; efficiency; financial analysis; pandemic

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1. Introduction

The impact of the COVID-19 pandemic on the economic and social situation in Poland [1–5], other European Union countries [6–8], and the world is unquestionable and multifaceted.

The occurrence of the COVID-19 pandemic and the economic and social restrictions caused by it has had a huge impact not only on the economies of individual countries but also on the financial situation of households and entrepreneurs. [9] The economic consequences of the COVID-19 pandemic and its impact on the global economy and the financial crisis of consumers and businesses have been analyzed by commercial research institutes and academic centers around the world: Teresiene [10], van der Wielen, and Barrios [11], Baker [9], Kanapickiene [12].

A significant decrease was observed in production and borrowing caused by COVID-19 [13], a negative impact on the performance of companies in many sectors of the economy [14]. The most significant losses were recorded in the following industries: airlines, automobiles, hotel facilities or restaurants [15]; many experienced a reduction in wages for work or were put out of work [16]. The negative impact of COVID-19 cases has been noted on the change in investor sentiment [17], pessimism, and risk aversion among investors, on the value of the stock market [9], Al-Awadhi [18], increasing the volatility of these markets Ashraf [19], and stock returns and thus on financial markets around the world [20], resulting in higher levels of stock market volatility, and negative impact on the stock market [18,21–23].

All over the world, solutions are still being sought to mitigate the sudden economic shock, to keep the primary sectors of the economies of individual countries [24] functioning in the face of rising social expectations [25].

At the EU level and in individual countries, it has forced the need for governmental, institutional, and individual actions to counter its financial, organizational, and social implications, address the underlying economic risks associated with the pandemic, and increase the resilience of economies [26–30]. Domestic restrictions and restriction of movement (lockdown) have had effects in many areas of life: a global recession, increased debt and reduced economic potential disparities [31], and accelerated digital economy development, including the services market [32]. The crisis caused by COVID-19 threatens global financial stability due to uncertainty about its sustainability and intensity, affects financial problems, corporate failures, and unemployment in the long term, asset prices that have fallen dramatically, market liquidity a decline in investor confidence [18,33,34].

It also generated the need to identify current research directions developed around COVID-19 and its impact on the business environment in different sectors of the economy [35–38].

In the first quarter of 2020, a slight price decrease was noticed on the European electricity and coal market [39,40]. The COVID-19 pandemic created uncertainty about the future of the national and world economies and introduced uncertainty about its course, including the implications for demand variability [41–44]. The economic downturn and constraints imposed by national authorities have caused a temporary fall in electricity demand by businesses (industry), while school closures and remote working have increased its consumption by households [45–50]. The pandemic highlighted the importance of energy in the social order through closures, disruptions in mobility, and the shift to digital modes of remote working. It also meant that action had to be taken, including at the EU level [27,28,30,51], to ensure the continued operation of the European energy system during the pandemic. It has created specific risks for the sector, and it has become critical to sustaining the security of supply to manage it effectively in the face of key risks (reduced demand for electricity, moratoriums on construction projects, reduced staff availability, and travel restrictions affecting access to and maintenance of operational assets) [52]. COVID-19 also impacted stakeholders in the power sector—shareholders, stockholders, lenders, insurers, brokers, and others. They analyze the impact of the pandemic on balance sheets and the overall risk landscape, including climate change and environmental and social governance (ESG) issues and the transformation of the risk landscape in the energy industry, which, beyond COVID-19, is becoming the most important business driver, not just for the energy industry [53].

On one side, the energy market consists of the production, transmission, distribution, and trade of fuels and energy, and on the other side, the energy recipients affect the shaping of the environment. It influences landscape changes caused by opencast coal mining, construction of hydroelectric power plants, or the generation of smog caused by excessive exhaust fumes in a specific area. It also directly impacts the entire economy, including product prices, wages, returns on investment, and even the direction of development. Its strong connection to the rest of the economy makes countries focus on energy security to protect their interests [54]. The energy policy of Poland, consistent with the European Union's policy, considers the climate and energy objectives to counteract climate change. Its assurance would not be possible without the ability of the power system to ensure the security of operation of the power grid and balance the supply of electricity with the demand for this energy [55]. However, the implementation of changes in the energy structure is not possible without financial outlays.

While extensive research has been carried out to show the impact of COVID-19 on the economy, the situation, and the financial standing of entrepreneurs in various countries from different industries, the impact of the pandemic on the energy sector in Poland has not been studied. For these reasons, it seemed appropriate to investigate and answer whether the emergency caused by COVID-19 affected the economic crisis of the largest listed energy companies operating in Poland. The aim of the research is to show that those capital groups which in the period preceding the outbreak of the epidemic made the largest investment outlays and at the same time their financial ratios and market valuation on the Warsaw Stock Exchange were the highest, also during the pandemic, they achieved the highest financial results—they had the most favorable economic situation. The authors hypothesized that companies investing in new solutions and technologies are best prepared for an exceptional situation.

2. Materials and Methods

The answer to the research question posed in the introduction will help to examine the impact that the epidemic state introduced in 2020 has had on the efficiency of companies in the energy sector.

The subject of the study was the financial data of the ten most significant in terms of electricity production Polish utility power plants belonging to four capital groups. The economic data of the capital groups, parent companies, and the electricity generation segment of the capital groups whose shares are listed on the stock exchange were analyzed. Financial data from consolidated financial statements of capital groups, financial data from individual financial statements of parent companies, and management reports on the companies' activities were used to determine the financial position of power generation companies. The study period covers the years 2014–2020.

The capital groups selected for the study are: Polska Grupa Energetyczna (PGE), Tauron, Enea and Zespół Elektrowni Pątnów-Adamów-Konin (ZE PAK). These capital groups are the largest electricity producers in Poland, as they own at least one of the ten largest power plants in Poland. The capital groups are vertically integrated companies, present in the entire energy value chain—from extraction through generation in conventional and renewable energy sources to the distribution and sale of electricity. The entities accepted for the study are involved in the following subsectors: generation, transmission, distribution, and sales of energy in the wholesale and retail market segments. The entities of the energy sector are presented in Figure 1.

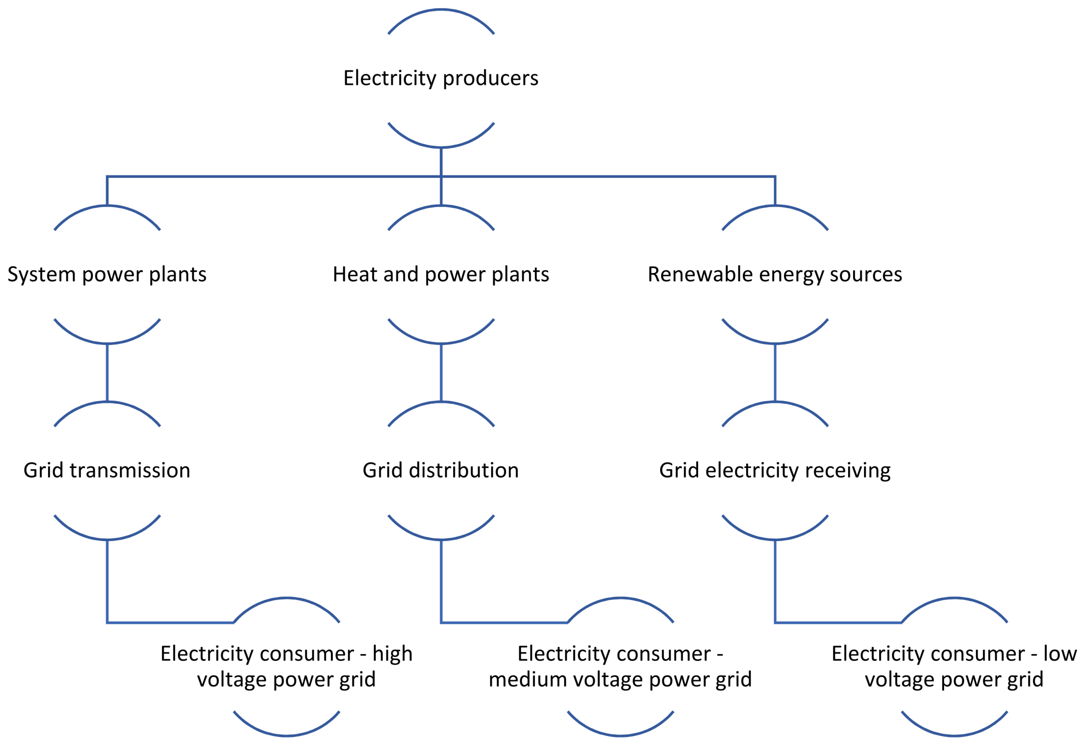

Figure 1. The energy sector in Poland.

In order to examine the effectiveness, the authors used ratio analysis tools were used, i.e., financial ratios, liquidity, debt, profitability, and efficiency.

The method of examining the efficiency of energy companies of the sector was divided into two parts. In the first part, ratio analysis of four capital groups, four parent companies, and selected indicators of the generation segment of each capital group was carried out. In particular, the data made available in the operating segment notes of the consolidated financial statements were examined. In situations where groups do not provide information necessary to calculate a given ratio, the data is determined based on the group's consolidated financial statements or estimated, e.g., information on the equity of the generation segment. In the next step of the research, the expenses, EBIT (Earning Before Interest and Taxes), and EBITDA of examined components are analyzed. The elimination of the cost of external capital will allow for a more accurate assessment of the operating efficiency of the segments. Due to the lack of studies in the literature on the impact of the ongoing situation on energy companies, an analysis will be carried out of the type and size of investments made in manufacturing operations and share price trends of parent companies, which will allow confirming the hypothesis that companies investing in new solutions and technologies will be best prepared for the emergency, will be the most effective. To confirm the hypothesis, it is necessary to achieve the aim of the study.

3. Results

3.1. Analysis of Equity Financial Data of Energy Groups

The analysis of financial data of the largest energy producers was preceded by a study of the electricity market situation. The research shows that in Poland, from 2014 to 2018 there was a systematic increase in electricity consumption and a decrease in consumption was marked in 2019 by 0.9% and by 2.3% in 2020. On the other hand, a decrease in electricity production occurred in the last three years studied, in 2018 by 0.38%, in 2019 by 3.9% and in 2020 by 4.1% compared to the previous year. On the other hand, the installed capacity in the national electricity system has been steadily increasing. In the last three years, the level of installed capacity increased by respectively: 5.8%, 1.9%, 5.2% [56].

The implementation of the main goal of the research required the determination of the financial situation of capital groups. The analysis of the Polish Energy Group's financial data for 2014–2019 indicates that the group's balance sheet total increased by PLN 11.449 billion, i.e., by 17%, and only in 2020 by another PLN 3.844 billion, i.e., in the entire period under review it increased by 22%. The level of the group's equity fluctuated during the period under review, decreasing by 3% by 2019 and increasing by 1% in 2020 (Table 1).

Table 1. Changes in total assets and equity of the PGE Capital Group from 2014 to 2020 (in PLN millions).

Year	Balance Sheet Total	Dynamics	Equity	Dynamics
2014	66,201	Not applicable	44,884	Not applicable
2015	61,296	−7%	40,417	−10%
2016	67,474	10%	42,775	6%
2017	72,106	7%	46,353	8%
2018	75,905	5%	47,801	3%
2019	77,650	2%	43,137	−10%
Change	11,449	17%	−1747	−3%
2020	81,594	5%	43,501	1%
Change	15,293	22%	−1383	−2%

Own study based on the annual consolidated financial statements of the capital group PGE for the years 2014–2020.

Based on the data obtained, it can be concluded that the group's business is constantly growing. The increase in the balance sheet total, along with the rise in equity and the decrease in the share of equity between 2014 and 2018, shows that the percentage of the company's liabilities has increased. Thus the company has been investing, which is confirmed by the number of investment expenditures made in the sector under study presented later in this paper.

Table 2 summarizes the net profits, net sales revenues, and tangible fixed assets of the group. During the period in question, investments were made in fixed assets. The item of tangible fixed assets increased by 12.003 billion PLN, which increased their value in the whole period in question by 23%.

Table 2. Net profit, revenues and tangible fixed assets of the PGE Capital Group (in PLN million) for 2014–2020.

Year	Net Profit	Revenues	Dynamics	Tangible Fixed Assets	Dynamics
2014	3657	28,137	Not applicable	49,738	Not applicable
2015	−3037	28,542	1%	47,068	−5%
2016	2566	28,092	−2%	51,365	9%
2017	2667	23,100	−18%	58,620	14%
2018	1511	25,946	12%	62,274	6%
2019	−3928	37,627	45%	59,690	−4%
Change	Not applicable	9490	41%	9952	20%
2020	148	45,766	22%	61,741	3%
Change	Not applicable	17,629	63%	12,003	23%

Own study based on the annual consolidated financial statements of the capital group PGE for the years 2014–2020.

In two years, i.e., 2015 and 2019, the PGE group recorded net losses due to increased cost of sales, in which it recognized impairment losses on fixed assets. By 2019, the PGE Group increased fixed assets by 20% and revenues by 41%, while revenues increased by another 22% in 2020 alone (Table 2).

In 2019, the PGE Group recognized impairment losses on financial and non-financial assets of the examined segments for PLN 8.347 billion. It reversed impairment losses on assets recognized in previous reporting periods in the Renewable Energy segment for

PLN 394 million. As a result of the impairment tests performed, the group recognized the creation and reversal of impairment losses on all non-current assets for PLN 7129 million under Depreciation and impairment losses. In total, the creation and reversal of write-downs for PLN 7518 million was recognized throughout 2019.

Table 3 shows the percentage of volumes characterizing the group's segments under study.

Table 3. Percentage share of conventional power generation and renewable power generation by line item in PGE's consolidated financial statements from 2014 to 2020.

Year	Revenues	Cost of Sales	Assets	Receivables	Liabilities
2014	48%	65%	59%	23%	41%
2015	47%	61%	60%	21%	47%
2016	44%	44%	58%	22%	36%
2017	60%	63%	64%	50%	36%
2018	67%	73%	66%	49%	40%
2019	70%	78%	55%	33%	49%
2020	68%	64%	60%	43%	51%
Average	58%	64%	60%	33%	43%

Own study based on the annual consolidated financial statements of the capital group PGE for the years 2014–2020.

The consolidated result of the PGE Group comprises the financial results of its individual operating segments. Between 2014 and 2020, the conventional and renewable energy segments held an average share of 58% in revenues, 64% in assets, and 43% in liabilities. The most significant change occurred in revenues and receivables, which increased their shares by ten percentage points. The Conventional Power Generation segment has the largest share in the group's result, together with the Renewable Energy segment accounting on average for almost 60% of annual EBITDA in the period under review [57].

The financial ratios calculated for PGE are presented in Table 4.

Table 4. Financial ratios of the PGE Capital Group in 2014–2020.

Liquidity Ratios	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
First coverage rate	0.86	0.82	0.79	0.74	0.72	0.66	0.65
Second coverage rate	1.13	1.08	1.11	1.01	0.95	1.01	1
Current ratio	1.93	1.54	1.74	1.06	0.73	1.06	1
Quick ratio	1.63	1.29	1.53	0.85	0.51	0.68	0.8
Working capital share in assets	0.1	0.07	0.08	0.01	−0.04	0.01	0.0008
Debt ratios	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
Debt ratio	32.20%	34.06%	36.61%	35.72%	37.03%	44.45%	46.69%
Equity ratio	67.80%	65.94%	63.39%	64.28%	62.97%	55.55%	53.31%
Debt-to-equity ratio	47.49%	51.66%	57.74%	55.56%	58.79%	80.01%	87.57%
Long-term debt ratio	31.31%	32.89%	39.75%	36.19%	32.59%	52.59%	53.04%
Fixed assets debt ratio	353.98%	354.03%	302.11%	349.49%	399.76%	263.10%	267.57%
Overall financial condition ratio	0.57	0.46	0.43	0.27	0.23	0.24	0.26
Activity ratios	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
Asset turnover ratio	0.43	0.47	0.42	0.32	0.34	0.48	0.56
Inventory turnover ratio	12.94	14.57	17.6	12.29	9.61	8.34	14.65
Inventory turnover ratio in days	28.21	25.05	20.74	29.69	37.97	43.74	24.91
Receivable turnover ratio	16.28	7.62	4.44	6.56	6.33	7.81	9.51
Receivable turnover ratio in days	22.42	47.93	82.18	55.65	57.71	46.71	38.38
Liabilities turnover ratio	23.87	7.23	7.9	7.15	7.18	10.35	13.06
Liabilities turnover ratio in days	15.29	50.45	46.2	51.05	50.83	35.27	27.95
Cash conversion cycle	35.34	22.53	56.71	34.29	44.85	55.18	35.34
Profitability ratios	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
EBITDA profitability ratio	28.85%	28.83%	26.26%	33.12%	24.57%	−11.10%	3.08%
Return On Assets	5.52%	−4.95%	3.80%	3.70%	1.99%	−5.06%	0.18%
Return On Equity	8.15%	−7.51%	6.00%	5.75%	3.16%	−9.11%	0.34%
Net profit margin	12.99%	−10.64%	9.13%	11.55%	5.82%	−10.44%	0.32%
Gross profit margin	16.39%	−13.16%	11.65%	14.24%	8.45%	−12.50%	0.69%
Gross profit margin on sales	22.77%	−5.34%	17.51%	23.74%	18.89%	−6.66%	9.08%

Own study based on the annual consolidated financial statements of the capital group PGE for the years 2014–2020.

The liquidity measurement during the period under review shows a deteriorating financial position, but not a bad one. The debt level of the group is increasing. The efficiency ratios reach very different stories. The cash cycle took its lowest level in 2019. Of particular note in Table 4 are the profitability ratios for 2015, which resemble a negative value. In 2015, the group raised its operating loss. This happened because the group wrote down the value of manufacturing assets to PLN 9.029 billion, wherein in other years, similar write-downs were for significantly lower amounts. Profitability ratios are decreasing from year to year. The lack of profitability is marked in 2015 and 2019. In summary, the year-on-year decline in profitability ratios, the financial liquidity ratios, and the increase in the share of short-term debt suggest that the company's financial position group deteriorated in the period under review.

The Tauron capital group's financial data analysis from 2014 to 2020 allows us to conclude that the group increased its assets by 15%. The balance sheet total was raised by PLN 4.852 billion (Table 5).

Table 5. Changes in the balance sheet total and equity of Tauron Capital Group in the years 2014–2020 (in PLN million).

Year	Balance Total	Dynamics	Total Equity	Dynamics
2014	34,559	Not applicable	17,997	Not applicable
2015	32,071	−7%	16,018	−11%
2016	33,457	4%	16,679	4%
2017	35,792	7%	18,068	8%
2018	37,097	4%	18,429	2%
2019	41,918	13%	19,093	4%
Change	7359	21%	1096	7%
2020	39,411	−6%	16,412	−14
Change	4852	−15%	−1585	−7%

Own study based on the annual consolidated financial statements of the capital group Tauron for the years 2014–2020.

By 2019, as the balance sheet total increased, equity also increased by 2%, resulting in a nominal increase of PLN 1.096 billion. This means that the group incurred additional liabilities during the period under review allocated to investments, highlighting a 12% increase in property, plant, and equipment by 2019 and another 11% in 2020.

Table 6 summarizes the group's net earnings, net sales revenues, and tangible fixed assets.

Table 6. Net profit, revenues and tangible fixed assets of Tauron Capital Group in 2014–2020 (in PLN million).

Year	Net Profit	Revenues	Dynamics	Tangible Fixed Assets	Liabilities
2014	1185	18,440	Not applicable	24,850	Not applicable
2015	−1804	18,375	0%	24,882	0%
2016	370	17,646	−4%	26,355	6%
2017	1382	17,416	−1%	28,079	7%
2018	207	18,121	4%	29,238	4%
2019	−12	20,065	11%	27,927	−4%
Change	Not applicable	1625	9%	3077	12%
2020	−2488	20,434	2%	31,099	11%
Change	Not applicable	1994	11%	6249	25%

Own study based on the annual consolidated financial statements of the capital group Tauron for the years 2014–2020.

The group recorded a net loss in 2015, 2019, and 2020. In 2015, this was due to impairment charges of PLN 3.6 billion (compared to PLN 0.52 billion in 2014). In the remaining years, the group achieved positive financial results. The increase in the cost of impairment losses on tangible fixed assets, and goodwill concerned the Generation segment.

In the year ending 31 December 2016, the group, after taking into account the following premises, prolonged persistence of the market value of net assets below the carrying amount, decreased the prices of renewable energy certificates of origin, introduced new regulations in the area of renewable energy, saw persistent unfavorable market conditions from the point of view of the profitability of the coal power industry, increased the risk-free rate, recognized impairment losses and reversed previously created write-downs of property, tangible fixed assets resulting from asset impairment tests. As a result of the tests, some of the assets of the Generation Segment were subject to additional write-downs for PLN 1942.9 million. The impairment tests also proved the reversal of impairment allowances in this segment for PLN 1208.2 million. The total impact of write-downs on the group's 2016 pre-tax profit amounted to PLN 0.787 billion (excess of creation over reversal).

In 2019, impairment losses on property, tangible fixed assets impacted the segment, resulting in the amount of PLN 0.635 billion (increase in write-downs for PLN 0.694 and decrease in the amount of PLN 0.059 billion). In 2020, the total impact on the result of the period was PLN 2.618 billion (an increase of write-offs for PLN 2.622 billion).

The increase in fixed assets did not result in a proportional increase in revenue. The group recorded an 11% increase in revenue over the entire period under review, including an 11% increase in 2019 alone (Table 6).

Table 7 shows the share of the conventional and renewable energy segment in the group's entire business. This share is significantly lower than in the case of the Polish Energy Group due to significant differences in the level of generation capacity and the classification of liabilities; in the case of the Tauron Group, most liabilities were not assigned to any of the activities.

Table 7. Percentage share of conventional and renewable energy in individual items of Tauron group's consolidated financial statements, 2014–2020.

Year	Revenues	Cost of Sales	Assets	Liabilities
2014	27%	32%	38%	10%
2015	29%	47%	34%	11%
2016	25%	33%	33%	12%
2017	26%	31%	33%	10%
2018	26%	27%	34%	7%
2019	21%	24%	36%	10%
2020	22%	36%	31%	11%
Average	25%	33%	31%	10%

Own study based on the annual consolidated financial statements of the capital group Tauron for the years 2014–2020.

The share of the generation segment for the Tauron group is virtually unchanged and did not change significantly in the period under review. In 2015, the share of assets fell from 38% to 34% due to the impairment charge, in the same year the segment also recorded the highest share in own costs at 47%. In 2020, the results obtained confirm the occurrence of a similar situation to that of 2015.

Table 8 presents selected financial indicators for the Tauron Group's generation business.

Table 8. Financial ratios of Tauron capital group in the years 2014–2020.

Liquidity Ratios	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
First coverage rate	0.64	0.57	0.57	0.58	0.57	0.54	0.52
Second coverage rate	1.06	0.88	0.98	0.99	0.92	0.97	1.01
Current ratio	1.33	0.53	0.9	0.95	0.63	0.87	1.05
Quick ratio	1.22	0.47	0.79	0.89	0.56	0.79	0.94
Working capital share in assets	0.05	−0.11	−0.01	−0.01	−0.07	−0.02	0.01
Debt ratios	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
Debt ratio	47.93%	49.96%	50.15%	49.52%	50.32%	54.45%	58.36%
Equity ratio	52.07%	50.04%	49.85%	50.48%	49.68%	45.55%	41.64%
Debt-to-equity ratio	92.03%	99.84%	100.59%	98.10%	101.31%	119.55%	140.13%
Long-term debt ratio	65.26%	53.49%	71.76%	70.50%	61.76%	78.37%	95.58%
Fixed assets debt ratio	211.60%	289.88%	220.20%	220.44%	256.87%	207.84%	178.02%
Overall financial condition ratio	0.25	0.14	0.15	0.16	0.14	0.16	0.17
Activity ratios	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
Asset turnover ratio	0.54	0.57	0.53	0.49	0.49	0.47	0.52
Inventory turnover ratio	35.21	42.41	36.3	58.97	35.55	28.59	26.21
Inventory turnover ratio in days	10.37	8.61	10.05	6.19	10.27	12.77	13.93
Receivable turnover ratio	9.69	10.04	9.32	8.57	8.13	8.54	8.62
Receivable turnover ratio in days	37.67	36.35	39.18	42.58	44.9	42.75	42.35
Liabilities turnover ratio	9.71	23.24	21.27	16.72	16.07	23.09	21.1
Liabilities turnover ratio in days	37.59	15.71	17.16	21.84	22.71	15.81	17.3
Cash conversion cycle	10.44	29.25	32.07	26.94	32.46	39.71	38.98
Profitability ratios	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
EBITDA profitability ratio	19.52%	−0.37%	14.00%	20.09%	13.86%	11.69%	4.61%
Return On Assets	3.43%	−5.63%	1.11%	3.86%	0.56%	−0.03%	−6.31%
Return On Equity	6.59%	−11.24%	2.22%	7.65%	1.12%	−0.06%	−15.16%
Net profit margin	6.38%	−9.82%	2.10%	7.94%	1.14%	−0.06%	−12.21%
Gross profit margin	8.06%	−11.91%	2.88%	10.09%	2.78%	−0.08%	−8.13%
Gross profit margin on sales	15.76%	−4.17%	10.93%	16.71%	9.30%	6.37%	−1.30%

Own study based on the annual consolidated financial statements of the capital group Tauron for the years 2014–2020.

Based on the results obtained, it can be observed that the group's financial condition is weak from 2015 to 2019. During this period, the group shows a lack of liquidity. Depending on the year, the cash cycle ranges between 26 and 39 days, and the longest falls in 2019. The most extended period of credit to customers falls in 2018. The asset productivity ratios ranged between 0.47 and 0.57, which is in a higher range than in the case of PGE. The profitability ratios take their lowest values in 2015, 2019, and 2020, i.e., the years with the highest asset impairment losses.

The deterioration of the group's financial position in the periods indicated was mainly influenced by impairment charges. Had these write-downs not occurred, the group would have shown positive values on each profitability ratio at a level similar to other periods. There are no significant concentrations of credit risk in the group related to its core business.

Financial data of the ENEA capital group, one of the largest distributors of electricity in Poland, which distinguishes the following business segments: extraction, generation, distribution, turnover, and other operations, is presented in Table 9 (balance sheet total and equity of the group, together with change dynamics).

Table 9. Balance sheet total and equity of the ENEA capital group in the years 2014–2020 (in PLN million).

Year	Balance Total	Dynamics	Total Equity	Dynamics
2014	18,108	Not applicable	12,064	Not applicable
2015	22,988	27%	12,123	0%
2016	24,536	7%	13,011	7%
2017	28,312	15%	14,000	8%
2018	29,965	6%	15,049	7%
2019	32,844	10%	15,480	3%
Change	14,736	81%	3416	28%
2020	29,890	−9%	15,859	3%
Change	11,782	65%	3795	31%

Own study based on the annual consolidated financial statements of the capital group ENEA for the years 2014–2020.

In the surveyed years 2014–2020, the group increased the value of its assets by 65%, increasing its balance sheet total by almost PLN 11.8 billion. This is the most significant change in nominal terms and by far the largest among the surveyed groups. Taking into account the percentage increase far surpasses the companies surveyed to date. Equity in the analyzed years increased by PLN 3.795 billion, which results in a rise of 31% in the entire period studied, including 28% until 2019. This shows that external financing mainly contributed to the increase in total assets.

Table 10 shows net income, tangible fixed assets from 2014 to 2020. The increase in the balance sheet total was significantly affected by investments in property, plant, and equipment, which increased by 57% until 2019 and decreased by only 1% in 2020.

Along with an increase in tangible fixed assets, the group's revenue increased by 85% during the period under review. Of the companies studied so far, only in the case of the ENEA group, there is a correlation between the growth of tangible fixed assets, and revenues. In 2015 and 2020 recorded a financial loss related to a write-down, which in the first case amounted to PLN 1.5 billion. In the remaining years, there were write-downs, but their value did not significantly impact the financial result.

The percentage share of revenues, costs, assets, and liabilities in the total values of the group is presented in Table 11. To determine the value of the segment's assets, information on the value of the segment's property, plant and equipment and the share of the group's property, plant and equipment in its assets was used.

Table 10. Net profit, revenues and property, Tangible fixed assets of ENEA Capital Group in 2014–2020 (in PLN million).

Year	Net Profit	Revenues	Dynamics	Tangible Fixed Assets	Liabilities
2014	909	9855	Not capplicable	13,702	Not capplicable
2015	−399	9848	0%	17,075	25%
2016	849	11,256	14%	18,382	8%
2017	1165	11,406	1%	20,417	11%
2018	719	12,673	11%	21,027	3%
2019	541	15,796	25%	21,471	2%
Change	Not applicable	5941	60%	7769	57%
2020	−2234	18,195	15%	21,404	−1%
Change	Not applicable	8340	85%	7702	56%

Own study based on the annual consolidated financial statements of the capital group ENEA for the years 2014–2020.

Table 11. Percentage share of the generation segment in particular items of the consolidated financial statements of the ENEA Group in the years 2014–2020.

Year	Revenues	Cost of Sales	Assets	Liabilities
2014	35%	32%	48%	7%
2015	36%	45%	40%	4%
2016	29%	31%	43%	3%
2017	40%	42%	46%	7%
2018	57%	58%	45%	6%
2019	51%	48%	44%	5%
2020	46%	66%	32%	4%
Average	42%	46%	35%	5%

Own study based on the annual consolidated financial statements of the capital group ENEA for the years 2014–2020.

The most significant change in the generation sector occurred in the revenue item, which increased from 29% to 57% in 2018. The share of segment assets declined from 48% to 32% in 2020 due to a write-down of the segment's assets of PLN 1.5 billion. The group's total assets increased by 65%. Thus, despite the decrease in the share of the segment's assets in the total assets of the group, in nominal terms, the value of the generation segment's assets increased from PLN 8.777bn to PLN 14.379bn in 2014–2019, to decrease by PLN 4.925bn in 2020. As in the case of the Tauron capital group, the ENEA group did not allocate the majority of its liabilities to any of the segments, which results in a low share of generation in the total amount of liabilities. Table 12 presents the financial ratios of the ENEA capital group.

Liquidity ratios were within the ranges defined in the literature, with a focus on over liquidity. We observed an increase in group debt and leverage. The rise in debt did not result in significant changes in the term debt ratio. During the study period, the cash turnover cycle decreased until 2018 to 2016 in 2019, influenced by a decrease in the receivables turnover ratio from 65 days to 44 days. From 2016 to 2018, there was an increase in the asset productivity ratio from 0.4 to 0.71, the best among the companies studied. Profitability ratios were positive in all years except 2015 and 2020. In 2015, as was the case with the other companies, an impairment charge was made, which significantly affected the company's financial result (without the cost, the ratios would have reached a level similar to 2014). Based on the financial ratios, it can be concluded that the financial position of the group improved during the period under review.

Table 12. Financial ratios of ENEA capital group in the years 2014–2020.

Liquidity Ratios	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
First coverage rate	0.84	0.67	0.67	0.63	0.65	0.65	0.6
Second coverage rate	1.13	1.13	1.11	1.09	1.09	1.11	1.06
Current ratio	2.03	1.99	1.73	1.47	1.44	1.39	1.2
Quick ratio	1.76	1.72	1.58	1.27	1.18	1.18	1.03
Working capital share in assets	0.11	0.1	0.09	0.07	0.07	0.08	0.04
Debt ratios	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
Debt ratio	33.38%	47.27%	46.97%	50.55%	49.78%	52.87%	56.19%
Equity ratio	66.62%	52.73%	53.03%	49.45%	50.22%	47.13%	43.81%
Debt-to-equity ratio	50.10%	89.64%	88.57%	102.24%	99.12%	112.17%	128.27%
Long-term debt ratio	34.73%	69.77%	66.15%	71.88%	67.18%	70.13%	76.44%
Fixed assets debt ratio	325.00%	201.88%	213.58%	202.89%	207.99%	197.79%	188.86%
Overall financial condition ratio	0.52	0.29	0.29	0.28	0.30	0.34	1.07
Activity ratios	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
Asset turnover ratio	0.56	0.44	0.47	0.41	0.43	0.48	0.61
Inventory turnover ratio	19.79	15.52	25.65	13.78	10.22	11.53	16.14
Inventory turnover ratio in days	18.44	23.52	14.23	26.49	35.72	31.66	22.61
Receivable turnover ratio	5.64	5.72	6.21	6.03	6.81	7.4	8.27
Receivable turnover ratio in days	64.77	63.76	58.81	60.54	53.59	49.33	44.11
Liabilities turnover ratio	8.83	8.13	9.68	5.53	4.97	7.8	8.4
Liabilities turnover ratio in days	41.33	44.89	37.73	66.01	73.48	46.77	43.43
Cash conversion cycle	41.88	42.39	35.32	21.02	15.82	34.22	23.29
Profitability ratios	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
EBITDA profitability ratio	19.43%	6.38%	19.81%	23.52%	19.84%	21.55%	−0.60%
Return On Assets	5.02%	−1.74%	3.46%	4.11%	2.40%	1.65%	−7.48%
Return On Equity	7.54%	−3.29%	6.52%	8.32%	4.78%	3.49%	−17.06%
Net profit margin	9.04%	−3.96%	7.37%	9.99%	5.56%	3.41%	−12.25%
Gross profit margin	11.37%	−4.06%	9.28%	12.58%	6.72%	5.49%	−14.27%
Gross profit margin on sales	12%	15%	12%	14%	7%	7%	9%

Own study based on the annual consolidated financial statements of the capital group ENEA for the years 2014–2020.

The analysis of the financial data of the capital group Zespół Elektrowni Pątnów-Adamów-Konin SA (ZE PAK) is presented in Tables 13–16. Table 13 shows the dynamics of changes in the balance sheet total and equity of the group.

Table 13. Balance sheet total and equity of the ZE PAK capital group in the years 2014–2020 (in PLN million).

Year	**Balance Total**	**Dynamics**	**Total Equity**	**Dynamics**
2014	6868	Nie dotyczy	3820	Nie dotyczy
2015	4974	−28%	1884	−51%
2016	4801	−3%	2143	14%
2017	4455	−7%	2264	6%
2018	3871	−13%	1687	−25%
2019	3118	−19%	1177	−30%
Change	−3750	−55%	−2643	−69%
2020	2879	−8%	949	−19%
Change	−3989	−58%	−2133	−75%

Own study based on the annual consolidated financial statements of the capital group ZE PAK for the years 2014–2020.

Table 14. Net profit, revenues and property, Tangible fixed assets of ZE PAK Capital Group in 2014–2020 (in PLN million).

Year	Net Profit	Revenues	Dynamics	Tangible Fixed Assets	Liabilities
2014	79	2680	Not applicable	5300	Not applicable
2015	−1880	2947	10%	3475	−34%
2016	250	2705	−8%	3391	−2%
2017	184	2443	−10%	3280	−3%
2018	−464	2305	−6%	2791	−15%
2019	−446	2878	25%	1960	−30%
Change	Not applicable	573	7%	−3340	−63%
2020	−227	2207	−23%	1661	−15%
Change	Not applicable	−671	−18%	−3639	−69%

Own study based on the annual consolidated financial statements of the capital group ZE PAK for the years 2014–2020.

Table 15. Percentage share of the generation segment in the individual items of the consolidated financial statements of the ZE PAK Group from 2014 to 2020.

Year	Revenues	Cost of Sales	Financial Costs
2014	81%	84%	58%
2015	74%	86%	56%
2016	81%	84%	78%
2017	86%	88%	72%
2018	86%	81%	51%
2019	83%	85%	42%
2020	84%	81%	28%
Average	82%	84%	55%

Own study based on the annual consolidated financial statements of the capital group ZE PAK for the years 2014–2020.

Table 16. Financial ratios of ZE PAK capital group in the years 2014–2020.

Liquidity Ratios	2014	2015	2016	2017	2018	2019	2020
First coverage rate	0.67	0.51	0.58	0.66	0.57	0.54	0.51
Second coverage rate	1	1	0.95	1	0.9	0.99	0.97
Current ratio	0.68	0.7	0.87	1.01	0.75	0.98	0.96
Quick ratio	0.49	0.57	0.78	0.91	0.66	0.87	0.89
Working capital share in assets	−0.06	−0.08	−0.04	0	−0.08	−0.01	−0.02
Debt ratios	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
Debt ratio	44.38%	62.11%	55.35%	49.18%	56.42%	62.27%	67.02%
Equity ratio	55.62%	37.89%	44.65%	50.82%	43.58%	37.73%	32.98%
Debt-to-equity ratio	79.80%	163.92%	123.98%	96.78%	129.46%	165.05%	203.18%
Long-term debt ratio	48.22%	97.08%	64.83%	52.64%	57.74%	84.01%	90.69%
Fixed assets debt ratio	287.73%	189.93%	244.02%	275.25%	286.52%	198.31%	192.86%
Overall financial conditio ratio	0.18	0.14	0.24	0.3	0.23	0.26	0.27
Activity ratios	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
Asset turnover ratio	0.39	0.59	0.56	0.55	0.6	0.92	0.77
Inventory turnover ratio	11.3	18.71	25.69	24.99	21.1	27.58	32.52
Inventory turnover ratio in days	32.29	19.5	14.21	14.61	17.3	13.23	11.22
Receivable turnover ratio	10.55	10.99	10.99	9.65	6.51	12.59	5.73
Receivable turnover ratio in days	34.59	33.2	33.2	37.84	56.09	28.99	65.43
Liabilities turnover ratio	25.83	36.51	533.58	474.75	200.98	24.44	11.41
Liabilities turnover ratio in days	14.13	10	0.68	0.77	1.82	14.94	32
Cash conversion cycle	52.75	42.7	46.73	51.67	71.57	27.29	44.65
Profitability ratios	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
EBITDA profitability ratio	18.67%	−48.00%	21.42%	19.88%	−12.22%	−8.35%	−6.25%
Return On Assets	1.14%	−37.79%	5.21%	4.12%	−11.98%	−14.31%	−7.87%
Return On Equity	2.05%	−99.73%	11.68%	8.11%	−27.48%	−37.92%	−23.85%
Net profit margin	2.93%	−63.77%	9.25%	7.51%	−20.12%	−15.50%	−10.26%
Gross profit margin	3.66%	−62.19%	11.38%	10.59%	−22.36%	−15.29%	−13.73%
Gross profit margin on sales	8.51%	−57.78%	17.13%	16.69%	−14.02%	−10.70%	−10.88%

Own study based on the annual consolidated financial statements of the capital group PAK for the years 2014–2020.

Between 2014 and 2020, total assets decreased by 58% from PLN 6.87 billion to PLN 2.88 billion, including a 55% decrease by 2019, In 2020, the value of assets decreased by 8% compared to 2019. The highest declines in value occurred in 2015, 2019, and 2018. In the period under review, equity decreased by 75%, or by more than PLN 2.1 billion. The highest decrease in equity value occurred in 2015 and amounted to 51%; the next one took place in 2019 at 30%. However, in 2018 there was a noticeable decrease in the value of equity at 25%.

As was the case with the other three groups, ZE PAK recorded a net loss in 2015 and 2020, when the group took asset write-downs. The first write-down amounted to nearly PLN 1.9 billion, resulting in a 51% reduction in equity. In 2018 and the subsequent periods under review, the group also made total write-downs of much lower values (PLN 227, 603, and 151 million, respectively). Table 14 summarizes the net financial results, revenue dynamics, and tangible fixed assets changes.

During the period under review, the group recorded losses four times. The highest in 2015 and consecutively in 2018, 2019, and 2020. However, if impairment losses were not taken into account, the group would have made a profit in 2015 and 2019, while in 2018, it would have made about half the loss. The value of property, plant, and equipment decreased by 69% over the entire period under review, the most in 2015 and 2019. On the other hand, the group's revenue declined by 18% over the whole period under review, the most in 2020, down 23% from the previous year. The group did not make investments on the same scale as its competitors in the years under review.

The group does not have current assets, liabilities, and expenditures allocated to segments. The generation segment (four companies, including the parent company) generates the largest share of revenues and costs (Table 15).

Due to the lack of disclosures in the group's consolidated financial statements about the assets and liabilities separated into individual business segments, the data adopted for the analysis, in addition to revenue and own costs, relate to financial expenses. Between 2014 and 2020, the generation segment had an average share of 82% of the group's revenue, a share of 84% in 2020. Own costs averaged 84% and were highest in 2015 and 2019. Finance costs averaged 55%, falling from 78% in 2016 to 28% in 2020. Segments other than generation account for a significantly smaller share of the group's business.

Table 16 shows the financial ratios calculated for the group.

The liquidity ratios of the group are at a superficial level (much lower than the optimal level indicated in the literature). During the period under review, the current liquidity increased from 0.68 to 0.98, with the lowest level of the ratio occurring in 2014. The quick liquidity ratio also performed below the minimum recommended threshold during the study period, with the highest level occurring in 2020. The general debt ratio was 0.44 in 2014 and was 0.67 at the end of 2020, which significantly affects the company's ability to incur future liabilities. The company enjoys high leverage, as evidenced by the debt-to-equity ratio increasing from 0.8 to over two during the period under review, with a high proportion of long-term liabilities rising in 2019 and 2020. During the period under review, the cash cycle peaked in 2017 at over 77 days and was over 44 days in 2020. Asset productivity during the period under review increased from 0.39 in 2014 to 0.77 in 2020. The group reached its highest productivity in 2019, with a ratio of 0.92. This increase is related to creating a write-down of fixed assets, which still retain the ability to generate income, and by reducing their book value, the productivity of assets increases. The study of the group's profitability showed its absence in 2015 and 2018 to 2020, i.e., the years in which the group made write-downs or closed power plants. The group achieved the lowest level of net profit margin in 2015.

3.2. Evaluating the Financial Position of Capital Groups during the COVID-19 Pandemic—A Summary of Results

The implementation of the research objective required a comparison of the financial situation of the surveyed capital groups. The following were compared: the scale of operation and investments made, profitability, and other indicators.

During the period under review, The Enea group recorded the most significant growth. The first six years under study increased its balance sheet total by 81% (Table 17). The reduction in the balance sheet total in 2020 resulted in a total increase in the value of assets in the period under the study of 65%.

Table 17. Changes in the quantities studied between 2014 and 2020.

Change (%)	PGE	Tauron	ENEA	ZE PAK	Leader
		Until 2019			
Total balance	17	21	81	−55	ENEA
Equity	−3	7	28	−69	ENEA
Revenues	41	9	60	7	ENEA
Tangible fixed assets	20	12	57	−63	ENEA
		Until 2020			
Total balance	22	15	65	−58	ENEA
Equity	−2	−7	31	−75	ENEA
Revenues	63	11	85	18	ENEA
Tangible fixed assets	23	25	56	−69	ENEA
		In 2020			
Total balance	5	−6	−9	−8	PGE
Equity	1	−14	3	−19	ENEA
Revenues	22	2	15	−23	PGE
Tangible fixed assets	3	11	−1	−15	Tauron

Own study.

The analysis of fundamental economic categories describing business activity indicates the ENEA Group as a leader, both until 2019 and with the volumes achieved in 2020 (Table 17). The ENEA group maintained growth in the level of equity in 2020. The leader in terms of property, plant, and equipment changes was the Tauron group, and in terms of generated revenues and total assets—the PGE group, The worst-ranked performer is the ZEPAK group, whose scale of operations decreased in every aspect except for payments. Furthermore, for the ZE PAK group, there were declines in all analyzed categories in the year of the pandemic occurrence. It should be mentioned that the group closed two power plants in both 2018 and 2020, and these circumstances were not related to the pandemic. They resulted from the group's implementation of its system transformation policy. In 2020, the PGE group recorded increases in all of the volumes studied.

In terms of profitability, the best performers are PGE and Enea (Table 18). PGE showed a lack of profitability in 2015 and 2019 when it made write-downs on fixed assets. In 2020, these ratios took a higher level 2019. On the other hand, ENEA showed a lack of profitability for the same reason as PGE in 2015 and 2019.

Table 18. Profitability ratios of capital groups from 2014 to 2020.

Year	Profitability Ratios	PGE	Tauron	ENEA	ZE PAK
2014	EBITDA profitability ratio	28.85%	19.52%	19.43%	18.67%
	Return on Assets	5.52%	3.43%	5.02%	1.14%
	Return on Equity	8.15%	6.59%	7.54%	2.05%
	Net profit margin	12.99%	6.38%	9.04%	2.93%
	Gross profit margin	16.39%	8.06%	11.37%	3.66%
	Gross profit margin on sales	22.77%	15.76%	12.00%	8.51%
2015	EBITDA profitability ratio	28.83%	−0.37%	6.38%	−48.00%
	Return on Assets	−4.95%	−5.63%	−1.74%	−37.79%
	Return on Equity	−7.51%	−11.24%	−3.29%	−99.73%
	Net profit margin	−10.64%	−9.82%	−3.96%	−63.77%
	Gross profit margin	−13.16%	−11.91%	−4.06%	−62.19%
	Gross profit margin on sales	−5.34%	−4.17%	−26.00%	−57.78%
2016	EBITDA profitability ratio	26.26%	14.00%	19.81%	21.42%
	Return on Assets	3.80%	1.11%	3.46%	5.21%
	Return on Equity	6.00%	2.22%	6.52%	11.68%
	Net profit margin	33.12%	20.09%	23.52%	19.88%
	Gross profit margin	3.70%	3.86%	4.11%	4.12%
	Gross profit margin on sales	5.75%	7.65%	8.32%	8.11%
2017	EBITDA profitability ratio	11.55%	7.94%	9.99%	7.51%
	Return on Assets	14.24%	10.09%	12.58%	10.59%
	Return on Equity	23.74%	16.71%	9.00%	16.69%
	Net profit margin	24.57%	13.86%	19.84%	−12.22%
	Gross profit margin	1.99%	0.56%	2.40%	−11.98%
	Gross profit margin on sales	3.16%	1.12%	4.78%	−27.48%
2018	EBITDA profitability ratio	5.82%	1.14%	5.56%	−20.12%
	Return on Assets	8.45%	2.78%	6.72%	−22.36%
	Return on Equity	18.89%	9.30%	7.00%	−14.02%
	Net profit margin	−11.10%	11.69%	21.55%	−8.35%
	Gross profit margin	−5.06%	−0.03%	1.65%	−14.31%
	Gross profit margin on sales	−9.11%	−0.06%	3.49%	−37.92%
2019	EBITDA profitability ratio	−10.44%	−0.06%	3.41%	−15.50%
	Return on Assets	−12.50%	−0.08%	5.49%	−15.29%
	Return on Equity	−6.66%	6.37%	13.00%	−10.70%
	Net profit margin	3.08%	4.61%	−0.60%	−6.25%
	Gross profit margin	0.18%	−6.31%	−7.48%	−7.87%
	Gross profit margin on sales	0.34%	−15.16%	−17.06%	−23.85%
2020	EBITDA profitability ratio	0.32%	−12.21%	−12.25%	−10.26%
	Return on Assets	0.69%	−8.13%	−14.27%	−13.73%
	Return on Equity	9.08%	−1.30%	−29.00%	−10.88%
	Net profit margin	0.32%	−12.21%	−12.25%	−10.26%
	Gross profit margin	0.69%	−8.13%	−14.27%	−13.73%
	Gross profit margin on sales	9.08%	−1.30%	−29.00%	−10.88%

Own study.

The Tauron group's profitability ratios deteriorated in 2020 compared to 2019. ZEPAK reported losses in 2018, 2019, and 2020, with the most significant losses in 2018 and lower in 2020 than in 2019 (Table 18). The results included in Table 18 are presented in Figure 2.

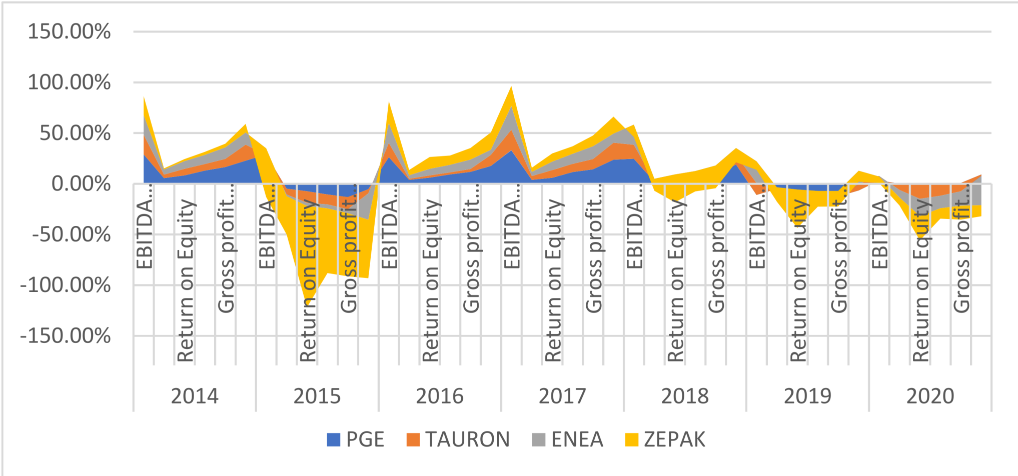

Figure 2. Profitability ratios of capital groups in the years 2014–2020 (Own study).

Profitability ratios achieved by the Generation segment are presented in Figure 2 and Table 19. The highest average EBITDA ratio is PGE (26%), followed by ENEA, Tauron, and ZE PAK (18, 15, and 13%). The assets of the PGE group have the highest capacity to generate profits, followed by the ENEA and Tauron groups.

Table 19. Profitability indicators of the production segment in the researched group.

Group	Profitability Ratios	2014	2015	2016	2017	2018	2019	2020
PGE	EBITDA profitability ratio	0.39	0.40	0.37	0.32	0.19	0.15	0.10
	Return on Assets	0.06	−0.05	0.04	0.03	0.02	−0.05	0.00
	Return on Equity	0.08	−0.07	0.05	0.04	0.02	−0.08	0.00
	Net profit margin	0.18	−0.15	0.13	0.11	0.05	−0.08	0.00
	Gross profit margin	0.22	−0.18	0.16	0.14	0.07	−0.10	0.01
	Gross profit margin on sales	−0.03	−0.42	0.17	0.19	0.12	−0.18	0.06
Tauron	EBITDA profitability ratio	0.16	0.14	0.13	0.12	0.16	0.23	0.14
	Return on Assets	0.01	−0.32	0.06	0.01	0.02	−0.01	−0.27
	Return on Equity	0.01	−0.38	0.08	0.01	0.02	−0.01	−0.34
	Net profit margin	0.01	−0.65	0.16	0.02	0.04	−0.03	−0.72
	Gross profit margin	0.01	−0.65	0.16	0.02	0.04	−0.03	−0.72
	Gross profit margin on sales	0.01	−0.65	−0.17	0.00	0.03	−0.04	−0.72
ENEA	EBITDA profitability ratio	0.21	0.25	0.16	0.16	0.12	0.20	0.18
	Return on Assets	0.04	−0.02	0.02	0.02	0.02	0.02	−0.11
	Return on Equity	0.04	−0.02	0.02	0.02	0.02	0.02	−0.11
	Net profit margin	0.10	−0.05	0.06	0.07	0.04	0.03	−0.12
	Gross profit margin	0.12	−0.05	0.07	0.09	0.04	0.05	−0.14
	Gross profit margin on sales	0.12	−0.26	0.05	0.09	0.07	0.13	−0.29
ZE PAK	EBITDA profitability ratio	0.17	0.12	0.17	0.18	0.05	0.14	0.06
	Return on Assets	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	Return on Equity	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	Net profit margin	0.03	−0.47	0.08	0.09	−0.10	−0.17	−0.03
	Gross profit margin	0.03	−0.87	0.10	0.12	−0.13	−0.17	−0.08
	Gross profit margin on sales	0.05	−0.84	0.14	0.14	−0.08	−0.14	−0.08

Own study.

The EBIDA ratio was profitable in all groups and in all periods. Thus, in the PGE group it took a clear decreasing trend, in the Tauron and ZE PAK groups a less clear trend. In the Tauron group, the highest occurred in 2019 (Figure 3).

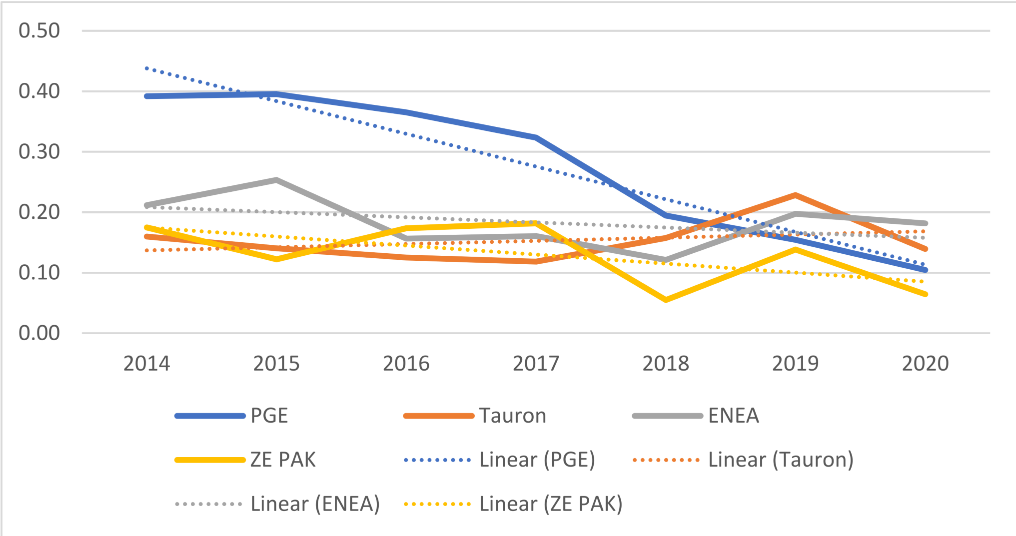

Figure 3. EBITDA ratios of the segments under review (Own study).

The values of other financial ratios were within the allowed ranges. A decrease in liquidity ratios can be observed. However, they are within the recommended range.

The financial performance of the group companies was shaped by several groups of factors: political, Market, and climate protection.

Political factors had an impact on the value of revenues achieved by the group companies, as on 28 December 2018, the Law on Amendments to the Excise Tax Law and Certain Other Laws was [58]. This Act was intended to stabilize the sales price of electricity to the end-user in 2019. Among other things, the law froze the level of electricity prices for end-users, and for retail companies, it introduced a compensation system.

In 2015, the prolonged unfavorable market situation for electricity generators and the resulting adoption of more cautious electricity price forecasts in the future influenced the creation of impairment losses on assets.

On the cost side, the growing prices of CO_2 emission permits had an impact. This factor becomes particularly important because in 2015, the ZEPAK Group purchased almost the entire amount of CO_2 emission permits, which is reflected in the growing importance of this factor in the cost structure.

Market and environmental factors particularly influenced the impairment of property, Plant, and equipment in 2015 and 2019 or 2020. The most significant factors for the creation of write-downs were the following:

- Rapid changes in the commodity markets, which affected price declines for almost all energy commodities in global markets;
- Long-term persistent market value of net assets at levels below the carrying value of net assets;
- Reduced future electricity generation;
- Faster than anticipated retirement of older generating units.

Additionally, there were circumstances in 2020 that increased the impairment charges. These included:

- High volatility of energy prices in the forward market;
- A decline in domestic electricity consumption due to increased winter 2019/2020 temperatures and the impact of the COVID-19 pandemic;
- Regulatory actions to limit energy price increases for end customers;
- Increased risk in commercial coal production;
- RES auctions and the very dynamic development of the prosumer and micro-installation sub-sector due to the support programs launched;

- Consequences of the introduction of the provisions of the winter package, including the emission standard, adversely affecting the possibility of participation in the power market of coal units after 1 July 2025;
- Tightening of emission standards and persistently unfavorable market conditions from the point of view of the profitability of conventional power generation;
- Decline in the risk-free rate.
- The need to write down assets in 2020 resulted in particular:
- From an increase in CO_2 emission allowance prices as a result of a change like the market, the reform of the EU CO_2 emission allowance trading system (EU ETS), as well as the European Union's climate policy, strongly focused on accelerating the pace of decarbonization in pursuit of Europe's climate neutrality as a realization of the European Green Deal,
- Projected decline in market margins in the short and medium-term as a result of rising CO_2 emission allowance prices and the increasing share of renewable energy sources and new, more efficient conventional sources in the domestic energy mix, which negatively impacts the projected electricity prices
- Decreased projected demand for steam coal due to progressive decarbonization in Europe and reduced operation period of hard coal mines in connection with adjustment to Poland's energy policy.

Unfavorable trends in external factors forced us to perform asset impairment tests. As a result of the analyses, the carrying value of generation and mining assets was reduced, which unfortunately harmed the financial results achieved in 2015 and 2019 or 2020, depending on the group. These operations did not affect the groups' liquidity.

In order to verify the hypothesis, it was necessary to examine the amount of financial expenditures for development. The PGE Group incurred the most capital expenditures in the generation segment. Tauron and Enea groups incurred four times less expensive than PGE. The financial statements of the ZE PAK group lack information on the expenditures incurred for individual operating segments. For this reason, information on the amounts of purchased property, plant, and equipment and performed overhauls attributed to the generation segment was used in the analysis (Table 20).

Table 20. Investment expenditure in PLN million.

Group	2014	2015	2016	2017	2018	2019	2020
PGE	4736	7426	6323	4980	4998	4167	3026
Tauron	404	1934	1661	1517	1300	1683	1377
ENEA	1846	1955	1390	1094	430	492	548
ZE PAK	694	418	126	108	72	31	1

Own study.

The PGE Capital Group incurred expenses on property, plant, and equipment, mainly on constructing new blocks of highly efficient conventional power generation, modernization of assets of the group's units, and purchase of machinery and equipment. Other significant investments include increasing the efficiency of the existing units and their environmental upgrades. The group is investing in the development of renewable energy sources—onshore and offshore wind farms. On 25 June 2020, two new wind farms were commissioned during the declared epidemic state. Despite the ongoing state of emergency, on 31 December 2020, the PGE Capital Group committed to incur further expenditures for property, plant, and equipment, mainly for the construction of new units, modernization of the assets of the group's teams and purchase of machinery and equipment. The group's further plans are connected with increased power capacity.

Essential capital expenditures in ENEA serve to maintain continuity of operations, ensure the effectiveness of the process of sources, and meet environmental standards. The group optimizes its investment expenditures relating to renewable energy sources, cogeneration sources, and heat networks. It focuses on the development of micro-and macro energy clusters, electromobility, and prosumer installations. In the field of renewable energy sources, the group focuses primarily on increasing the operating efficiency of the assets it already owns, seeing its opportunity in the development of hybrid RES [59].

Despite the difficult economic situation, the ZE PAK Group has undertaken modernization and development activities. It is carrying out an investment program encompassing modernization of the power generation assets and replacing worn-out power generation units with modern technologies. It continues with current investments in maintenance of the currently operated open-pit mines and the launch of a highly efficient team generating electricity and heat from a gas/steam unit.

At the beginning of 2018, the Adamów power plant was shut down after more than 50 years of operation. The decrease in production in 2020 occurred not only due to the pandemic but also due to the shutdown on 30 June 2020, of two coal-fired units in the Pątnów power plant with a capacity of 200 MW each, commissioned in 1968/69. The shutdowns of the power units naturally resulted in a decrease in the scale of operations of the ZE PAK SA Group.

The Strategic Investment Program for ZE PAK SA, which considers the assumptions of the Polish Energy Policy valid in 2008, was prepared in a period promising favorable conditions for investment in gas-fired equipment. Unfortunately, the Polish economy did not have excellent conditions to construct the steam-gas unit planned for the Adamów power plant. After analyzing the requirements, the decision to develop this project was suspended. During the pandemic in 2020, ZE PAK SA entered into a contract to build the most prominent photovoltaic farm in Poland with a capacity of 70 MWp.

Figure 4 compares the capital expenditures incurred in the generation segment with the EBITDA achieved by the elements.

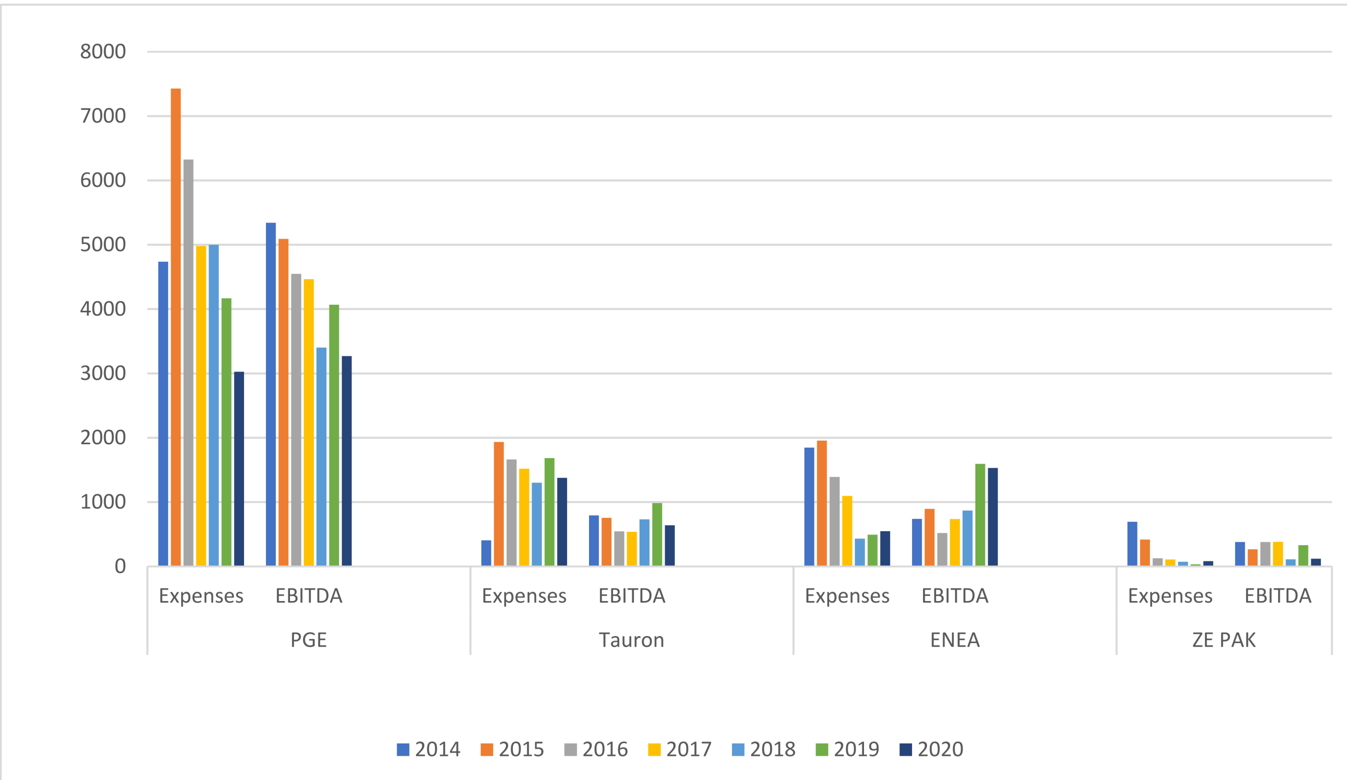

Figure 4. EBITDA ratios of the segments under review (Own study).

Table 21 presents the share of achieved EBITDA in the capital expenditures incurred.

Table 21. Share of achieved EBITDA in the capital expenditures incurred.

Group	2014	2015	2016	2017	2018	2019	2020
1	Tauron	PGE	ZE PAK	ZE PAK	ENEA	ZE PAK	ENEA
2	PGE	ZE PAK	PGE	PGE	ZE PAK	ENEA	ZE PAK
3	ZE PAK	ENEA	ENEA	ENEA	PGE	PGE	PGE
4	ENEA	Tauron	Tauron	Tauron	Tauron	Tauron	Tauron

Own study.

An analysis of the capital expenditures incurred by the groups in the generation segment and the EBITDA achieved in these segments shows that the ZEPAK group performs the highest return. Three times in the period under review, it reached the highest share of EBITDA in capital expenditures. The second group with the highest return is the PGE group.

The Pearson correlation of investment expenditures made by the groups in the generation segment with EBITDA showed a moderate correlation in the PGE group (r = 0.62). The correlation strength was also average for the ENEA group, with a negative correlation (r = −0.62). The correlation study of the two variables in the Tauron group showed no linear relationship (r = −0.1), and for ZE PAK, a weak correlation (r = 0.35).

The study of the Spearman correlation coefficient confirmed that in PGE and ZEPAK groups, EBITDA increases moderately and weakly with increased expenses, respectively (Table 22). In Tauron, the relationship is so weak that it can be concluded that it does not exist. In ENEA, there is a negative relationship—in 2014–2017, with high expenses, EBITDA decreases, and in turn, in 2018–2020, with low costs, EBITDA increases. The costs incurred by ENEA are used to maintain the continuity of operations.

Table 22. Spearman correlation coefficient.

	Group			
Result	PGE 0.5	Tauron 0.07	ENEA −0.36	ZE PAK 0.44

Own study.

The index analysis is completed by examining the share prices of the capital market indicators of the studied parent companies on the Warsaw Stock Exchange from 1 January 2014 to 31 December 2020. Figure 5 shows the share prices of the companies Polska Grupa Energetyczna, Tauron, ENEA and ZE PAK in the selected period.

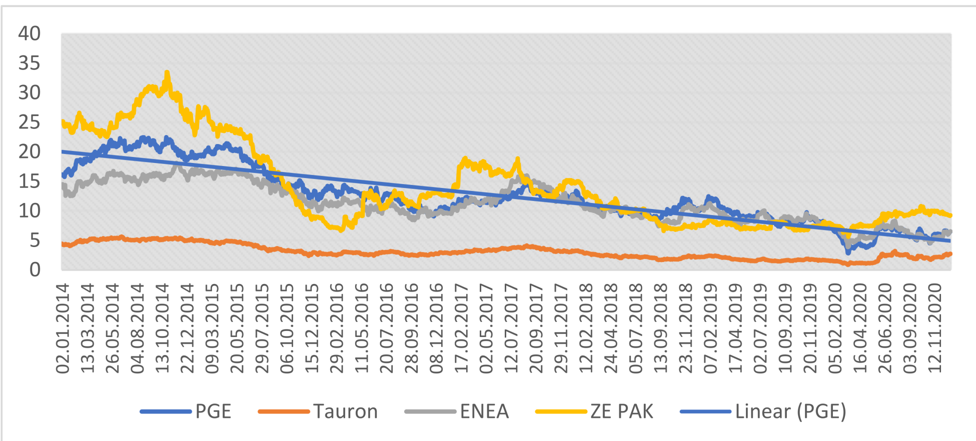

Figure 5. Share prices of PGE, TAURON, ENEA and ZE PAK during the period from 2 January 2014 to 30 December 2020 (Own study based on Warsaw Stock Exchange statistics for 2014–2020).

Figure 5 shows the unfavorable trends in the share prices of the companies under study. The share value of each company fell below the reference value of 2 January 2014 at the end of the period under study. Table 23 shows selected values from Figure 5.

Table 23. Maxima and minima of the value of shares of the surveyed companies in the examined period.

Group	Max. Price	Date	Min. Price	Date	Total Change (%)		
					2 January 2014–30 December 2019		2 January 2020–30 December 2020
PGE	22.85	18 June 2014	2.52	6 March 2020	−39	−36	5
Tauron	5.69	20 June 2014	0.823	16 March 2020	−64	6	73
ENEA	18.11	25 November 2014	3.54	6 March 2020	−21	−27	−4
ZE PAK	33.75	24 October 2014	5.52	13 March 2020	−74	−51	27

Own study based on Warsaw Stock Exchange statistics for 2014–2020.

Based on the data from the stock exchange, ZE PAK capital group was the worst-rated throughout the period under study. Its shares took the most significant drop in value, the change in the period under study is more than 51%. The share values of the ZE PAK and Tauron group companies by 2019 fell by 74 and 64%, respectively. At the same time, only in 2020, the change in the value of Tauron shares occur by 73%, and ZE PAK company by 27%. By 2019, ENEA and PGE group companies' shares were the best valued by the market, with ENEA's share value decreasing by 4% in 2020 and PGE's increasing by 5%. Throughout the study period, the minimum share values of all companies were recorded in March 2020.

The efficiency of the groups' operations was also examined based on the measure of the market price of shares to the book value of companies (P/BV-price/book value) (Figure 6).

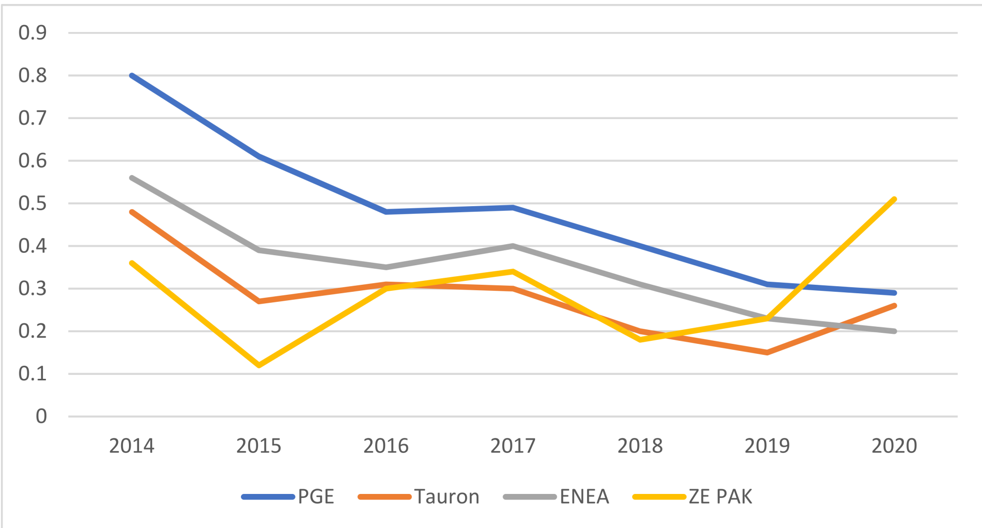

Figure 6. Group functioning efficiency (P/BV) (Own study based on Warsaw Stock Exchange statistics for 2014–2020).

A ratio below unity (Figure 6) indicates undervaluation by the market and poor asset utilization. Among the surveyed groups, PGE achieved the highest percentages. This situation continued in 2019, which means that it invested the most.

It should be emphasized that share prices depend on many factors, such as the situation on global stock exchanges, forecasts for the sector, the condition of the stock market, the company's development potential, government policy, and others, and not only on the manufacturing activities of the companies under study.

Based on the economic and market situation analysis, it can be noted that the value of market capitalization of groups that own mines remains at a level lower than the carrying value of net assets. It should be noted that this premise was already present at the end of 2019 and was the main reason for performing an impairment test.

In 2020, there was a further, albeit no longer as significant, decline in the share price and thus in the market capitalization. This situation is primarily due to factors beyond the groups' control, such as political factors and EU climate policy, the low liquidity of the shares, and the low level of shares in free float.

4. Conclusions

The spread of the SARS-CoV-2 virus causing COVID-19 disease and the numerous restrictions introduced in the country to contain it caused disruptions in Poland's economic and administrative system and the world. The pandemic caused repercussions in the social and economic spheres [60], limiting economic activity to a different extent and affecting the work of industrial plants and companies in the segment of small and medium-sized enterprises [2], therefore it was decided to investigate whether the COVID-19 pandemic contributed to the economic issues of the largest listed energy companies operating in Poland. In order to answer this question, the financial data of the ten largest Polish professional power plants in terms of electricity production, belonging to four capital groups, listed on the stock exchange, were analyzed. The capital groups selected for the study are: Polska Grupa Energetyczna (PGE), Tauron, Enea and Zespół Elektrowni Pątnów-Adamów-Konin (ZE PAK). The capital groups are the largest producers of electricity in Poland, they own at least one of the ten largest power plants in Poland. The aim of the research was to show that those capital groups which in the period preceding the outbreak of the epidemic made the largest investment outlays and at the same time their financial ratios and market valuation on the Warsaw Stock Exchange were the highest, also during the pandemic achieved the highest financial results—they had the most favorable economic situation. The implementation of the goal confirmed the hypothesis that companies investing in new solutions and technologies are best prepared for crisis situations.

Readings of economic indicators confirmed that the effects of the pandemic have a significant impact on the financial situation. Among other things, the level of industrial production and investment declined, contributing to a decrease in domestic electricity consumption and thus affecting the reduction of electricity production. However, the decline in production in power plants by about 4% compared to the same period of the previous year is not a significant reduction [60]. Furthermore, the decrease in recorded electricity consumption may be related to increased installed capacities, such as renewable energy sources by prosumers, whose consumption is not directly recorded by metering equipment. The impact of COVID-19 on the financial results of the PGE group in 2020 was limited [61]. Similarly, the ENEA group's business was not materially affected by the risks associated with the virus [62,63] (pp. 124–125). In the first half of 2020, a significant reduction in demand for thermal coal from commercial power and district heating was evident, but this is due to a warm and windy winter. In the third quarter of 2020, non-pandemic factors were joined by geological and mining factors limiting coal yields. These difficulties proved to be temporary [63]. The pandemic did not significantly disrupt production, the supply chain was not interrupted, which was the case and significantly weakened some sectors of the economy, especially exporters in trade relations with Germany and the entire euro area [5]. Although the mining sector—due to the technologies and working conditions used—did not protect itself against the wave of infections of mine workers, the measures taken by the government maintained the continuity of employment.

Contracts concluded in previous years for the sale of electricity, obtaining a higher average sales price as a result of an increase in tariff rates and higher electricity prices on the market or a higher volume due to assets put into use [64] ad an impact on limiting the impact of the pandemic. In 2020, after freezing electricity prices in 2019, there were significant increases, especially in the group of customers connected to the low voltage network.

The groups' financial results were affected by asset write-downs during the period under review. The pandemic phenomenon was not the primary indication of a possible impairment of non-current assets but only an additional signal, necessitating an impairment test. The impairment losses on fixed assets performed in 2015 by all the companies under review testified that these assets were less adapted to generate revenues in the new realities of the energy sector.

All of the groups studied identify risk factors that may affect financial results due to the COVID-19 pandemic [65] (pp. 61, 98) and closely monitor the situation and the level of this threat while taking numerous measures to minimize adverse effects. Factors that directly affected the business operations of the groups were the increased number of employees on vacation, sick leave, and working remotely through increased employee absenteeism and increased operating costs. Considering the entire value creation chain, the identified factors at the group level in 2020 did not have a material impact. As of 31 December 2020, the result from the anticipated increase in payment congestion, particularly on receivables from small and medium-sized companies, was not material. There was no liquidity risk. However, there is no additional risk of non-payment of receivables above the current level [61] (p. 81) [64], or it was not essential [63].

The pandemic outbreak prompted individual groups to introduce new or changes to existing credit risk management policies. As part of the credit risk management policies changes, the criteria for assigning internal ratings and credit limits to counterparties were changed.

In addition, increased price volatility in the financial and commodity markets, particularly the prices of electricity and carbon emission allowances, are of great importance for the groups as changes in the prices of these instruments affect liquidity and future financial results [66].

As a result of the research, conclusions were drawn that as a result of the pandemic, energy companies adapted their financial strategies and financial risk management strategies. The COVID-19 pandemic also resulted in certain impediments to strategic investment projects. In the case of power unit construction investments, these occurred during the initial period of the pandemic as a result of the implementation of strict infrastructure access controls and additional security procedures.

The pandemic accelerated the introduction of activities related to preparing entire organizations for changes to meet the challenges posed to energy companies related to decarbonization. As a result of the pandemic, all groups surveyed have established crisis teams at the parent company level and at the level of individual subsidiaries. Their purpose is to monitor the situation and prevent negative consequences of the pandemic. The tasks of these teams include, among others, suggesting organizational changes aimed at protecting employees and at the same time guaranteeing continuity of production.

Thus, the COVID-19 pandemic has affected the organization of work, particularly in manufacturing units. In many cases, this involves additional costs, such as the purchase of protective materials for employees.

Since the beginning of the pandemic, groups have implemented work rules to reduce the risk of employee illness as much as possible. They have undertaken work redesign activities to ensure continuity and protect employees' health and lives, including implementing remote and rotating work, building awareness of essential coronavirus protection, prevention, and quarantine. These measures include, but are not limited to, temporarily limiting travel and business meetings, increasing the availability and extent of use of cleaning, disinfecting and protective products, implementing appropriate work procedures (e.g., shift work, disinfecting rooms, placing limits on employees in rooms, maintaining safe distances between employees), and monitoring travel destinations of employees, including their families for high-risk countries. In the area of retail customer service, the groups focused primarily on expanding remote service channels.

Organizational adaptation to the new conditions (to the conditions of the pandemic) in conjunction with the investment outlays in the preceding period ensured the continuity of electricity supply. Summarizing, the conducted research must conclude that companies from the energy sector which made the most significant investments achieve the best financial results. It is worth noting that changes in the conditions of the energy market in the area of energy generation technologies and legislative changes shaping the future energy market model force companies operating in the energy sector to adapt by introducing new technologies. Significant throughout the study were the regulatory changes that resulted in two periods: 2015 and 2019 or 2020. All the groups studied took an impairment loss, significantly affecting the results presented in the financial statements. Hence, the objective was to investigate which of the selected generating companies were performing the best and which factors had the greatest impact on the increase or decrease in their performance.

The study of the financial statements of the power generation activities of energy groups confirms the hypothesis that companies investing in new solutions and technologies will be the most effective. In the analyzed period, capital groups that made the largest investments achieved at the same time financial ratios at the appropriate level and the stock exchange valuation was the highest.

Changes in the trend of sales and price fluctuations in the energy market of the countries affected by the pandemic in the first phase of its development were similar. The initial disturbance in energy demand and decline in sales levels subsided after a few months. By the second half of the 2020 year, most of them had achieved sales levels similar to those recorded in the year prior to the pandemic year and, by managing the change efficiently, were ready to operate under further pandemic-induced restrictions. The stability and good financial condition of the sector were confirmed by the share prices of the surveyed companies remaining at similar or even higher levels than before the pandemic. In contrast to the catering, tourism, hotel or training industry, whose revenues decreased year-on-year in some cases by more than 90%, the energy sector ended the first year of the pandemic with rates not significantly different from the forecast.

Uncertainty, which has appeared in almost all sectors of each economy (except the, IT, high-tech or telecommunications sectors), affects the energy sector indirectly, but this impact may be significant and its direction is unknown yet. Critical to national and global economic stability is the targeting of financial support to the industries most affected by the pandemic. This may result in a lack of funds for the originally planned investments in the energy sectors and delay the achievement of the energy mix and CO_2 emission reduction targets, or even necessitate a review of the assumptions of the agreements concluded in this area at the international level.

The authors were not able to verify the actual share of RES in energy production due to the lack of figures on energy consumption by prosumers (they are not recorded). Given the scope of the data analysed covering the first year of the pandemic and its expected duration, the study should be continued. The scope of the study was also limited by the scarce availability of literature on the subject (in particular, relating to the response to the pandemic situation in the energy market in Poland), which is mainly due to the nature of the phenomenon under investigation: this is the first ever pandemic with a global reach and, at the same time, such a strong impact on societies and economies.

The analysis of the conclusions and the identified limitations of the study indicate the need to continue the research started by the authors of the article. It is suggested that their scope should be extended to a larger group of companies in the energy sector.

The purpose of this research should be to determine the impact of prosumers' electricity production on the economic situation of energy listed companies. In addition, it seems important to answer the question of how quickly the Polish energy sector will meet its CO_2

emission reduction commitments, taking into account the current energy mix and costs of necessary investments.

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Article

Companies' Stock Market Performance in the Time of COVID-19: Alternative Energy vs. Main Stock Market Sectors

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Abstract: The paper aims to detect the differences in stock market performance between companies from the alternative energy sector and main stock market sectors in the first and second years of the COVID-19 pandemic. We used Global Industry Classification Standard to analyse eleven main stock market sectors and the alternative energy sector. Based on the one-factor variance analysis—ANOVA, we reveal the statistically significant differences between the analysed stock market sectors in both 2020 and 2021. The analysis implied that the performance of stock market companies during COVID-19 is sector-specific. Tukey's Honestly Significant Difference (HSD) test for pairwise comparison indicates that the alternative energy sector shows the most differentiation. Its average rate of return in 2020 is the highest and is significantly different for all eleven stock market sectors, while the top constituents from the conventional energy and financial sectors suffered the most. In 2021, a reverse trend in the stock prices can be observed. Companies from the conventional energy and financial sectors achieved the highest positive average weekly rates of return among all of the analysed stock market sectors, while the alternative energy sector performed significantly worse than the other sectors did. Nevertheless, throughout the entire analyses period of 2020–2021, the companies from the alternative energy sector turned out to be the biggest stock market beneficiaries. This study might imply that the COVID-19 pandemic has not hampered but has instead accelerated growing concerns about the environment and climate change.

Keywords: COVID-19; novel coronavirus pandemic; alternative energy; stock market sectors; stock market companies

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1. Introduction

Pandemics, i.e., large-scale outbreaks of infectious diseases, not only disturb the health status of the population and contribute to the depopulation of the Earth, but also hamper economic growth and induce uncertainty and panic in the financial market. The COVID-19 pandemic should teach us a lesson that economic health is dependent on and is as significant as public health [1]. Moreover, even if we cannot prevent infectious diseases from emerging, we should be better prepared to dampen their socio-economic effects [2].

The paper focuses on the stock market. Changes in share prices reflect market expectations in current and future situations in a given industry but also change in terms of macroeconomic variables such as demand and restrictions in supply [3]. Moreover, stock market prices are more readily available than macroeconomic indicators such as the unemployment rate and GDP growth rate, so they allow the effects of a crisis period to be analysed, even during the crisis' initial phases.

Stock market performance reacts to major unexpected and expected events [4], including political events [5], environmental issues [6], disasters [7], news [8], and sports events [9]. Stock markets also respond to pandemic outbreaks [10,11], e.g., SARS [12–14], MERS, and

Ebola [15,16]. The novel coronavirus pandemic has significantly affected global financial markets [17,18], as stock markets display patterns that are clearly different from those that were observed before and that have been observed after the COVID-19 outbreak [19]. Global financial markets have labelled the pandemic as a giant black swan event [20,21]. The stock markets in all of the world's major economies immediately nosedived after the rapid global spread of the COVID-19 outbreak in February 2020 [22,23]. Due to increased uncertainty, the pandemic has reduced the confidence that investors usually have in the stock market [24]. Chakrabarti et al. [25] indicate that COVID-19 has caused contagion in the global equity market. Nevertheless, according to Okorie and Lin [26], the COVID-19 pandemic's contagion effects on the world's stock markets lapse when considered from medium- and long-term perspectives. The strongest stock market reaction was observed in the initial phase of the pandemic [27,28].

The reactions of stock markets to epidemics are not homogenous in terms of stock market sectors. Chen et al. [29] indicate that SARS negatively impacted tourism and the wholesale and retail sectors but positively affected biotechnology. Ichev and Marinc [15] conclude that during the EBOLA epidemic, the biotechnology, food and beverage, and healthcare industries were characterised by growth in stock prices, while the epidemic had a significant impact on other stock market industries. The stock market response to the novel coronavirus pandemic also seems to be industry-specific [4,30].

This paper concentrates on the performance of the companies from 11 MSCI main stock market sectors in the first and second years of the COVID-19 pandemic. Griffith et al. [3] compared the reactions of individual stock market sectors. However, they analysed this issue using data from companies listed on London Stock Exchange for the period of January–May 2020, i.e., the initial phase of the COVID-19 pandemic. Narayan et al. [31] and Shahzad et al. [32] applied a sector-based classifications similar to ours. The classification that was developed by Narayan et al. [31] was based on the Australian stock market and covered the period of April–September 2020 period. They observed that the healthcare, information technology, and consumer staple sectors benefitted from the pandemic, while other sectors were either negatively impacted or were not affected at all. Similarly, Al-Awadhi et al. [4] suggested that the stock returns for the information technology and medicine manufacturing sectors performed significantly better than the market, while the stock returns for the beverage, air transportation, water transportation, and highway transportation sectors performed substantially worse than the market during the initial COVID-19 outbreak. Shahzad et al. [32] revealed the adverse impact on the aggregate indices. According to them, the real economic impact of the COVID-19 outbreak has spread to several equity sectors, triggering heavy losses, especially in the financial, energy, industrial, and consumer discretionary sectors. Our contribution to the literature is that we are not only focusing on the initial stage of the COVID-19 pandemic, as most researchers are, but are instead comparing the impact of COVID-19 on the stock market during the first and second pandemic years. Additionally, compared to our paper, most studies do not compare the effects of COVID-19 on all of the main stock market sectors, but instead focus on one or a few of them.

The food industry represents one of the stock market beneficiaries from the first period after the COVID-19 pandemic was announced [23]. Nicola et al. [20] indicated that the food sector was facing increased panic-buying-driven demand and the stockpiling of food products at that time. Hohler and Lansink [33], who analysed food supply chain companies during the first wave of COVID-19, found that the stock prices of food retailers were characterised by low price volatility, while the stocks of food manufacturing and distributing companies represented high price volatility. Alam et al. [23], who developed a classification based on the Australian stock market, observed that the healthcare sector also exhibited impressive positive returns during the early stages of the COVID-19 pandemic.

Haroon and Rizvi [34] observed even greater price volatility in the sectors that were perceived to be the most affected by the novel coronavirus outbreak. Goodell [35] showed that the financial sector was substantially hit by the first wave of the pandemic due to the increase in non-performing loans. Anh and Gan [36], who analysed the Vietnamese stock market, also confirmed that the financial sector suffered the most during the COVID-19 outbreak. Moreover, the COVID-19 pandemic adversely affected both the conventional energy sector and conventional energy commodity prices [37–40]. The Great Lockdown triggered by the rapid spread of COVID-19 led to a substantial decrease in the global demand for energy, particularly oil, squeezed companies' profit margins from the energy sector, and brought about significant decreases in their stock prices [32]. Zhang et al. [41] present the interrelationship between pandemics and oil prices and show that COVID-19 has reduced the demand for oil, causing a decrease in oil prices. Su et al. [42] indicate that the correlation between pandemics and oil prices might be affected by other economic or geopolitical factors that trigger market uncertainty.

The present paper aims to assess how companies from the alternative energy sector perform during the COVID-19 pandemic compared to companies from other main stock market sectors. To our knowledge, there is no such study comparing the response of the alternative energy sector to all of the main stock market sectors. The novel coronavirus has had an unprecedently effect on the alternative energy sector. Liu et al. [43] found that the COVID-19 pandemic had a more significant impact on the alternative energy sector than the global financial crisis did in terms of stock price returns and volatilities. Studies on the impact of COVID-19 on the alternative energy sector indicate the adverse effects of the pandemic during its initial phase. Hosseini [44], whose research was based on the novel coronavirus' first global spread, observed that COVID-19 has struck renewable energy manufacturing facilities, supply chains, and companies and has slowed down the world's transition to a world using more sustainable energy sources. He built a pessimistic scenario for the renewable energy market based on an initial COVID-19-induced price plunge in the stock market while analysing the short-term period. Wang and Cheng [45] present a similar view regarding the short-term impact of COVID-19 on the stock prices of solar enterprises.

However, it was later determined that the COVID-19 pandemic period, particularly 2020, was a period of prosperity for the alternative energy market, and the share prices of companies from this sector were characterised by a substantial increase. Zhao [46] reveals that uncertainty in the oil market accelerated the use of clean energy sources and led to the stock prices of clean energy corporations to increase. Ghabri et al. [47] observed a significant increase in the returns of clean energy stocks during the first wave of the pandemic. Contrary to conventional energy, renewable energy sources experienced growth in demand in the aftermath of the novel coronavirus pandemic and became the most-COVID-19-resilient sector among stock market sectors [48]. Corbet et al. [44] claim that this was due to the fact that investors considered hat renewable energy sources could more reliably generate a long-term supply than fossil fuels could, particularly oil. The advantages of cleanness, green, and broad geographical scope make renewable energy the best energy raw material for the future [49,50]. Moreover, the increasing global environmental pollution and energy crisis has resulted in renewable energy becoming something that investors are currently concerned about [51]. Sovacool et al. [52] claim that the novel coronavirus pandemic will lead to the viability of both energy companies and global energy supply chains. This increased interest in alternative energy could be related to Schumpeter's theory referring to new combinations and creative destruction [53].Technologies that are based on alternative energies are replacing those that are based on oil energy, just coal technologies gave way to oil technologies in the energy sector in the past. New innovative companies unseat established companies through processes of creative destruction, and the COVID-19 pandemic outbreak might have been the accelerating force in this process [54]. It should be stressed that according to Schumpeter, the largest companies are the main drivers of innovation, i.e., new combinations [55].

Kuang [56] showed that clean energy stocks provide risk diversification benefits for investors with conventional energy stocks. Most of the studies that were conducted in the pre-COVID-19 period present a positive relationship between these two sectors [57,58]. Kocaarslan and Soytan [59] only showed the existence of this positive relationship from a short-term perspective, but this relationship turned out to be negative when analysed in the long-term. However, COVID-19 seems to have had a significant impact on the direction of this relationship. Czech and Wielechowski [27] revealed the considerable differences between the responses of the alternative and conventional energy sectors to the COVID-19 pandemic. They reveal that compared to the conventional energy sector, the alternative energy sector was characterised by lower volatility and was less affected by COVID-19-related indicators. This may suggest that the performance of the alternative energy sector during the COVID-19 pandemic distinguished itself among other sectors, which justifies the importance and relevance of the issue that is discussed in the present paper.

The main contribution of the present research is the comparison of the performance of the alternative energy sector with the other main stock market sectors. Moreover, we focus on companies, not indices. In contrast to other studies, our analysis covers more than just the first phase of the pandemic and covers a more extended period, i.e., January 2020–September 2021, that is divided into two sub-periods. To our knowledge, no studies similar to the one that is described here have been conducted as of yet.

The results of our research might be helpful for investors in making investment decisions to minimise risk by diversifying their portfolios. Moreover, by focusing on the alternative energy sector, our study indirectly indicates the importance of renewable energy sources, particularly during a time when there growing concerns about the environment and climate change.

The paper is organised as follows: The next section sets out the methodology. The posterior section presents the empirical findings and discussion, and the final section offers concluding remarks.

2. Materials and Methods

The present paper aims to detect the differences in stock market performance between companies from the alternative energy sector and main stock market sectors in the first and second years of the COVID-19 pandemic.

To achieve the main aim of the paper, we have formulated two research hypotheses:

Hypothesis 1 (H1). *Stock market performance during the COVID-19 pandemic differed across sectors.*

Hypothesis 2 (H2). *Companies from the alternative energy sector performed better in the stock market during COVID-19 than companies from all of the other main stock market sectors.*

We analysed the stock market industries using the Global Industry Classification Standard (GICS). The classification was developed by MSCI and by Standard & Poor's Dow Jones Indices, which were introduced in 1999. This classification aims to provide an efficient investment tool that is able to capture the economic sectors' liquidity (breadth and depth) and evolution. The GICS is a hierarchical classification system that consists of 11 sectors, 24 industry groups, 68 industries, and 157 sub-industries. Classification is mainly based on a company's revenues, which are used to determine the company's principal business activity. Table A1 in the Appendix A presents the industry structure of the each of 11 stock market sectors.

In the present study, we consider companies from the alternative energy sector (A) and 11 main sectors stock market sectors, i.e., (conventional) energy (1), materials (2), industrial (3), utilities (4), healthcare (5), financial (6), consumer discretionary (7), consumer staples (8), information technology (9), communication services (10), and real estate (11).

An analysis is conducted on the weekly rates of return based on the daily prices of the top 5 companies from the 11 main stock market sectors and from the alternative energy sector using GICS classification. In total, approximately 24,000 daily observations are used. Table 1 presents the list of analysed companies.

Table 1. Top five companies from alternative energy and main stock market sectors: based on MSCI stock market sectors.

Stock Market Sector	Company 1	Company 2	Company 3	Company 4	Company 5
Alternative energy	VESTAS WIND SYSTEMS	ORSTED	ENPHASE ENERGY	SOLAREDGE TECHNOLOGIES	XINYI SOLAR HOLDINGS
Energy	EXXON MOBIL	CHEVRON	TOTALENERGIES	BP MIDSTREAM PARTNERS	ROYAL DUTCH SHELL B
Materials	LINDE	BHP GROUP	L AIR LIQUIDE	RIO TINTO	SHERWIN-WILLIAMS
Industrial	HONEYWELL INTL.	UNITED PARCEL SER.'B'	RAYTHEON TECHNOLOGIES	UNION PACIFIC	SIEMENS
Utilities	APPLE	MICROSOFT	NOKIA	ALIBABA HLTH.INFO. TECH.	INTEL
Healthcare	JOHNSON & JOHNSON	UNITEDHEALTH GROUP	ROCHE HOLDING	PFIZER	THERMO FISHER SCIENTIFIC
Financial	BERKSHIRE HATHAWAY 'A'	BANK OF AMERICA	WELLS FARGO & CO	CITIGROUP	JPMORGAN CHASE
Consumer disclosure	AMAZON.COM	TESLA	HOME DEPOT	TOYOTA MOTOR	LVMH
Consumer Staples	NESTLE 'R'	PROCTER & GAMBLE	WALMART	COCA COLA	PEPSICO
Information technology	APPLE	MICROSOFT	NVIDIA	VISA 'A'	ASML HOLDING
Communication services	FACEBOOK CLASS A	ALPHABET A	ALPHABET 'C'	WALT DISNEY	NETFLIX
Real estate	AMERICAN TOWER	PROLOGIS REIT	CROWN CASTLE INTL.	EQUINIX REIT	PUBLIC STORAGE

Source: Authors' own elaboration based on MSCI.

In addition to descriptive statistics, ANOVA was used for the analysis. ANOVA is a parametric statistical technique that is used to compare the mean values of selected datasets. This method was introduced by Fisher and Mackenzie [60] and Fisher [61]. ANOVA is used to determine statistically significant differences between the means of multiple groups of observations. The one-way analysis of variance concerns a situation in which we examine the influence of one factor, i.e., a qualitative variable, on the qualitative dependent variable. The general form of the ANOVA model for the random variable Y, where y_{ij} refers to i-th observation from the j-th group, is as follows:

$$y_{ji} = \mu + \alpha_j + \varepsilon_{ji} \tag{1}$$

where μ is the mean in the entire population, α_j is the deviation from μ caused by factor A at the j level ($j = 1, \ldots, p$), and ε_{ji} is a normally distributed random deviation that is related to the i-th observation ($i = 1, \ldots, n_j$) for the j-th level of factor A.

The null hypothesis assumes that all factor levels equally affect the dependent variable Y. This means that all of the means in the p groups are the same. The hypotheses in the ANOVA test are as follows:

$$H0: \ \forall j \ \alpha j = 0 H1: \ \exists j \ \alpha j \neq 0 \tag{2}$$

The total variation of the dependent variable Y (total sum of squares, SST) is the sum of the intergroup variation that is caused by the factor (sum of squares for treatment, SSTR) and the intra-group variation that is caused by the random effects (sum of squares for errors, SSE).

$$SST = SSTR + SSE \tag{3}$$

$$\sum_{j=1}^{p} \sum_{i=1}^{n_j} \left(y_{ji} - \overline{\overline{y}} \right)^2 = \sum_{j=1}^{p} n_j \left(\overline{y}_j - \overline{\overline{y}} \right)^2 + \sum_{j=1}^{p} \sum_{i=1}^{n_j} \left(y_{ji} - \overline{y}_j \right)^2, \tag{4}$$

where $\overline{\overline{y}}$ is the overall mean value of all observations, and where $\overline{y}_j$ is the average value of all of the observations at the j level of factor A.

The test statistic follows F distribution with the numbers of degrees of freedom $p - 1$ in the numerator and $n - p$ in the denominator, where $n = n_1 + \ldots + n_p$ is the sample size, and p is the number of groups of the random variable Y.

$$F_{(p-1,n-p)} = \frac{SSTR/p-1}{SSE/n-p} \quad (5)$$

The F statistic takes on higher values when the intergroup differentiation that is caused by the selected factor is greater compared to the intragroup differentiation that is caused by random effects. The critical area of the F-test is the right-sided area. The rejection of the null hypothesis means that at least two means in the groups differ from each other, i.e., factor A significantly affects the dependent variable y_{ji}.

The results of the F-test indicate that there are at least two means that differ significantly from each other, but it is not known to which groups it applies to precisely. For this reason, the analysis of variance is usually supplemented with so-called post hoc tests, also known as pairwise or multiple comparison tests. One of the most popular tests is Tukey's Honestly Significant Difference (HSD) test (Tukey, 1953). Tukey's HSD test allows any pair of means with the level of significance established for all comparisons to be compared. In Tukey's test, statistics are determined as follows:

$$T = q_{p,n-p,\alpha}\sqrt{\frac{SSE}{n-p}\left(\frac{1}{n_j}\right)} \quad (6)$$

where $q_{p,n-p,\alpha}$ is the appropriate quantile of the studentized range at p i $n - p$ degrees of freedom and at significance level α.

In this article, we check whether the response of stock prices during the COVID-19 pandemic differed depending on the sector represented by the stock companies. The study determines whether the average rates of return on the shares of the five largest companies in the selected twelve sectors differ significantly from each other. Belonging to a given sector was assumed as a qualitative variable. to the variable p represents the number of stock market sectors (Equations (4)–(6)). In the null hypothesis, we assume that the average rates of return of the shares of the companies representing all 12 sectors are the same.

The research covers the period of January 2020–September 2021 and two corresponding sub-periods from the first and the second years of the COVID-19 pandemic, specifically January–September 2020 and January–September 2021. The periods of January–September 2020 and January–September 2021 were analysed separately to see if the response of the share prices differed during different phases of the COVID-19 pandemic. The length of the research period was dependent on data availability.

In the entire analysis, we apply R.

3. Results and Discussion

The outbreak of the novel coronavirus and the rapid increase in COVID-19 cases worldwide resulted in growing international socio-economic concerns. The COVID-19 pandemic has affected financial markets, including stock markets.

Figure 1 presents the MSCI ACWI Index, a broad global equity index that represents large and mid-cap equity performance across 23 developed and 27 emerging markets. The index comprises more than 2900 constituents from all 11 stock market sectors (using the Global Industry Classification Standard) and represents approximately 85% of market capitalisation in each market.

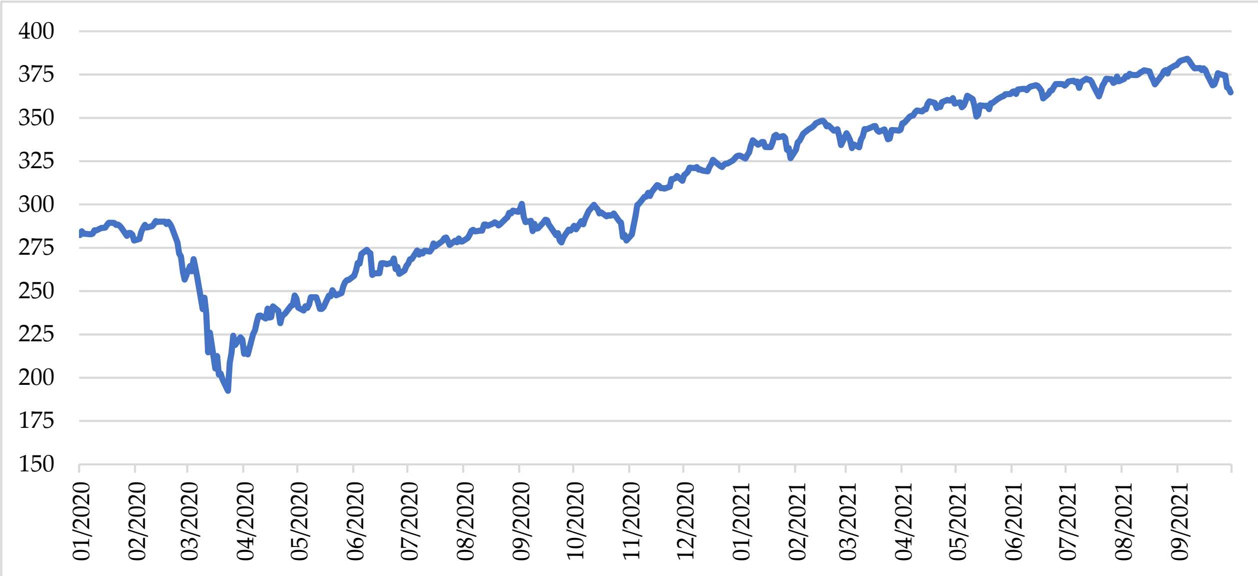

Figure 1. The MSCI ACWI Index performance in January 2020–September 2021. Source: Authors' own calculations and elaborations based on Refinitiv Datastream.

Throughout the entirety of the analysed period, i.e., January 2020–September 2021, the index value increased by almost 30%. However, it should be noted that the financial markets reacted strongly to the onset of COVID-19 during the early stage of the epidemic, i.e., between 20 February and 23 March 2020, when the index lost 1/3 of its value. This is in line with Hassan et al. [28] and Czech and Wielechowski [27], who observed the that the stock market reacted the most strongly during initial phase of the novel coronavirus pandemic. Nevertheless, by the end of the third quarter of 2020, the index had fully recovered. In the first nine months of 2021, the index increased gradually by over 10%.

We analysed the response of the alternative energy sector and all eleven main stock market sectors to the novel coronavirus. We also provide our analysis for the period of January 2020–September 2021. Figure A1 in the Appendix A depicts the sector performance based on the average weekly rates of return of the top five companies from each sector.

We observe the visible differences in the average weekly rates of return among the ana-lysed stock market sectors. Furthermore, the sector performance varies throughout the analysed period. During the first months of the pandemic in 2020, greater reaction can be observed, while the second year of the COVID-19 pandemic was characterized by lower price volatility among the majority of the analysed stock market sectors. This indicates that the performance of the different stock market sectors has in the two years since the onset of the novel coronavirus pandemic. Therefore, for further analysis, we considered both the entire research period, i.e., January 2020–September 2021, and two nine-month-long sub-periods, i.e., January–September 2020 and January–September 2021. The length of the periods is dependent on data availability.

Table 2 presents descriptive statistics for the average weekly rates of return among the analysed stock market sectors (based on top five companies) in the January 2020–September 2021 period.

Table 2. Descriptive statistics for average weekly rates of return of alternative energy and main stock market sectors: based on the performance of the top give companies in January 2020–September 2021.

Stock Market Sector	Avg.	SD	CV	Min	Max
Alternative energy	0.933	7.48	10.05	−36.24	36.33
Energy	−0.017	5.09	24.78	−19.51	23.79
Materials	0.090	4.24	312.52	−32.09	20.87
Industrial	0.242	4.52	32.18	−19.18	25.94
Utilities	0.369	5.14	22.38	−24.56	24.66
Healthcare	0.124	3.15	27.34	−10.55	21.85
Financial	0.082	4.88	63.94	−17.50	21.32
Consumer discretionary	0.391	4.88	13.50	−22.17	20.88
Consumer staples	0.049	2.71	34.47	−16.70	13.08
Information technology	0.434	3.78	12.33	−14.56	17.41
Communication services	0.412	3.61	87.63	−12.27	13.40
Real estate	0.360	3.89	11.39	−14.93	22.26

Source: Authors' own calculations and elaborations based on Refinitiv Datastream.

The results in Table 2 demonstrate that 11 out of the 12 analysed stock market sectors are characterised by a positive average weekly rate of return during the first 21 months of the COVID-19 pandemic. The alternative energy sector demonstrates the best performance, as its average weekly rate of return is 0.93%. A total of four out of the five top companies from this sector recorded an increase in their share prices of over 100% (Table A2 in the Appendix A). Moreover, the coefficient of variation for the alternative energy sector is the lowest of all of the analysed sectors, although the difference between the lowest and the highest average weekly rate of return is the largest in this sector. The alternative energy sector is characterised by weekly rate of return that is two times greater than those seen for the information technology and communication services sectors, although the information technology and communication services sectors were big beneficiaries of the pandemic and the implementation of lockdowns.

Surprisingly, the (conventional) energy sector demonstrated the worst performance among all main stock market sectors and is only characterised by the negative average rate of return in the January 2020–September 2021 period. The share prices of all of the top five companies from this sector lost at least 15% of their value (Table A2 in the Appendix A). Moreover, the consumer staples, financial, and materials sectors are characterised by the slightly positive average weekly rates of return in the analysed period.

Table 3 shows descriptive statistics for the average weekly rates of return among the analysed stock market sectors in the first analysed sub-period, i.e., January–September 2020.

The results in Table 3 show that during the first nine months of the COVID-19 pandemic, 10 out of the 12 analysed stock market sectors were characterized by a positive average weekly rate of return. The alternative energy sector recorded the highest average weekly rate of return, i.e., close to 1.6%. All of the top five companies in this sector experienced a substantial increase in their share prices (Table A3 in the Appendix A). This corresponds to the findings by Zhao [46] and Ghabri et al. [47], who observed a significant increase in the share prices of clean energy companies in the aftermath of the COVID-19 outbreak.

Similarly, throughout the entire research period of January–September 2020, the coefficient of variation for the alternative energy sector was the lowest of all of the analysed sectors even though the range of the average weekly rates of return was the largest in this sector.

Table 3. Descriptive statistics for average weekly rates of return of alternative energy and main stock market sectors: based on the performance of the top five companies in January–September 2020.

Stock Market Sector	Avg.	SD	CV	Min	Max
Alternative energy	1.579	7.70	4.78	−27.77	36.33
Energy	−0.846	6.50	29.28	−19.51	23.79
Materials	0.351	4.94	20.32	−32.09	20.87
Industrial	0.192	5.94	20.31	−19.18	25.94
Utilities	0.498	5.66	12.07	−24.56	18.23
Healthcare	0.339	3.67	13.57	−10.55	21.85
Financial	−0.643	6.25	13.72	−17.50	21.32
Consumer discretionary	0.375	5.53	12.11	−22.17	18.21
Consumer staples	0.105	3.46	33.04	−16.70	13.56
Information technology	0.572	4.60	10.21	−14.56	17.41
Communication services	0.144	4.04	40.63	−12.27	11.70
Real estate	0.474	4.99	11.45	−14.93	22.26

Source: Authors' own calculations and elaborations based on Refinitiv Datastream.

The average rates of return for the information technology, utilities, and real estate sector oscillated at around 0.5%. This corresponds to the findings by Narayan et al. [31] and Al-Awadhi et al. [4]. This implies that these stock market sectors not only lost but also gained as a result of the outbreak of the novel coronavirus pandemic.

At the same time, the (conventional) energy and financial sectors suffered the most, i.e., experienced negative average weekly rates of return at −0.85 and −0.64%, respectively. In the period of January–September 2020, the shares of all of the top five companies from these two sectors fell by several dozen percentage points (Table A3 in the Appendix A). Our results are in line with those of Anh and Gan [36], Goodell [35], and Shahzad et al. [32], who observed that the financial and energy sectors suffered the most during the early stage of the pandemic.

Furthermore, the results that are presented in Table 3 reveal a substantial difference between the performances of the alternative and conventional energy sectors. This might imply that only the alternative energy sector was COVID-19-resistant, while the (conventional) energy sector suffered the most during the analysed sub-period. This corresponds to the findings of Czech and Wielechowski [27].

Table 4 shows descriptive statistics for the average weekly rates of return among the analysed stock market sectors in the second sub-period that was analysed, i.e., January–September 2021.

Table 4. Descriptive statistics for average weekly rates of return of alternative energy and main stock market sectors: based on the performance of the top five companies in January–September 2021.

Stock Market Sector	Avg.	SD	CV	Min	Max
Alternative energy	−0.450	7.89	336.14	−36.24	22.09
Energy	0.411	3.84	10.08	−9.95	13.38
Materials	−0.197	3.08	12.87	−13.94	10.54
Industrial	0.316	2.79	32.06	−9.23	14.80
Utilities	−0.003	3.99	2555.22	−16.13	24.66
Healthcare	−0.006	2.42	24.15	−6.93	8.23
Financial	0.553	3.22	7.00	−10.59	12.07
Consumer discretionary	0.193	3.90	76.99	−18.36	20.88
Consumer staples	−0.142	1.80	18.66	−5.81	4.76
Information technology	0.401	3.42	27.51	−14.55	10.34
Communication services	0.404	3.08	5.89	−9.23	12.66
Real estate	0.300	2.55	11.39	−6.66	11.59

Source: Authors' own elaborations based on Refinitiv Datastream.

Based on the results in Table 4 for the January–September 2021 period, we are able to observe the most remarkable trend reversal for the alternative energy, conventional energy, and financial sectors. The average weekly rate of return for the alternative energy sector was −0.45% (a decrease from plus 1.58% in the same period of the previous year). The top five companies from this sector recorded share price decreases between 13 and 37% (Table A4 in the Appendix A). It is worth emphasising that the price decreases that were observed in this period were lower than the increases that were observed in the corresponding period from the previous year, and the balance (price changes) for the entire analysed period is definitely positive.

In contrast to the alternative energy sector, the top five companies from the (conventional) energy and financial sectors achieved the highest positive average weekly rates of return in the period of January–September 2021. However, the increase in the share prices for the top five companies from the (conventional) energy sector did not make it possible to make up for all of the losses that were incurred from 2020. Among the other sectors that experienced a change from a positive to a negative average weekly rate of return are the materials, consumer staples, healthcare, and utilities sectors.

To depict the differences between the average weekly rates of return among the analysed stock market sectors for both the entire research period and for two sub-periods, box plots are presented in Figure 2.

Stock market sectors that are presented in Figure 2 are marked with the A and the numbers from 1 to 11. A refers to the alternative energy sector, 1—energy, 2—materials, 3—industrial, 4—utilities, 5—healthcare, 6—financial, 7—consumer discretionary, 8—consumer staples, 9—information technology, 10—communication services, and 11—real estate. Figure 2 indicates the existence of substantial differences in the average rates of return among the analysed stock market sectors, both in the entire analysed period of January 2020–September 2021 and in the two sub-periods, i.e., January–September 2020 and January–September 2021. These findings specifically concern the alternative energy sector, which stands out from all of the other sectors. These findings confirm the relevance of our research objective.

To verify whether the differences that can be observed between the 12 analysed stock market sectors, i.e., the 11 main stock market sectors and the alternative energy sector, are statistically significant, we applied one-factor variance analysis—ANOVA. In the study, the analysed sectors represent the factors, while the dependent variable refers to the average weekly rates of return.

Table 5 presents the results of the ANOVA for the entire research period, i.e., January 2020–September 2021, and for the two sub-periods, i.e., January–September 2020 and January–September 2021.

Table 5. Results of one-factor analysis of variance—ANOVA.

Period	F Statistics	*p*-Value
January 2020–September 2021	4.233	<0.001
January–September 2020	7.105	<0.001
January–September 2021	3.328	0.002

Source: Authors' own calculations and elaborations based on Refinitiv Datastream.

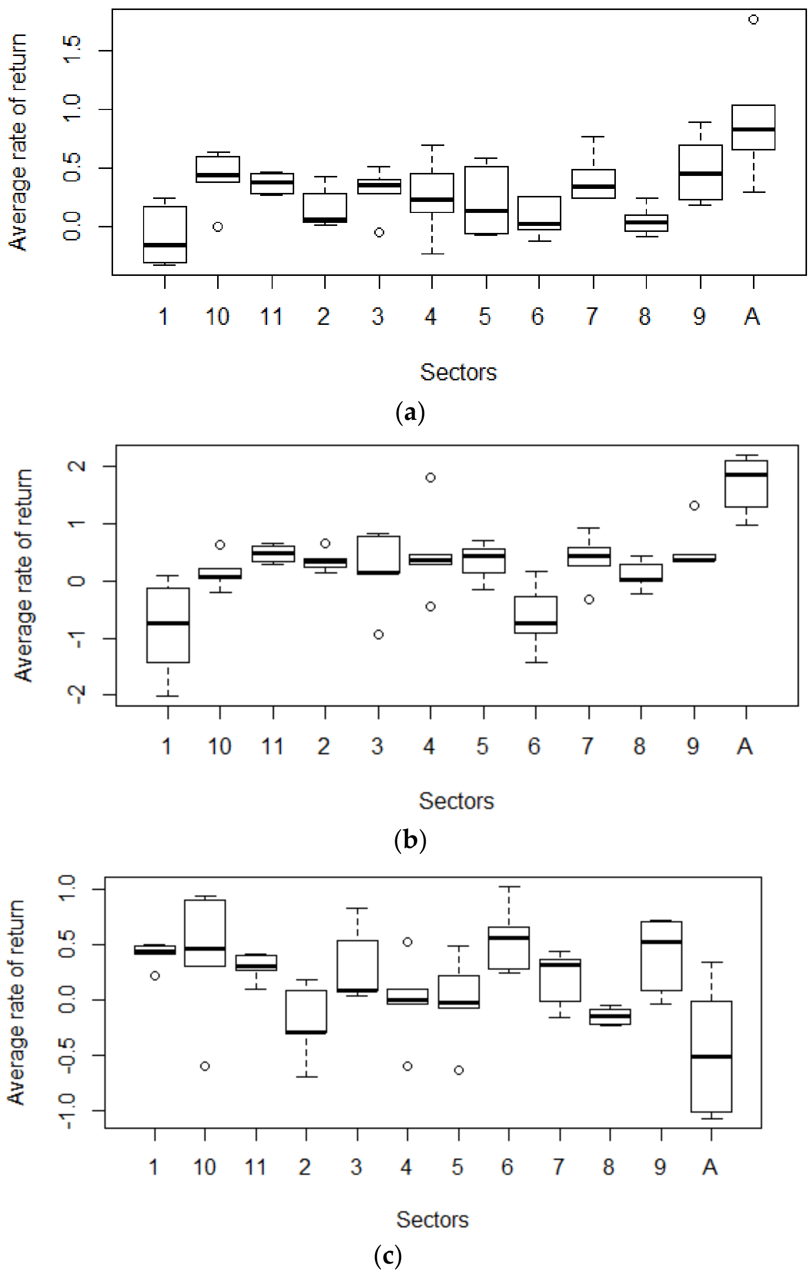

Figure 2. Average weekly rates of return for alternative energy and main stock market sectors: (**a**) January 2020–September 2021; (**b**) January 2020–September 2020; and (**c**) January 2021–September 2021. Source: Authors' own calculations and elaborations based on Refinitiv Datastream.

The results in Table 5 imply significant differences in the mean values of the weekly rates of return for analysed stock market sectors at a 1% significance level throughout the entire research period and during the two sub-periods. The ANOVA results show that at least two stock market sectors reacted differently to the COVID-19 pandemic. This implies that the performance of the stock market during the novel coronavirus pandemic is sector specific. This corresponds to the results of Haroon and Rizvi [34] and Shahzad et al. [32].

Based on Tukey's HSD test, we were able to verify whether the significant differences that refer to the average rate of return of the 12 analysed stock market sectors are related to all analysed sectors or to only the selected ones throughout the entire research period and during the two sub-periods.

The results of Tukey's HSD test for the entire research period show the existence of significant differences in the mean values of the weekly rates of return between the alternative energy sector and six out of the eleven main stock market sectors, i.e., the energy, materials, industrial, utilities, healthcare, financial, and consumer staples sectors. Moreover, we are able to observe a significant difference between the (conventional) energy sector and the information and technology sector (Table 6).

Table 6. Tukey's honest significance test results (Tukey's HSD test).

Sectors	January 2020–September 2021		January–September 2020		January–September 2021	
	Diff	*p*-Value	Diff	*p*-Value	Diff	*p*-Value
Alternative energy–Energy	0.99	<0.001	2.529	<0.001	−0.861	0.029
Alternative energy–Materials	0.754	0.005	1.333	0.010	−0.253	0.995
Alternative energy–Industrial	0.615	0.044	1.491	0.002	−0.766	0.081
Alternative energy–Utilities	0.663	0.021	1.185	0.036	−0.447	0.759
Alternative energy–Healthcare	0.695	0.013	1.344	0.009	−0.444	0.765
Alternative energy–Financial	0.842	<0.001	2.327	<0.001	−1.003	0.005
Alternative energy–Consumer_disc.	0.502	0.196	1.308	0.013	−0.643	0.248
Alternative energy–Consumer_st.	0.866	<0.001	1.579	0.001	−0.308	0.975
Alternative energy–Inf_technology	0.426	0.418	1.111	0.064	−0.851	0.032
Alternative energy–Communication	0.506	0.186	1.539	0.002	−0.854	0.031
Alternative energy–Real_estate	0.549	0.110	1.209	0.030	−0.75	0.095
Energy–Materials	−0.237	0.969	−1.196	0.033	0.608	0.323
Energy–Industrial	−0.375	0.610	−1.038	0.108	0.095	0.999
Energy–Utilities	−0.327	0.781	−1.344	0.009	0.414	0.835
Energy–Healthcare	−0.295	0.873	−1.185	0.036	0.417	0.830
Energy–Financial	−0.149	0.999	−0.202	0.999	0.142	0.999
Energy–Consumer_Disc.	−0.489	0.227	−1.221	0.027	0.218	0.999
Energy–Consumer_st.	−0.124	0.999	−0.95	0.191	0.553	0.465
Energy–Inf_technology	−0.564	0.090	−1.418	0.005	0.010	0.999
Energy–Communication	−0.484	0.239	−0.99	0.149	0.007	0.999
Energy–Real_estate	−0.441	0.366	−1.32	0.012	0.111	0.999
Materials–Industrial	−0.138	0.999	0.159	0.999	−0.513	0.578
Materials–Utilities	−0.091	0.999	−0.147	0.999	−0.194	0.999
Materials–Healthcare	−0.058	0.999	0.012	0.999	−0.192	0.999
Materials–Financial	0.088	0.999	0.994	0.145	−0.751	0.094
Materials–Consumer_disc.	−0.252	0.952	−0.024	0.999	−0.39	0.881
Materials–Consumer_st.	0.112	0.999	0.246	0.999	−0.056	0.999
Materials–Inf_technology	−0.328	0.779	−0.222	0.999	−0.598	0.347
Materials–Communication	−0.247	0.957	0.207	0.999	−0.601	0.340
Materials–Real_estate	−0.205	0.990	−0.123	0.999	−0.497	0.624
Industrial–Utilities	0.048	0.999	−0.306	0.999	0.319	0.968
Industrial–Healthcare	0.080	0.999	−0.147	0.999	0.321	0.966
Industrial–Financial	0.226	0.978	0.835	0.360	−0.237	0.997
Industrial–Consumer_disc.	−0.114	0.999	−0.183	0.999	0.123	0.999
Industrial–Consumer_st.	0.251	0.954	0.087	0.999	0.458	0.731
Industrial–Inf_technology	−0.19	0.995	−0.38	0.999	−0.085	0.999
Industrial–Communication	−0.109	0.999	0.048	0.999	−0.088	0.999
Industrial–Real_estate	−0.066	0.999	−0.282	0.999	0.016	0.999
Utilities–Healtcare	0.032	0.999	0.159	0.999	0.003	0.999
Utilities–Financial	0.178	0.997	1.141	0.051	−0.556	0.456
Utilities–Consumer_disc.	−0.161	0.999	0.123	0.999	−0.196	0.999
Utilities–Consumer_st.	0.203	0.990	0.393	0.988	0.139	0.999

Table 6. *Cont.*

Sectors	January 2020–September 2021		January–September 2020		January–September 2021	
	Diff	*p*-Value	Diff	*p*-Value	Diff	*p*-Value
Utilities–Inf_technology	0.237	0.969	−0.074	0.999	−0.404	0.855
Utilities–Communication	−0.157	0.999	0.354	0.995	−0.407	0.850
Utilities–Real_estate	−0.114	0.999	0.024	0.999	−0.303	0.978
Healthcare–Financial	0.146	0.999	0.982	0.156	−0.559	0.449
Healthcare–Consumer_disc.	−0.194	0.993	−0.036	0.999	−0.199	0.999
Healthcare–Consumer_st.	0.171	0.998	0.234	0.999	0.136	0.999
Healthcare–Inf_technology	−0.269	0.926	−0.233	0.999	−0.407	0.850
Healthcare–Communication	−0.189	0.995	0.195	0.999	−0.409	0.845
Healthcare–Real_estate	−0.146	0.999	−0.135	0.999	−0.305	0.976
Financial–Consumer_disc.	−0.34	0.738	−1.019	0.123	0.36	0.926
Financial–Consumer_st.	0.025	0.999	−0.748	0.526	0.695	0.160
Financial-Inf_technology	−0.416	0.455	−1.216	0.028	0.152	0.999
Financial–Communication	−0.335	0.755	−0.787	0.448	0.149	0.999
Financial–Real_estate	−0.292	0.879	−1.118	0.061	0.254	0.995
Consumer_disc.–Consumer_st.	0.364	0.649	0.27	0.999	0.335	0.954
Consumer_disc.-Inf_technology	−0.076	0.999	−0.197	0.999	0.208	0.999
Consumer_disc. –Communication	0.005	0.999	0.231	0.999	−0.211	0.999
Consumer_disc. –Real_estate	0.047	0.999	−0.099	0.999	−0.101	0.999
Consumer_st. –Inf_technology	−0.44	0.369	−0.468	0.957	−0.543	0.493
Consumer_st. –Communication	−0.36	0.667	−0.039	0.999	−0.546	0.485
Consumer_st. –Real_estate	0.047	0.999	−0.369	0.993	−0.441	0.773
Inf_technology–Communication	0.08	0.999	0.428	0.977	−0.003	0.999
Inf_technology–Real_estate	0.123	0.999	0.098	0.999	0.101	0.999
Communication–Real_estate	0.043	0.999	−0.33	0.997	0.104	0.999

Source: Authors' own calculation and elaboration based on Refinitiv Datastream.

Moreover, the results of Tukey's HSD test show that the differences between the analysed stock market sectors are more pronounced during the first year of the COVID-19 pandemic than they are in the second pandemic year. Additionally, the descriptive statistics imply that the reaction to the novel coronavirus among the analysed stock market sectors fizzles over time which, corresponds to the results of Okorie and Lin [26].

In the January–September 2020 sub-period, significant differences between the alternative energy sector and all of the eleven main stock market sectors can be observed. Moreover, significant differences can also be detected between the energy sector and six other main sectors (i.e., materials, utilities, healthcare, consumer discretionary, information technology, and real estate) and between the financial and utilities, information technology, and real estate sectors.

In the January–September 2021 period, statistically significant differences can only be observed between the alternative energy sector and six stock market sectors (i.e., conventional energy, industrial, financial, information technology, communication services, and real estate) and between the materials and financial sectors.

The results for the first year that was analysed show that the market price changes of the analysed companies from the conventional energy, alternative energy, and financial sectors are the largest and are significantly different from the other stock market sectors. These results are in line with Zhao [46], Ghabri et al. [47], Anh and Gan [36], Goodell [35], and Shahzad et al. [32]. Nevertheless, the performance of the alternative energy sector during the novel coronavirus pandemic was positive, while the conventional energy and financial sectors suffered the most. The results of the descriptive statistics analysis (Table 3) show that during the first year of the COVID-19 pandemic that was analysed, the energy and financial sectors achieved average rates of return that were significantly lower than those of the other sectors, while, surprisingly, the alternative energy sector achieved substantially higher rates of return. These results are in line with those from Czech and Wielechowski [27], who showed that the alternative energy sector was more resistant to COVID-19 than the conventional energy sector. Moreover, our results correspond to Schumpeter's theory on new combinations and creative destruction [53–55].

The results for the second year of the pandemic (January–September 2021) indicate that the alternative energy sector was the most different from the other analysed stock market sectors. Surprisingly, descriptive statistics show that this sector was characterised by the lowest negative rate of return in 2021.

The results of Tukey's HSD test indicate that the equity market response to the COVID-19 pandemic is stock market sector-specific. Throughout the entire period of the pandemic, the alternative energy sector stands out from other sectors. This concerns mainly the first year of the COVID-19 pandemic, when the alternative energy sector achieved surprisingly high average rates of return. Additionally, in the aftermath of the novel coronavirus outbreak, the energy and financial sectors performed the worst, i.e., they were characterised by the lowest and most negative rates of return among all of the analysed stock market sectors.

We show that stock market performance during the COVID-19 pandemic is sector-specific, which confirms Hypothesis 1. Moreover, we reveal that companies from the alternative energy sector performed better on the stock market during the first year of the COVID-19 pandemic than companies from all of the main stock market sectors did, which is in line with Hypothesis 2.

4. Conclusions

The COVID-19 pandemic has substantially affected stock market performance.

We reveal that during the first nine months of 2020, the biggest stock market beneficiaries were companies from the alternative energy sector, while the top five constituents from the conventional energy and financial sectors suffered the most. In 2021, we observed a reversal of this trend. Companies from the conventional energy and financial sectors achieved the highest positive average weekly rates of return out of all of the analysed stock market sectors in the period of January–September 2021. The alternative energy sector experienced a substantial negative average weekly rate of return. Overall, throughout the entire studied period, i.e., January 2020–September 2021, the companies representing the alternative energy sector experienced the most significant increases in their share prices.

ANOVA confirms the preliminary analysis results, as it shows the statistically significant differences between analysed stock market sectors. This implies that stock market performance during the COVID-19 pandemic was sector-specific. Tukey's HSD test indicates that the alternative energy sector shows the most differentiation when compared to other analysed stock market sectors. We show the existence of significant differences in the mean values of the weekly rates of return between the alternative energy sector and in six out of the eleven main stock market sectors, i.e., energy, materials, industrial, utilities, healthcare, financial, and consumer staples.

The results that were obtained here might imply that the reaction of the stock market reaction to such as the COVID-19 pandemic is sector-specific. They indicate that our study might be helpful for investors when making decisions to minimise risk by diversifying their portfolios.

The positive reaction of the alternative energy market sector during the first year of the COVID-19 pandemic can be seen as a positive symptom. It might imply that the novel coronavirus pandemic has not hampered but has instead accelerated growing concerns about climate change and environmental pollution. The following years will bring an answer to the question of whether the increased above-mentioned concerns will be permanent or temporary. This will largely depend on decision-makers and their beliefs on the importance of alternative energy sources for socio-economic development and environmental persistence in the future.

We are fully aware of the limitations of the study. The top five companies representing the entire stock market sector might not entirely reflect the sector's performance. Moreover, it is impossible to isolate the sole effect of COVID-19 on stock market sectors. This study mainly concerns the energy sector, which has been exposed to various non-COVID-19-driven factors.

A deeper analysis of the impact of the COVID-19 pandemic on the alternative energy sector stands out as a challenge for future research. As the alternative energy sector is not homogeneous, we would like to verify how companies representing different renewable energy sources (solar, wind, hydropower, fuel cells, biogas, biomass, tidal, geothermal, etc.) have performed during the novel coronavirus pandemic.

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

Appendix A

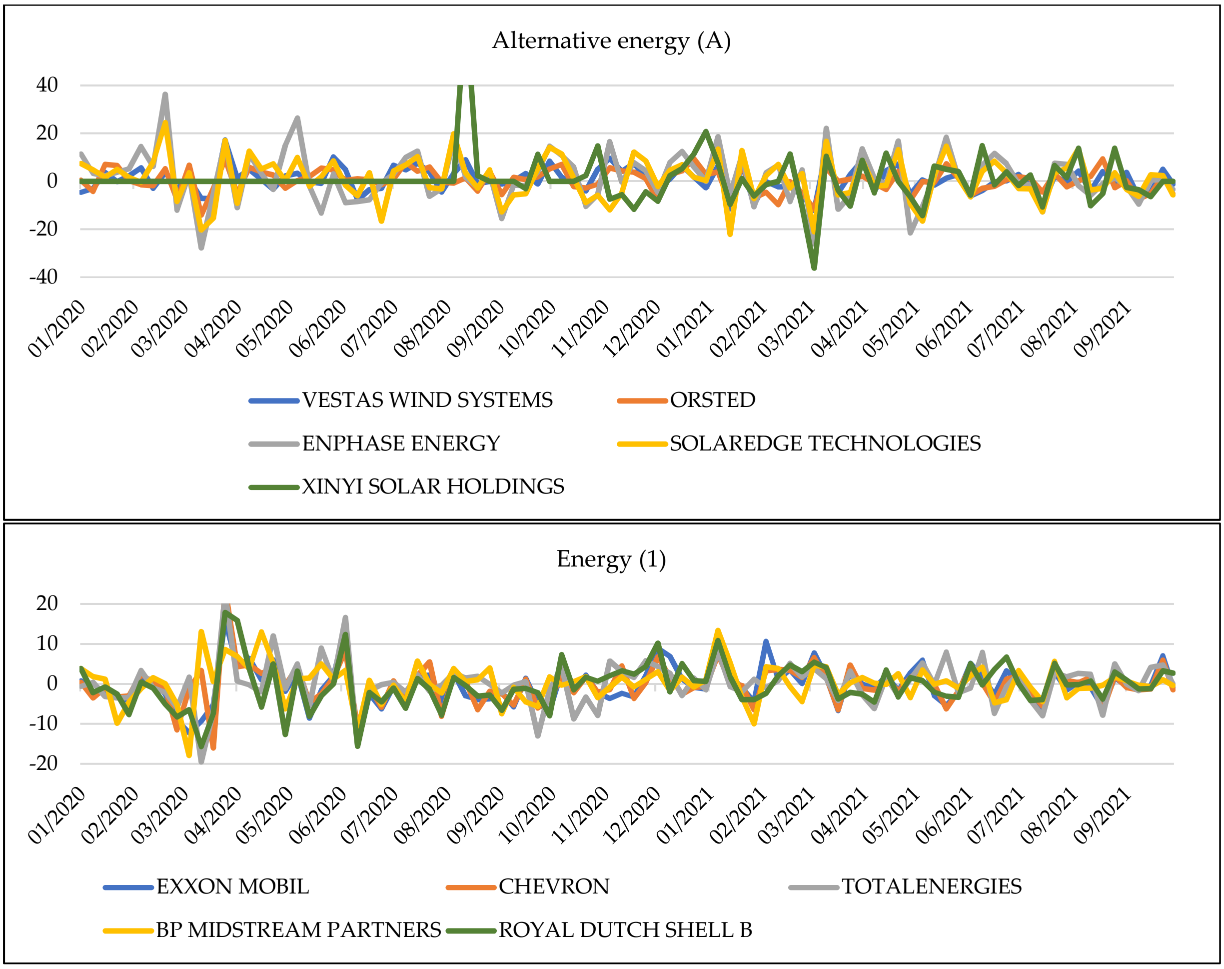
Table A1. Global Industry Classification Standard (GICS): stock market sector structure.

Sector	Industry Structure
Energy	1. Energy equipment and services 2. Oil, gas and consumable fuels
Materials	1. Chemicals 2. Construction materials 3. Containers and packaging 4. Metals and mining 5. Paper and forest products
Industrial	1. Capital goods (aerospace and defence, building products, construction and engineering, electrical equipment, industrial conglomerates, machinery, trading companies and distributors) 2. Commercial and professional services (commercial services and supplies, professional services) 3. Transportation (air freight and logistics, airlines, marine, road and rail, transportation infrastructure)
Utilities	1. Electric utilities 2. Gas utilities 3. Multi-utilities 4. Water utilities 5. Independent power and renewable electricity producers
Healthcare	1. Healthcare equipment and services (equipment and supplies, providers and services, technology) 2. Pharmaceuticals, biotechnology and life sciences (tools and services)
Financial	1. Banks (banks, thrifts and mortgage finance) 2. Diversified financials (diversified financial services, consumer finance, capital markets, mortgage real estate investment trusts) 3. Insurance

Table A1. *Cont.*

Sector	Industry Structure
Consumer discretionary	1. Automobiles and components 2. Consumer durables and apparel (household durables, leisure products, textiles, apparel and luxury goods) 3. Consumer services (hotels, restaurants and leisure, diversified consumer services) 4. Retailing (distributors, internet and direct marketing retail, multiline retail, specialty retail)
Consumer staples	1. Food and staples retailing 2. Food, beverage and tobacco 3. Household and personal products
Information technology	1. Software and services (IT services, software) 2. Technology hardware and equipment (communications equipment, technology hardware, storage and peripherals, electronic equipment, instruments and components) 3. Semiconductors and semiconductor equipment
Communication services	1. Telecommunication services (diversified and wireless services) 2. Media and entertainment (media, entertainment, interactive media and services)
Real estate	1. Equity real estate investment trusts (REITS) 2. Real estate management and development

Source: Authors' own elaborations based on MSCI.



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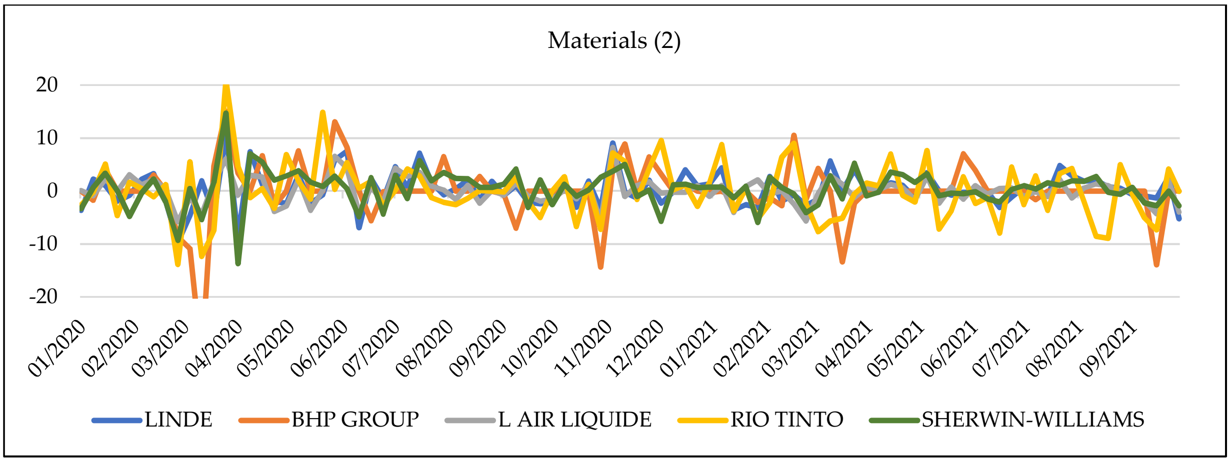

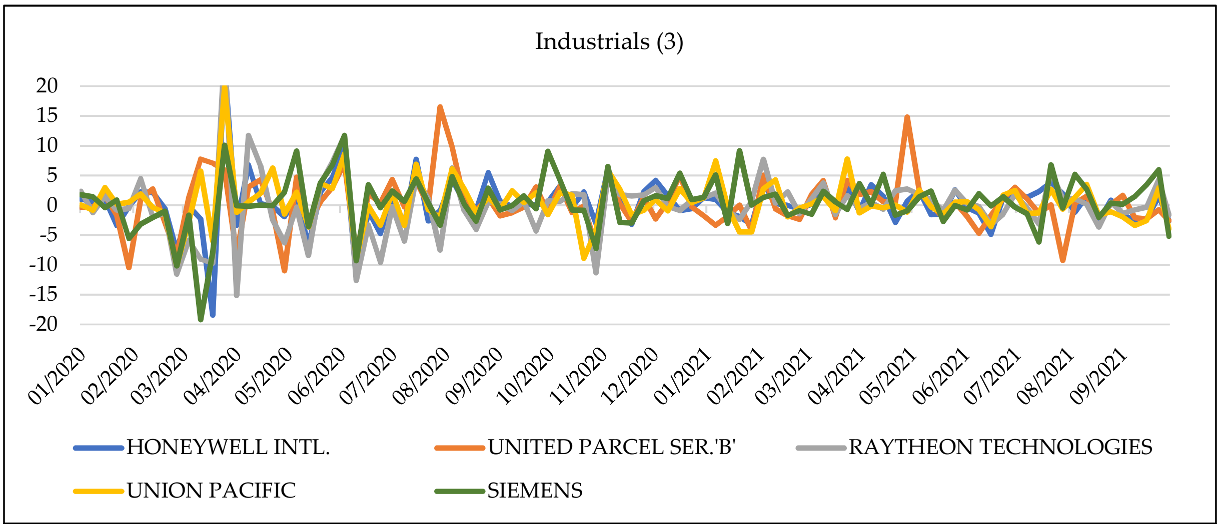

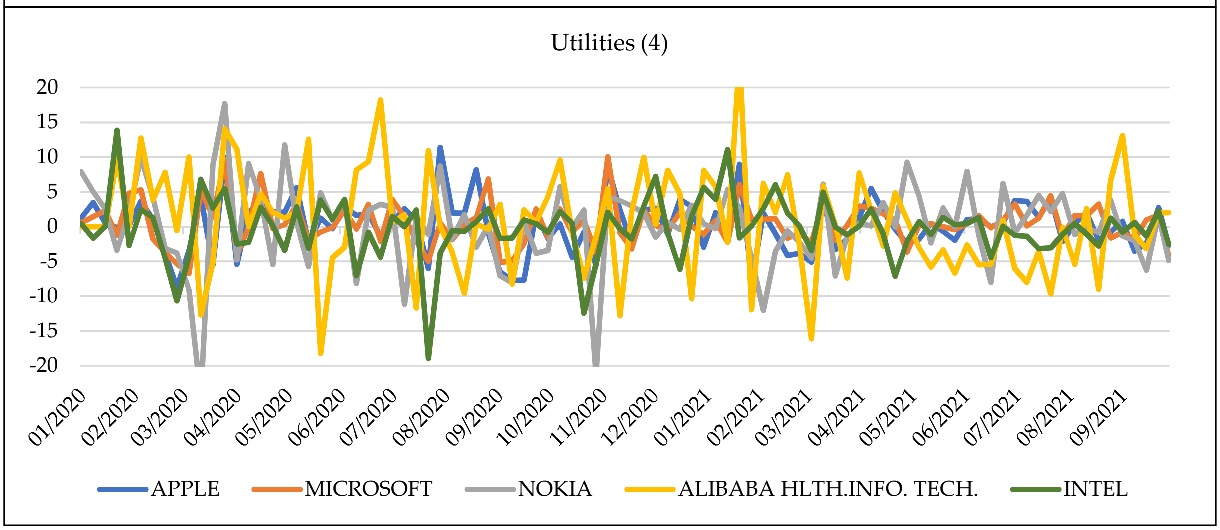

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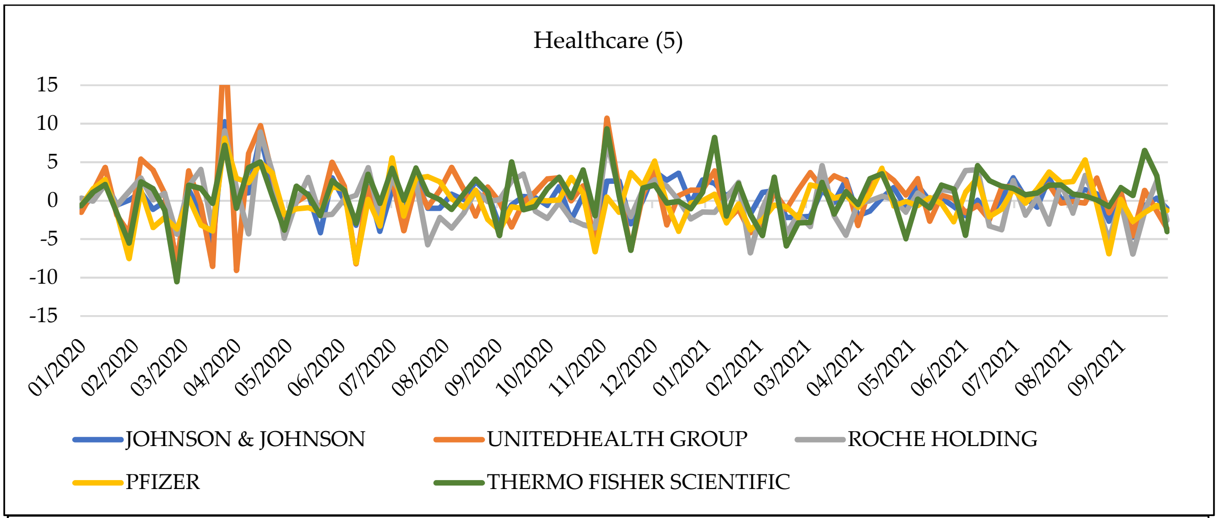

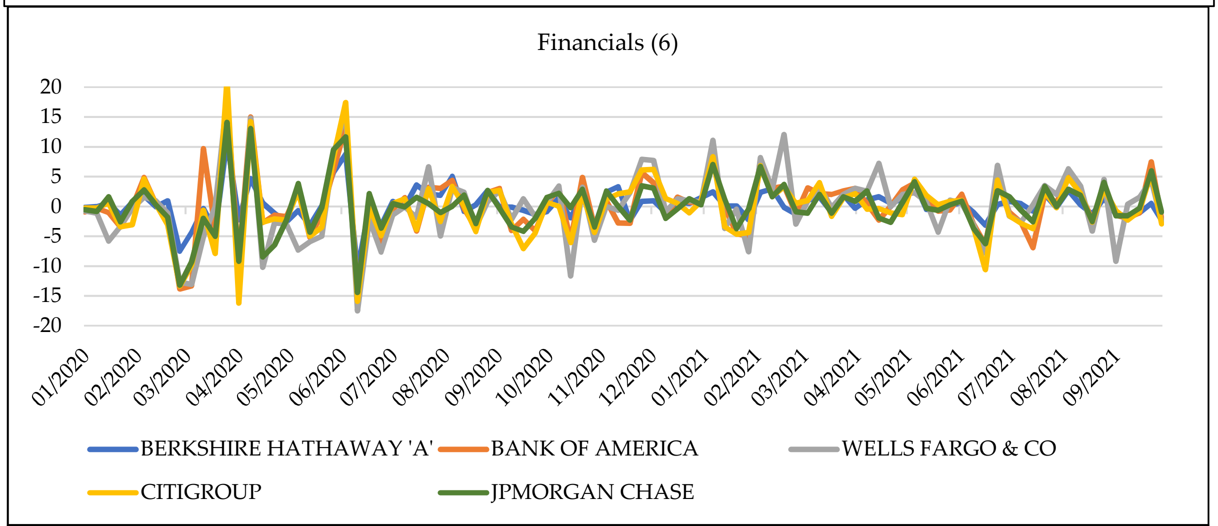

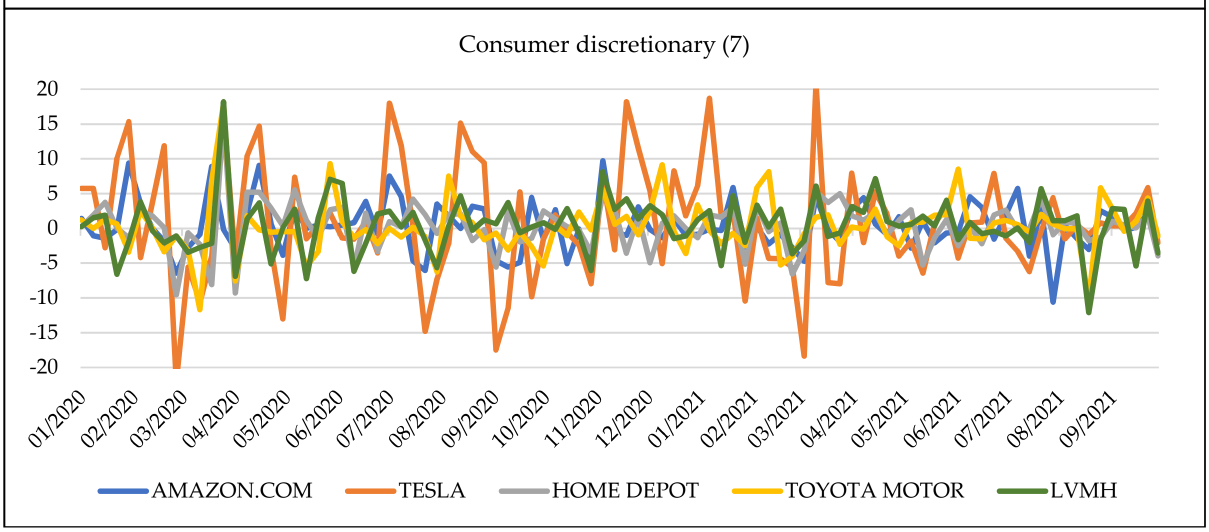

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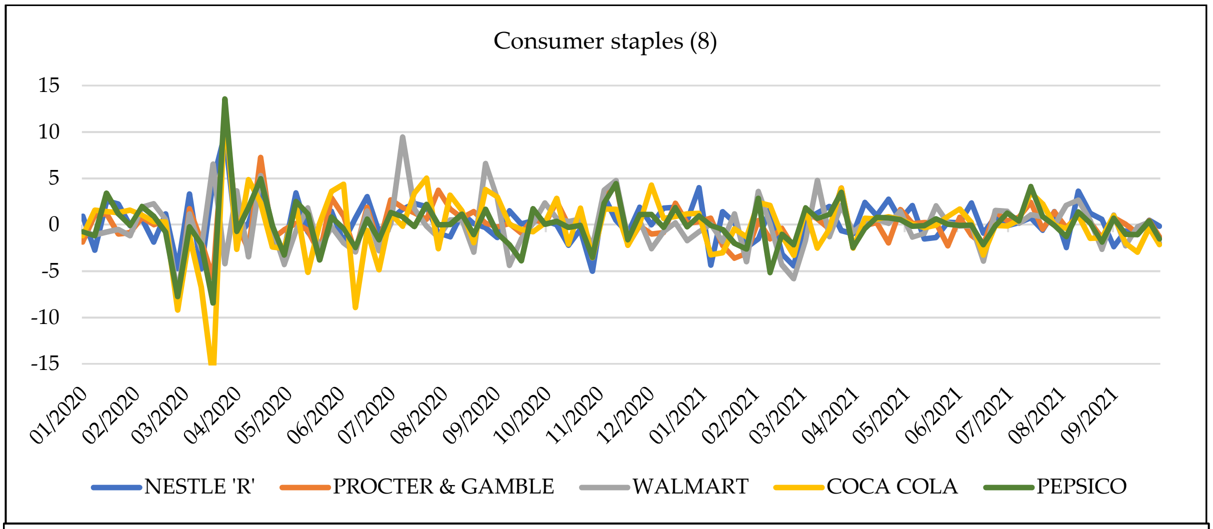

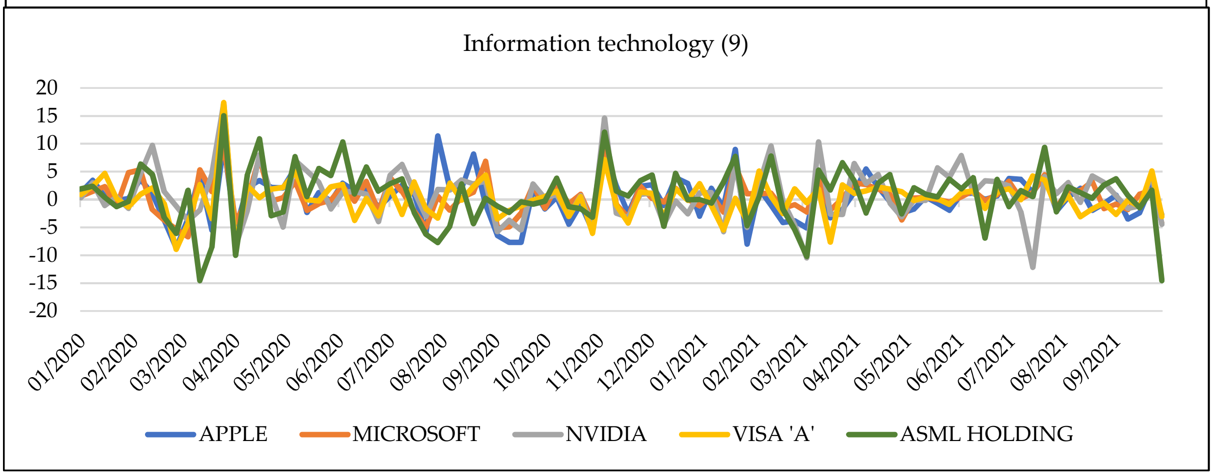

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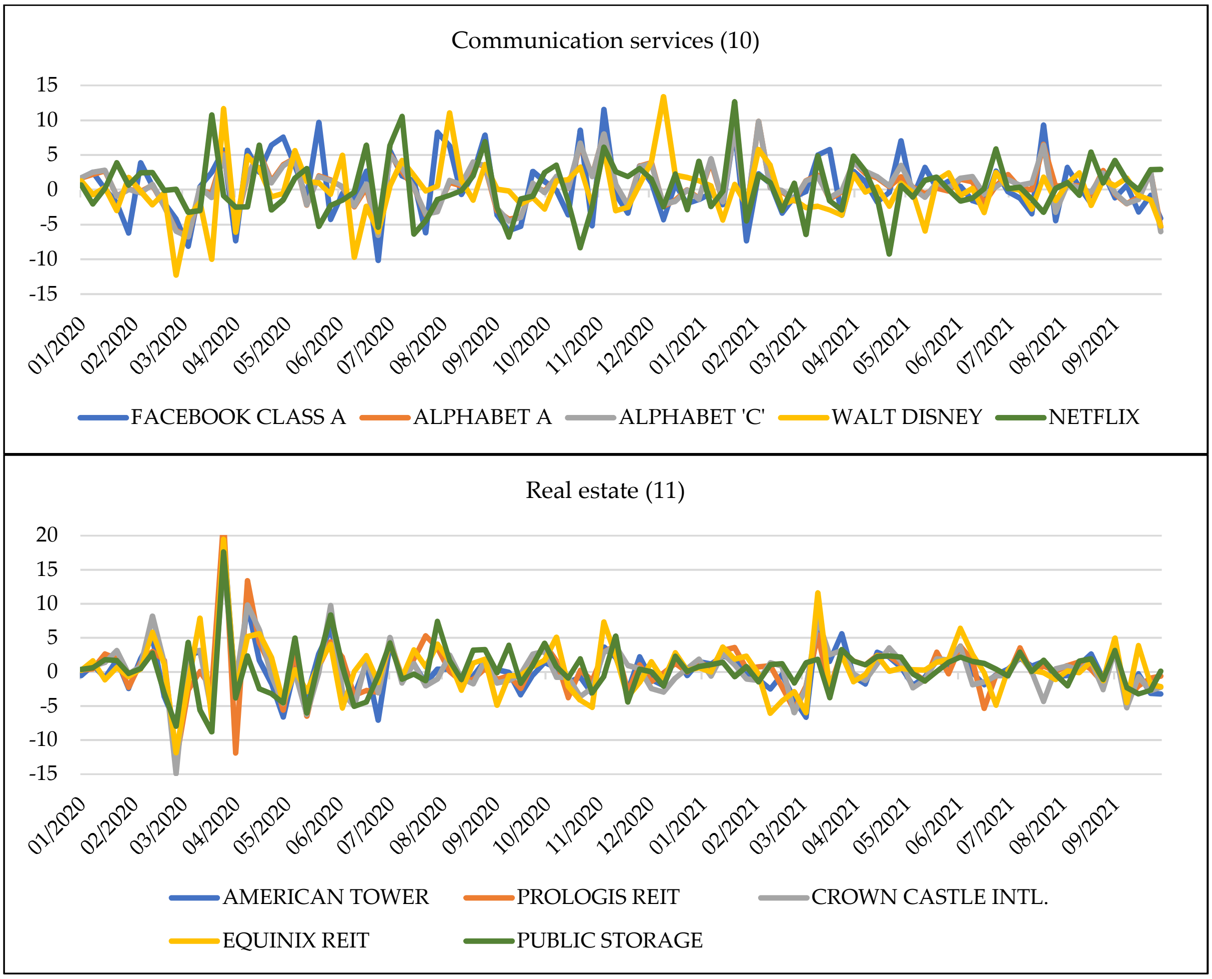

Figure A1. Average weekly rates of return of top five companies from alternative energy and main stock market sectors in January 2020–September 2021. Source: Authors' own calculations and elaborations based on Refinitiv Datastream.

Table A2. Descriptive statistics for average weekly rates of return and daily prices: based on top five companies from stock market sectors. January 2020–September 2021.

Sector	Company *	Weekly Rates of Return					Daily Prices					
		Avg.	SD	CV	Min	Max	Avg.	SD	CV	Min	Max	RoR **
Alternative energy	1	0.656	5.31	8.10	−12.08	17.25	10.63	3.26	0.31	4.58	17.29	100.77
	2	0.282	4.87	17.28	−14.12	9.42	142.18	29.68	0.21	81.00	224.72	31.30
	3	1.762	10.67	6.06	−27.77	36.33	111.14	57.54	0.52	23.99	213.76	473.94
	4	1.035	9.07	8.77	−22.09	24.49	217.61	76.50	0.35	69.48	365.97	178.91
	5	0.818	10.51	12.85	−36.24	73.46	1.44	0.71	0.49	0.59	3.25	247.46
Energy	1	−0.308	5.03	16.34	−14.88	16.12	49.67	9.88	0.20	31.45	70.90	−15.71
	2	−0.168	4.89	29.15	−16.01	23.79	93.81	12.37	0.13	54.22	121.43	−15.82
	3	0.168	5.68	33.83	−19.51	22.54	42.35	5.81	0.14	21.68	55.55	−12.58
	4	0.240	4.75	19.79	−17.90	13.38	12.21	1.82	0.15	6.89	16.93	−15.12
	5	−0.332	5.53	16.67	−15.67	17.84	18.09	3.91	0.22	9.80	30.65	−25.32

Table A2. *Cont.*

Sector	Company *	Weekly Rates of Return					Daily Prices					
		Avg.	SD	CV	Min	Max	Avg.	SD	CV	Min	Max	RoR **
Materials	1	0.272	41.07	0.17	150.00	315.64	37.80	247.80	6.56	0.17	315.64	37.80
	2	0.006	4.93	0.20	12.00	32.87	10.70	24.39	2.28	0.20	32.87	10.70
	3	0.056	3.28	0.10	21.46	36.21	14.62	31.42	2.15	0.10	36.21	14.62
	4	0.027	14.24	0.21	34.85	93.46	11.43	67.30	5.89	0.21	93.46	11.43
	5	0.422	41.51	0.18	132.23	308.70	43.81	231.78	5.29	0.18	308.70	43.81
Industrial	1	0.278	4.42	15.90	−18.43	23.42	187.63	33.63	0.18	103.86	234.18	19.93
	2	0.352	4.40	12.50	−10.96	16.53	154.00	39.13	0.25	86.17	217.50	55.56
	3	−0.059	5.35	90.52	−15.14	25.94	73.05	11.73	0.16	44.21	92.50	−2.68
	4	0.400	3.92	9.81	−10.10	19.83	194.39	25.41	0.13	114.04	229.48	8.42
	5	0.505	4.42	8.75	−19.18	11.74	132.93	30.35	0.23	60.78	177.58	39.72
Utilities	1	0.222	3.86	17.43	−8.69	11.40	112.29	26.54	0.24	56.09	156.69	92.75
	2	0.450	3.06	6.80	−6.71	10.05	221.20	40.81	0.18	135.42	305.22	78.77
	3	0.113	6.13	54.43	−24.56	17.70	4.40	0.81	0.18	2.28	6.81	52.96
	4	0.692	7.50	10.85	−18.23	24.66	2.43	0.63	0.26	1.20	3.92	18.33
	5	−0.239	4.27	17.86	−18.96	13.87	56.02	5.67	0.10	44.11	68.47	−10.98
Healthcare	1	0.132	2.58	19.44	−8.16	10.27	154.46	11.69	0.08	111.14	179.47	10.72
	2	0.508	4.13	8.13	−9.07	21.85	337.77	51.76	0.15	194.86	429.71	32.91
	3	−0.066	3.07	46.66	−6.93	9.08	348.60	21.16	0.06	282.40	409.99	13.02
	4	−0.081	2.84	35.13	−8.08	8.12	36.93	4.02	0.11	27.01	50.42	15.80
	5	0.581	3.15	5.42	−10.55	9.35	433.06	80.10	0.18	255.30	609.78	75.86
Financial	1	0.248	2.76	11.10	−10.72	11.08	348,634.39	55,496.88	0.16	240,000.00	439,460.00	21.14
	2	0.245	5.14	20.97	−14.13	17.79	31.60	7.16	0.23	18.08	43.27	20.53
	3	−0.033	6.07	181.95	−17.50	18.17	35.27	9.57	0.27	21.14	53.80	−13.74
	4	−0.133	5.54	41.73	−16.19	21.32	60.91	12.53	0.21	35.39	81.91	−12.15
	5	0.017	4.45	266.24	−14.42	14.13	126.49	26.46	0.21	79.68	168.50	18.52
Consumer Discretionary	1	0.241	3.62	15.03	−10.60	9.73	2949.07	532.26	0.18	1676.61	3731.41	77.78
	2	0.758	8.33	10.99	−22.17	20.88	466.30	247.26	0.53	72.24	883.09	826.88
	3	0.333	3.53	10.63	−9.56	15.99	273.80	40.34	0.15	152.15	341.41	50.32
	4	0.232	4.03	17.36	−11.69	17.90	14.60	2.00	0.14	10.97	19.60	29.25
	5	0.480	3.95	8.23	−12.11	18.21	576.09	150.04	0.26	305.04	840.00	53.43
Consumer Staples	1	0.242	2.28	9.40	−5.02	9.74	115.11	7.35	0.06	91.97	130.01	10.83
	2	0.088	2.45	27.71	−8.52	12.01	131.02	9.84	0.08	97.70	145.68	11.93
	3	−0.042	2.69	64.38	−7.72	9.46	134.52	11.31	0.08	104.05	152.79	17.28
	4	−0.094	3.44	36.40	−16.70	13.08	51.52	4.26	0.08	37.56	60.13	−5.20
	5	0.026	2.57	97.10	−8.45	13.56	140.50	8.81	0.06	103.93	158.91	10.05
Information technology	1	0.222	3.86	17.43	−8.69	11.40	112.29	26.54	0.24	56.09	156.69	92.75
	2	0.450	3.06	6.80	−6.71	10.05	221.20	40.81	0.18	135.42	305.22	78.77
	3	0.890	4.75	5.34	−12.18	17.25	128.20	46.25	0.36	49.10	228.43	252.16
	4	0.175	3.46	19.73	−8.96	17.41	207.10	20.70	0.10	135.74	250.93	18.55
	5	0.685	5.10	7.43	−14.56	15.06	485.22	178.90	0.37	189.50	889.92	154.32
Communication services	1	0.439	4.33	9.85	−10.17	11.57	269.78	56.39	0.21	146.01	382.18	65.35
	2	0.598	3.09	5.17	−6.76	9.84	1848.74	497.00	0.27	1054.13	2904.31	99.61
	3	0.624	3.14	5.03	−6.75	9.84	1863.48	512.26	0.27	1056.62	2916.84	99.35
	4	−0.012	3.88	330.47	−12.27	13.40	149.78	30.81	0.21	85.76	201.91	16.97
	5	0.371	3.87	10.44	−9.23	12.66	482.33	68.17	0.14	298.84	610.34	88.63
Real estate	1	0.271	3.59	13.24	−7.76	19.88	247.12	22.06	0.09	179.09	303.62	15.49
	2	0.455	4.11	9.03	−13.00	22.26	103.82	14.92	0.14	62.82	138.99	40.71
	3	0.267	3.81	14.27	−14.93	15.72	168.35	16.44	0.10	116.98	203.28	21.93
	4	0.447	4.03	9.02	−11.86	19.47	719.65	76.43	0.11	489.14	882.83	35.37
	5	0.366	3.44	9.40	−8.80	17.60	238.34	41.81	0.18	160.61	331.04	39.51

* Full names of companies are described in Table 1; ** rate of return achieved in January 2020-September 2021 period based on daily prices. Source: Authors' own calculations and elaborations based on Refinitiv Datastream.

Table A3. Descriptive statistics for average weekly rates of return and daily prices: based on top five companies from stock market sectors. January–September 2020.

Sector	Company *	Weekly Rates of Return					Daily Prices					
		Avg.	SD	CV	Min	Max	Avg.	SD	CV	Min	Max	RoR **
Alternative energy	1	−0.510	5.62	11.03	−12.08	12.96	13.30	1.17	0.09	11.16	17.29	−13.59
	2	−1.066	4.75	4.46	−11.66	9.30	158.87	19.34	0.12	132.60	224.72	−36.87
	3	0.343	10.30	30.00	−26.15	22.09	166.21	22.28	0.13	114.61	213.76	−14.53
	4	−0.006	9.09	1625.60	−22.09	16.68	275.49	29.62	0.11	204.01	365.97	−16.89
	5	−1.012	9.71	9.60	−36.24	14.90	2.04	0.34	0.17	1.36	3.25	−36.92
Energy	1	0.484	4.08	8.43	−6.68	10.61	56.81	4.95	0.09	41.22	64.66	42.70
	2	0.219	3.52	16.11	−6.78	7.25	102.35	6.16	0.06	84.45	111.56	20.13
	3	0.502	4.09	8.15	−7.99	8.14	45.51	2.21	0.05	40.12	50.63	8.59
	4	0.410	3.89	9.47	−9.95	13.38	13.09	0.95	0.07	10.55	15.68	25.00
	5	0.439	3.63	8.27	−4.57	10.85	19.20	0.95	0.05	17.00	22.30	29.59
Materials	1	0.185	2.40	13.02	−5.26	5.68	285.17	20.63	0.07	242.91	315.64	11.34
	2	−0.288	3.86	13.40	−13.94	10.54	29.17	1.61	0.06	25.94	32.87	−1.82
	3	−0.285	1.94	6.81	−5.69	2.91	33.81	1.36	0.04	30.04	36.21	−2.25
	4	−0.692	5.00	7.23	−8.93	9.03	81.27	6.19	0.08	64.02	93.46	−10.84
	5	0.093	2.22	23.91	−5.96	5.24	268.56	24.41	0.09	219.85	308.70	14.19
Industrial	1	0.092	2.18	23.67	−4.90	3.85	219.29	10.16	0.05	195.37	234.18	−0.20
	2	0.038	3.59	95.30	−9.23	14.80	186.62	20.43	0.11	155.00	217.50	8.14
	3	0.535	2.33	4.35	−3.61	7.71	80.91	6.54	0.08	65.50	89.45	20.21
	4	0.083	2.77	33.26	−4.47	7.76	216.31	8.16	0.04	194.33	229.48	−5.86
	5	0.830	3.11	3.74	−6.14	9.17	162.58	6.82	0.04	143.75	177.58	14.09
Utilities	1	−0.035	3.16	89.93	−7.98	8.97	135.14	9.98	0.07	116.36	156.69	6.64
	2	0.522	2.13	4.08	−4.25	6.07	259.17	25.98	0.10	212.25	305.22	26.75
	3	0.098	4.40	44.91	−12.01	9.28	4.95	0.79	0.16	3.83	6.81	40.49
	4	−0.600	7.27	12.12	−16.13	24.66	2.51	0.72	0.29	1.35	3.92	−53.06
	5	0.000	2.98	12,625	−7.15	11.08	57.46	4.04	0.07	49.67	68.26	6.95
Healthcare	1	−0.024	1.70	69.44	−4.72	2.98	166.05	5.19	0.03	153.07	179.47	2.62
	2	0.218	2.31	10.61	−4.58	3.90	386.70	31.60	0.08	324.34	429.71	11.42
	3	−0.637	2.82	4.42	−6.93	4.55	357.54	24.76	0.07	318.50	409.99	7.82
	4	−0.076	2.29	30.18	−6.90	5.29	39.59	4.14	0.10	33.49	50.42	16.84
	5	0.491	2.99	6.09	−5.87	8.23	499.75	42.11	0.08	439.85	609.78	22.66
Financial	1	0.285	1.51	5.29	−3.14	4.00	403,228	29,063	0.07	341,820	439,460	18.28
	2	0.657	3.54	5.39	−6.90	8.00	38.60	3.55	0.09	29.65	43.27	40.05
	3	1.023	4.63	4.52	−9.17	12.07	42.08	5.50	0.13	29.70	51.15	53.78
	4	0.244	3.57	14.67	−10.59	8.34	70.20	4.64	0.07	57.99	79.86	13.82
	5	0.556	2.85	5.12	−6.22	7.02	152.77	9.39	0.06	124.43	168.50	31.40
Consumer Discretionary	1	−0.010	3.16	315	−10.60	5.88	3315.89	165.63	0.05	2951.95	3731.41	0.86
	2	−0.154	6.83	44.32	−18.36	20.88	703.65	76.75	0.11	563.00	883.09	9.89
	3	0.323	2.71	8.39	−6.56	5.29	307.50	24.56	0.08	250.93	341.41	23.58
	4	0.370	3.28	8.86	−10.37	8.53	16.50	1.35	0.08	14.03	19.60	16.02
	5	0.436	3.53	8.09	−12.11	7.14	729.93	69.27	0.09	598.57	840.00	14.41
Consumer Staples	1	−0.042	1.82	43.26	−4.46	3.61	119.33	6.64	0.06	104.33	130.01	−1.28
	2	−0.212	1.55	7.33	−3.61	3.97	135.92	5.57	0.04	122.15	145.68	0.47
	3	−0.147	2.14	14.54	−5.81	4.76	141.18	5.07	0.04	127.53	151.45	−3.31
	4	−0.226	1.82	8.05	−3.29	3.92	53.53	2.57	0.05	48.15	57.48	−4.32
	5	−0.083	1.67	20.13	−4.76	4.13	146.02	7.82	0.05	128.83	158.91	1.42
Information technology	1	−0.035	3.16	89.93	−7.98	8.97	135.14	9.98	0.07	116.36	156.69	6.64
	2	0.522	2.13	4.08	−4.25	6.07	259.17	25.98	0.10	212.25	305.22	26.75
	3	0.726	4.59	6.33	−12.18	10.34	167.84	33.42	0.20	115.93	228.43	58.68
	4	0.086	2.63	30.76	−7.61	5.11	224.56	12.40	0.06	193.25	250.93	1.84
	5	0.706	4.56	6.46	−14.55	9.33	668.97	104.40	0.16	488.80	889.92	48.28

Table A3. *Cont.*

Sector	Company *	Weekly Rates of Return					Daily Prices					
		Avg.	SD	CV	Min	Max	Avg.	SD	CV	Min	Max	RoR **
Communication services	1	0.311	3.52	11.33	−7.34	9.30	317.13	39.52	0.12	245.64	382.18	24.25
	2	0.899	2.89	3.21	−5.39	9.84	2344.53	329.34	0.14	1722.88	2904.31	52.54
	3	0.936	2.98	3.18	−6.00	9.84	2375.84	339.08	0.14	1728.24	2916.84	52.14
	4	−0.595	2.37	3.99	−5.92	5.79	180.79	7.00	0.04	163.03	201.91	−6.63
	5	0.468	3.63	7.76	−9.23	12.66	530.98	30.47	0.06	484.98	610.34	12.87
Real estate	1	0.268	2.65	9.90	−6.66	8.00	254.49	27.22	0.11	198.66	303.62	18.24
	2	0.405	2.42	5.98	−5.55	5.42	116.29	12.26	0.11	93.91	138.99	25.86
	3	0.101	2.64	26.05	−5.96	7.80	180.41	15.94	0.09	146.77	203.28	8.88
	4	0.303	3.28	10.81	−5.99	11.59	754.16	70.46	0.09	594.92	882.83	10.63
	5	0.420	1.77	4.20	−3.79	3.28	275.96	34.97	0.13	213.82	331.04	28.65

* Full names of companies are described in Table 1; ** rate of return achieved in January-September 2020 period based on daily prices. Source: Authors' own calculations and elaborations based on Refinitiv Datastream.

Table A4. Descriptive statistics for average weekly rates of return and daily prices: based on top five companies from stock market sectors. January–September 2021.

Sector	Company *	Weekly Rates of Return					Daily Prices					
		Avg.	SD	CV	Min	Max	Avg.	SD	CV	Min	Max	RoR **
Alternative energy	1	1.291	5.08	3.94	−7.67	17.25	7.25	1.62	0.22	4.58	10.77	59.88
	2	0.973	4.66	4.79	−14.12	9.20	115.47	17.67	0.15	81.00	144.15	38.78
	3	2.194	11.66	5.32	−27.77	36.33	50.72	15.17	0.30	23.99	82.59	216.07
	4	1.858	9.39	5.06	−20.34	24.49	139.98	43.32	0.31	69.48	238.35	150.66
	5	2.102	11.73	5.58	−3.15	73.46	0.71	0.27	0.38	0.59	1.40	137.29
Energy	1	−1.431	5.95	4.16	−14.88	16.12	47.12	9.95	0.21	31.45	70.90	−50.80
	2	−0.735	6.35	8.64	−16.01	23.79	91.02	13.59	0.15	54.22	121.43	−40.25
	3	−0.135	7.25	53.64	−19.51	22.54	40.26	6.64	0.16	21.68	55.55	−37.58
	4	0.080	6.09	76.51	−17.90	13.09	11.82	2.14	0.18	6.89	16.93	−36.52
	5	−2.007	6.89	3.43	−15.67	17.84	18.06	5.31	0.29	9.80	30.65	−58.64
Materials	1	0.240	4.25	17.73	−9.74	10.94	211.32	27.14	0.13	150.00	260.23	11.85
	2	0.134	7.15	53.26	−32.09	15.08	20.06	3.21	0.16	12.00	24.00	−6.01
	3	0.328	2.82	8.61	−5.80	6.59	28.79	3.18	0.11	21.46	33.90	13.40
	4	0.392	5.87	15.00	−13.87	20.87	54.07	7.04	0.13	34.85	66.30	0.35
	5	0.661	4.64	7.01	−13.73	14.73	193.29	23.85	0.12	132.23	239.20	19.40
Industrial	1	0.144	6.22	43.23	−18.43	23.42	154.25	17.25	0.11	103.86	183.23	−7.00
	2	0.781	5.41	6.92	−10.96	16.53	116.54	24.69	0.21	86.17	168.90	42.35
	3	−0.935	7.52	8.04	−15.14	25.94	67.63	12.53	0.19	44.21	92.50	−34.86
	4	0.818	4.91	6.01	−10.10	19.83	170.73	19.10	0.11	114.04	202.37	8.89
	5	0.151	5.66	37.37	−19.18	11.74	103.34	18.29	0.18	60.78	129.30	10.16
Utilities	1	0.455	4.50	9.90	−8.69	11.40	86.83	18.39	0.21	56.09	134.18	57.75
	2	0.371	3.72	10.04	−6.71	9.61	185.48	21.80	0.12	135.42	231.65	33.37
	3	0.298	7.39	24.78	−24.56	17.70	4.01	0.59	0.15	2.28	5.09	11.27
	4	1.809	7.69	4.25	−18.23	18.23	2.22	0.53	0.24	1.20	3.24	102.50
	5	−0.441	5.02	11.38	−18.96	13.87	57.03	5.90	0.10	44.61	68.47	−13.48
Healthcare	1	0.129	3.21	24.79	−8.16	10.27	145.24	7.08	0.05	111.14	155.51	2.06
	2	0.708	5.38	7.60	−9.07	21.85	289.94	22.70	0.08	194.86	323.70	6.05
	3	0.438	3.26	7.45	−5.73	9.08	343.03	16.47	0.05	282.40	372.80	6.37
	4	−0.147	3.28	22.29	−8.08	8.12	34.38	2.36	0.07	27.01	38.59	−6.33
	5	0.567	3.23	5.71	−10.55	7.19	354.82	46.07	0.13	255.30	441.52	35.91
Financial	1	0.168	3.78	22.52	−10.72	11.08	300,189	29,085	0.10	240,000	344,970	−5.77
	2	−0.270	6.74	24.99	−14.13	17.79	26.24	4.51	0.17	18.08	35.64	−31.60
	3	−1.438	7.33	5.10	−17.50	18.17	31.61	9.59	0.30	22.53	53.80	−56.30
	4	−0.924	7.40	8.01	−16.19	21.32	54.97	13.16	0.24	35.39	81.91	−46.04
	5	−0.753	6.00	7.97	−14.42	14.13	105.16	17.24	0.16	79.68	140.14	−30.84
Consumer Discretionary	1	0.575	4.02	6.98	−6.45	9.41	2502.59	527.20	0.21	1676.61	3531.45	70.40
	2	0.935	9.92	10.61	−22.17	18.02	213.72	110.91	0.52	72.24	498.32	412.77
	3	0.432	4.44	10.28	−9.56	15.99	239.92	29.95	0.12	152.15	291.93	27.17
	4	−0.320	4.75	14.83	−11.69	17.90	12.92	0.79	0.06	10.97	14.50	−6.42
	5	0.254	4.53	17.84	−7.23	18.21	430.83	42.68	0.10	305.04	503.44	1.33

Table A4. *Cont.*

Sector	Company *	Weekly Rates of Return					Daily Prices					
		Avg.	SD	CV	Min	Max	Avg.	SD	CV	Min	Max	RoR **
Consumer Staples	1	0.445	2.66	5.98	−4.77	9.74	110.77	6.55	0.06	91.97	121.97	10.04
	2	0.287	3.18	11.08	−8.52	12.01	123.21	9.07	0.07	97.70	140.51	11.28
	3	−0.001	3.31	3605.60	−7.72	9.46	124.11	8.54	0.07	104.05	147.68	17.73
	4	−0.218	4.78	21.97	−16.70	13.08	49.44	5.12	0.10	37.56	60.13	−10.80
	5	0.011	3.39	321.36	−8.45	13.56	134.44	6.89	0.05	103.93	146.99	1.41
Information technology	1	0.455	4.50	9.90	−8.69	11.40	86.83	18.39	0.21	56.09	134.18	57.75
	2	0.371	3.72	10.04	−6.71	9.61	185.48	21.80	0.12	135.42	231.65	33.37
	3	1.310	4.75	3.63	−8.52	17.25	86.87	24.24	0.28	49.10	143.47	130.01
	4	0.355	4.20	11.84	−8.96	17.41	190.51	15.55	0.08	135.74	216.48	6.42
	5	0.371	5.81	15.66	−14.56	15.06	323.53	45.47	0.14	189.50	397.00	27.71
Communication services	1	0.625	4.92	7.88	−10.17	9.70	221.25	35.30	0.16	146.01	303.91	27.60
	2	0.033	3.20	98.05	−6.76	5.51	1410.79	133.85	0.09	1054.13	1717.39	9.42
	3	0.058	3.23	55.18	−6.75	5.25	1412.37	133.56	0.09	1056.62	1728.28	9.92
	4	−0.208	4.70	22.55	−12.27	11.70	120.86	15.02	0.12	85.76	148.20	−14.21
	5	0.213	4.16	19.52	−6.82	10.77	425.70	63.23	0.15	298.84	556.55	54.54
Real estate	1	0.338	4.68	13.85	−7.76	19.88	244.78	15.51	0.06	179.09	271.29	5.18
	2	0.487	5.67	11.64	−13.00	22.26	92.37	8.81	0.10	62.82	106.17	12.88
	3	0.597	5.04	8.45	−14.93	15.72	158.46	10.66	0.07	116.98	174.56	17.13
	4	0.651	4.79	7.36	−11.86	19.47	677.46	69.75	0.10	489.14	799.61	30.23
	5	0.298	4.75	15.94	−8.80	17.60	204.01	15.30	0.07	160.61	232.82	4.58

* Full names of companies are described in Table 1; ** rate of return achieved in January-September 2021 period based on daily prices. Source: Authors' own calculations and elaborations based on Refinitiv Datastream.

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Overview of Taken Initiatives and Adaptation Measures in Polish Mining Companies during a Pandemic

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Abstract: The emergence of the new SARS-CoV-2 virus two years ago strongly affected economic life and labour markets around the world. The pandemic affected many sectors, including the mining industry. Coal companies have had to cope with the challenges and adapt their operations to the situation. Due to the peculiarities of the mines, not only to the hazardous factors and conditions prevailing underground but also to the large number of employees who usually move in groups in the plants, the emergence of a new threat caused by a biological agent posed a real challenge for them. The aim of this paper was to present the initiatives and measures taken in the coal mining sector to ensure the safety of workers during a pandemic. The guidelines for the operation of mining plants during the SARS-CoV-2 epidemic were analysed, as well as the identification of locations in mining plants particularly vulnerable to infection with the virus. We also presented how the pandemic period affected the operations of a selected coal company in Poland from an economic point of view.

Keywords: COVID-19; pandemic; mining sector; initiatives and adaptation measures; economic situation

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1. Introduction

"Maintaining occupational safety in mining has been one of the important objectives of its operation for decades" [1]. Both the deposits of raw materials and the ongoing activities of mining companies aimed at extracting a useful, energy-generating mineral such as hard coal are characterised by peculiarities [2,3]. Conducting works in the rock mass is burdened with high risk, mainly due to the possible occurrence of natural hazards (methane, rock bumps, fire, water). Therefore, the operation of mining companies and the execution of individual works are based on a number of procedures. Since it is the task of the employer, who has legal obligations, to create a safe working environment, i.e., to ensure the safety of all employees, especially those working in underground workings—it is most important that procedures are followed [1,4].

In late 2019 and early 2020, the new SARS-CoV-2 virus, which causes the COVID-19 respiratory disease, began to spread worldwide. The virus reached Poland two years ago, in March 2020. Time has shown how dangerous this disease can be, having a very severe course with subsequent complications and possibly even leading to the death of infected individuals. The occurrence of this epidemic threat in Poland and the rapidly increasing number of infections meant that the government had to introduce many restrictions, which not only limited the activities of the public to date but also affected the operation of many businesses, including those in the mining sector.

Border closures, halting investments or the economic downturn, as well as a drop in demand for the raw material produced and reorganisation of work were just some of the difficulties faced by the mining industry during the epidemic. Despite the existence of the

Act of 5 December 2008 on the Prevention and Control of Infections and Communicable Diseases in Human Beings by Epidemiological Threats and the need to take the preventive measures set out in Article of the Act, the industry was not prepared for a threat of this nature and magnitude. This was due to the fact that there had not been an epidemic of this magnitude in the past few decades and there had been no efforts to develop procedures for the operation of companies and the actions they would take in the event of a biohazard. The biggest problem it had to face was ensuring a sense of security for its employees and their relatives, as the fear emerging among employees at the time resulted in their absence from work, as well as a lack of ensuring the continuity of plant operations. The challenges posed to mining companies during the coronavirus outbreak were framed in three areas [5]:

- Economic (including the withholding of many investments, a decline in demand for the raw material produced, loss of strategic customers, loss of liquidity, a reduction in employee wages, a decline in the company's stock market value and the need to find additional capital to purchase protective measures for employees);
- Organisational (e.g., limiting contact between employees to the minimum necessary, organising underground transport in accordance with the guidelines for the number of people, reorganising working hours, introducing remote working for some positions, supplying mines with an adequate amount of protective and disinfecting agents, organising teams to supervise the disinfection process of premises and workplaces, the need to temporarily ban external stakeholders from entering the mine site);
- Health-related (e.g., problems with access to protective equipment, insufficient quantity in the initial phase, workers' fear of illness, organisation of medical points or preparation of workplace accident management).

The management of companies and mining plants had to meet the aforementioned challenges and develop rules and procedures which, on the one hand, would ensure economic security and continuity of planned investments to maintain operations [6,7] and also guarantee a sense of calm and security for all employees performing their tasks during an epidemic. Developing a strategy for mining companies in the event of an epidemic crisis is a difficult, complex and intricate task, all the more so given the impossibility of completely shutting down underground mining operations for the duration of a pandemic (huge material losses and even the need to shut down the plant in question). The situation that arose in 2020 can be said to have been a crisis of sorts for the energy sector and the hard coal mining industry in particular, inter alia, due to the need to cope with many difficulties at the same time, both economically, organisationally and epidemically. A responsible and sustainable approach to the changes implemented and the mine's operating strategy during the pandemic ensured that high standards were maintained in the ESG (environmental, social and governance) areas. The companies took a comprehensive approach to the emergency response mechanisms put in place while maintaining sustainability and corporate social responsibility objectives.

This paper presents a description of the functioning of mining companies in Poland during the epidemic crisis, with particular emphasis on how mining companies coped by introducing a number of initiatives and adaptation measures. A breakdown of the initiatives is presented according to the ESG pillars (environmental, social, governance). The authors also discussed selected economic and social impacts of the COVID-19 pandemic in the energy sector using the example of the coal mining sector.

In the last two years, the mining sector has worked on recommendations to overcome the consequences of the pandemic. First of all, this article is a literature review of the recommendations that have been developed and adopted by Polish mining companies. Secondly, which is the contribution of the authors, we present a description of the functioning of mining companies in Poland during the epidemic crisis and show what has been done in some mining companies in Poland and how they coped by introducing a number of initiatives and adaptation measures. The breakdown of initiatives is presented according to the ESG pillars (environmental, social, management). Further research focuses on a particular mining company LW Bogdanka S.A. The authors also discussed the selected economic and social effects of the COVID-19 pandemic in the analysed sector.

2. Literature Review

The raw materials sector, and in particular the hard coal sector, plays a key role in the Polish economy [8]. The applicable regulatory provisions of the European Union and the transition of the sector from a traditional to a low-carbon economy have started to pose increasing challenges to companies in the mining sector, which are, at the same time, the difficulties faced by the sector today [9–17]. It is not only about meeting environmental requirements or reducing greenhouse gas emissions; it is also about social and economic challenges. The implemented policy of decarbonisation of the Polish economy also means a reduction of both products in power coal mining and the liquidation of jobs [8,18]. These difficulties were joined two years ago by the pandemic caused by the SARS-CoV-2 virus.

"COVID-19 dealt a devastating blow to the global economy" [8,19]. The energy sector (along with the mining sector) is the primary economic development industry of most countries and has been battling a global pandemic since 2020 [20–23]. The emergence of the COVID-19 pandemic affected the mining sector very quickly and unexpectedly [22].

A number of studies can be found in the literature outlining the impact of the pandemic on the energy sector and its sustainability. Siksnelyte-Butkiene [24] identified five areas affected by the pandemic (energy consumption and demand, air pollution and quality, investment in new renewable energy projects, household energy poverty and energy system flexibility). In turn, Gersdorf T. et al. [25] signalled that the pace and magnitude of pandemic-influenced corporate change could be analysed in areas such as the macroeconomic environment, technology and infrastructure, electric vehicle offerings and demand. A study by Kumar A. et al. [26] emphasised the link between pandemic and greenhouse gas emissions, the air pollution index was also the subject of work by [27,28], and in Lu H.F. et al. [29] highlighted the impact of the pandemic on energy demand and prices, energy policy issues and countermeasures. In the papers [30–32], one can find the impact of the evolution of the pandemic on the level of electricity consumption. Some studies also focus on assessing the level of energy poverty during the pandemic [33–38]; others analyse the impact of the pandemic on the energy expenditure of local government units in Poland [39]. In the literature, it is difficult to find broader, aggregate studies on the conduct of mining plant operations under conditions of epidemic risk. Most are short articles on the websites of individual coal companies.

It should be mentioned that the main strength of the hard coal sector is people or human capital [40]. Mining companies employ a huge number of workers who perform their work down in the mines and on whom the situation of the mining plants depends. Figures provided by the Higher Mining Office show that in 2020 (data as of 31 December 2020), there were a total of 72,234 own employees in 21 coal mines, and 28,986 in service companies, making a total of 101,220 mining plant employees. In addition, the structures of Spółka Restrukturyzacji Kopalń S.A. (including service entities) had 2342 employees [41]. On the other hand, in 2021 (data as of 31 December 2021), a total of 68,081 own employees worked in 20 coal mines and 26,381 in service companies, making a total of 94,462, while 2246 employees worked in Spółka Restrukturyzacji Kopalń S.A. [42]. As can be seen, mines are concentrations of people and their work underground takes place in difficult as well as dangerous conditions in which the SARS-CoV-2 virus could spread quite rapidly. Therefore, the most important thing during this difficult period was to ensure an adequate level of health and safety for all employees [1,43].

The outbreak of the global pandemic has meant that mining operations have had to reorganise their existing operating rules to combat the bio-threat caused by the coronavirus effectively. The scale of the problem could be seen when it was reported that by 10 July 2020, i.e., during the four months of the pandemic, more than 6500 workers had been infected with the coronavirus in total from mines located in Silesia. The only mine where no infection was reported was LW Bogdanka S.A.

A summary of the number of infections in the three coal companies shows how the number of new cases developed during the initial periods of the pandemic (Figure 1).

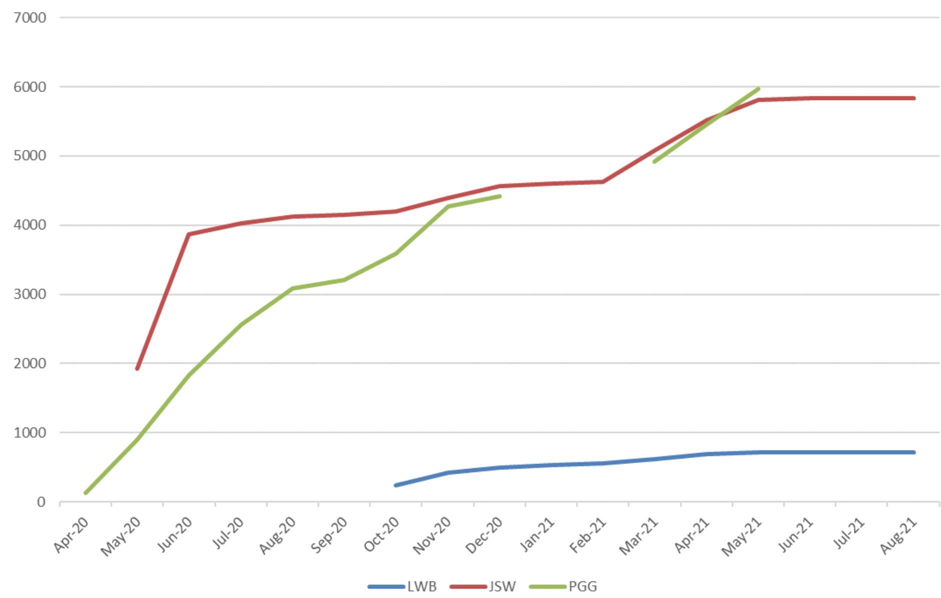

Figure 1. Comparison of infection models in three selected coal companies in Poland in the period from April 2020 to August 2021.

The epidemiological crisis in the coal mining sector began in March 2020. At that time, the first Crisis Staff in mining companies started to be established. The first cases of coronavirus infection in mines in Poland emerged in April. In Polska Grupa Górnicza SA (PGG SA), the first case was reported on 16 April 2020 at the Jankowice mine in Rybnik. The situation was similar at Jastrzębska Spółka Węglowa SA (JSW SA), where the first case of infection occurred on 26 April 2020 at the Pniówek mine. In contrast, the first cases at LW Bogdanka S.A. were not reported until 7 October 2020 (Figure 1).

In the presented model of the course of infections in the Polska Grupa Górnicza, it is possible to observe the individual waves in which the SARS-CoV-2 virus attacked with increased activity. From 20 March to 21 June, 1836 infections were recorded in the Polska Grupa Górnicza. This represents 30.41% of all infections that occurred at Poland's largest mining company. The holiday months are particularly noteworthy. Approximately 1450 new cases were recorded then, accounting for 24% of all infections during the pandemic. The situation was significantly different for the whole country during the second wave, which took place in autumn 2020. At that time, 971 infections were reported in the Polska Grupa Górnicza, when there were already more than 120,000 infections in the entire Silesian Province since the beginning of the epidemic. At the end of December, counting from the beginning of the epidemic, there were already 4412 employees infected. The situation was much worse during the third wave of the coronavirus epidemic. At that time, 1564 workers were infected, 26% of the total number of infections.

At JSW SA, which employs less than 23,000 people, representing 29% of all employees in the coal mining industry, 5358 infections have been detected since the beginning of the epidemic.

This shows that 23.2% of all employees had infections in the period presented. In the case of this company, an increase in SARS-CoV-2 virus activity can be observed. The vast majority of infections were recorded during the first period of the epidemic. From 26 April 2020 to 21 June 2020, 3840 workers were infected, representing 65.8% of the total number of infections since the beginning of the epidemic. Only 306 workers were infected during the holiday period. During the second epidemic wave of the coronavirus, 452 employees became ill at JSW SA, representing 7.7% of all infections contracted. During the third epidemic wave, 1237 infections were recorded, representing 21% of all infections in the company. From June to August 2021, not a single case of infection was detected. According to communications from the Press Office of Jastrzębska Spółka Węglowa, the vast majority of infections among employees were asymptomatic.

At LW Bogdanka S.A., the number of infected workers was definitely low compared to the previously described companies. The ratio of coal mine infections to the total number of cases in Poland has changed over time in favour of the mining industry. The case of LW Bogdanka S.A. is quite interesting due to the fact that the first case in this coal company appeared much later. Therefore the authors decided to analyse the initiatives taken by this company.

During the pandemic, companies took a number of measures to prevent and minimise the risk of workers becoming infected (described in Section 4.3). These measures helped to mitigate the consequences of the pandemic, but before the first wave of the coronavirus outbreak could be contained, a decision was taken in some mines to stop mining for two or three weeks. Such decisions were due to the sudden increase in infections. At the time, the mines were operating with minimal occupancy to protect the pits from existing water, fire, methane or other hazards. The companies also conducted vaccination campaigns, during which a large number of employees (with their families) were able to receive a dose of the vaccine.

3. Materials and Methods

The main objective of the study was to present the initiatives and activities undertaken in the hard coal mining sector in terms of ensuring the safety of employees during a pandemic, taking into account their economic and social consequences.

As part of the research undertaken by the authors to achieve the main goal of this article, specific goals were set, which were related to:

1. Analyse the guidelines for the operation of mining plants during the SARS-CoV-2 epidemic;
2. Analyse miners' behaviour in relation to the introduced restrictions;
3. Identification of sites in mining plants particularly exposed to virus infection;
4. Review of actions taken and initiatives by the selected coal company;
5. Indications and analyses of the effects of a pandemic from the social and economic perspective.

To respond to the set research goals, we used qualitative methods in the research, in particular:

- Analyse publicly available materials, reports and publications on the pandemic in the mining industry,
- Analyse orders and procedures in force in coal companies during the pandemic,
- IDI—In-depth interviews with representatives of mines, mining companies and industry experts, in which we supplemented the previously obtained information,
- Analyse materials and data provided by the mining company,
- Analyse industry and sector data regarding mining and the analysed company contained in the EMIS database.

4. Results and Discussion

This section has been divided into five parts in accordance with the objectives of the article: analysis of guidelines for the operation of mining plants during a pandemic, identification of sites particularly vulnerable to virus infection in mining plants, review of actions taken and initiatives by a selected mining company, and analysis of the effects of the pandemic in terms of economic and social.

4.1. Guidelines for the Operation of Mining Plants during a SARS-CoV-2 Outbreak

The outbreak of the pandemic worldwide also meant that mining operations had to reorganise their existing operating rules to combat the bio-threat caused by the coronavirus effectively. The scale of the problem could be seen when it was reported that by 10 July

2020, i.e., during the four months of the pandemic, more than 6500 employees had been infected with the coronavirus in total from mines located in Silesia. The only mine where no infection was reported was LW Bogdanka S.A.

Mines are specific workplaces mainly because of the dangerous factors and conditions that occur in their working environment. With the emergence of a new threat caused by a biological agent in the Polish mining industry, certain measures have been taken to ensure the safety of workers in mining plants and service companies.

The Chief Sanitary Inspector, together with the Minister of State Assets, prepared guidelines for the operation of mines during the SARS-CoV-2 outbreak. The recommended guidelines were aimed at managing the difficult epidemiological situation faced by mining plants in spring 2020 (March 2020). The procedures developed for this purpose were primarily aimed at limiting the spread of the virus by reducing the number of contacts on the premises, as well as organising work in such a way as to maintain the proper functioning of mining plants [44]. The Chief Sanitary Inspectorate (GIS) issued recommendations for the operation of industrial plants during the epidemic threat. These were divided into three groups: prevention, containment and emergency management.

Key recommendations and procedures to limit the spread of the virus included [44,45]:

- providing workers with the means to protect their mouths and noses and covering them compulsorily were indicated by law; this obligation applies to all suppliers and visitors moving on the premises;
- use of distance barriers (e.g., glass, plexiglass to protect the worker from the possibility of infection from sick persons;
- maintaining a safe distance between workstations (1.5 m) as far as possible;
- reducing the number of working shifts and reducing working hours to six hours, use of distance barriers (e.g., glass, plexiglass to protect the employee against the possibility of infection from sick people;
- reducing contact between employees (changing the work system and identifying where employees congregate, introducing remote working where possible, halving the number of people entering the shaft hoist cage and being transported by transport equipment, and increasing the number of descents in shafts);
- restricting the use of communal spaces (different break times, closing canteens or limiting the number of people who can be there, the possibility of a breakfast break at the workstation, limiting the number of people using the baths);
- use of routine personal protective equipment by underground workers;
- updating cleaning and preventive decontamination procedures for rooms and areas (e.g., circulation paths, offices, cloakrooms, sanitary rooms, lamp rooms, refreshment points, stairwells);
- displaying instructions in the sanitary and hygiene rooms on hand washing, donning and doffing masks and gloves;
- suspension of periodic in-house training and introduction of online training;
- limitation of external cooperation;
- staff briefings should take place in an open space and meetings and deliberations, if necessary, with windows open;
- designating crisis management centres that make decisions depending on the situation.

Detailed guidelines for the aforementioned procedures have been developed by the Emergency Management Team at Underground Mining Plants (Polish: Nadzwyczajny Zespół ds. Zagrożeń w Podziemnych Zakładach Górniczych) appointed by the President of the State Mining Authority.

In addition to these key procedures, precautionary procedures have also been developed outlining the course of action to be taken if an infection is suspected in any of the employees. These included such provisions as [44]:

- if there are symptoms of infection, workers should not come to work,
- an employee who has developed symptoms of infection should report to the nearest sanitary-epidemiological station,

- introduction of non-contact temperature measurement before entering the establishment; if a temperature above 37 degrees Celsius or if a person is observed to have a persistent cough, malaise or difficulty breathing, such a worker should not be allowed to enter the establishment,
- preparing the room to isolate the worker who develops symptoms of infection,
- prominently displayed numbers for medical services and sanitary and epidemiological stations.

Of course, if a worker is diagnosed with the virus, the recommendations of the state health inspector must be followed, and in particular: it is necessary to determine in which area of the plant the infected worker has moved to carry out decontamination in accordance with company procedures, identify a list of employees or customers with whom the infected person has had contact, and, if production has to be completely stopped, it is advisable to maintain critical infrastructure for the proper maintenance of the mining plant. The introduction of adaptation measures initially did not have the expected results. The number of infections continued to rise and managers of mining plants decided to introduce organisational changes to reduce the number of workers in the cages of shaft lifts or transport machinery, among others. Mass screening was carried out at a number of plants, but as the situation did not improve and the number of infected continued to rise, the government decided to suspend work at twelve mines for three weeks completely. After this period, as of 6 July 2020, all mines returned to normal operations (but with all the 50% restrictions respected). It can be concluded that the period of suspension of the mines was crucial and had an effect. Difficult, from an economic point of view, decisions influenced the control of the situation and stopped the growth of infection. From the beginning of July 2020, with the continued adherence to the developed guidelines and the ongoing adaptation measures in the mines, the extinction of the coronavirus outbreak and the suppression of its growth in the coal mines became apparent.

In addition, in 2020, the Higher Mining Authority (WUG) carried out 1206 inspections to check the state of safety in the operation of mining plants and how the recommendations on procedures for dealing with epidemic risks are implemented at these plants [41,42]. These inspections did not reveal any irregularities.

4.2. Need to Identify Plants Particularly Vulnerable to Coronavirus Infection

The emergence of the new virus in Poland posed a huge threat to mining plants. This is because they are specific workplaces where large concentrations of people gather at the same time. Due to the specific nature of the SARS-CoV-2 virus, which spread very quickly and persisted for a long time on surfaces, close contact of workers with each other could prove very dangerous. The virus causes acute respiratory illness that can even lead to death. It was, therefore, a major challenge for managers to organise miners' work in such a way that the risk of infection was minimal. There are many such areas in mining plants where there is increased social contact between workers. Thus, they are exposed to a higher risk of contracting coronavirus. Mines, through the limited possibilities related to the specific infrastructure, the nature of the work carried out and the existence of so-called common areas within the plant where large numbers of people congregate at one time, have faced an extremely difficult challenge regarding compliance with the rules of imposed spatial distance (1.5 m spacing between workers).

Due to the specific nature and potential for the spread of the virus, places particularly vulnerable to coronavirus infection have been identified. Such public places, where many workers congregate and the risk of infection is increased, include:

- employee transport;
- entrance/exit gates;
- main traffic routes;
- guildhalls—Places where work is shared;
- sanitary and hygienic facilities;
- lamp room;

- above the shaft and below the shaft—Places where the crew goes down and up;
- underground transport by passenger trains and overhead rail;
- beverage dispensing points.

Employee transport is used by local residents who work at the same mining plant but in different departments. When transport is shared, there is an increased possibility of the virus spreading and in an uncontrolled manner. The Decree of the Council of Ministers of 6 May 2021 on the establishment of certain restrictions, orders and prohibitions in connection with the outbreak of an epidemic—on collective transport of more than nine persons says [46]: "by a given means of transport or vehicle, no more persons may be transported, at the same time, than 100% of the number of seats or 50% of the number of all seating and standing places specified in the technical documentation or the technical and operating documentation for a given type of means of transport or vehicle while leaving at least 50% of the seats unoccupied in the means of transport or vehicle". This means that an employee transport (coach) with 52 seats, according to the technical and operating documentation, could only be used by 26 employees.

The second dangerous area is the main entrance/exit gates. Each employee has to bounce a card at the gate, in the room where the time readers are located. During the start hours of the first shift, up to 1000 people pass through the gate within 20 min. Due to the introduced requirement to measure temperatures, disinfect hands and maintain a 1.5 m queue distance at the entrance, there could be considerable congestion before entering the plant. These resulted in employee delays at the workstation.

The infrastructural constraints in the plants (a large number of workers at one time) also apply to the main circulation routes. These are mostly narrow corridors that connect: offices, guild halls, baths, as well as refreshment points or lamp rooms. Before the start of work (before each shift), the passageways are used by a very large number of miners (most before the first shift) in the 30 min prior to the descent. The passageways are, therefore, a huge obstacle to maintaining the required distance between workers and are a particularly vulnerable place for virus infection.

Another place in mines where a lot of workers congregate are the guild halls, where the offices of all the divisions are located and where the division of work and duties for the miners takes place before each of their descents. The nature of work in a mine means that the mine foreman assigns to the workers each time the tasks and duties that await them on a given day.

It is only in the guildhall, i.e., the miners' changing room (Figure 2), just before the ride down, the miner learns which area of the mine they have to go to on a given day, what task they have to perform and what equipment they need to prepare to carry out the order (electric meters, oxygen sensors, specialised tools taken from the surface).

Figure 2. A guildhall in LW Bogdanka S.A. Source: photo provided by LWB.

The sanitation and hygiene facilities, which include chain baths and showers, can be the most challenging (Figure 3). Before descending, workers leave clean clothes on the clean side of the chain bath and walk to the other side, where each worker has their own hook with work clothes. This system of hanging up clothes allows all clothes to dry well after finishing work. However, the nature of the bathhouse during the epidemic posed a serious risk. Mainly because of the very high accumulation of workers in the bathhouse compartments. The distribution of workers in the bathhouse is not orderly in terms of ward and work areas. Workers from the surface, longwall, face and workshop departments may meet in the same compartment. If an infection was detected in any of them, there was a high probability that the rest of the workers were also infected.

Figure 3. A chain bath in LW Bogdanka S.A. Source: photo provided by LWB.

In turn, the place where workers meet (both before and after the descent) is the lamp room (Figure 4). From this place, underground mine workers retrieve the necessary equipment for the task, i.e., escape apparatus, oxygen detectors, front mining lamps and personal protective equipment, among others. The number of people picking up and putting down equipment at the same time, as well as the narrow aisles between lamp loading stations or escape apparatus shelves, make the lamp room an impossible place to maintain a 1.5 m distance. This is related to an infrastructure that does not allow for the reorganisation of stations (the lamps are at a very short distance from each other) and the workers tend to be close to each other.

Figure 4. A lamp room in LW Bogdanka S.A. Source: photo provided by LWB.

An extremely important place in any mine is the top and bottom of the shaft. This is where the descent and departure of the crew takes place. Each shaft has a separate area where the workers wait for their turn to descend. On the other hand, there are waiting areas in the shaft where miners go as soon as a passenger train or overhead train arrives. This is a walkway where benches have been built so that the crew can wait quietly for their departure. Figure 5 shows the waiting and entering of the cage miners.

Figure 5. A coal mine top shaft in LW Bogdanka S.A. Source: photo provided by LWB.

In addition, mention should be made of the regular descents and ascents that take place by the mine shaft hoists of the mine plant using a shaft cage known as a "shola" or hoisting vessel. The cage has several floors, usually 2 to 4. The permissible number of persons per floor, depending on the number of floors of the vessel, varies (the most common is 16–20 persons for a cage with four floors and two hoisting vessels and 40–50 persons for a cage with two floors and one hoisting vessel. The cages have a small space where workers stand one next to the other.

A key issue to ensuring the smooth operation of any mining facility is the underground transport of workers. The infrastructure associated with underground transport includes passenger stations, waiting for areas for transport and various means of transport, depending on conditions and needs (Figures 6 and 7).

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

Figure 6. Underground transport means used in LW Bogdanka S.A.: an underground railway passenger carriage (**a**) and overhead passenger cabin/rail (**b**). Source: photos provided by LWB.

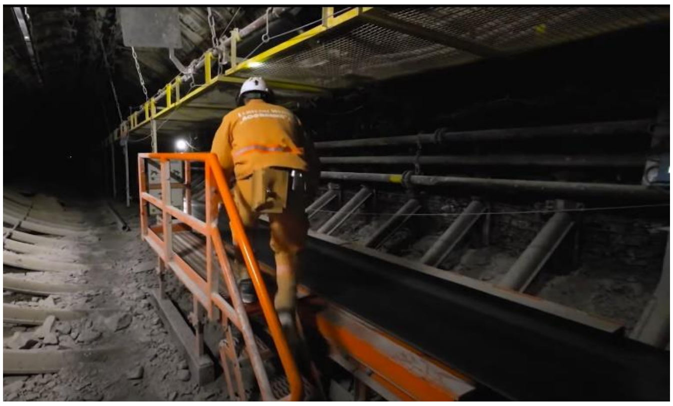

Figure 7. Underground transport means used in LW Bogdanka S.A.—Belt conveyor for transporting people. Source: photo provided by LWB.

Most often, workers are transported to the various areas of the mine either by mine underground rail (Figure 6a), by overhead rail (Figure 6b) or by the special bench. In some cases, people are also transported by specially adapted belt conveyors (Figure 7).

The passenger rolling stock can carry more than 140 people to the work area. One passenger wagon accommodates 12 people in a small space, and there can be up to 12 or 13 carriages coupled together.

A typical wagon is just under 4 m long and about 1.4 m wide. The space of the wagon is divided into three compartments, each accommodating four people. This puts those workers at risk of infection on the way to or from the workstation. The railway moves along a crosscut—A horizontal corridor excavation. During transport, there is also a high turnover of workers from different departments, who wait in narrow galleries for the train to arrive and then swap with the crew who have arrived for the next shift in the mine area. These circumstances mean that transport by underground rail, especially during the epidemiological crisis, posed a high risk of infection among workers.

The second most common underground means of transport are overhead railways. The nature of their work makes it possible to negotiate numerous inclines, i.e., workings with an inclination of up to 45°. The trains often supplement underground rail transport. Transport by overhead rail can be using passenger cabins or passenger transport benches. Cabins are usually eight-seaters. Personnel transport is carried out in two-person compartments. The length of the cabin is approximately 4 m and the width is a maximum of 1.1 m. Up to five cabs can be connected together, giving the possibility of transporting 40 workers to the workplace.

Workers are also transported by a different type of passenger overhead rail, which is a passenger bench. It is approximately 3.5 m long and less than one metre wide. It can carry up to 8 people. Like the overhead rail, the passenger bench complements underground rail transport. It can negotiate gradients of up to 30°.

The last identified location with a risk of contracting the virus was at the beverage dispensers. Standing in close proximity to a queue and using one water dispenser could also have resulted in the spread of the virus.

The so-called "common places" in the mining establishments shown represent places where workers are particularly vulnerable to infection with the SARS-CoV-2 virus. The situation that occurred in 2020 required appropriate action on the part of the management of the mining companies (employers) to ensure the safety of all workers, as well as to ensure continuity in the operation of the establishments. Mining companies were forced to take many initiatives and measures to adapt to the new emergency situation.

4.3. Adaptation Initiatives and Activities Undertaken at a Selected Mining Company

It should be mentioned that the last two years of operation of mining plants have taken place during an epidemiological crisis. Every crisis is a worrying phenomenon for an organisation, especially as it is the result of unplanned events. The undertaking of various activities, initiatives or recommendations, both by the Boards of Directors and by the Crisis Staffs established in the mining companies, took place in conditions of the high risk associated with the increase in infection among the crews and uncertainty as to the effects of the initiatives undertaken by them. The mining companies took many anti-crisis measures during this period. These measures were preventive and adaptive to the situation. Their aim was to limit the spread of the virus within the sites and to reduce the incidence of COVID-19 among mine workers.

The actions taken and implemented over the last two years at a selected mining company in Poland, which was LW Bogdanka S.A., are presented. A summary of the measures is presented in Table 1. According to the new corporate governance rules, the so-called Best Practices 2021, companies listed on the Main Market of the WSE are required to develop a business strategy that takes into account environmental, social and governance (ESG) objectives [47]. ESG has recently been gaining popularity mainly because it is based on the three pillars of ratings and non-financial assessments of a company [48] and is, therefore, an important element in building the business strategy of many companies and firms in different economic areas, including mining. Therefore, the activities analysed are presented in a breakdown of the ESG pillars (environmental, social, governance).

Table 1. Actions and initiatives taken by LW Bogdanka S.A. during the pandemic period.

ESG Pillar	Action, Initiative
Governance	establishment of the Crisis Staff monitoring the situation and reporting to the Management Board development of ongoing recommendations implementation of preventive measures development of a plan for maintaining the continuity of the mine's operations analysis of the financial situation establishment of accounting accounts to monitor costs associated with the prevention and control of coronavirus developing procedures for dealing with symptoms of coronavirus detected in an employee isolation of persons likely to come into contact with the virus definition of new rules for cooperation with external companies
Social	obligation to use personal protective equipment against infection temperature measurement obligation information campaigns disinfection of equipment, appliances and workstations distribution of disinfectants throughout the plant division of crews into smaller groups telephone contact indicated, online contact suspension of business trips the introduction of remote working for jobs that do not require on-site presence

The activities carried out by LW Bogdanka S.A. during this period were focused on two areas: the management area and the social area (Table 1), as the most important thing was to ensure the safety of employees and the continuity of the company's operations. The actions taken in the management pillar were related to the guidelines issued by the Chief Sanitary Inspector and the President of the Higher Mining Authority. A Crisis Staff was set up in the company to, among other things, monitor the situation and report to the Company's Management Board to develop a plan for maintaining the continuity of the mine's operations. In addition, the Staff developed procedures for dealing with symptoms of coronavirus detected in an employee, implemented preventive measures and developed ongoing recommendations. LW Bogdanka S.A. introduced isolation of persons who could come into contact with the virus and defined new rules for cooperation and contact with external companies during the pandemic. In addition, to improve the analysis of the company's financial situation, it has set up accounting accounts to monitor costs related to the prevention and control of the coronavirus.

In the social pillar, there were also a number of measures focused on the protection and safety of workers from infection with the new virus. The most important was the obligation for employees to use personal protective equipment against infection. In addition, the company made it mandatory to measure the temperature before entering the mine site, disinfected equipment, facilities and workstations, and distributed disinfectants throughout the site. In accordance with the guidelines, there was a division of crews into smaller groups to minimise the risk of infection mainly due to the contact of employees in common areas (described in Section 4.2). At that time, LW Bogdanka S.A. suspended business trips, introduced remote working for positions that did not require presence at the plant and switched to a form of telephone and online contact. The company also conducted various information campaigns using the necessary internal communication tools.

The initiatives and actions taken by LW Bogdanka S.A. did not include psychological support for employees, the introduction of a helpline on pandemic issues or the possibility of screening employees for the coronavirus, which would certainly have accelerated the identification of infections and the initiation of the necessary steps and procedures.

4.4. Behavioural Response of the Mining Community to the Tightening Measures Introduced

COVID-19 has undeniably affected the behaviour of miners in coal mines. The whole situation related to the rapidly spreading virus, as well as the COVID-19 restrictions introduced by the Coal Companies, has made the whole mining community strongly responsible. This is evidenced, among other things, by the research carried out and presented in [49]. Already in the initial period of the emergence of the threat and after the first restrictions were introduced in the country, as well as the tightening in the mining plants, it could be seen what the adaptation behaviour of the people working in the mines to the situation was like. On the one hand, new obligations were imposed on employees, such as wearing masks, washing hands and using disinfectants, or reducing the number of people using transport, while on the other hand, it was important for miners to adhere to and comply with them. The aforementioned research was carried out based on a checklist among employees working underground in mines undergoing decommissioning. All respondents were concerned about the restrictions and idle time pay introduced due to the COVID-19 hazard, as well as the restrictions due to the miners being barracked at the mine. Selected responses from respondents on what was affected by the pandemic are shown in Figure 8.

"The outbreak of the COVID-19 pandemic clearly showed the importance of social aspects of work organisation and their consequences on the employees' environment" [50]. For all respondents, the pandemic caused significant changes in their lifestyles. All the restrictions introduced in relation to forms of active leisure, the closure of places of public use such as entertainment outlets for families and children, gyms, cinemas or theatres, the cancellation of mass events, and their extension in the form of restrictions on meetings with friends and family during festive periods, i.e., the so-called social isolation, affecting both physical health (24%) and mental health (14%). Such a condition indicates that "Poles are under the influence of the trauma of the pandemic" [51]. Difficulties in adapting to all the restrictions were declared by almost half of the respondents. The miners' psychological burden was all the more intensified because, knowing that there was a high probability of being infected with the virus (32% were convinced that they would become infected soon), they worried about their family and loved ones. Fear of infecting the family was high at 72%. Therefore, 98% of respondents followed the ministry's advice and stayed at home except for necessary matters such as going to work or shopping for food. The economic situation of the miners' families was negatively affected during this period, with 26% stating that the pandemic worsened their economic situation at home due to a much lower total income for all family members, which certainly had an even more negative impact on their mental health.

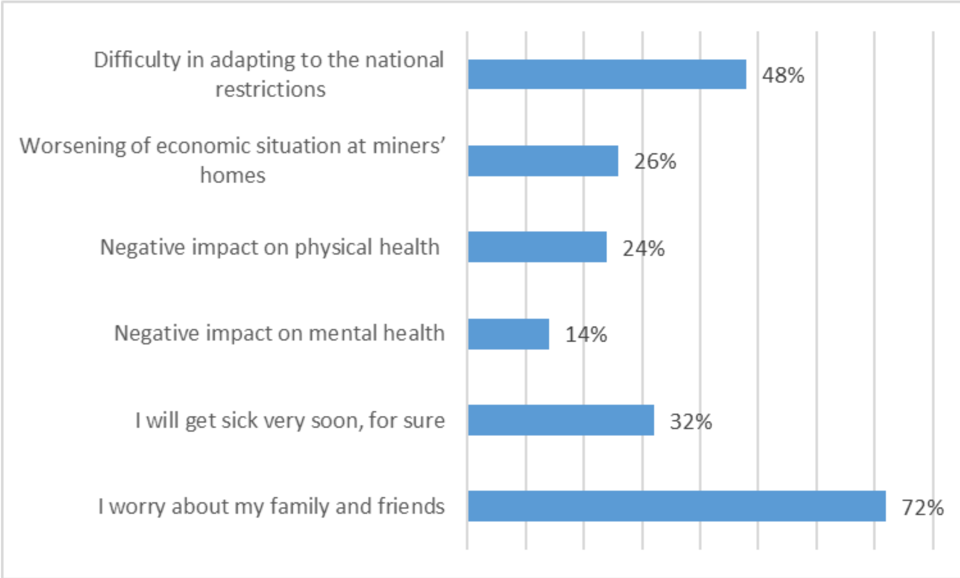

Figure 8. Impact of the pandemic through the eyes of miners. Own study based on [49].

The high percentage of those worried about their families shows how respondents complied with the restriction at the mining plants (Figure 9). All stayed away from others by observing to keep a safe distance. Almost all, 98%, stayed at home, choosing to take an overdue holiday to avoid contact with others and thus reduce the risk of illness. 86% use disinfectants and 42% use face masks.

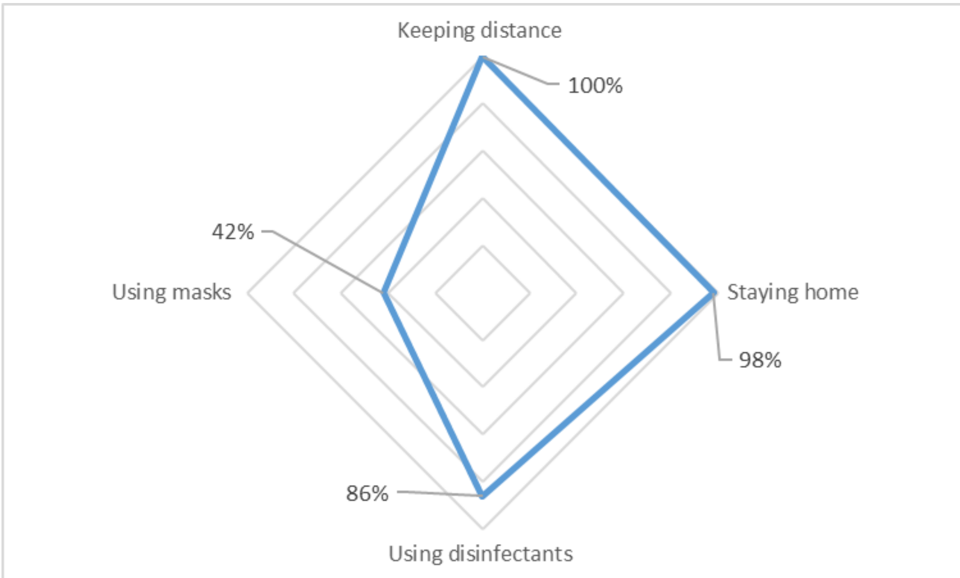

Figure 9. General activities to which miners adhered. Own study based on [49].

The described behaviour of the miners shows that the mining community is responsible. Everyone, with a view to the well-being not only of themselves but also of other employees, followed the guidelines, rules or instructions that had been introduced. It can be said that this collective responsibility has mainly contributed to the reduction of infections in mining companies.

4.5. Economic and Social Impact of the COVID-19 Pandemic on Mining Facilities and Miners

The mining industry in Poland is crucial in terms of supplying raw materials for electricity generation. During the COVID-19 pandemic, Poland's energy consumption fell to 157 TWh (and from coal to 109 TWh or about 10% year-on-year), as shown in Figure 10.

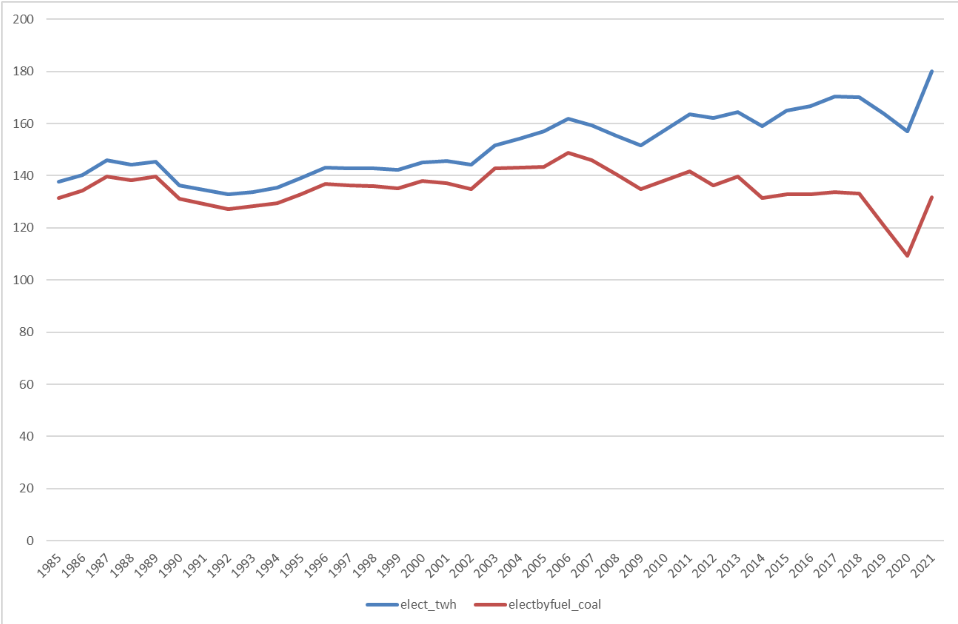

Figure 10. Electricity consumption in Poland overall and based on hard coal.

Due to this fact, the demand for coal in this period also decreased—which directly affected the financial results of mining companies. Taking the example of LW Bogdanka S.A., the financial result in 2020 was more than 76% lower than in 2019. The reduction in the level of the financial result directly affected the deterioration of a number of financial indicators (e.g., such as ROA and ROE). This situation was also reflected in the market value of LW Bogdanka S.A.—which is mainly represented by the company's share prices—Figure 11 shows LWB's share prices as the company's appearance on the Warsaw Stock Exchange.

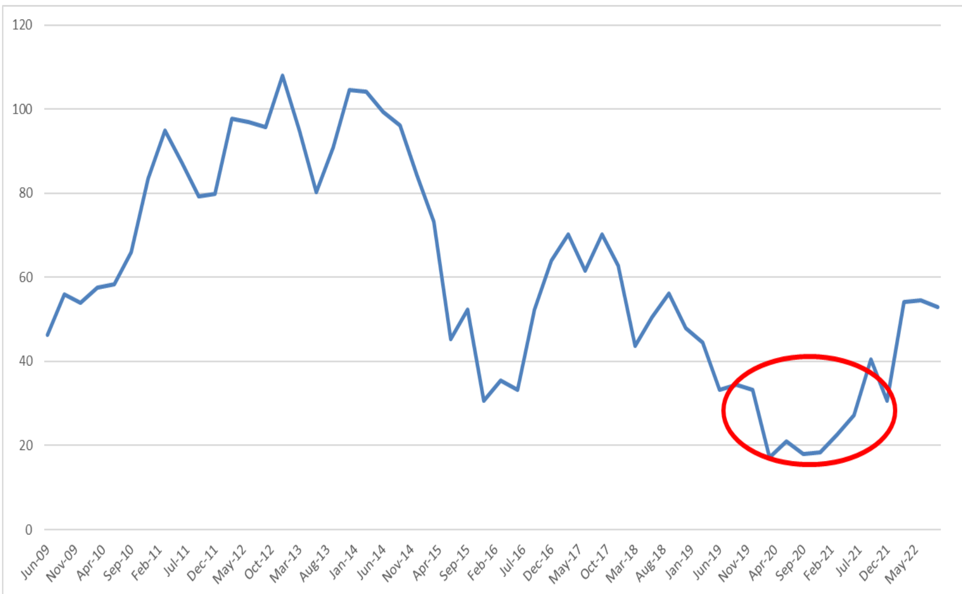

Figure 11. LW Bogdanka S.A. share prices.

As the figure shows, share prices have been declining since 2017—nevertheless, 2020 saw the lowest share value since their issue (price per share of PLN 14.17). When considering the dynamics of LWB's share price changes, it should also be noted that the first quarter of 2020 saw the strongest share price decrease since the share issue, i.e., by 48.6% quarter-on-quarter, as shown in Figure 12.

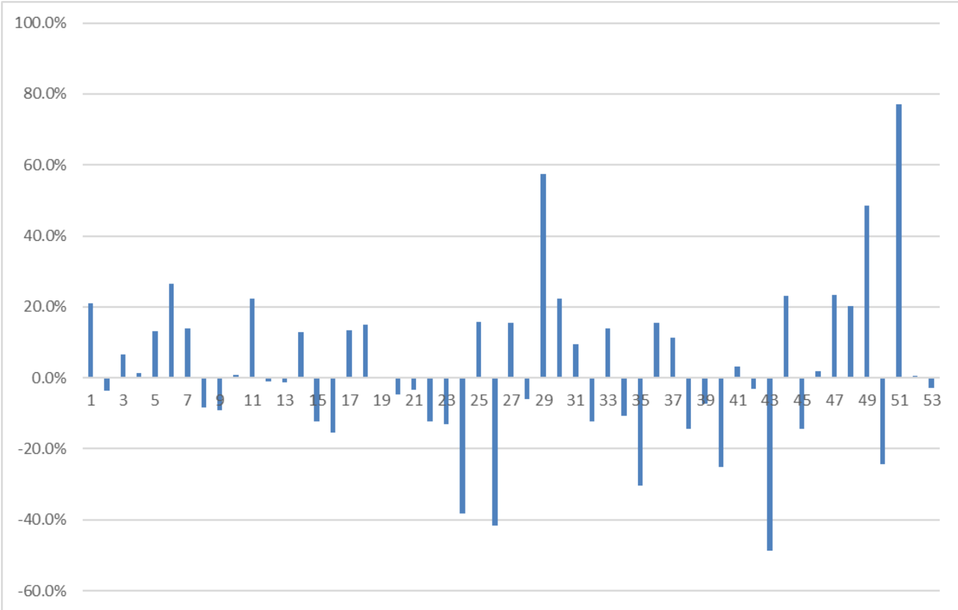

Figure 12. Dynamics of changes in the price of LW Bogdanka S.A. shares.

Despite the lower demand for coal for electricity generation, coal mining cannot be stopped overnight (it was assumed that the pandemic situation was a temporary one—and stopping part of the production and then restarting it could cost much more than maintaining constant production), so maintaining adequate coal mining was essential even during the COVID-19 pandemic. Maintaining adequate mining is directly linked to ensuring an adequate number of production workers at the coalfaces—so proper preventive action and speed of detection of infected people was a priority for mining companies during this period. These activities generate certain costs—it was decided here to present, using the example of LW Bogdanka S.A., how these costs evolved in the years of the pandemic period, i.e., 2020 and 2021.

During the period, LW Bogdanka S.A. kept a separate record of costs related to prevention and counteracting the effects of COVID-19 virus infections. The records were kept by type, among others, and included such items as:

- Remuneration;
- Employee benefits;
- Materials;
- Depreciation;
- Outsourced services;
- Other costs by type.

In the context of total costs by type, the costs incurred for COVID-19 were not significant. In 2020, the share of these costs in total costs was around 0.25%, while in 2021, this share fell to 0.12%. Comparing pandemic costs alone year-on-year, it should be noted that in 2021 there was a decrease in these costs of around 50%. The breakdown of generic costs in 2020 and 2021 is shown in Figure 13.

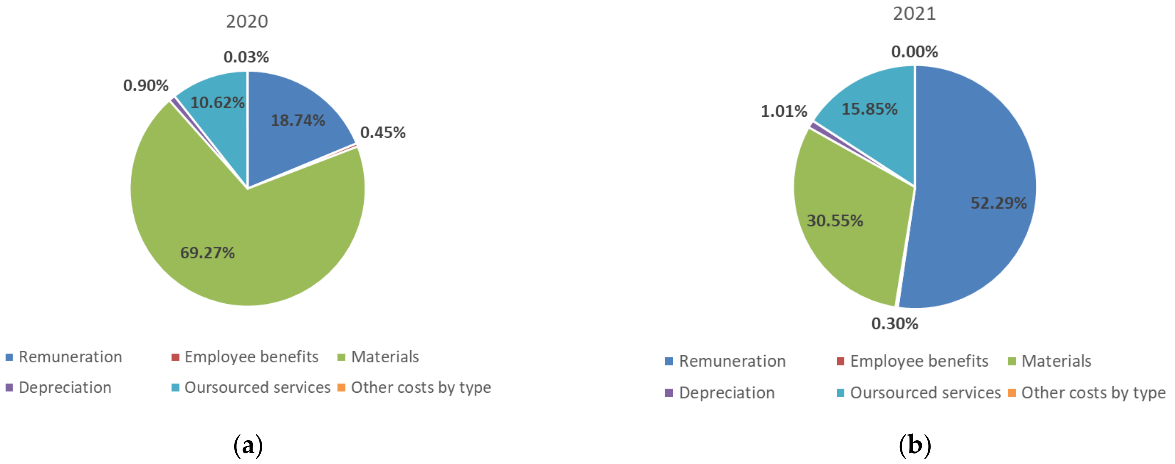

Figure 13. Percentage of individual generic costs incurred for the COVID-19 pandemic in 2020 (**a**) and 2021 (**b**).

Many factors contributed to the significantly higher costs in 2020, undoubtedly including the surprise of a rapidly spreading pandemic. In 2020, there was a significant increase in the need for all kinds of safety measures to prevent the spread of a pandemic, such as protective masks and disinfectants. Due to the significant increase in demand for these resources and their scarcity, material prices in 2020 were significantly higher than in 2021, where the market met the demand for such products.

The decrease in costs in 2021 is also a result of a lower number of virus infections. LW Bogdanka S.A. responded adequately to the number of infected people, as presented in Figure 14.

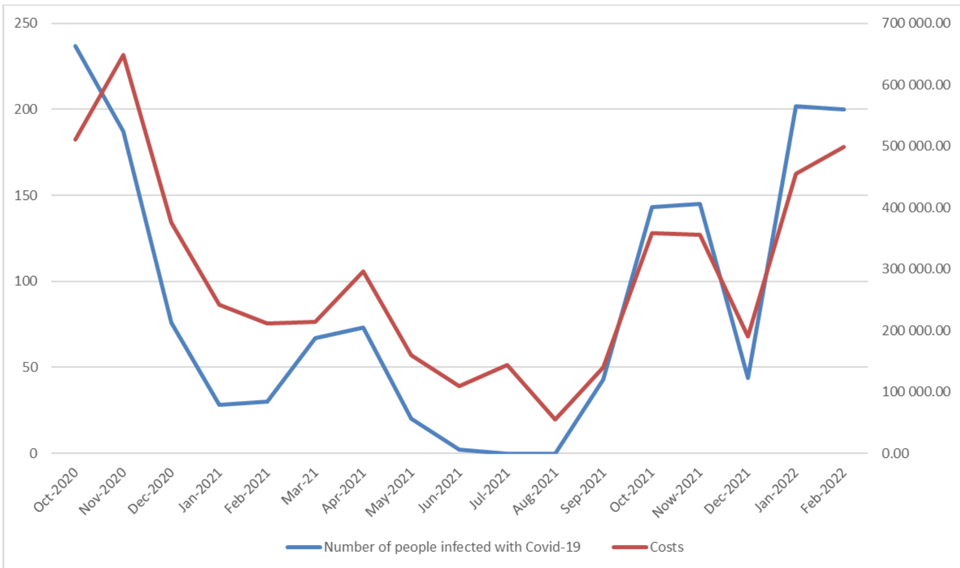

Figure 14. The number of people infected with COVID-19 and costs incurred for the same period, i.e., October 2020 to February 2022.

As can be seen from the Figure 14 shown, the costs during this period were commensurate with the number of infected people. The correlation coefficient for these variables is 0.92.

5. Conclusions

The outbreak of the COVID-19 coronavirus had a huge impact on various areas of activity of mining companies in Poland. As a consequence of the situation, companies were unable to meet their production plan (especially in the initial phase of the pandemic). According to data from the Higher Mining Office, hard coal output decreased from 61,623.0 thousand tonnes in 2019 to 54,385.9 thousand tonnes in 2020, a decrease of 7237.1 thousand tonnes. In 2021, the volume of mining was higher than in 2020 and amounted to 55,006.4 thousand t, although this was still a decrease relative to 2019 by 6616.6 thousand t [41,42]. The consequence of the introduction of COVID restrictions in the commercial area was a reduction in the volume of total coal sales, and the difficult staffing situation related to employee absenteeism resulted in the unpreparedness of planned enabling works, which resulted in the failure to implement the face works plan. For the entire period of the pandemic, the companies incurred additional labour costs related to the sickness of employees, remaining in quarantine or reorganising working conditions and carrying out preventive measures such as the introduction of the so-called "standstill" and various information campaigns [52]. However, there were no redundancies due to the worsening situation in the industry, and the dismissals were dictated by the implementation of the decarbonisation strategy and early retirements. The raw material market in Poland is currently in constant transformation (technological, technical, organisational and legal) [8].

Nevertheless, from the research and analysis of the initiatives undertaken and the adaptation measures taken at one of the Polish mining companies, LW Bogdanka S.A., it appears that it has coped with the challenges posed by the pandemic, ensuring the safety of all employees as well as the continuity of the plant's operations. The procedures and rules of conduct developed over the last two years will certainly constitute mechanisms for responding to a crisis situation, which we hope will not be repeated. The company's provision of a sense of security to employees (particularly the measures taken to reorganise work, including the division of crews into smaller groups, as well as the provision of personal protective equipment and disinfectants throughout the plant) and the employees' compliance and adjustment to the procedures introduced by the Boards and Crisis Staff have demonstrated the responsible attitude of the entire mining community of the company. This responsible and balanced approach to the introduced changes in the functioning of LW Bogdanka S.A. during the pandemic ensured that high standards in ESG areas were maintained. The measures taken and the associated increased costs related primarily to ensure the safety of employees and the purchase of necessary materials in the form of, e.g., masks, soaps, and disinfectant fluids had a positive effect in reducing the number of infections among employees.

The topic discussed in the article certainly requires exploration and comparison of initiatives and adaptation activities undertaken by LW Bogdanka S.A. with similar studies from other countries. It will be one of the Authors' future research directions.

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Article

Development of Electromobility in European Union Countries under COVID-19 Conditions

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Abstract: The introduction of electromobility contributes to an increase in energy efficiency and lower air pollution. European countries have not been among the world's leading countries in this statistic. In addition, there have been different paces in the implementation of electromobility in individual countries. The main purpose of this paper is to determine the directions of change and the degrees of concentration in electromobility in European Union (EU) countries, especially after the economic closure as a result of the COVID-19 pandemic. The specific objectives are to indicate the degree of concentration of electromobility in the EU and changes in this area, especially during the COVID-19 pandemic; to determine the dynamics of changes in the number of electric cars in individual EU countries, showing the variability in this aspect, while also taking into account the crisis caused by COVID-19; to establish the association between the number of electric cars and the parameters of the economy. All EU countries were selected for study by the use of the purposeful selection procedure, as of December 31, 2020. The analyzed period covered the years 2011–2020. It was found that in the longer term, the development of electromobility in the EU, measured by the number of electric cars, is closely related to the economic situation in this area. The crisis caused by the COVID-19 pandemic has influenced the economic situation in all EU countries, but has not slowed down the pace of introducing electromobility, and may have even accelerated it. In all EU countries, in the first year of the COVID-19 pandemic, the dynamics of introducing electric cars into use increased. The growth rate in the entire EU in 2020 was 86%, while in 2019 it was 48%. The reason was a change in social behavior related to mobility under conditions of risk of infection. COVID-19 has become a positive catalyst for change. The prospects for the development of this type of transport are very good because activities related to the development of the electromobility sector perfectly match the needs related to the reduction of pollution to the environment.

Keywords: decarbonizing transport; energy efficiency; electrify transport; zero-emissions vehicles; sustainable transport; electric car charging points

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1. Introduction

1.1. Negative Externalities of Car Use

Use of cars contributes to climate change. In addition, global car mobility continues to grow [1]. This is because transport is a key factor for the regional, national and international economy. Personal mobility is also important. Motor vehicles continue to depend on oil as their main source of energy. According to estimates, road transport directly contributed to around 20% of CO_2 emissions in Europe [2–5]. In addition to climate change caused by greenhouse gases, toxic tailpipe emissions and road noise pose an increasing threat to air quality and life in urban areas. Cars, trucks, vans and buses have been the biggest polluters of NO_x in cities [6]. Road traffic also contributes significantly to the emission of soot particles, directly increasing the risk of lung disease [7]. According to data from the World Health Organization (WHO), much more people die from poor outdoor air quality due to road traffic than from accidents [8,9]. According to the European Environment Agency's (EEA) Air Quality in Europe 2018 report, road transportation is a major source of atmospheric pollution, and the upper emission limits for the most harmful—ground-level ozone (O_3) nitrogen oxides (NO_x), and particulate matter were significantly exceeded [10]. The EU has estimated that 100 million people have been impacted by harmful noise levels outside 55 dB in the day and 60 million people above 50 dB at night. The dominant source of noise was road traffic. Such exposure resulted in deterioration of health and even death [11].

1.2. Electric Cars as an Element of Reducing Negative Externalities

Emissions of pollutants and noise from the propulsion of the vehicle can be avoided. Trains, trams and subways were electrified decades ago, and in the early years cars were also electric. For example, in 1914, 2.4% of the Dutch automobile fleet was battery powered [12]. After its initial success, however, electrification was delayed for practical reasons. The range of this type of car was too limited, and the batteries were too large, heavy, and expensive while oil was much more energy dense and cheaper [13,14]. Nowadays, thanks to improved electronics and batteries, electric vehicles can travel 500 km on a single charge and quickly recharge the batteries. This range has been confirmed in the authors' research on the example of the British market. The average range of the top 10 electric cars was 491 km, with the smallest range being 350 km and the largest 610 km [15]. The charging time of an electric car is directly dependent on the power of the charging station. Zero exhaust emissions from the exhaust pipe of electric vehicles and zero engine noise have a positive effect on local air quality and living conditions [16]. Depending on the energy source used, emissions in the energy supply chain and production can also be very low or even zero. The total environmental impact of vehicles powered by electricity generated from hard coal is better than in the case of a car with an internal combustion engine [17,18]. In many countries, public charging stations deliver electricity from renewable energy sources like water, sun and wind power, in which case electric cars can truly be called emission-free. Electric vehicles are also seen as providing storage capacity for variable renewable energy production [19,20].

Breakthrough technologies such as electrification, automation and the sharing economy, mean renewable energy can make the automotive industry more sustainable [21,22]. Changes in the automotive industry should have a positive impact on ecology and the economy [23]. In addition to technology, a key factor in this transformation is willingness to change, which is the social part of the innovation process. The refusal to continue tolerating the negative aspects of transport for the environment is often the cause of public acceptance [24–28].

1.3. Types of Electric Cars

There are several types of electric cars. The division criterion is the type of drive. battery electric vehicle (BEV) cars are fully electric, i.e., they do not have an internal combustion engine and their only drive unit is a battery. The batteries are charged from the socket, which one can do at home. The operating costs of such a vehicle can be reduced by charging the battery at night, when electricity rates are lower. The battery capacity determines the range of the vehicle, which is why such a car is best suited for city driving or short distances. This limitation is a disadvantage of BEVs. Its mechanics should be considered an advantage, as it is much simpler than in conventional drive vehicles (fewer parts and less liquid to top up). BEVs powered only by a battery do not emit any harmful substances into the atmosphere [29].

The hybrid electric vehicle (HEV) car has two types of drive, i.e., a combustion engine and an electric drive (the so-called hybrid). This vehicle does not have the option of recharging the battery from external energy sources. The car uses conventional fuel for the internal combustion engine and the energy generated by the vehicle when braking during various maneuvers. The most "recycled" energy is generated, for example, when driving in city traffic jams, and not much on the motorway [30].

The plug-in hybrid electric vehicle (PHEV) car is a hybrid electric car with the possibility of charging. The vehicle is partly conventional and partly electric. It can be refueled at a gas station and the batteries can be charged from an external energy source. This combination makes the PHEV a very popular type of electric car. While driving the internal combustion engine can be used, then one may switch to electric drive or to hybrid mode [31]. Compared with other types of electric cars, PHEVs have a better range. In addition to the electric drive, they use an internal combustion engine. Usually, PHEV have smaller fuel tanks due to the placement of batteries. This range has been confirmed in the authors' research on the example of the ranking conducted by Forbes. The average range of the 11 best PHEV cars was 716 km, with the lowest range being 515 km and the highest 966 km [32]. The disadvantage of the PHEV is the need for more expensive maintenance of two power units with different energy sources. The production costs of such cars are higher, and so are their market prices [31].

Additionally, there are several types of partially electric cars. The mild hybrid electric vehicle (MHEV) car is another type of hybrid, the so-called soft hybrid. The construction of such a drive system is the same as in the case of the HEV. The difference lies in the size and power of the electric motor used (it is much weaker). Its main role is to start the engine and take over the function of the alternator. The reduction in fuel consumption can be up to 15%. The range extended electric vehicle (REEV) car is one of the vehicles with extended range, which is also the opposite of the MHEV. The internal combustion engine in this case plays a supporting role by charging the batteries, while the electric unit is the main driving force. The fuel cell electric vehicle (FCEV) is the most secretive car. Hydrogen and its reaction with oxygen are responsible for the generation of electricity going to the battery. Instead of supplying a portion of electricity, users refill the fuel cells with hydrogen [33–35].

1.4. The COVID-19 Pandemic and Its Impact on the Global Electric Car Market

COVID-19 has been determined as an acute infectious illness of the respiratory system caused by infection of the SARS-CoV-2 virus [36]. It was first recognized and described in December 2019, in central China, in the city of Wuhan, Hubei province [37–40]. There have been many cases that have spread beyond the borders of China, to virtually all countries of the world. On 11 March 2020, the World Health Organization (WHO) recognized the series of COVID-19 incidents since December 2019 as a pandemic. At that time, there were over 118 thousand confirmed cases of infection in 114 countries and 4291 people died [41]. The pandemic's pace and course varied. By 4 November 2021, 248 million cases of infection had been confirmed worldwide, and 5 million people had lost their lives. There were 78 million infections and 1.44 million deaths in Europe [42]. The continued spread of the disease in the first year was due to the lack of a vaccine and effective therapeutic agents against this new virus [43,44]. Many countries have introduced movement restrictions and some activities have been officially banned. Thus, the pandemic had a big impact on social life and the economy. Scenarios for dealing with the outbreak varied from country to country [45].

In the world, sales of electric cars in the second decade of the 21st century grew very quickly, at a rate of 46–69% per year. Only in 2019 was there a visible slowdown, because worldwide the number of light electric vehicles increased by 9% compared with 2018. This meant a clear deviation from the pace of growth in the previous six years. The reason for this change was the decline in sales in the second half of 2019 in the two largest markets, i.e., China and the USA. However, even with the stagnation in these markets, global sales of electric vehicles continued to grow, mainly in Europe, which saw an increase of several dozen percent. The COVID-19 pandemic and the ensuing economic slowdown had a negative impact on the global market for all types of cars. As a result, the prospects for global sales of electric vehicles in 2020 were uncertain. However, time has shown that 2020 has turned out to be surprisingly positive despite the pandemic and its effects. Global electric vehicle sales have risen 43% from 2019 and global electric car market share has risen to a record 4.6% in 2020. Given the decarbonization challenge that most leading countries now take seriously, 2021 is a breakthrough in the history of electric vehicle sales and about 6.4 million vehicles (BEV and PHEV combined) will be sold by the end of the year worldwide. This would then mean an increase of 98% year on year [46].

In 2019, the global market for electric vehicles was valued at USD 162 billion, and is forecast to reach a value of approximately USD 800 billion by 2027, with an average annual growth rate of 23%. The Asia-Pacific markets should continue to dominate, and it is estimated that they will generate USD 358 billion by 2027 (with an average annual growth rate of 20%). In the North American market, revenues should be USD 194 billion, with an annual growth rate of 28%. Markets in North America and Europe together accounted for 40% of the world market in 2019. According to forecasts, in 2027 the share of these two segments will reach 51% of the total electric car market in the world [47].

1.5. Justification, Aims and Structure of the Article

The subject matter of the article is important and up to date. Transport is a significant energy consumer. The use of electric cars contributes to the reduction of negative externalities in the form of environmental pollution, noise and energy consumption. The share of electric cars is still small, especially on the European continent. Some hope lies in the high pace of introducing electric cars into use. The outbreak of the COVID-19 pandemic may have contributed to a slowdown in this regard. This can be judged by the example of many industries that have been affected by the crisis caused by the global pandemic. An example is the automotive industry, which is slowing down quite sharply. In the EU countries, the effects of the crisis were quite visible, because the automotive industry was based on components imported from Asia. As a result of the interruption of supply chains, many factories of automotive concerns have had to reduce their production.

There is a research gap that this article can fill. The literature review shows no previous studies on the situation in the electromobility sector during the COVID-19 pandemic. We did not find publications that reported the situation of the electromobility market in EU before and during COVID-19. In addition, our research will cover the area of the EU, which is still quite diverse. Europe still has considerable electromobility market development potential. It will be interesting to determine whether this development stopped during the COVID-19 pandemic and how it unfolded in individual countries. The above aspects make the research necessary and original. The novelty of the article is the presentation of the situation and changes in the field of electromobility under COVID-19 pandemic conditions, as well as the relationship between the grade of economic development and the development of electromobility. This type of research has not been performed so far.

The main goal of the article is to determine the directions of change and the degree of concentration in electromobility in European Union (EU) countries, especially after the economic closure as a result of the COVID-19 pandemic.

The specific objectives are:

- identifying the degree of concentration of electromobility in EU and changes in this area, especially during the COVID-19 pandemic;
- determining the dynamics of change in the number of electric cars in individual EU countries;
- showing the variability in number of electric cars, while also taking into account the crisis caused by COVID-19;
- establishing an association between the number of electric cars and the parameters of the economy, including during the COVID-19 pandemic period.

Three research hypotheses are formulated in the paper:

Hypothesis 1. *Electric car concentration is decreasing in the EU, and the COVID-19 pandemic has accelerated these changes.*

Hypothesis 2. *In EU countries, the dynamics of introducing electric cars into use has decreased in the first year of the COVID-19 pandemic.*

Hypothesis 3. *The development of electromobility in the EU, measured by the number of electric cars, is closely related to the economic situation in this area.*

The organization of this paper is as follows: Section 1 provides an introduction to the subject. The impact of road transport in negative externalities is presented. The possibility of using electric cars is shown. Concerns related to the COVID-19 pandemic on the development of electromobility are also presented. This section also contains justification and aims of the article. Section 2 proposes methods to identify differences and changes in electromobility in EU states. In Section 3, the research findings are presented. Section 4 includes reference to other research studies that have dealt with the relationships tested. Section 5 concludes this paper.

2. Materials and Methods

2.1. Data Collection, Processing, and Limitations

All EU countries were selected for this research using the purposeful selection method, as of 31 December 2020. In total, 28 EU states were examined. Great Britain was a member of the EU until 31 January 2020. Until the end of 2020, there was a transition period in mutual relations between Great Britain and the EU. Relationships in all areas were conducted on the basis of previous conditions. In addition, the country is one of the leaders in electromobility in the EU. Therefore, it was decided to include Great Britain in the research.

The research period covered the years 2011–2020. Adopting such a period is substantively justified. Before 2011, electromobility was developed in a few EU countries. In 2011, electric cars were already in use in most EU countries (in 19 countries). In 2014, electric cars were already available in all countries. Until 2019, changes in electromobility resulting from the normal functioning of the economy can be observed. In 2020, there was an economic crisis caused by the COVID-19 pandemic. The European continent has been severely hit by the effects of COVID-19. The year 2020 was the last in which complete research data is available.

The research used data on the total number of BEV and PHEV electric cars. These were cars that used batteries and required the use of charging stations. Other forms of electromobility, such as electric micromobility (bicycles, scooters, scooters) are becoming more and more popular. They were not tested.

The data used in the study comes from Eurostat for the years 2011–2020. Data collection is limited by the lack of detailed and timely information on electromobility. Additionally, these data are aggregated at the country level, so there is a problem with performing analyses at the regional or city level.

The study is a result of the authors' previous research on transport. Quite recently, the field of the writers' interest has been power engineering. These two areas are closely connected because without energy, transport is impossible. The vast majority of authors are economists. Therefore, the aspect related to economics was raised. Additionally, it was noted that there is no current academic studies on the relationship between electromobility and economic development.

2.2. Applied Methods

The research was sectional into stages. Figure 1 shows a scheme of the conducted research.

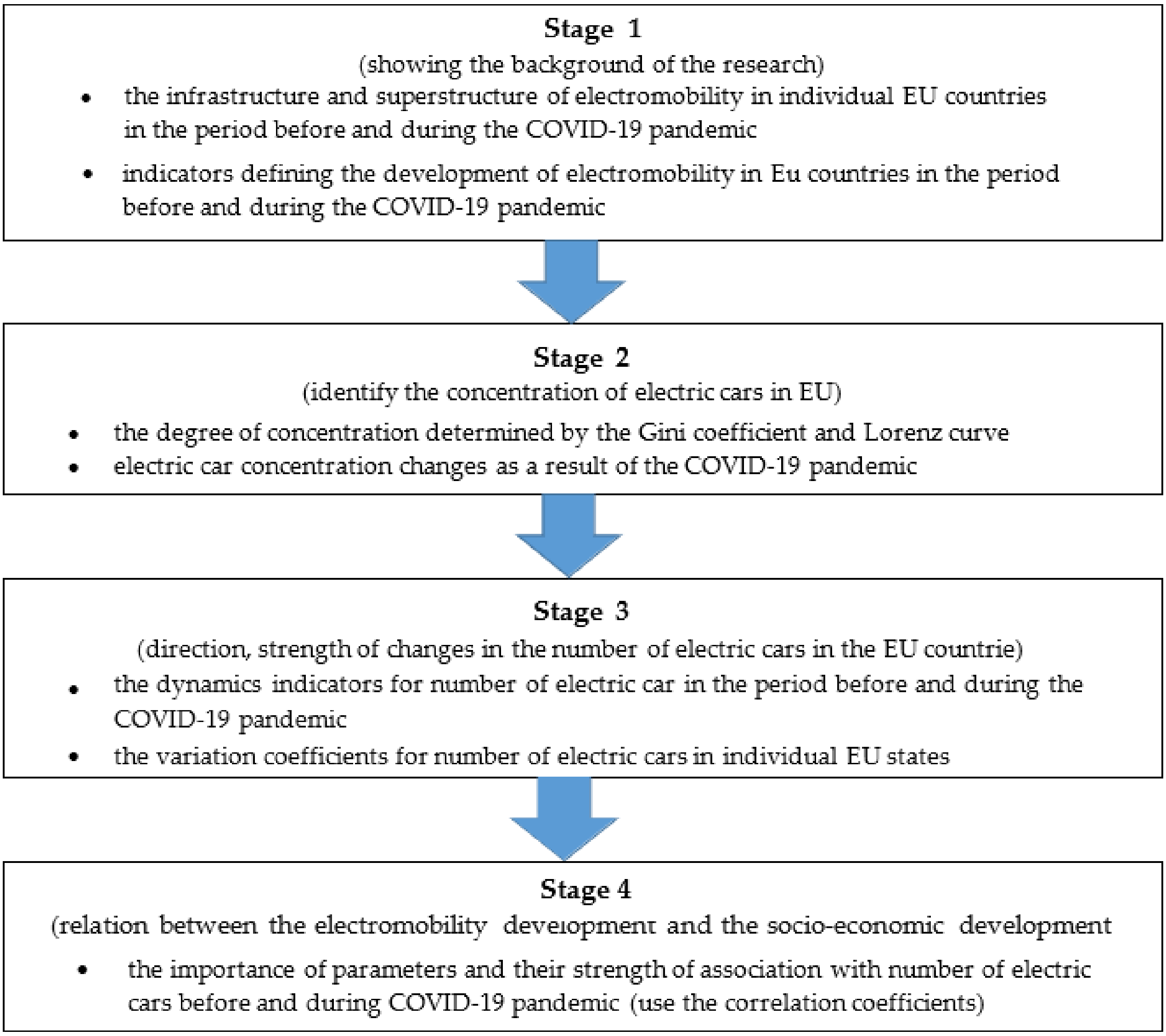

Figure 1. Scheme of the conducted research.

The first stage of the research presents the situation in all EU countries in the period before and during the COVID-19 pandemic (2019–2020) in terms of the number of electric cars. Such raw data do not always make it possible to determine the significance and development of electromobility in individual countries. Therefore, it was decided to calculate the basic indicators. Such indicators are needed because individual countries vary in terms of population, area of the country, the total number of cars, and the length of highways (roads of the best quality). The aim of this part was to present the actual leaders and outsiders in the field of electromobility in the EU in the period before and during the pandemic.

In the second stage of the research, the concentration of electric cars in total in individual EU states is presented. Changes in this respect are also shown. Gini's associate was utilized for this aim. The degree of concentration is determined by the number of electric cars in the EU. If these values concern merely one nation, the coefficient would be 1. If, on the other hand, they are spread for more countries, the coefficient is lower; the closer to 0, the more even the decomposition of the volume of consumption of renewable energy amongst EU countries. The degree of concentration can be represented graphically, for which the Lorenz curve is used.

Concentration ratios were calculated every four years and additionally in 2020, as the period of the crisis caused by the COVID-19 pandemic. Therefore, the results relate to the years 2011–2020. Such a comparison allows us to determine the direction and speed of the changes taking place in the concentration of the number of electric cars in the EU.

The Gini coefficient is used to measure the unevenness (concentration) of decomposition of a random variable. In cases where the observations are sorted in ascending order, the coefficient can be presented by the formula [48]:

$$G(y) = \frac{\sum_{i=1}^{n}(2i - n - 1) \times y_i}{n^2 \times \overline{y}} \quad (1)$$

where:
n—count of observations,
y_i—value of the "i-th" measurement,
$\overline{y}$—the average value for all observations, i.e., $\overline{y} = \frac{1}{n}\sum_{i=1}^{n} y_i$.

The Lorenz curve defines the degree of concentration for a one-dimensional random variable decomposition [49]. With sorted observations y_i, being non-negative values $0 \leq y_1 \leq y_2 \leq \ldots \leq y_n$, $\sum_{i=1}^{n} y_i > 0$, the Lorenz curve can be referred to as a polyline with apexes (x_h, z_h), for h = 0, 1, ... , n, having the following coordinates:

$$x_0 = z_0 = 0,\ x_h = \frac{h}{n},\ z_h = \frac{\sum_{i=1}^{h} y_i}{\sum_{i=1}^{n} y_i} \quad (2)$$

The Gini coefficient means the area between the Lorenz curve and the secant of a unit square multiplied by two.

The third stage of the research presents data on changes in the total number of electric cars in individual EU countries. Dynamics indicators for the number of electric cars were calculated. As a result, the directions and strength of the analyzed variables were obtained. It was not until 2014 that the first electric cars appeared in several countries. Therefore, the dynamics indicators for the two periods 2011–2020 and 2014–2020 were calculated. Admitting the years 2014–2020 to the research allows for more reliable results. In 2014, electric cars were already in use in all countries. Two types of dynamics indicators were used.

In this paper the chain simple dynamic indicators were used as follows [50]:

$$i_{t,t-1} = \frac{y_t}{y_{t-1}} * 100 \quad (3)$$

where:
y_t—level of the occurrence in a certain period,
$y_{t\text{-}1}$—level of the phenomenon during one period earlier.

The dynamics indices on a constant base were utilized for the research too. The constant-based dynamics indicator has the following formula [50]:

$$i = \frac{y_n}{y_0} \text{ or } i = \frac{y_n}{y_0} \times 100\% \quad (4)$$

where:
y_n—the level of the phenomenon in a certain period,
y_0—level of the phenomenon during the reference period.

In the third phase, the variation coefficients for the number of electric cars in individual EU states were calculated too. As a result, it was possible to determine whether the number of electric cars is stable or is subject to substantial fluctuations.

The variation coefficient referred to as C_v eliminates the unit of estimate from the standard deviation of a set of number. This is done by receiving the quotient of standard deviation divided by the arithmetic mean. For sequence of N numbers, the variation coefficient is counted as follows [51]:

$$C_v = \frac{S}{M} \tag{5}$$

where:
S—standard deviation of the exemplar set of numbers,
M—arithmetic mean from the exemplar set of numbers.

In the fourth stage, the relationship between the number of electric cars in the EU and the parameters related to socio-economic potential. For the calculations, parameters were selected that are components of simple indicators that actually assess electromobility. These indicators are presented in the first stage of the research. The following variables were used: population (million), area of the country (square kilometer), number of cars, the length of the highways (kilometer), value of gross domestic product (GDP)(million euro), GDP per capita (euro per capita). The research was performed for four periods. Two of these concerned the time before the COVID-19 pandemic, i.e., the years 2011–2019 and 2014–2019. The next two already included 2020, i.e., a full year related to functioning in the conditions of the COVID-19 pandemic (2011–2020 and 2014–2020). The logic of carrying out the tests for different periods was the same as for the dynamics indicators.

Thanks to this study, it is possible to determine the importance of parameters and their strength of association with the number of electric cars before and during COVID-19 pandemic. In this phase of the study, two non-parametric tests were used to define the correlation between the parameters. The first is Kendall's tau correlation coefficient. This indicator is established on the dissimilarity between the probability that two variables decrease in the same sequence (for the commentate data) and the plausibility that these factors are different. This coefficient has a fluctuation in the range of values $<-1, 1>$. Value 1 means full match, value 0 indicates no adjust of order, and value -1 indicates the complete reverse. The Kendall coefficient indicates not only the robustness but also the trend of the interdependence. It is an appropriate tool to represent the resemblance of the ordered sets of information. The following formula can be utilized to calculate Kendall's tau correlation coefficient [52]:

$$\tau = P[(x_1 - x_2)(y_1 - y_2) > 0] - P[(x_1 - x_2)(y_1 - y_2) < 0] \tag{6}$$

This formula evaluates Kendall's tau to give a statistical sample. At the beginning, all possible pairs of the research trial are combined. In the next step, the pairs are split to three potentially units:

P—compatible pairs, in which the analyzed factors about two observations fluctuate in the identic trend, i.e., either in the first remark both are higher than in the second, whether both are less meaningful,

Q—incompatible pairs, in which the factors are different against each other in the opposite tendency, i.e., one of them is much more significant for this observation in the couple, while the other is lower,

T—related couple, when one of the variables has similar values in both tested observations.

The Kendall tau coefficient is then counted from the following formula:

$$\tau = \frac{P - Q}{P + Q - T} \tag{7}$$

Moreover,

$$P + Q + T = \binom{N}{2} = \frac{N(N-1)}{2} \tag{8}$$

where:
N—sample volume.

The pattern can be quantified as:

$$\tau = 2\frac{P - Q}{N(N-1)} \tag{9}$$

The second form of non-parametric research trial is the Spearman's rank correlation coefficient, that describes the strength of the correlation of couple characteristics. It is used to study the relationship between quantitative parameters for the small amount of tested observations. Spearman's rank correlation coefficient is calculated according to the following formula [53]:

$$r_S = 1 - \frac{6\sum_{i=1}^{n} d_i^2}{n(n^2-1)} \tag{10}$$

where:

d_i—disagreement between the range of the corresponding parameters x_i and feature y_i (i = 1, 2, . . . , n)

The value of Spearman's rank coefficient oscillates in the range $-1 \leq r_s \leq +1$. A positive digit means a positive correlation, while a negative number indicates a negative correlation. The more identic modulus (absolute value) of the correlation coefficient, the stronger a correlation between analyzed variables.

MS Excel was used to calculate the basic electromobility indices as well as the dynamics indicators and coefficient of variation. The Gnu Regression, Econometrics and Time-series Library (GRETL) econometric package was used to determine the degree of concentration of electric cars in the EU, with Kendall's tau correlation coefficient and Spearman's rank coefficient [54].

Descriptive, tabular and graphic methods were also used to present some of the findings.

3. Results

3.1. Electromobility in Individual EU Countries before and during the COVID-19 Pandemic

The development of electromobility can be measured in several ways. One of the most obvious and accurate is the number of electric cars. In EU countries, the idea of electromobility began to gain particular importance in the second decade of the 21st century. In 2011, electric cars were used in 19 EU countries, and in 2014, in all member states. In 2011, a total of 15,000 electric cars were used in the EU, and in 2020 already 2.5 million. Of course, there are differences between countries in the scale and speed of introducing electric cars into service. In 2020, every fourth electric car in the EU was used in Germany (Figure 2). This country has been a leader in the field of electromobility. Certainly, the location of significant car concerns in this country could be one of the factors explaining Germany's position. Great Britain, France, the Netherlands, and Sweden are also among the top five countries in terms of the number of electric cars. They were the most economically developed countries. In turn, among the five countries with the lowest number of electric cars was Cyprus, Latvia, Croatia, Estonia and Bulgaria. They are economically developing countries. Malta and Cyprus are among the smallest countries in terms of area. In 2020, the number of electric cars in all EU countries increased, which means that the effects of the crisis caused by COVID-19 did not considerably affect this part of the automotive industry.

Appropriate infrastructure in the form of public charging stations contributes to the development of electromobility. Such points are located in the largest cities. The situation in this respect is improving year by year. Individual countries were compared in terms of infrastructure using the indicator of the number of electric cars per one public charging point (Figure 3). It turns out that the largest number of cars for such a point was in countries with a relatively small number of vehicles, such as Portugal, Malta and Lithuania. Probably in this case the development of infrastructure did not keep up with the increase in sales of this type of cars. The case of Germany is interesting, where in 2019 there were 6.2 electric cars per public charging point, and in 2020 it was already 13.3. The reason for such a large increase in the indicator was the very high sales of electric cars in 2020 (an increase of 143%

compared with 2019), with a small increase in public charging points (by 14%). A similar situation also occurred in the case of Malta, Ireland, Denmark and Luxembourg. Only a few countries have seen a lower load on public charging stations, i.e., Greece, Cyprus, Bulgaria and Austria. This was due to large investments in infrastructure. In most EU countries, the changes were not large. Of course, the COVID-19 pandemic could have had an impact on electromobility development strategies in individual countries. This problem requires closer examination. The presented results show that there has been no single path for the development of electromobility in individual EU countries.

In the next stage, the basic indicators determining the development of electromobility in individual countries are compared (Table 1). Data are compiled for the two years before and during the COVID-19 crisis. The three highest results for a given indicator are marked in blue, and the three lowest in red. The Netherlands is the country with the best indicators in each category. Almost all of the highest indicators are also in Sweden. It can therefore be concluded that these are the most developed countries in the field of electromobility. Greece is at the other extreme, as is Croatia. In most of the categories, the indicators are relatively low in Poland and Bulgaria. In these countries, the development of electromobility has been quite weak compared with the potential. Interestingly, Germany is in the middle of the field in all indicators. Of course, the number of electric cars is impressive, but it should be remembered that it is a country with the largest population of people, a very large area, developed motorization and transport infrastructure. The indicator determining the share of electric cars in the total number of cars in a given country is particularly interesting. In Sweden, the Netherlands and Denmark, it is at the level of 2–4%. It must be added that these countries are leaders. Objectively assessing the share of electric cars in the total number of cars, it is very low. The still low popularity of this type of vehicle, and the undeveloped infrastructure causes a vicious circle. Infrastructure in the form of public charging stations is particularly required. Without it, the number of electric cars will not grow rapidly.

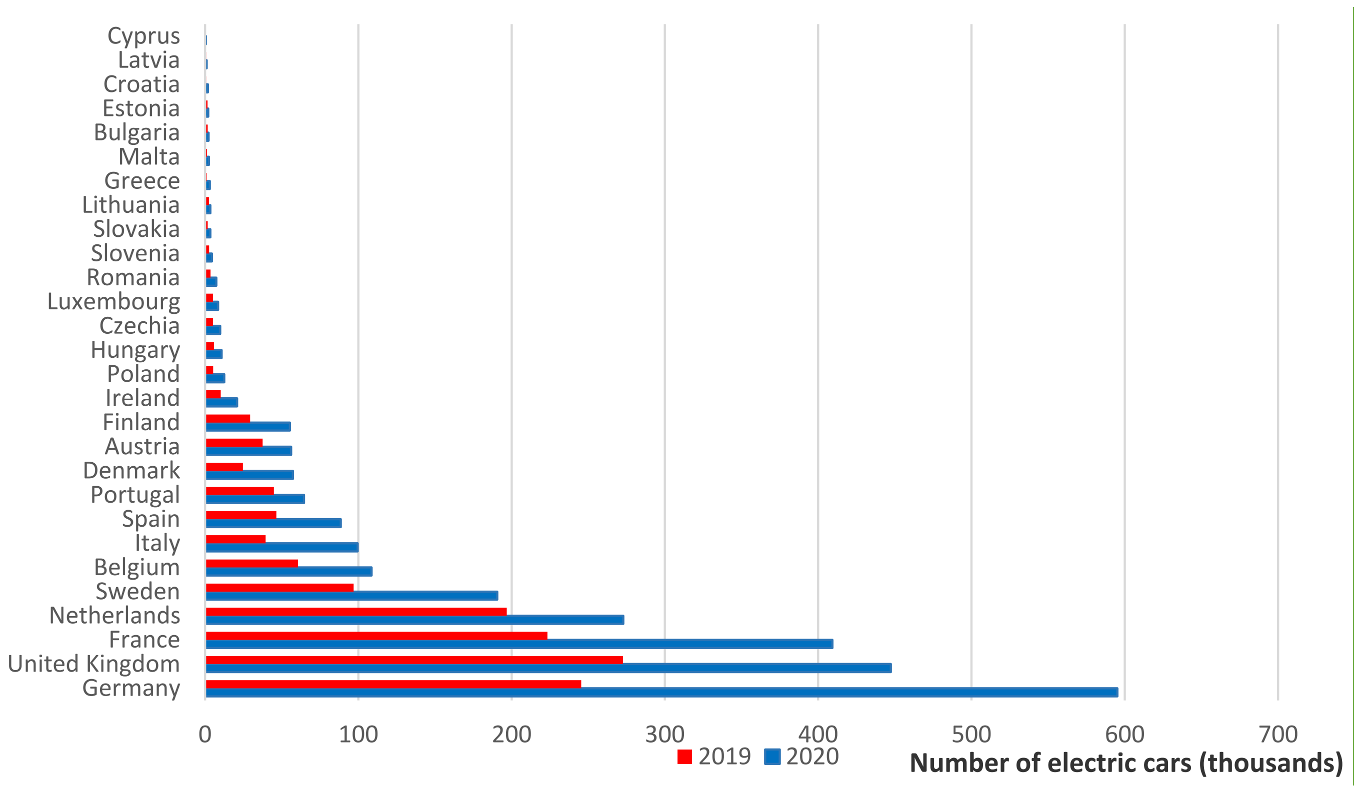

Figure 2. Number of electric cars in EU countries in 2019 and 2020.

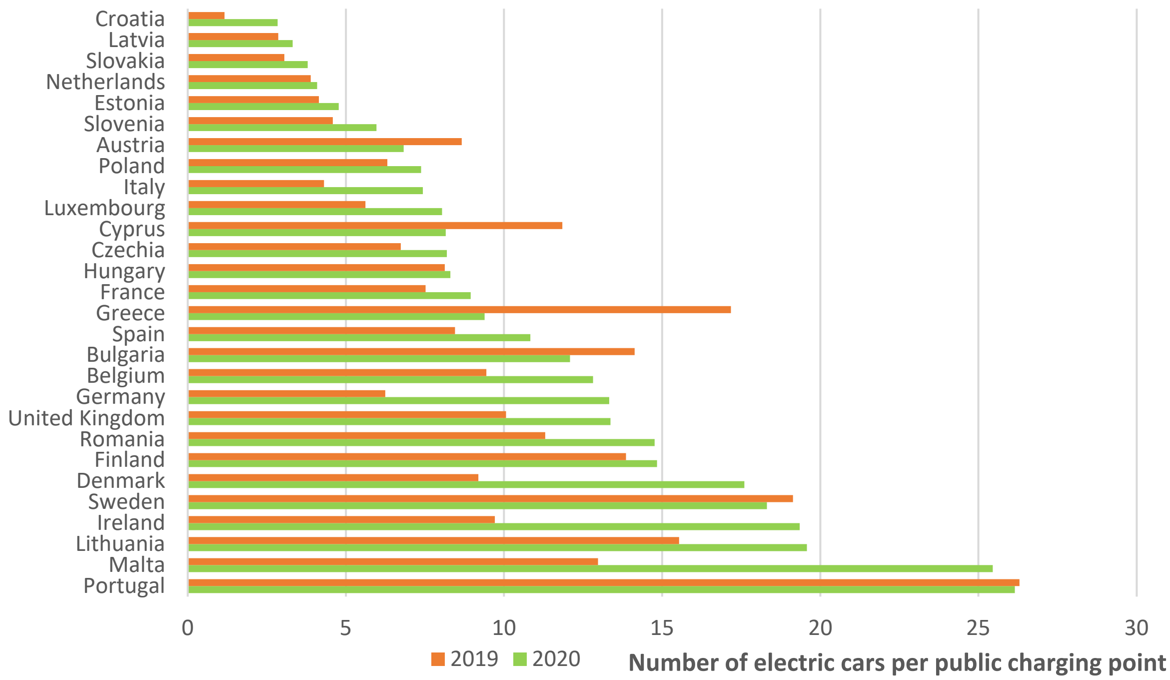

Figure 3. Number of electric cars per public charging point in EU countries in 2019 and 2020.

Table 1. Indicators assessing the development of electromobility in EU countries in 2019-2020.

Countries	Electric Cars per Thousand Inhabitants		Electric Cars Per Square Kilometer		Electric Cars Share in Total Cars		Electric Cars per Kilometer of Motorway	
	2019	2020	2019	2020	2019	2020	2019	2020
Austria	4.24	6.31	0.45	0.67	0.74	1.10	21.55	32.24
Belgium	5.30	9.43	1.98	3.54	1.03	1.81	34.43	61.65
Bulgaria	0.25	0.34	0.02	0.02	0.06	0.08	2.18	2.84
Croatia	0.17	0.47	0.01	0.03	0.04	0.11	0.54	1.45
Cyprus	0.51	0.64	0.05	0.06	0.08	0.10	1.75	2.22
Czechia	0.49	0.92	0.07	0.12	0.09	0.16	4.09	7.61
Denmark	4.26	9.83	0.58	1.33	0.93	2.11	18.40	42.58
Estonia	1.22	1.52	0.04	0.04	0.20	0.25	10.02	12.58
Finland	5.32	10.01	0.09	0.16	0.83	1.55	31.71	59.74
France	3.33	6.08	0.41	0.75	0.69	1.25	19.14	35.04
Germany	2.96	7.16	0.69	1.66	0.51	1.23	18.61	45.09
Greece	0.09	0.29	0.01	0.02	0.02	0.06	0.43	1.36
Hungary	0.60	1.10	0.06	0.12	0.15	0.28	3.38	6.01
Ireland	2.08	4.22	0.15	0.30	0.45	0.92	10.27	20.53
Italy	0.66	1.67	0.13	0.33	0.10	0.25	5.65	14.12
Latvia	0.35	0.55	0.01	0.02	0.09	0.14	-	-
Lithuania	0.91	1.25	0.04	0.05	0.17	0.23	6.28	8.69
Luxembourg	8.35	13.65	1.97	3.29	1.20	1.95	31.06	51.81
Malta	2.68	5.00	4.19	8.14	0.43	0.82	-	-
Netherlands	11.39	15.68	5.27	7.30	2.27	3.10	70.56	97.18
Poland	0.14	0.33	0.02	0.04	0.02	0.05	3.15	7.31
Portugal	4.37	6.27	0.50	0.72	0.82	1.18	14.65	21.07
Romania	0.18	0.38	0.01	0.03	0.05	0.11	4.06	8.13
Slovakia	0.33	0.64	0.04	0.07	0.07	0.15	3.60	7.07
Slovenia	1.28	2.13	0.13	0.22	0.23	0.38	4.26	7.15
Spain	0.99	1.87	0.09	0.18	0.19	0.36	2.98	5.64
Sweden	9.48	18.46	0.22	0.43	1.98	3.83	45.45	89.40
United Kingdom	4.09	6.67	1.12	1.83	0.86	1.39	70.89	116.20

3.2. Changes in the Concentration of Electric Cars in EU Countries

The next stage of the research was to present the concentration of the number of electric cars in individual countries and changes in this regard. The Gini coefficient was used to determine the concentration degree of the number of electric cars. In 2011, the Gini coefficient calculated from the sample was 0.83, and the estimated coefficient for the population was 0.86. This meant a very high concentration of electric cars in one or several EU countries. In the following years, the degree of concentration decreased systematically. The existing differentiation was as well shown by means of the Lorenz concentration curve (Figure 4). Among the leaders there are countries from Western Europe, the most economically developed. In 2020, the top five countries (Germany, Great Britain, France, the Netherlands, Sweden) accounted for 75% of the total number of electric cars in the EU. In the top ten countries, there were 92% of such cars in total. This group included only Western European countries.

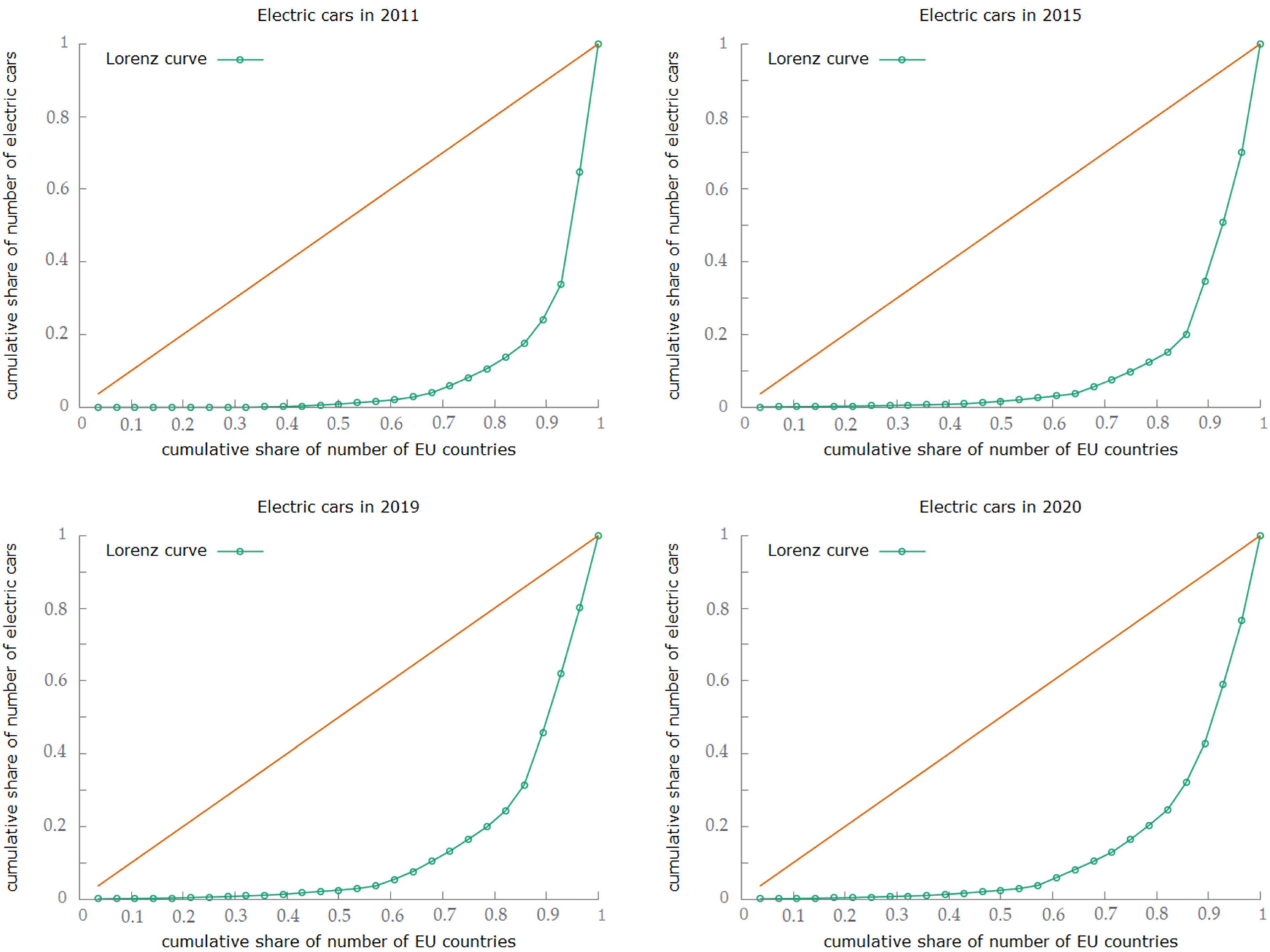

Figure 4. Lorenz concentration curves for number of electric cars in the EU countries in 2011–2020.

Concentration coefficients were as well calculated for the earlier periods, every four years, and additionally in 2020, as the period of the crisis caused by the COVID-19 pandemic. As a result, the effects relate to the years 2011–2020. Such a comparison allows us to determine the direction and pace of the changes taking place in the concentration of the number of electric cars in the EU. Generally, it can be noticed that the concentration level of electric cars is decreasing in several countries (Table 2). Such a phenomenon is positive because it proves the development of this type of transport in many EU countries. Interestingly, the period of the crisis resulted in a slight increase in concentration. Probably in less developed countries, the focus has been on other problems. Therefore, the most developed countries in the field of electromobility have increased their advantage.

Table 2. Gini coefficients for number of electric cars in the EU countries in 2011–2020.

Type of Coefficient	Gini Coefficients in Years			
	2011	2015	2019	2020
from the sample	0.83	0.79	0.72	0.73
estimated	0.86	0.82	0.75	0.76

3.3. Directions of Changes of Number of Electric Cars in EU Countries before and during the COVID-19 Pandemic

The number of electric cars in the EU countries varies. The dynamics of their changes are also different (Table 3). The three countries with the highest dynamics of changes in a given year or period are marked in blue, and three countries with the lowest dynamics are marked in red. In fact, there is no country that would be the growth leader in the following years. The reason is also because there are different levels from which individual countries began to develop electromobility. Very high dynamics indicators were achieved for the years 2011–2020. The largest of these are in Greece, Romania and Hungary, i.e., in countries that have not been the largest tycoons in the field of electromobility. In turn, the lowest rates are obtained in Croatia, Estonia and Bulgaria, which were most often indicated as the least developed in electromobility. For the years 2014–2020, the dynamics indicators are still very high, but still much lower than for the period 2011–2020. This time, the fastest growth in the number of electric cars is in Portugal, Romania and Finland. On the other hand, the slowest rates are in Estonia, Latvia and the Netherlands. There may have been some market saturation in the Netherlands. In addition, the country had begun to develop electromobility very quickly. That said, the more than fivefold increase in the number of electric cars in six years cannot be considered a poor result. Overall, it must be said that the number of electric cars grew rapidly in all countries. The pace of change depended on the initial number of electric cars and the stage of electromobility development in a given country. In 2020, compared with 2019, the number of cars increased in all EU countries. There was no COVID-19 crisis in sight here. On the contrary, the growth rate in the entire EU in 2020 was 86%, while in 2019 it was 48%.

3.4. Variability of the Number of Electric Cars in EU Countries

The variability of the number of electric cars over several periods was also determined. Again, the three best results are marked in blue, with the lowest variability indicating stable, steady growth. In turn, the three highest results, i.e., countries with very large fluctuations in the number of electric cars, are marked in red. The greatest stabilization is in Estonia, the Netherlands and Latvia (Table 4). In turn, the greatest changes are found in Malta, Romania and Greece. In the case of adopting a shorter period (from 2014), the level of variability in the number of cars is lower than for the longer period (from 2011). Additionally, a comparison of the results for the periods before the COVID-19 pandemic with the periods including the year 2020 allowed us to state a certain regularity. The COVID-19 pandemic resulted in greater variability in the number of electric cars in individual EU countries. Based on the results of the dynamics study, it can be concluded that in 2020, as a rule, the dynamics of change accelerated, the number of cars increased significantly. Therefore, the coefficient of variation deteriorated when taking into account the year 2020.

Table 3. Dynamics indicators for the number of electric cars in EU countries in 2011–2020.

Countries	Dynamics of Changes in the Years (Previous Year = 100)										(Base Year = 100)	
	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2011–2020	2014–2020
Greece	-	100	300	2067	200	135	213	164	171	315	313,500	5056
Croatia	-	-	-	100	368	157	111	141	178	267	4332	4332
Italy	100	656	247	172	169	156	154	175	171	252	85,059	3051
Germany	100	182	179	172	166	154	149	153	163	243	12,791	2298
Poland	100	189	156	250	190	158	221	180	172	236	35,643	4854
Denmark	100	208	152	210	260	117	113	145	160	231	12,289	1841
Romania	100	200	480	165	197	199	218	201	258	211	148,200	9380
Ireland	100	302	128	241	194	159	146	196	194	205	32,714	3513
Slovakia	100	102	100	467	146	121	153	261	126	197	8348	1744
Sweden	100	343	211	268	205	181	164	153	147	197	52,098	2688
Malta	-	100	129	186	133	114	138	173	403	194	6766	2825
Spain	100	199	195	156	170	164	174	172	162	190	15,588	2571
Finland	100	423	193	203	176	201	218	216	189	188	98,780	5974
Czechia	100	188	150	197	164	137	137	136	134	188	5820	1053
EU-28	100	222	345	132	193	150	144	146	148	186	16,889	1673
Hungary	100	1189	119	146	164	203	272	223	156	185	119,478	5812
France	100	189	189	168	178	141	149	137	138	183	7733	1293
Belgium	100	343	134	217	218	224	179	147	138	179	32,062	3201
Slovenia	-	100	325	274	247	194	205	167	151	168	37,142	4165
Luxembourg	100	419	248	226	125	133	178	148	160	167	27,574	1171
United Kingdom	100	256	976	53	240	182	154	151	138	164	30,125	2282
Latvia	-	100	210	938	119	114	129	154	128	153	10,420	529
Austria	100	155	162	168	157	174	163	143	142	150	5682	1350
Portugal	100	137	133	127	245	245	282	227	169	144	21,531	9321
Netherlands	-	100	1365	153	200	124	108	117	142	139	12,995	624
Lithuania	-	-	100	1283	236	205	228	189	157	138	58,400	4551
Bulgaria	-	100	125	161	135	155	162	186	179	137	3101	1541
Cyprus	-	100	600	233	314	191	231	155	150	127	57,100	4079
Estonia	100	1080	119	154	104	103	104	112	117	126	3616	184

Table 4. Coefficients of variation for the number of electric cars in EU countries in 2011–2020.

Countries	Coefficients of Variation for Number of Electric Cars in Years			
	2011–2019	2011–2020	2014–2019	2014–2020
Estonia	0.44	0.47	0.14	0.22
Netherlands	0.78	0.83	0.40	0.51
Latvia	0.88	0.95	0.46	0.60
Czechia	0.85	1.04	0.53	0.75
Austria	0.99	1.05	0.67	0.75
France	0.91	1.08	0.58	0.78
United Kingdom	1.01	1.10	0.70	0.81
Cyprus	1.25	1.18	0.85	0.83
Luxembourg	1.04	1.16	0.69	0.84
EU	0.98	1.15	0.65	0.85
Bulgaria	1.18	1.19	0.85	0.88
Belgium	1.13	1.22	0.75	0.89
Denmark	0.92	1.24	0.57	0.93
Lithuania	1.35	1.29	0.94	0.93
Sweden	1.11	1.27	0.73	0.93
Slovenia	1.24	1.29	0.85	0.94
Slovakia	1.15	1.29	0.79	0.96
Spain	1.15	1.31	0.81	0.99
Portugal	1.46	1.38	1.07	1.04
Germany	1.04	1.38	0.71	1.06
Hungary	1.38	1.44	1.01	1.09
Croatia	1.09	1.47	0.68	1.10
Ireland	1.27	1.46	0.91	1.11
Finland	1.44	1.50	1.05	1.14

Table 4. *Cont.*

Countries	Coefficients of Variation for Number of Electric Cars in Years			
	2011–2019	2011–2020	2014–2019	2014–2020
Italy	1.15	1.49	0.80	1.15
Poland	1.29	1.53	0.92	1.17
Malta	1.54	1.62	1.19	1.28
Romania	1.58	1.67	1.18	1.29
Greece	1.26	1.69	0.85	1.30

3.5. Relation between the Number of Electric Cars and Parameters Related to Socio-Economic Potential in the EU before and during the COVID-19 Pandemic

In the next step, the Kendall tau correlation coefficient and Spearman's rank correlation coefficients were calculated. The aim was to find the relationship between the number of electric cars in the EU and the parameters related to the socio-economic potential (Tables 5 and 6). We used $p = 0.05$ to specify the border value of the significance level. Correlation coefficients were calculated for the entire EU for different periods. A research project attempted to test a correlation that does not indicate that one factor influences another, but that there is a strong significant or weak secondary relationship. The number of electric cars in the EU was used for the calculations.

Table 5. Kendall's tau correlation coefficients between the number of electric cars and social and economic parameters in EU.

Tested Parameters	Kendall's Tau Correlation Coefficient in Years							
	2014–2019		2014–2020		2011–2019		2011–2020	
	τ	*p*-Value	τ	*p*-Value	τ	*p*-Value	τ	*p*-Value
Correlation coefficients between the number of electric cars and								
Population (million)	1.000	0.009 **	0.905	0.007 **	1.000	0.001 ***	0.956	0.001 ***
Area of the country (square kilometer)	−0.730	0.037 *	−0.756	0.022 *	−0.624	0.028 *	−0.683	0.012 *
Number of cars	1.000	0.009 **	1.000	0.003 **	1.000	0.001 ***	1.000	0.001 ***
The length of the highways (kilometer)	1.000	0.009 **	1.000	0.003 **	1.000	0.001 ***	1.000	0.001 ***
Value of GDP (million euro)	1.000	0.009**	0.810	0.016 *	1.000	0.001 ***	0.911	0.001 ***
GDP per capita (euro per capita)	1.000	0.009 **	0.905	0.007 **	1.000	0.001 ***	0.956	0.001 ***

* *p*-value ≤ 0.05, ** *p*-value ≤ 0.01, *** *p*-value ≤ 0.001.

For all parameters, significant relationships with a strong connection with the number of electric cars were found. In most cases, this relationship was very strong. The EU population is steadily growing, as is the number of cars and the length of highways. For these parameters, very good compliance with the increase in the number of electric cars was obtained. The surface area of the EU remains basically the same, so the correlation was negative for this parameter. Economic parameters such as total GDP value and per capita also showed a close relationship with the number of electric cars in the EU. Such results were noted in both tests. Based on previous analyses and correlation studies, it can be concluded that a higher standard of living has been associated with more electric cars in the EU. On the other hand, the deterioration of the economic situation in 2020 did not stop the upward trend in the number of electric cars. It can be said that, on the contrary, the introduction of electromobility has even accelerated. Interestingly, the results for the periods containing the years 2011–2019 and 2014–2019 indicate a higher correlation than for the periods containing 2020. They confirm that the crisis caused by COVID-19 had an impact on the economic situation in the EU but did not slow down changes related to the introduction of electromobility. Additionally, in longer periods (from 2011), more strict dependencies were visible than in shorter periods (from 2014). Based on the research, a general conclusion can be drawn that the development of electromobility is progressing despite the crisis caused by COVID-19. This is probably largely influenced by the policies of the EU and individual countries. Such issues may pose a new problem to be solved in future research.

Table 6. Spearman's rank correlation coefficients between the number of electric cars and social and economic parameters in EU.

Tested Parameters	Spearman's Rank Correlation Coefficient							
	2014–2019		2014–2020		2011–2019		2011–2020	
	τ	*p*-Value	τ	*p*-Value	τ	*p*-Value	τ	*p*-Value
Correlation coefficients between the number of electric cars and								
Population (million)	1.000	0.010 **	0.964	0.010 **	1.000	0.010 **	0.988	0.010 **
Area of the country (square kilometer)	−0.828	0.050 *	−0.866	0.050 *	−0.725	0.050 *	−0.798	0.010 **
Number of cars	1.000	0.010 **	1.000	0.010 **	1.000	0.010 **	1.000	0.010 **
The length of the highways (kilometer)	1.000	0.010 **	1.000	0.010 **	1.000	0.010 **	1.000	0.010 **
Value of GDP (million euro)	1.000	0.050 *	0.893	0.050 *	1.000	0.010 **	0.964	0.010 **
GDP per capita (euro per capita)	1.000	0.010 **	0.964	0.010 **	1.000	0.010 **	0.988	0.010 **

* p-value ≤ 0.05, ** p-value ≤ 0.01, *** p-value ≤ 0.001.

4. Discussion

The development of electromobility in Europe has its motivators, but also barriers. According to Biresselioglu et al. [55,56] the main barriers are the lack of charging infrastructure, economic constraints and high-cost concerns, technical and operational constraints, as well as a lack of trust, information, and knowledge. In turn, the most important drivers appear to be the environmental, economic, and technical benefits of electric vehicles, as well as personal and demographic factors. It seems that economic and environmental factors have the greatest influence here. Haddadian et al. point to the higher price of an electric vehicle compared with a vehicle powered by conventional energy [57]. Such analysis should take into account the life cycle costs of the vehicles. Such studies were performed by Gass et al. [58], Thiel et al. [59] and Ogden et al. [60]. The results were inconclusive and often the electric car was not the best option. The introduction of new technologies depends largely on economic factors. Incentives for car buyers are necessary. Mock and Yang [61] analyzed the tax incentive policy for electric vehicles around the world. They found that there is a significant relationship between supporting national incentive systems and the level of use of electric vehicles. The most effective incentives are direct subsidies (a one-time bonus when buying an electric vehicle) and tax breaks. Li et al. [62], using the example of the US market, found that a federal income tax credit of up to USD 7500 for electric vehicles buyers contributed to about 40% of sales of these cars during 2011–2013. Different forms of support were used in individual EU countries, which also translated into an interest in purchasing electric cars. The different forms and amounts of support may partially explain the disparities between countries in the field of electromobility development, which were found in our research [63]. According to Zubaryev et al. [64] an adequate charging infrastructure is one of the most important factors for the large-scale deployment of electric vehicles in Europe. Harrison and Thiel [65] drew attention to the appropriate ratio between public charging points and the number of cars, especially in the early stages of introducing electromobility. The optimal ratio of electric vehicles to charging points is from 5 to 25. In our research, the highest rate was obtained in Sweden in 2020, with 18.46 cars per public charging point. In most countries (16 countries) the indicator was below five. The situation is better than in 2019 when too low an indicator was found in 23 countries. Improving this indicator to the optimal one may contribute to the faster development of electromobility in individual EU countries. Hall and Lutsey [66] report in their study that the indicator of the number of electric cars per public charging point is not interpreted in the same way. In

2014, the European Parliament recommended that this ratio should be 10. In our research, exactly this ratio was achieved by 2020 in only Finland, Denmark and Belgium. It was higher in three countries and lower in others. These results show that EU countries in most cases developed different aspects of electromobility unevenly.

Another problem in the development of electromobility in the EU is the inadequate attitude of car dealers. In studies by de Rubens et al. [67] made at 82 car dealerships in Denmark, Finland, Iceland, Norway, and Sweden, it was found that dealers disregarded electric vehicles, misled buyers about vehicle specifications, omitted electric vehicles in sales talks, and strongly suggested vehicles with gasoline and diesel engines. Additionally, the sale of electric cars requires the adaptation of business models and entire supply chains, which is a problem [68–70]. Dealerships are also discouraged by the reduced number of required parts and services for electric cars, which represent significant profits for dealers for conventional cars [71,72]. These are additional factors that could lead to poor performance in the take-up of electric cars. During the COVID-19 pandemic, contacts between buyers and dealers were reduced. It can be assumed that many buyers of electric cars drew their knowledge from the internet. At that time, they were not as subject to sellers' suggestions as they were before the pandemic. Perhaps the pandemic thus contributed to the more frequent choice of electric cars by buyers. In 2020, every tenth car sold in the EU was electric [73].

Tucki et al. [74] indicated that the leaders of the electromobility sector in the EU were the Netherlands, France, Germany, and the United Kingdom. In 2017, the total number of electric car registrations in these countries accounted for around 70% of all registrations in the EU. The results obtained by us for the years 2019–2020 are similar. The same countries dominated and their share was similar to the data from 2017. Tucki et al. [74] stated that the leaders of electromobility were highly developed countries and it ranks very high in terms of economic conditions. At the same time, in these countries, the dynamics of changes in the number of electric cars was much lower than in developing countries such as Poland. We obtained similar results in our research. In many articles, the authors focus on the nominal number of electric cars or new registrations, equating the obtained results with the level of electromobility development. An example is the work of Tucki et al. [75], Drożdż [76], Sendek-Matysiak and Łosiewicz [77]. More complex methods of electromobility assessment in the form of indicators were used, among others, by Feckova Skrabulakova et al. [78], Schuh et al. [79] and Silvestri et al. [80]. Overall, however, such composite indicators have not been used very often. In our research, we proposed the use of indicators assessing the development of electromobility, such as the number of electric cars per population, as well as the area of the country, the total number of cars, and the length of highways (roads of the best quality). Thanks to this, we were able to assess the actual development of electromobility in a given country. It turned out that the leaders were not the largest countries anymore. The highest levels of electromobility development were found in Sweden and the Netherlands. We should also distinguish Luxembourg for the number of electric cars per thousand inhabitants, Belgium and Malta for electric cars per square kilometer, Denmark and Luxembourg for electric cars share in total cars, Great Britain for electric cars per kilometer of motorway.

We have not found any papers in which the authors analyze the relationship between the level of economic development of the country and the number of electric cars used. Our research fills the research gap in this aspect. We found that such relationships exist. Other authors most often assessed the development of electromobility as the cause, and not the result, of economic development. They argued that as a result of developing electromobility, many new jobs were created and the economy was developing. This statement is of course also true. This type of regularity was found, among others, by Daňo and Rehák [81], Połom and Wiśniewski [82], Drożdż and Starzyński [83], Castelli and Beretta [84]. A different view is represented by Mönnig et al. [85] who, based on Germany, state that initially the development of electromobility has a positive impact on economic development, but in the long run it leads to a reduction in the value of GDP and employment. According to estimates, the technology change will lead to the loss of 114,000 jobs by the end of 2035. The entire German economy will lose almost EUR 20 billion (0.6% of GDP). A certain explanation is the functioning of many automotive concerns in Germany. Electric cars compete with cars powered by conventional fuels. In addition, they do not require as much maintenance as cars with a gasoline or diesel engine. Another example is Russia. According to Kolpakov and Galinger [86], increasing the market share of electric vehicles will worsen macroeconomic indicators. Higher material consumption of low-emission technologies ensures increased production in the country, but their disadvantage is the need for additional import of elements and subassemblies. Additionally, Russia would experience a decrease in revenues from the sale of crude oil and gas.

According to Ivanov and Dolgui [87], the COVID-19 pandemic was one of the most serious supply chain disruptors in recent world history. Baldwin and Tomiura [88] state that the spread of the disease from China to other industrial powers in the US and the EU has caused massive supply disruptions. Additionally, these supply disruptions would cascade onto other manufacturing sectors in countries less affected by knock-on effects in the supply chain. The automotive sector is highly internationalized, with highly specialized suppliers that make short-term substitution difficult [89,90]. In the automotive industry, the effects of the pandemic and the domino effect were very visible. The decreases in production in Germany affected suppliers from, among others, Hungary, Spain, Italy, and the USA. At the same time, the demand for German cars was falling, e.g., in the USA, China, Austria [91]. The automotive industry has been one of the industries most affected by COVID-19 in the first period of the pandemic. The supply chains of the European automotive industry have been disrupted by downtime in Chinese factories [92]. However, shutdowns in factories in Europe from March to May 2020 were more severe. In EU member states, automotive factories have been shut down for an average of 30 days, with the shortest downtime in Sweden (15 days) and the longest time in Italy (41 days) [93]. In the first half of 2020 for the automotive industry, the EU suffered a production loss of 3.6 million vehicles, reflecting a loss of EUR 100 billion [94]. A new wave of infections and restrictions introduced in EU countries since November have caused further problems in the automotive industry. Dealers had to close, and overall consumer economic uncertainty has increased. Some incentives to buy cars at that time were higher tax breaks and subsidies for purchases from governments [95]. Overall, about 24% fewer cars were sold in 2020 than in 2019, which corresponds to about 9.9 million units [96].

The impact of COVID-19 on electric vehicles is smaller than the impact on the sector as a whole [97]. The average share of electric car sales in total car sales has grown from 3.4% in 2019 to 7.8% in the first half of the year 2020, with a peak of 11% in April and around 8% in May and June. Also, in terms of world sales, electric cars suffered less than non-electric cars [98]. Anticipated for the first wave of the pandemic, electric vehicles were predicted to further expand their market participation to 10.5% of the total EU car market [99]. Plug-in and clean and mild hybrid cars increased their market share to 26.8% and outperformed diesel car sales in the last months of 2020 [100]. The COVID-19 pandemic has accelerated the growth of the electric vehicle market. There are several reasons for this. Consumer behavior is shifting towards greater private mobility rather than public mobility to reduce the risk of infection. In addition, regulatory authorities are intensifying actions to protect the climate in the mobility sector. As a result, green transition subsidies are offered that encourage investment in this sector [101]. We obtained similar results in our research. There was an acceleration in the dynamics of introducing new electric cars in the EU countries.

Factors limiting the development of electromobility were analyzed by Coffman et al. [102] and Sierzchuli et al. [103]. Coffman et al. [102] group these factors into internal, external and applied policies. In the first class, there is a higher initial investment [104–106], extended charging time, and limited range [107]. Second, Coffman et al. [102] take into account the relative fuel prices [103] and the characteristics of potential buyer, but the literature is ambiguous. The availability of charging stations is also significant, which was one of the most important factors in making the decision to buy an electric vehicle. In the latter group, Coffman et al. [102] mentions financial and non-financial incentives, public support for building charging infrastructure and awareness-raising. Of course, in poorer countries there are fewer incentives and there is less purchasing power for consumers than in economically developed countries, which causes natural limitations in the development of electromobility in developing countries.

The success of the electromobility sector in the EU should be associated with a change in social behavior. There are already many examples of how COVID-19 has modified social behavior and transport patterns. An example is the work of Wang and Wells [108], Griftyhs et al. [109], Benita [110], De Vos [111], Abdullah et al. [112], Przybylowski et al. [113], Scarabaggio et al. [114] and Santamaria et al. [115]. Promoting sustainable transport is also important. According to Holden et al. [116] electromobility is one of the elements of such transport (others include collective transport 2.0 and societies with limited mobility). Activities related to the development of the electromobility sector perfectly match the needs related to the reduction of pollution in the environment. Therefore, they will be promoted even more by the governments of EU countries. It can therefore be concluded that the pandemic has become a positive catalyst for change. Policymakers should use incentive funding, social bias, and perceptions induced by COVID-19 to influence long-term changes in the transport system that can positively impact climate action [109,117].

5. Conclusions and Recommendations

5.1. Conclusions

The conducted research allows for a few generalizations.

1. Taking into account the socio-economic potential of the EU countries, the most developed countries in the field of electromobility were the Netherlands and Sweden, and the least developed countries were Greece and Croatia. There were large disparities between countries.
2. The level of concentration of electric cars in several EU countries was very high, but it was systematically declining. The phenomenon is positive because it proves the development of this type of transport in many EU countries. During the COVID-19 pandemic, the trend was reversed (Hypothesis one was partially confirmed).
3. In all EU countries, in the first year of the COVID-19 pandemic, the dynamics of introducing electric cars into use increased. The growth rate in the entire EU in 2020 was 86%, while in 2019 it was 48%. During the crisis, the development of electromobility in the EU accelerated (the second hypothesis was verified negatively).
4. The COVID-19 pandemic resulted in a greater average annual variation in the number of cars in individual EU countries. The reason was the very rapid introduction of electric cars during the pandemic.
5. The development of electromobility in the EU, measured by the number of electric cars, is closely related to the economic situation in this area. As a rule, a higher standard of living was associated with a greater number of electric cars (the third hypothesis was verified positively).
6. The crisis caused by the COVID-19 pandemic affected the economic situation in all EU countries but did not slow down the pace of introducing electromobility. The prospects for the development of this type of transport are very good.

5.2. Recommendations

The relationship between the number of electric cars and the economic situation has not been the subject of research. There is a lack of research on such relationships during the COVID-19 pandemic. This is a new situation, so it needs some explanation. Furthermore, there were no such studies related to the EU. The reason may be the introduction of electric cars for use only from a few or several years in EU countries. It was only in 2014 that electric cars were widely used in all EU countries.

The limitations in conducting such academic studies are the lack of available current and detailed data on electromobility. A possible direction of further research is linking electromobility with environmental pollution and economic development. Research could also concern these dependencies on the example of large urban agglomerations. Electric cars are mainly used in cities. Another direction of academic analysis is the examination of dependencies occurring in regions, differing in their level of economic development.

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Article

The Impact of the COVID-19 Pandemic on the Development of Electromobility in Poland. The Perspective of Companies in the Transport-Shipping-Logistics Sector: A Case Study

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Abstract: Negative processes occurring in the natural environment, under dynamic economy development, have become a factor for taking actions limiting destructive human activity. An important area in which initiatives are taken to improve the state of the natural environment is that of companies in the Transport-Shipping-Logistics Sector (TSL sector). The main objective of this article was to analyse the impact of the COVID-19 pandemic on the development of electromobility among companies in the Polish TSL sector, and identify factors that positively influenced or hindered its development during this time. For this purpose, qualitative and quantitative data analyses were carried out based on a literature review, statistical data, and direct research results. Descriptive statistics, chi-square test of concordance, and contingency coefficients were used to process the data. The results showed that the pandemic period did not affect the development of electromobility among TSL companies. Only a few companies own electric cars in Poland. Many of them did not plan to purchase this type of vehicle during the pandemic. The main factors influencing the decisions of entrepreneurs during the study period were the availability of charging infrastructure and electricity price uncertainty. The results of the study can be used by stakeholders of this sector in Poland.

Keywords: electromobility; companies in the Transport-Shipping-Logistics Sector; pandemic-COVID-19; development

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1. Introduction

The redefinition of the energy model and the search for alternative energy sources are linked to problems that emerged in the second half of the 20th century in connection to the dynamic development of the Western world's economy. This development negatively affected the environment and the depletion of non-renewable natural resources, among other things. The great fuel crisis of the 1970s happened when emphasis was placed on renewable energy sources [1–3]. From that moment, a phase began in which electricity became the basis for the functioning of many societies. The result of these changes was an over 100% increase in electricity production compared with the 1960s [4]. Thus, electricity became the driving force of civilisation. The natural consequence is its use in transport [1–3]. Many years have passed since the first idea of using electricity in transport appeared [5,6]. During this time, enormous progress has been made in the field of electromobility. This has been driven by national governments, car manufacturers, the energy sector, researchers, and other stakeholders and organisations interested in electromobility [1–8]. These entities see the need to take action to address the ongoing processes associated with environmental degradation by transport [9,10]. The scope of these activities is evident in the increase in number of electric vehicles sold and the development of infrastructure necessary for their operation [11,12]. To illustrate the scale of the phenomenon, quantitative data may be quoted. In 2010, there were only roughly 17,000 electric cars on the roads worldwide. By 2019, this number increased to 7.2 million [12]. In 2020, about 3 million new electric cars were registered. In Europe, this amounted to 1.4 million new registrations. China was second with 1.2 million registrations, and the US registered 295,000 new electric cars [12]. According to Swedish consultancy EV-volumes.com, electric vehicles will account for 4.2% of all passenger car sales worldwide in 2020 [13].

Quantitative data shows [11,12] that the dynamic growth in the number of electric vehicles is largely within passenger vehicles and buses. This trend is a result of actions taken by many countries, found in policy documents which aim to reduce the negative environmental impact of transport [14–17]. In the European Union, passenger cars together with commercial vehicles are the source of 15% of greenhouse gas (GHG) emissions [18]. In turn, heavy duty vehicles are the source of 5% of GHG emissions. However, taking into account the continuous increase in the number of heavy duty vehicles and the environmental risks associated with this trend, the European Union is implementing specific policies and regulations aimed at the gradual decarbonisation of the vehicle fleet and the price reduction of zero-emission technologies. In 2019, the European Union adapted Regulation (EU) 2019/1242 [19], which sets CO_2 emission standards for heavy duty vehicles up to 2030. Compared with the average CO_2 emissions per kilometre for new vehicles sold between 1 July 2019 and 30 June 2020, new vehicles sold between 2025 and 2030 will have to emit on average 15% and 30% less CO_2 respectively. Initially, the standards only apply to larger trucks, but the scope may be extended when these standards are reviewed in 2022 [20].

The assumptions may have a significant impact on the replacement of vehicle fleets of TSL companies. The replacement of vehicles by operators is determined by the development of electric trucks, charging infrastructure, and energy supply. At the same time, the pace and scale of the changes taking place in enterprises is influenced by the COVID-19 pandemic [21–24]. This impact was noted by Gersdorf T., Hensley R., and Hertzke P., Schaufuss P. [22], and can be analysed in the following areas:

- macroeconomic environment—the COVID-19 pandemic on one hand reduced the purchasing power of consumers and on the other contributed to a significant drop in oil prices and thus reduced the difference in maintenance cost of electric vehicles and combustion vehicles. This change may have affected the sales of electric vehicles [22,23],
- technology and infrastructure—some governments are investing in charging infrastructure as part of programmes to stimulate the economy even during the pandemic period [22,24],
- electric vehicle offers—the pandemic caused factories to close and stopped assembly lines around the world. As the automotive industry prepares to reopen, some are prioritising EV production either to meet expected strong demand or to meet regulatory requirements such as the European Union's stringent CO_2 target [22,25–27],
- demand—in many countries, consumer demand for EVs has remained relatively stable during the crisis compared with demand for other vehicles. Globally, EV manufacturers offering online sales saw particularly high demand as the COVID-19 pandemic caused a lockdown [22,28].

Taking into account the European Union guidelines on CO_2 emission standards for heavy goods vehicles by 2030 [19], the rationale for the development of vehicles using alternative energy sources in road freight transport [21,28,29], the size of Poland's medium and heavy commercial vehicle fleet in relation to other European Union countries [30], and the impact of the COVID-19 pandemic on enterprises [31], a significant need for research was recognised.

The aim of the study is to analyse the impact of the COVID-19 pandemic on the development of electromobility among companies in the TSL sector in Poland, and to identify factors that could positively influence or impede its development during the pandemic period. In addition, three sub-objectives were defined to:

- determine the potential for electric cars among the surveyed companies and to identify the demand for such vehicles,

- identify factors which in the period of the COVID-19 pandemic had an impact on the potential and real need to purchase electric cars by companies in the TSL sector,
- to indicate the impact of the identified factors on the development of electromobility among companies from the TSL sector.

The structure of the article is as follows: Section 2 contains the literature review, Section 3 presents the aim and method of the research, Section 4 presents the results of the research, Section 5 contains the discussion, and Section 6 presents conclusions, limitations, and suggestions for future research.

2. The COVID-19 Pandemic and the Development of Electromobility in Poland

2.1. Electromobility in a Sustainable Transport Concept

Sustainability appears to be a modern concept that encompasses many ideas, but its meaning has evolved over time, with the most common connotation being something that lasts, is eternal, or that by its nature remains present, without consuming something externally harmful, and applying this to many areas of knowledge or society [32]. It is widely accepted "that sustainable development meets the needs of the present without compromising the ability of future generations to meet their own needs" [33]. The concept therefore identifies interrelated domains that constitute the dimensions of sustainable development: environment, economy, and society [34–36]. In this dimension, there is a growing interest worldwide in the phenomenon of sustainable development and its implications for the planning and operation processes of transport systems [37,38]. In practice, however, great difficulties arise in developing transport in the convention of integrated management (Table 1), that is, in the context of a broad understanding of sustainable transport.

Table 1. Dimensions of sustainable transport development.

Sustainability		
Social dimension: • mobility • availability • liquidity • security • social cohesion • system integrity transport	The economic dimension: • competitiveness • working conditions in the sector • infrastructure (development/modernisation/investment/carrying capacity/quantity and quality of networkstransport) • intermodality	Environmental dimension: • environmental friendliness • transport (minimising environmental impacts) • prevention and eradication • transport implications • environmental risks

Source: [39].

Borys' [38,39] review of the definitions of sustainable transport showed both narrow and broad approaches to it in literature. At the same time, it is worth emphasising that the broad approach to the sustainable development of transport is considered the contemporary interpretation of the new development paradigm. Sustainable transport development means that the transport of people and goods will be carried out in a way that simultaneously takes into account environmental, social, and economic criteria (Table 1). It is, therefore, among other things, affordable, supports a growing economy, offers a wide choice of transport modes, reduces emissions and waste, minimises consumption of non-renewable resources and land use, and reduces noise pollution. This approach allows electromobility to fit into the concept of sustainable development. As with the concept of sustainability, there is no single accepted definition of electromobility [40,41]. According to Caternì [40,42], electromobility is one of the most studied topics in transport and is a very complex issue, as it cannot be interpreted within a single theoretical structure. An important factor in the discussion of electromobility is that an electric vehicle cannot be implemented by the automotive industry without the parallel development of charging infrastructure, service networks, technical approval processes, and tax and legal incentive mechanisms [42–45]. In the most general terms, electromobility encompasses issues related to electric vehicles, both in individual transport (cars and motorbikes) and mass transport (buses, trolleybuses, trams, trains). Electromobility also includes all technologies related to the production of e-vehicles, energy management, and charging infrastructure, as well as modern transport strategies [8,46].

An area that still requires analysis is the issue of electromobility in road freight transport. Many publications in this area refer to the problems of alternative power sources [47–49] and, in this context, the issues related to the electricity sector and its impact on the environment [50–53] concerning decarbonisation are very important.

2.2. Impact of COVID-19 on the Evolution of the Electric Vehicle Market

One important aspect related to the development of electromobility is the change in the number of electric vehicles being purchased. An electric vehicle is defined as a vehicle that is powered by at least one electric motor. Electric vehicles also include hybrid cars—HEVs, PHEVs, and fuel cell vehicles—FCHEVs [18,45]. While the demand for electric buses and passenger vehicles is increasing both in Poland and in most European Union countries [30], the share of heavy duty vehicles powered by alternative energy sources is low (Figure 1).

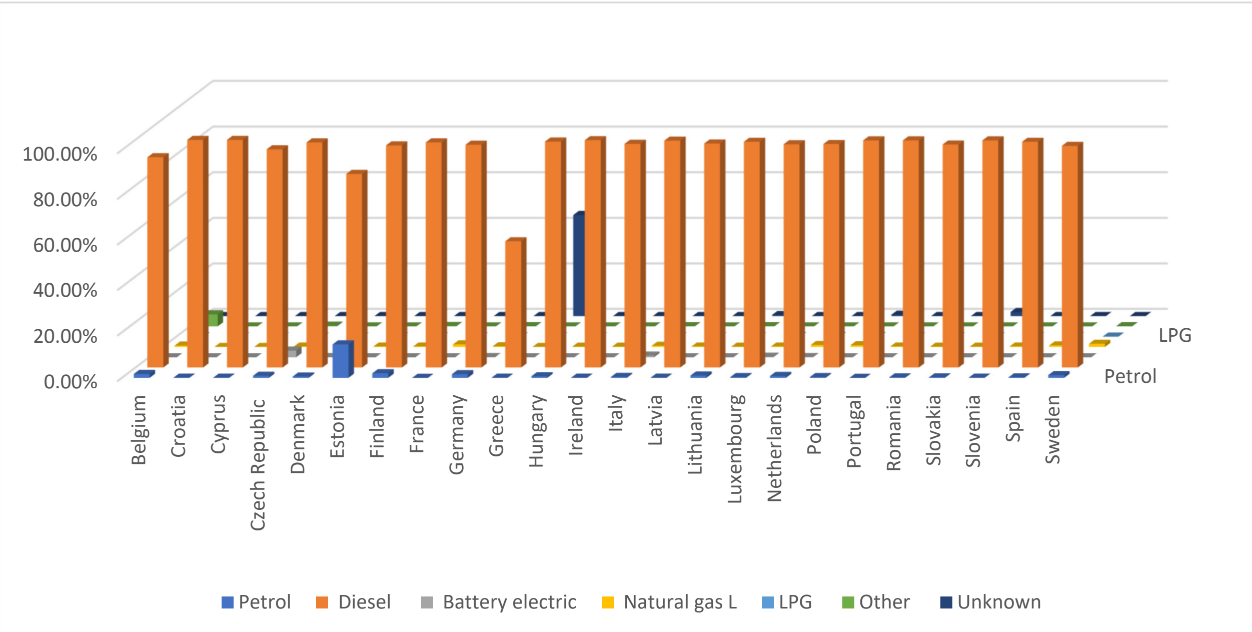

Figure 1. Medium and heavy commercial vehicles by fuel type in EU in 2020 [30]. (no data from some UE countries).

Analysing the percentage share of individual types of vehicles by fuel type in European Union countries, it may be observed that vehicles with combustion engines dominate, accounting for more than 90% of all medium and heavy vehicles (Figure 1). There is a small share of BEV in countries such as the Czech Republic—2.9%, Latvia—0.7%, Luxembourg—0.2%, and Denmark, Germany, and the Netherlands—0.1%. Plug-in hybrid and hybrid electronic vehicles are not found among medium and heavy vehicles. As indicated by H. Quak et al. [54], the low share of electric vehicles among HGVs may be affected by several factors:

- the specific type of vehicle in a given model has a strong influence on the technolo-gical performance and reliability of the vehicle,
- the lack of and high cost of effective manufacturer support in the event of repair needs,

- the development of ICT support is indispensable for the further integration of electric HGVs into daily business of transport companies,
- limited production and availability, especially of heavy electric freight vehicles,
- the need for new investment and adaptation of existing infrastructure.

Electromobility development activities are of a different nature and scope in different countries. At the same time, many studies point to the role played by authorities at various levels in this field [16,55].

When analysing the years 2019–2020, when the world was facing the COVID-19 pandemic, no significant contribution to the growth of vehicles powered by alternative power sources was observed (Figure 2).

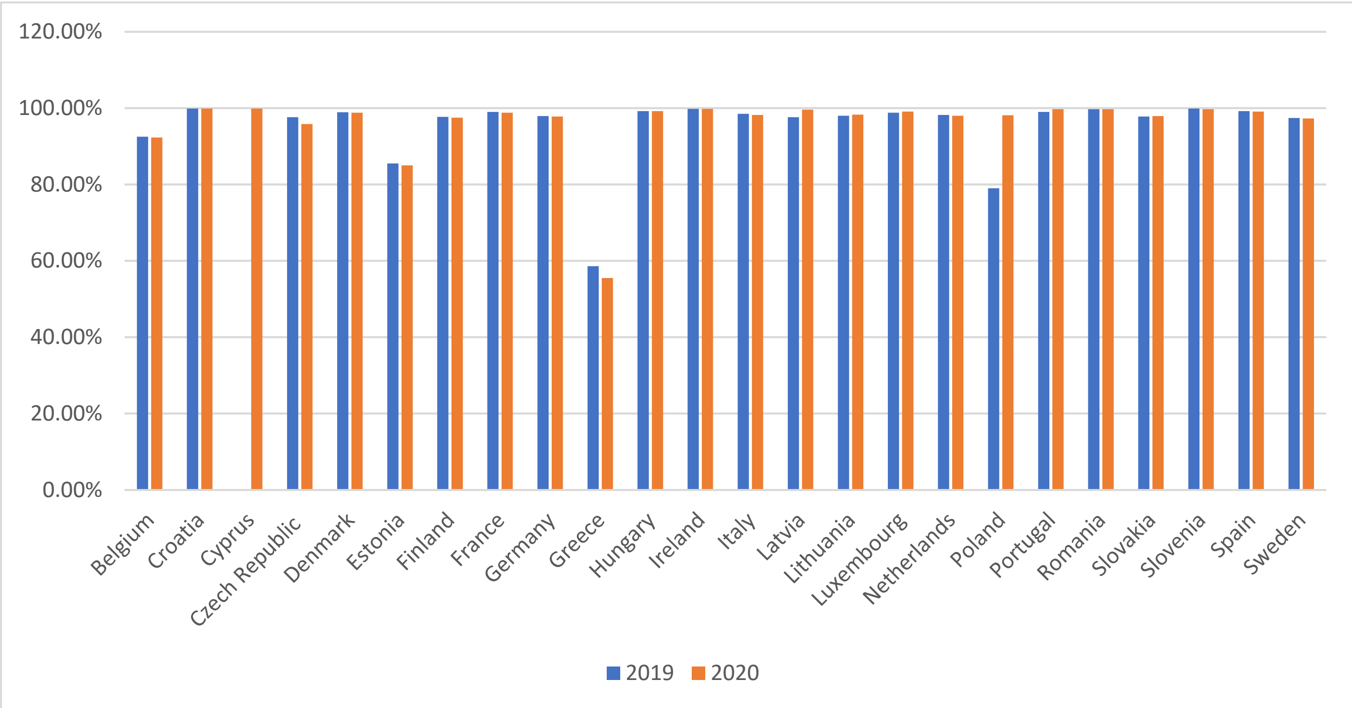

Figure 2. Medium and heavy duty diesel commercial vehicles in the EU [30,56]. (no data from some EU countries.).

Despite efforts to develop electromobility in road transport, there has been no significant decline in the share of diesel vehicles in individual EU countries. In most cases, the decline has been around 0.1%. At the same time, there are countries, including Poland, which recorded an increase in the share of diesel-powered vehicles in the total number of medium and heavy commercial vehicles during the COVID-19 pandemic. Apart from Poland, an increase was recorded in such countries as: Latvia, Lithuania, Luxembourg, Slovakia, Slovenia, and Spain. However, these countries, compared with Poland, have a much smaller number of medium and heavy vehicles. Thus, in 2020 those countries had medium and heavy commercial vehicles in the following numbers: Latvia—22,513 vehicles, Lithuania—69,780, Luxembourg—13,784, Slovakia—78,959, Slovenia—37,674, Spain—614,147, and Poland—as many as 1,184,677.

Taking into account the total number of cars analysed by fuel type in Poland, electric cars in 2020 will represent only 0.05% of all trucks (Figure 3). At the same time, during the COVID-19 pandemic period, i.e., 2019–2020, a slight increase in their number was observed in each of the vehicle groups.

In 2020, the number of heavy electric vehicles reached 1729 units, an increase of almost 68% compared with 2016. Considering the period of the COVID-19 pandemic, there was no downward trend in the total number of vehicles (electric cars and diesel cars). Thus, the COVID-19 pandemic did not affect the purchase of alternative-powered HGVs, but this may be due to insufficient knowledge about electromobility or insufficient charging infrastructure, among other factors. A positive aspect in this area is the research on the possibility of using vans and trucks with TSL companies [13,57].

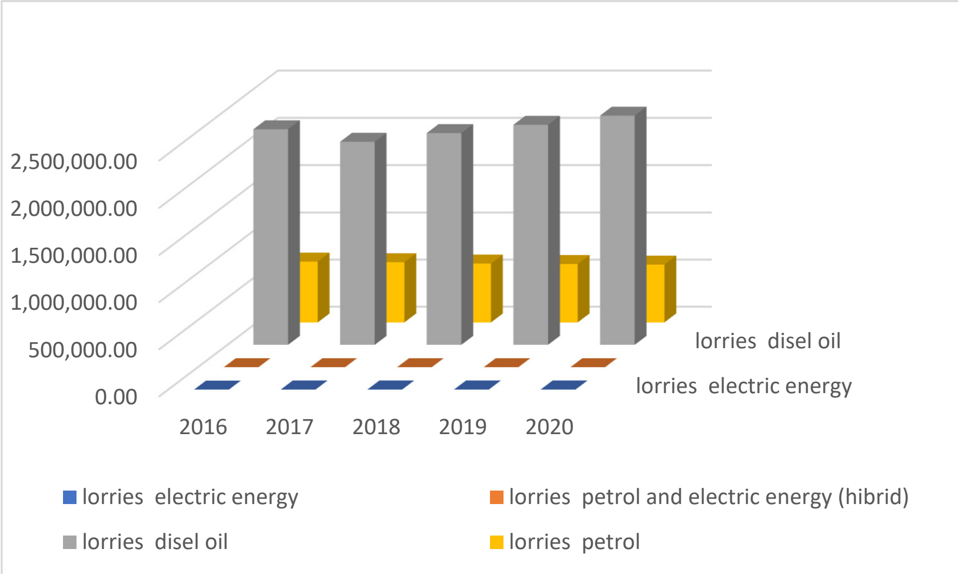

Figure 3. Breakdown of vehicles by fuel used in Poland [58–61].

According to Gajewski J., Paprocki W., and Pieriegud J. [7], the electrification of the transport sector in Poland in the period before the COVID-19 pandemic was slower than in other European markets. This applied both to the number of electric cars registered and to system solutions supporting the development of electromobility. Therefore, the authors of the study indicate that one million electric vehicles on the roads in 2025, which is the strategic goal of the Polish Electromobility Development Programme, is practically unattainable. Nevertheless, the legislative, economic, and technological changes taking place in Poland make it possible to assume that the sales of EVs will continue to grow dynamically. At the same time, these changes are related to transformations in the energy sector, which in Poland require changes due to the use of coal for energy production [62].

2.3. The Impact of the COVID-19 Pandemic on the Development of Charging Infrastructure

The development of charging infrastructure is influenced by state actions. Poland, through the Strategy for Responsible Development, as well as detailed plans for the development of electric transport, including the development of charging infrastructure [63], is trying to catch up with countries that impose a pace of change in the electromobility sector [7]. In 2017, the Plan for Electromobility Development in Poland [14] was developed, the main objective of which was to create conditions for the development of this sector in the country. It assumed that building charging infrastructure would be an additional pro-demand factor. The network will be fully prepared to supply 1 million electric vehicles, and those vehicles will be stabilisers of the power system. The pandemic had no impact on the expansion of charging infrastructure between 2019 and 2021, and an increase in the availability of charging stations during this period did occur [64].

As can be seen from the EAFO quantitative data (Figure 4), there has been a very large increase in the number of charging points in Poland. In the case of fast charging points, taking 2016 as the base year, in 2019 the increase was 182%, and in 2020 more than 300%. According to the estimates of the PSPA Research and Analysis Centre [65], the increase in the number of widely available charging points for electric cars should definitely accelerate. This may be facilitated by the 'e-tariff' in force from 1 April 2021 [66], which will make i66t possible to reduce the fixed costs of operating chargers, and by the planned introduction of a system for subsidising the infrastructure [65]. On the other hand, the cost of creating new stations should be taken into account. In 2018, the cost of creating a new charging station was around 40 thousand PLN, and in the case of fast charging stations, the cost rose to 100–190 thousand PLN. At the same time, the rising level of inflation in Poland has already increased these costs significantly. Access to public stations is free of charge and is usually used to promote a particular company or the idea of electromobility itself. The Ministry of Energy has declared that, according to their estimates, the profitability of a charging station can be achieved when sales reach 32.85 MWh for an ordinary station and 452.6 MWh for a fast charging station. However, a large margin should be added to these figures as they are calculated based on an energy price that is no longer used on the market [67].

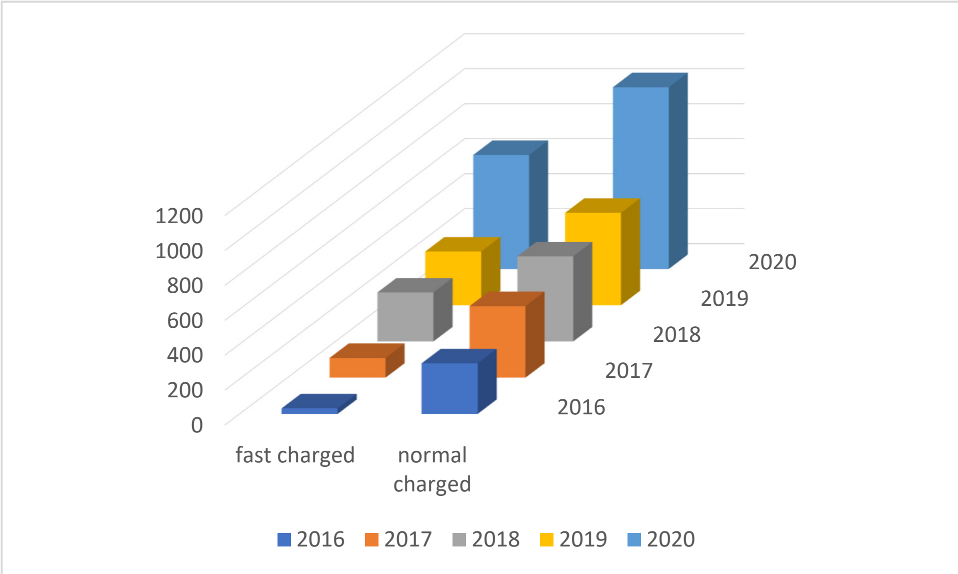

Figure 4. The total number of normal and high-power public recharging points [18].

At the same time, Poland is not a country with a large number of charging points (Figure 5).

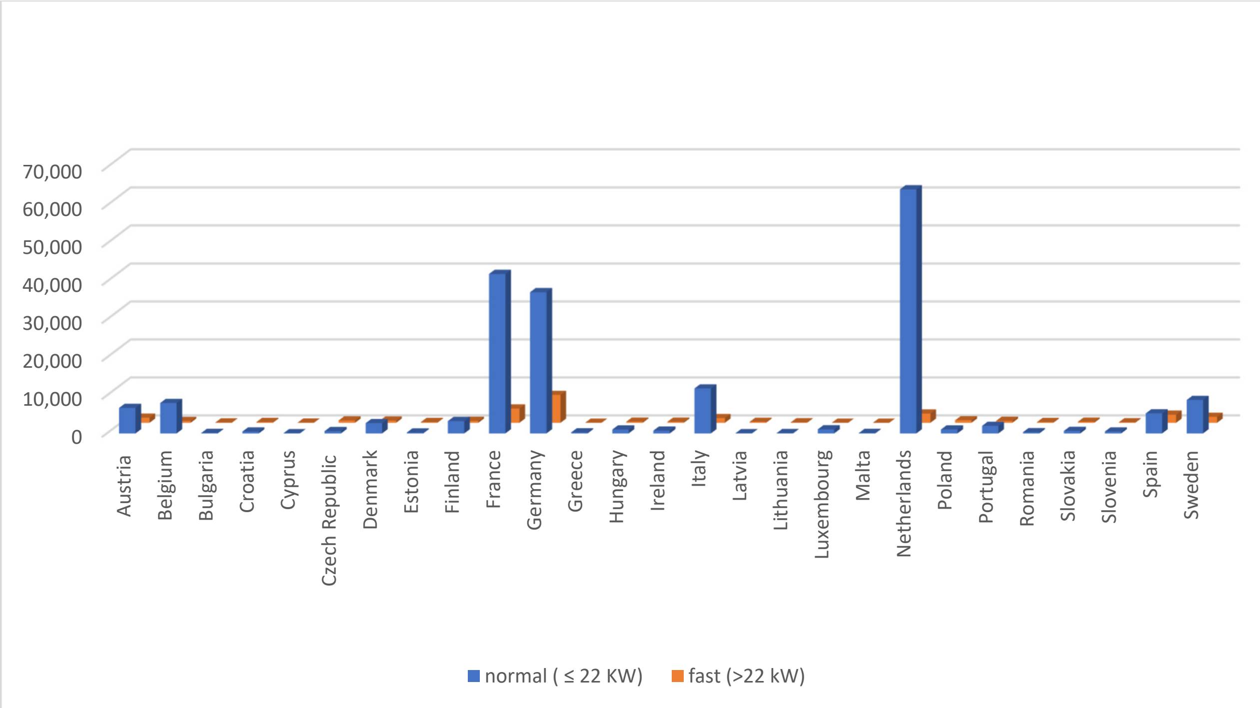

Figure 5. Normal and fast charging points in European Union (2020) [67].

Among European Union countries, the highest number of charging points is found in the Netherlands (66,665), followed by France (45,751), Germany (44,538), Italy (13,073), and Sweden (10,370). However, these countries have the highest number of fast charging points. These countries also have the highest number of fast charging points (Germany—7325, France—3751, the Netherlands—2429). This situation may have a negative impact on the replacement of the vehicle fleet among companies in the TSL sector. Taking into account the trucks used in the TSL sector and the number of fast charging points in the entire European Union (25,000 public chargers), it can be concluded that one of the main problems in the development of electromobility is not the COVID-19 pandemic, but the lack of available charging infrastructure. However, to enable the right direction for the development of electric vehicle charging infrastructure, it is necessary to take into account their establishment in locations with high charging potential, identified by different criteria such as demand density or length of travel [68,69].

3. The COVID-19 Pandemic and the Development of Electromobility in the TSL

3.1. Materials and Methods

The survey method was used in order to answer the research questions. Surveys play an important role in research processes by creating formal basis and translating theoretical assumptions into empirical procedure language. These methods are of an analytical nature and are widely used in social sciences, making it possible to identify the designated opinions of people (respondents) in relation to specific socio-economic phenomena occurring in the organisation [70].

The survey approach used in the study aimed to link the impact of the COVID-19 pandemic on the development of electromobility among TSL companies. The survey questions were structured to capture two aspects. The first was the issue of the purchase of electric vehicles by companies in the TSL sector during the COVID-19 pandemic, taking into account the company's reach and period of operation and to identify factors that, in addition to the coronavirus, influenced vehicle purchase decisions.

The questionnaire was divided into three parts. In the first part, in order to define the respondent's profile, five variables were presented: the organisational and legal form of the company, the area of operation, the range of operation, the period of operation, and the number of employees. The second part of the survey questionnaire identified companies with electric vehicles and their preferences regarding the purchase of this type of vehicle since the beginning of the COVID-19 pandemic. The third part of the sheet concerned the assessment of the impact of the COVID-19 pandemic on the development of electromobility among companies in the TSL sector. In this part of the worksheet, a Likert-type scale was used [71], where 1 meant no impact and 5 meant a very strong impact. Prior to the survey, the questionnaire was tested by people who are scientifically involved in electromobility and representatives of TSL sector companies. This test was to ensure the relevance of the questions and to assess the acceptability of the wording that was used, as well as the understanding of the questions. The online survey was created using Microsoft Forms software. It was then distributed to companies in the TSL sector. The data collection period spanned three months, from July to September 2021. The survey was a pilot study and represents the initial stage of research related to the development of electromobility in Poland among companies in the TSL sector. The results constitute a case study. In order to analyse the obtained results, structure indicators and the χ^2 test of independence and the contingency coefficient φ [72] were used.

3.2. Profile of Study Participants

The survey involved 71 respondents whose answers were checked and verified for completeness as well as correctness and reliability of information. This was to eliminate irregularities in the completed questionnaires. The first part of the survey questionnaire was designed to record the basic variables of the participating companies (Table 2).

Table 2. Characteristics of respondents.

Demographic Characteristics	Participation	Percentage (%)
	The legal and organisational form of the company	
corporation	29	40.85
partnership	25	35.21
sole proprietorship	17	23.94
	Scope of action	
logistics company	24	33.80
transport and shipping company	26	36.62
transport company	21	29.58
	Range of action	
national	33	46.48
international	38	53.52
	Period of operation	
up to 10 years	32	45.07
over 10 years	39	54.93
	Number of employees	
up to 10	21	29.58
11 to 49	18	25.35
from 50 to 249	12	16.90
above 249	20	28.17

Among the researched entities, taking into account their organisational and legal form, there were capital companies, including mainly limited-liability companies. The choice of this form of business results from the relatively low costs of establishment in comparison with other types of capital companies. In terms of other variables (Table 2), the share of respondents was comparable, except for the number of employees variable. The analysis of the number of employees was dominated by companies employing up to 10 people (29.58%). Among the companies in the TSL sector, entities employing up to 10 people constitute a significant group of enterprises. At the same time, the second most numerous group participating in the survey were enterprises employing more than 249 persons (28.17%). This group of enterprises is represented by the smallest number of entities in the TSL sector in Poland.

4. Test Results

4.1. Impact of the COVID-19 Pandemic on the Purchase of Electric Vehicles

The first issue raised in the survey questionnaire was the question of companies' ownership of electric vehicles and their willingness to purchase them since the beginning of the COVID-19 pandemic. The reconnaissance showed that only 14.08% of respondents indicated that they have electric vehicles in their fleet. These companies primarily own cars and vans. Only two of the companies surveyed indicated that they have electric trucks. This group consisted primarily of logistics companies with international operations, employing more than 249 people and operating for more than 10 years. However, in the group of companies employing up to 10 people, none had an electric vehicle. Only two of the surveyed companies indicated that they have electric trucks and these were companies operating in transport and forwarding, with international reach, for more than 10 years. Furthermore, only 16 companies planned to purchase an electric vehicle in 2020. These were also primarily logistic companies with more than 249 employees. This means that the purchase of electric vehicles is considered primarily by large entities, which comes from the scale of their business activity and financial capabilities. The results of the survey are consistent with other studies, which indicate that as many as 51% will not electrify their fleet [1]. As Polish transport companies have an almost 30% share in international road transport in the EU [20], it was checked whether the company's range of operation has an influence on the purchase of an electric vehicle. For this purpose, the study was carried out using the χ test^2. The assumption was made, hypothesis H0, that there is a relationship between the range of transport operations and the purchase of an electric vehicle, and an alternative hypothesis was made, H1, in which it was assumed that there is no relationship between the purchase of an electric vehicle and the range of operation of the company. The test yielded a result of $\chi^2 = 0.1114$, with $\alpha = 0.05$. The contingency coefficient $\varphi = 0.040$ was then determined, its magnitude indicating a very weak relationship between the variables. Hypothesis H1 was rejected (CHI_TEST > α), i.e., the relationship between the two characteristics was not statistically significant. Therefore, it can be concluded that, in this case, it was not the COVID-19 pandemic that directly influenced the lack of demand for electric vehicles. Since the COVID-19 pandemic has an impact on the health of many operators, the relationship between the willingness of companies in the TSL sector to purchase electric vehicles and the period of operation was examined. An assumption was made, hypothesis H0, that there is a relationship between the operational period of the company and the purchase of an electric vehicle, and an alternative hypothesis was made, H1, in which it was assumed that there is no relationship between the purchase of an electric vehicle and the operational range of the company. The test yielded a result of $\chi^2 = 0.2068$, at $\alpha = 0.05$. Hypothesis H1 was rejected (CHI_TEST > α), i.e., the relationship between the two characteristics is not statistically significant. Therefore, it can be concluded that in this case, it was not the COVID-19 pandemic that directly influenced the purchase of electric vehicles in the group of surveyed entities, but the limited availability of charging infrastructure. Next, the contingency coefficient $\varphi = 0.054$ was determined; its magnitude indicated a very weak relationship between the variables.

4.2. Influence of Selected Factors on the Purchase of an Electric Vehicle by Companies in the TSL Sector

Three groups of factors may have influenced the purchase of electric vehicles by TSL operators, during the COVID-19 pandemic, based on literature recognitions [22,28]. These are economic factors, which include the uncertain economic situation of the country and the condition of the surveyed companies. Another group of factors influencing the development of electromobility include state actions, including the system of incentives and the stability of electricity prices. An important group of factors for companies in the

TSL sector includes the accessibility to infrastructure. In this aspect, analyses are presented based on the obtained research results. The first factor examined was the economic situation of the country (Figure 6).

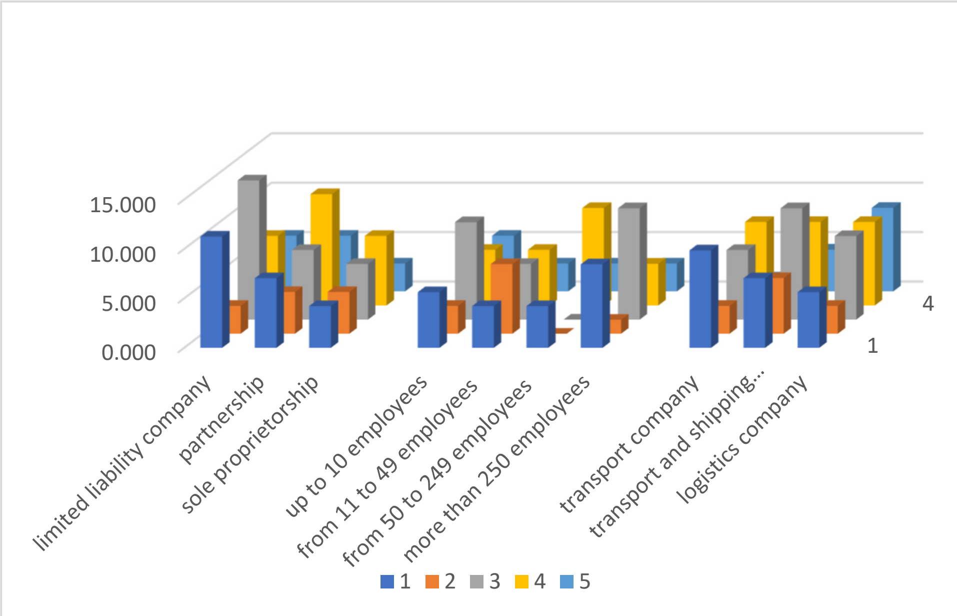

Figure 6. National economic situation and demand for electric vehicles—criteria organizational and legal form, employment structure, and scope of activity.

The impact of the country's economic situation on the demand for electric vehicles in the group of entities studied should be considered; taking into account the organisational structure of enterprises, it had the strongest impact on partnerships with enterprises divided by employment structure into companies employing between 50 and 249 people and those providing logistics services. In contrast, the weakest interest in purchasing vehicles during the COVID-19 pandemic was characterised by incorporated companies, with more than 250 employees and providing transport services. It is worth noting that the coronavirus pandemic has fundamentally changed the Polish TSL market; on one hand, it contributed to the dynamic growth of e-commerce, creating new development opportunities, and on the other hand it forced the enterprises to adapt to the changing reality. The report of the Polish Economic Institute shows that companies in the TSL sector have the highest economic situation index of all branches. At the same time, the lack of interest in electric vehicles is not connected with investment expenditures. The TSL sector is one in which more than half of the enterprises incurred investment expenditures. In more than every fifth company investment, expenditures increased. The increase in investment is most often associated with TSL companies (27%) as well as large and small enterprises (25% each) and medium-sized enterprises (24%) [73].

Since charging infrastructure is associated with EV ownership, whether the availability of fast charging infrastructure especially along motorways and expressways influenced the purchase of an electric car during the coronavirus period was investigated (Figure 7). As can be seen, the companies surveyed indicated that during the COVID-19 pandemic period, the availability of fast charging points had an impact on the demand for electric vehicles. Taking into account the organisational and legal form, the highest number of indications for the strong impact related to the availability of fast charging points was indicated by capital companies and partnerships, while in the case of sole proprietorships, the availability of fast charging points was not so important. On the other hand, taking into account the number of employees, it should be stated that for each of the groups of enterprises the availability of fast charging points was significant, especially among enterprises employing

11–49 employees. Despite the fact that transport companies should mainly care about the availability of fast charging points, research shows that these companies indicated a weaker influence of the location of fast charging points compared with transport and forwarding or logistics companies. This research corresponds to the research conducted among Polish drivers, who indicate that the interest in electric vehicles is affected by the lack of sufficiently developed public charging infrastructure [74].

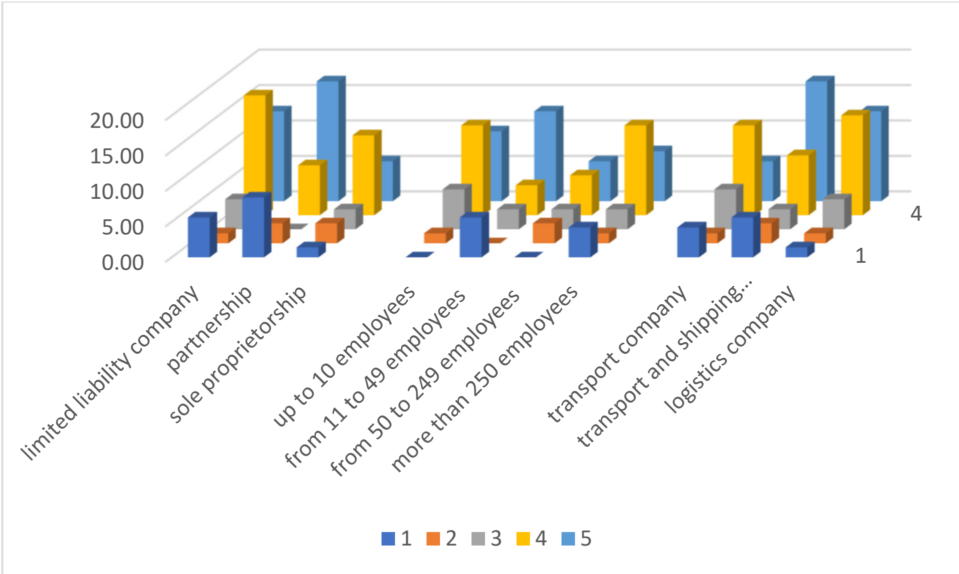

Figure 7. Availability of fast charging points at motorways and expressways and demand for electric vehicles—criteria organisational and legal form, employment structure, scope of activity.

The last factor presented in the study—uncertainty related to energy access—should be considered as significantly affecting the demand for electric vehicles in the group of entities studied (Figure 8). A comparable impact of this factor is characteristic of capital companies and sole traders. However, among sole traders, there was no reply about the total lack of influence of uncertainty in energy prices on the demand for electric vehicles. Uncertainty related to electricity prices is particularly important for enterprises with up to 10 employees. In this group of enterprises, none of the respondents, as in the case of sole proprietorships, marked answer 1—no impact. On the other hand, taking into account the scope of activity of the company, it can be seen that price issues are important for transport, transport-forwarding, and logistics companies. Although the cost of driving an electric vehicle is not high (for the MAN e-TGE 136KM/35.8KWh car, Greenway operator, tariff: Energy Standard (charging with power from 70 to 140 KW)), the cost of driving 100 km is 74.33 PLN. The respondents' indications may have been influenced in the period under study by government actions related to fuel increases and the dispute between Poland and the Czech Republic over the Turów mine. Moreover, an increase in the number of electric cars is associated with an increase in demand for electricity and this, in turn, may translate into an increase in electricity prices [75]. The legislative package called "Fit for 55" (12 directives) adapted by the European Commission on 14 July 2021, which concerns climate protection and the development of energy based on renewable sources, may have a significant impact on the results of respondents' answers. According to the European Union, greenhouse gas emissions are to be reduced by 55% by 2030. The "Fit for 55" programme assumes reduction of overall energy consumption, which in turn may have a negative impact on the development of electromobility in the TSL sector.

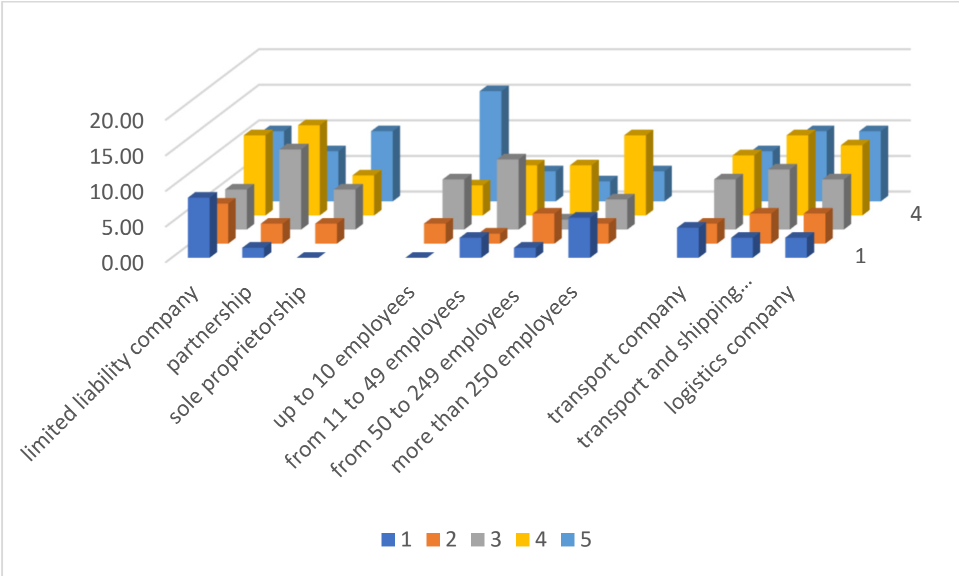

Figure 8. Energy price uncertainty and demand for electric vehicles—criteria organisational and legal form, employment structure, scope of activity.

5. Discussion

The COVID-19 pandemic did not directly affect the need to replace the fleet among companies from the TSL sector. The lack of interest was caused by, among other things, the lack of knowledge on electric vehicles among entities from the TSL sector. This was confirmed by the research performed by Higureas-Castillo E. et al. [76] which indicated the poor knowledge of consumers about electric vehicles. Fiscally, most consumers do not know how an electric vehicle works [77,78].

As can be seen from the research carried out, an important aspect that constitutes a barrier to the purchase of electric cars is the availability of charging infrastructure. Research by Raczyński A. et al. [79] indicated that the fundamental issue in electromobility development among TSL companies from the economic point of view is the high cost of purchase and operation of both the vehicles themselves and charging infrastructure. In the case of trucks and delivery vehicles, the most frequently indicated barrier in replacing the conventional fleet with an electric one was the cost of vehicle purchase and the periodic cost of battery replacement, which significantly exceeds the cost of purchasing a traditional fleet vehicle. The same factors affecting the vehicle purchase barrier were confirmed by Durak et al. [80]. They reported that the main barriers to the development of electromobility among heavy-duty vehicles are the high cost of vehicles as a result of high battery prices and the availability of the infrastructure itself, which limits the ability of electric vans or tractor units to move. These conclusions correspond directly with the results of our research, since the availability of charging infrastructure was one of the main factors influencing the purchase of electric vehicles. This was also confirmed by Osiecko K. et al. [81], who pointed out that one of the criteria used to assess the degree of development of electric freight transport in the European Union is the number of charging stations in individual countries. Moreover, the researchers acknowledge that there is a need to expand the infrastructure and plan it in such a way that will allow free transport of goods not only between EU member states.

A problem taken up in the study and referred to in other studies is the issue of electricity price volatility. This factor was important for the surveyed companies. Full electrification of the Polish automotive industry in its current state would require at least 45 billion kWh of additional supply per year. Given the problems with the Turów mine and the Fit for 55 package, the issue of electricity prices and their impact on electromobility requires additional research because of a research gap in this area. Changing socio-economic conditions provide a different perspective on the energy sector and the transport sector. The COVID-19 pandemic should motivate us to take on an approach [82] based on a long-term, sustainable perspective, and reinforce the importance of energy security by exploiting the benefits of greater enforcement of sustainable fuels (including truly sustainable-renewable-electric transport). The post-pandemic restart should provide an opportunity to steer the energy system towards more resilient, secure, competitive, and sustainable models.

The post-COVID-19 period should be strongly seized, as it is an unprecedented opportunity to boost transport towards decarbonisation while supporting EU economic activity.

The study shows that the economic situation in the country during the COVID-19 pandemic period had no impact on the development of electromobility in the TSL sector. As indicated by Świtała M. and Łukasiewicz A. [83], despite the slowdown in the economy in most cases, carriers did not reduce their rolling stock and workforce. The results of the research indicated that the prevailing belief was that the drastic fall in demand would be temporary rather than permanent, which turned out to be quite an accurate assumption.

The research results obtained may contribute to deeper research on the development of electromobility in the TSL sector in the context of changes in road transport and the energy sector.

6. Conclusions, Limitations and Suggestions for Future Research

Many publications on the impact of the COVID-19 pandemic point to its negative consequences [24,84–86]. However, it is possible to identify areas of socio-economic activity where, under the influence of the COVID-19 pandemic, one can see the absence of negative consequences or notice positive aspects. Based on the collected research material and analyses made on its basis, it can be noted that:

- Diesel-powered vehicles dominate among companies in the TSL sector. Electric vehicles constitute a small percentage of all vehicles. Their number in the general structure of trucks increased despite the COVID-19 pandemic. An important aspect related to the development of electric vehicles is conducting research projects with the participation of companies from the TSL sector.
- The number of publicly available charging points has not changed. The increase was significant especially in 2020. However, the number of charging points from the point of view of TSL companies is insufficient. For this group of vehicle users, fast charging points on motorways and expressways are the most important.
- In the studied group of entities, few entrepreneurs had electric vehicles and few were interested in purchasing them. Taking into account the scope of operations, undoubtedly, companies carrying out international transport must take into account the legal regulations in other countries on limiting CO_2 emissions. Moreover, companies operating on the market for more than 10 years may plan to replace their fleet with new vehicles adapted to meet the restrictive requirements. Lack of interest in electric vehicles among the surveyed entrepreneurs results from, among other things, low levels of knowledge of electromobility and lack of awareness of the benefits of electric vehicles or incentive systems for their purchase.
- An important factor which influences the decision not to purchase electric vehicles is the still insufficient number of charging points, including fast charging points. Taking into account the fact that Polish carriers carry out transport all over Europe, the lack of availability of charging infrastructure is a significant argument discouraging companies from replacing their fleets of vehicles.
- Of great importance for TSL sector entities is the situation in the energy sector, including instability of electricity prices. Entrepreneurs point to two important issues that concern the energy sector. On one hand, Fit for 55, which will affect costs in the energy sector, which may be partly transferred to the transport sector, and on the other hand, the issues of decarbonisation, or problems related to incurring penalties by Poland for coal mining in the Turów mine,

- The economic situation of the country, compared with the development of charging infrastructure and uncertainty of energy prices, was not so important for the surveyed companies in the period of the COVID-19 pandemic. As can be seen, the period of the COVID-19 pandemic even influenced its development thanks to the increase in online shopping, which affected mainly small entrepreneurs delivering in agglomerations. Nevertheless, the share of electric vehicles in the fleets of Polish companies increased only slightly during this period.

To sum up, we may say that the COVID-19 pandemic had no direct impact on the development of electromobility both in Poland and among the surveyed companies. Despite the fact that the surveyed entities constituted a small fraction of the entire sector, citing other studies, they exhibited behaviours similar to those shown by more than 51% of companies in the TSL sector [14].

Some limitations were encountered in the implementation of the study. One of them was the low participation of companies with electric vehicles. The study could be repeated only in a group of transport companies increasing their number accordingly. It would also be possible to conduct research on the impact of the energy sector on transport companies in the context of electricity affordability and charging infrastructure. Research related to development of electromobility among business entities could also include other groups of actual and potential users of electric vehicles and be conducted among such entities as taxi companies, courier companies, and entities owning fleets of vehicles intended for their own needs (used by sales representatives). On their basis, it would be possible to create a multi-criteria assessment of the possibility of electromobility development during the COVID-19 pandemic or take into account other factors influencing the development of electromobility in road freight transport.

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Article

Determinants of Electric Cars Purchase Intention in Poland: Personal Attitudes v. Economic Arguments

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Abstract: Urban e-mobility, seen as a part of complex and multidimensional European Green Deal plan, is essential for cities. However, it cannot be implemented without a common social commitment accompanied by a shared, strong belief in its advantages. Even if urban authorities and central governments would encourage their citizens to buy or share an electric vehicle (EV), the shift to EV will not be significant without people convinced that the idea of becoming zero-emission is economically viable and rational to them privately. This is especially true and important in countries like Poland—which is classified as an "EV readiness straggler". The main purpose of this study is to develop a robust forecasting model with the aid of advanced machine learning methods. Based on the survey conducted, we identified factors useful for predicting consumer behaviour in terms of willingness to purchase an EV. The proposed machine-learning tool (specifically, the Random Forest algorithm) will allow automotive companies to more effectively target factors supporting the promulgation of urban individual e-mobility.

Keywords: electric vehicles market and policy; electric vehicles; purchase intention; e-mobility; consumers preferences; consumer decision making; social values; delay discounting; cultural factors; economic factors; machine learning methods; sustainability

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1. Introduction

Humanity is currently finding itself at a crossroads, challenged by the transformation towards greener and more sustainable economy, especially in terms of energy consumption. During previous oil crises in the 1970s, societies and authorities missed the opportunity to reduce oil-dependence, they did not discern the warning signs of negative consequences of relying on fossil fuels delivered mostly by autocratic countries. At that time, this sin of omission was partially explained by ineffective, immature technologies. Today the world is in a different situation, as renewable technology is widely available. It seems that consumers' willingness to buy electric cars (EVs) might be the most serious obstacle now.

The significant consequences of fuel-dependence are clearly visible especially today, as people around the world suffer the economic consequences of war in Europe (Russian aggression towards Ukraine [1]). The associated migration and economic crises (economic sanctions and general economic instability caused by the war) undermine the global sustainability, already endangered by the climate disaster and the COVID-19 pandemic.

"If we do not get rid of cars, then we must make our cars better" [2]—this direct quote from Gary L. Brase addresses the choice faced by contemporary societies both in developed and developing countries: on one hand consumers around the world are not ready for substantial changes in their consumption patterns (i.e., consume less, share instead of own, recycle), on the other hand it is impossible to maintain those consumption patterns unchanged at a worldwide scale. The recipe provided by Brase is an attempt to compromise: if humanity is not ready to give up individual cars (as people are too used to the comfort and convenience provided by them), it should be ready to make them less polluting.

Which specific technology will dominate the alternative-fuel cars market in the years to come is in some ways irrelevant: no matter if it is solid fuel cells, hydrogen in gas or paste form, etc.—the more important issue is people's willingness and readiness for this change. This paper will focus on alternatively-fuelled cars such as battery electric vehicle (BEV) and hydrogen cars. It will not take into consideration hybrid electric vehicle (HEV) or plug-in hybrid electric vehicle (PHEV) as those types still require fossil fuels to drive.

Given that the contemporary world is mostly urban [3], it is especially important to make cities more sustainable in terms of transportation. Cities are those spatial structures that are largely responsible for climate disaster. City dwellers produce pollution (mainly as negative externalities of urban transport and inefficient, obsolete heating systems) but they are also vulnerable to urban pollution. As traditional transport, fossil fuel combustion emits particulate matter ($PM_{2.5}$) harmful to public health [4], limiting internal combustion engine (ICE) cars appears to be one of desired directions in changes of urban landscape (the others are: zero emissions zones, massive switch towards public transport, and priority for pedestrians and cyclists).

The definition of "sustainable city" coined by Gehl [5] is based on its transport means: "the sustainable city is strengthened generally if a large part of the transport system can take place as "green mobility", that is travel by foot, bike or public transport. These forms of transport provide marked benefits to the economy and the environment, reduce resource consumption, limit emissions, and decrease noise levels." Urban transport is a particularly important component because it is responsible for a large share of energy consumption, which results in substantial pollution and carbon emissions.

Air pollution is one of the largest challenges in Poland, and is responsible for around 93,000 premature deaths annually [6]. As indicated by European Environment Agency, Polish citizens are highly (above EU standards) exposed to selected air pollutants (namely: PM_{10}, $PM_{2,5}$, O_3, NO_2 and BaP): in 2018 the 100% of population was overexposed to benzopirene and 82.3% of population was overexposed to PM_{10} [7]. While Poland may be an extreme case, many other locations around the world—especially urban areas—face similar challenges.

In Poland the average age of a car is over 12 years, and the motorization rate is 747 (747 cars for 1000 inhabitants—which is the second highest result in Europe) [8]—but only 25 thousand (out of 24.3 million [9]) were PHEV and BEV cars as of 2021 [10]. The existing inefficient and outdated car fleet is a significant source of pollution harmful to the health of city dwellers, as well as excess carbon emissions harmful to the globe. Therefore, it is clear that substantial transition is needed in this field. One possible and desirable change is a shift towards electric passenger cars. Unfortunately, both Italy and Poland are classified as "EV readiness stragglers". In 2020, Poland was the third-worst European state in terms of EV registration rate (0.12 EV/1000 inhabitants) [11].

Despite noticeable dynamics of new EV registrations in 2021, the promulgation of zero-emission passenger cars in Poland is still a thing of the future. Even if urban authorities and the central government would encourage their citizens to buy or share an electric vehicle, the shift towards electric vehicles will not be a massive wave without people convinced that the idea of becoming zero-emission is economically viable and rational to them privately. The annual "New Mobility Barometer" [12] discovered a growing share of Poles who would consider EV while purchasing a new car (in 2017: only 12%, in 2018: 17%, in 2019: 28%, in 2020: 29% and in 2021: almost 33%). However, considering an EV during the market search for a new car does not necessarily translate into practice—the purchase of EV.

Societies around the world share similar reservations regarding the features of EVs. According to various studies, potential buyers question: range [13] (sometimes described as range anxiety), availability of public charging points [14,15], the cost of ownership (and the cost of buying). Usefulness and ease of use of electric vehicle is also questioned [16]. As Nordhaus [17] underlines, energy-cost myopia may be a substantial obstacle in one's decision-making process: consumers do not fully value future savings from energy efficiency improvements, and they prefer spending less money today than saving more in the future [17]. The purchase of an EV is characterised by delayed returns—it means that a higher up-front cost for an EV is later compensated by lower operating costs [18]. However, there is already an extensive psychological and economic knowledge on how individuals differ in their perception of discounting future returns and valuating them [2]. Moreover, one also should bear in mind that sometimes some people simply don't have the money now. Even if they properly valued future returns, their cash flow situation is too difficult now to act on it. In the light of this reservation, a well-tailored subsidy system that would ameliorate the financial situation of the less well-off, is a great challenge for public administration. The authors will address this issue later in the text.

The 'delayed returns aspect' leads to a conclusion, shared by Tu and Yang, that electric vehicles need increased publicity in order to attract consumers [19] and convince them that e-mobility is a part of solution to prevent the world from climate disaster (or losing in the climate casino—to use Nordhaus' metaphor). This publicity will be effective and efficient only to the extent that academia and the business world deeply understand the values and priorities of potential EV customers.

Beyond carbon emissions and other pollutants associated with urban mobility, it is important to mention the rare metal issue [20]: there is a danger that, as demand for the rare earth elements needed to produce EVs, wind turbines, photovoltaic panels, etc. increases, humanity will find itself dependent on fixed supplies of these metals. In other words, dependence on fossil fuels will change to dependence on rare earths. Metal mining is not indifferent to the environment. It also raises serious social effects and associated ethical risks [21]. As Sobiech-Grabka [22] pointed out, there are three approaches to address this issue: effective recycling, technological innovations (such as solid fuel cells) or a war for rare metals (the last one is not acceptable from moral and human point of view).

Another substantial challenge, related to the "dirty" production of electricity from coal, is presented at greater length in the literature review section.

On the basis of the above initial observations and literature review, the authors formulated research questions with the aim of describing the economic concerns and decision-making processes of Polish consumers: Do Poles perceive these same EV characteristics as disadvantages? Who is the most likely to buy an EV? Is it possible to predict the probability of EV purchase using machine learning techniques?

Those questions will be addressed in the present paper. With the use of a machine learning (ML) model followed by logistic and linear regression models, the authors discern the most influencing factors in the Polish case. These results will be helpful for EV manufacturers and car showrooms: the authors clearly point out what values are shared by their potential future customers in Poland, a promising EV market. This is also very important due to the fact that in 2021 Poland was only ranked 15th among EU countries in terms of sustainable energy development (SISED) [23].

The subject of the paper is relevant and current, as there is a research gap regarding the economics and psychology of buying electric cars in Poland. Moreover, there are many other developing countries, like Poland where successful EV transitions are crucial to global sustainable energy transformation.

The paper also adds to the literature in terms of methods used; the authors confirmed that advanced machine learning methods are an important addition to previously used research tools.

The structure of this paper clearly addresses the questions posed above. The literature review in Section 2 describes significant additions to the scholarship achieved to date. Next, Section 3 provides the methods description and in the following section presents the core results. In the discussion the results are compared with earlier findings, and it also presents limitations and potential areas of future work. The paper concludes by summarising its contributions to scholarship in this area and providing some practical recommendations.

2. Background and Literature Review

2.1. Previous Research on EV Purchase Intention

In the first step, literature published between 1998 and early 2022, investigating EV adoption, EV diffusion and EV purchase intention, was analysed. The following databases were searched: *Science Direct*, *SpringerLink*, *Scopus*, *Semantic Scholar*, *Web of Science*, *ResearchGate* and *Google Scholar.* A "citation chaining" approach was applied for searching both backward and forward in the literature to find more relevant papers. The results were then filtered to exclude papers focusing on sophisticated technological issues.

Early investigations on consumers' adoption of electric cars were focused on Western countries (such as Norway, Belgium, Germany, the Netherlands, the UK or the US) that were vanguards in EV promotion at the moment (cf. [19,24–26], [16,18–22]). The rising popularity of the concept of zero-emission cars in developing countries (especially China and India) resulted in more studies in the field. However, the research of electric cars in post-communist countries such as Poland is still in the early stage, resulting in significant knowledge gaps.

Individual e-mobility adoption is strongly related to a decision-making theoretical framework. Previous researchers in the field applied various approaches: from traditional economic paradigms (such as rational choice theory, RC) to theories originating in environmental or social psychology, behavioural economics, ecological economics, marketing or innovation diffusion theories—just to name a few [17,18]. Rezvani et al. [26] concluded that consumer adoption of EVs has been investigated prevailingly within five categories of theoretical frameworks (Figure 1):

1. Ajzen's theory of planned behaviour (TB) [27] and rational choice theory;
2. normative theories (e.g., Stern's value-belief-norm theory, VBN [28]) and environmental attitudes;
3. symbols, self-identity and lifestyle (based on psychological and sociological theories such as: Saussure's sign model [29], self-image congruency theory by Sirgy [30], narratives of self by Giddens [31], and Miller's costly signalling theory [32];
4. diffusion of innovations theory (DOI) by Rogers [33] and consumer innovativeness;
5. consumer emotions—proposed by Moons and De Pelsmacker [34] to be treated as an additional dimension to the theory of planned behaviour by Ajzen.

On the basis of literature review it was possible to discern groups of factors influencing EV purchase decisions (Figure 2).

According to some research, economic factors (purchase price and maintenance costs) constitute a very powerful hurdle, resulting in low demand for EVs, despite ostensible interest in buying them [27,28]. Jensen et al. [35] investigated individual preferences of consumers who experienced an EV for a three-month trial. They concluded that even if environmental concerns influence the preference for EVs positively, it does not translates into a purchase decision. On the other hand, various studies reveal the existence of a large cohort of consumers who would pay a higher up-front cost with the aim of gaining lower fuel costs [36].

Another important aspect for the uptake of zero-emission vehicles is their residual value. Wróblewski et al. [37] made a pioneering attempt to forecast residual values of low-emission BEVs and PHEVs compared to ICEVs based on the expert method. To-date, the loss in residual value for Poland BEVs is very large, as compared to ICEVs. While beyond the scope of this study, the issue of residual value (like the issue of up-front costs and cash flow for the less affluent) could be addressed by policies (some of which are mentioned in Section 5).

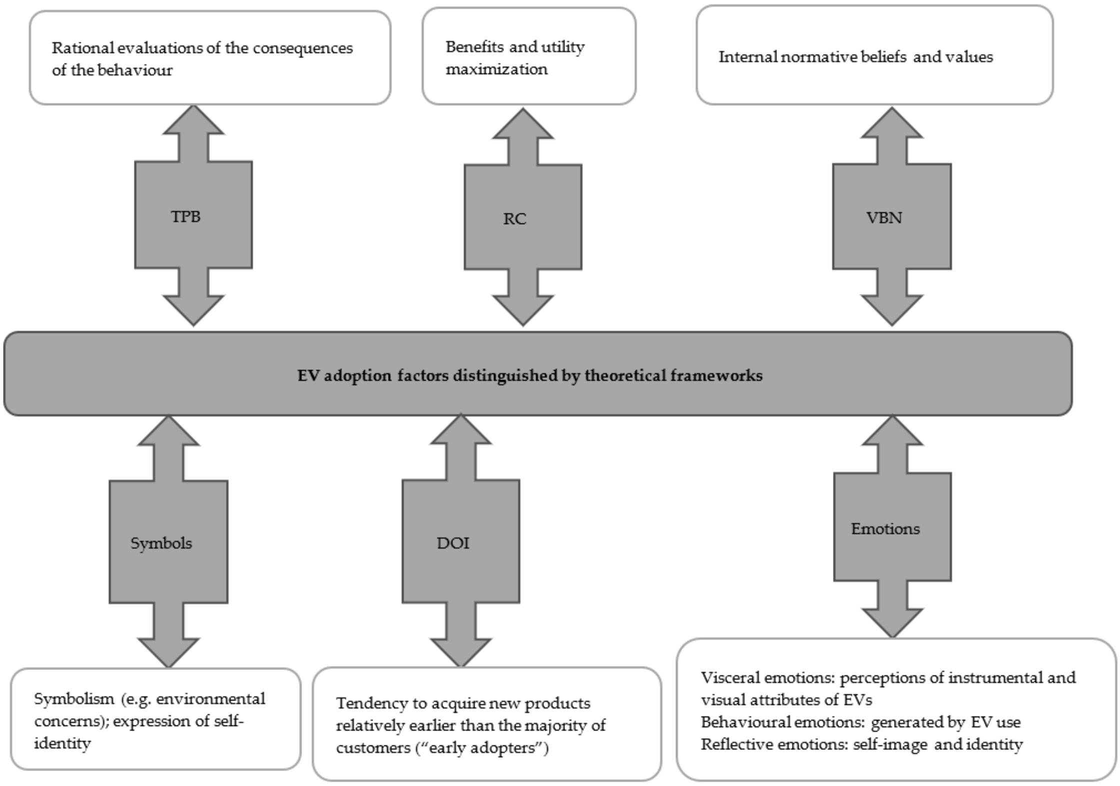


Figure 1. Basis of consumers' behaviour according to various theoretical frameworks. Source: own study, based on [26].

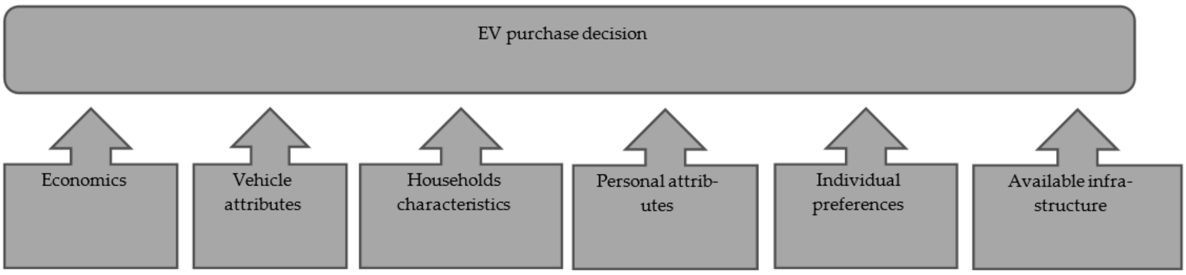


Figure 2. Groups of factors influencing EV purchase decisions.

Brase [2] investigated the perception of EV versus gasoline-powered vehicles in the US, using regression models. Respondents perceived the latter as "better" in terms of safety, performance, suitability for long trips and availability of fuel/charging stations. Electric cars were seen as "better" in terms of making a values statement, daily driving needs, energy independence and environmental conservation [2]. Based on the evidence, the author recommended focusing more on the vehicle-associated values and immediate performance issues in order to strengthen EV position in market share.

Norway, the European leader in EV implementation, is an especially interesting country to focus on. Haugenland and Hauge asked the Norwegians about their user experiences with e-mobility. The survey was conducted among a group of 3405 EV users/owners. The results shows that most of the respondents have used their EV for less than one year (60%), have higher education (76%) and have two cars in household (61%). Moreover, they are very satisfied as EV owners (91%), and most of them would buy an EV again (74%). In contrast, a survey of the entire Norwegian population shows that only 21% would consider an EV for their next car, and 35% would consider a plug-in hybrid. Current EV owners decided to buy an EV mainly for three reasons: save money (48%), save the environment (27%), and save time (12%). A smaller group (13%) decided to buy for reasons other than mentioned above. The researchers pointed out—as one of the most important conclusions—that one satisfied EV user can persuade three people to buy an EV [38].

Consumers' perceptions of EVs depend to some extent on EVs' features, but people's beliefs and identities also play a crucial role in EV adoption. Research by Schuitema et al. conducted in 2013 in the UK discerned that customers characterized by pro-environmental attitudes have positive perceptions of attributes of electric vehicles. As of 2013, intentions to purchase plug-in hybrid electric vehicles were stronger than battery-electric vehicles [39]. The 2013 observation of Schuitema et al. was confirmed by Mandys in 2021: the possibility of being an early EV adopter increases for people who are younger, better-educated, being a student, living in the more southern parts of the UK and being married [40]. Surprisingly, the very early adopters of EVs in Germany were middle-aged men living in suburbs or rural areas. Major German city dwellers, to whom pro-environmental identity may more likely be assigned, were not as keen on shifting towards zero emission cars [41].

A large-scale study by Novotny et al. [42] (on a sample of 21 countries), based on Hofstede's concept of different cultural dimensions (power distance, uncertainty avoidance, individualism vs. collectivism, masculinity vs. femininity, long-term vs. short-term orientation, and indulgence vs. restraint) aimed to determine the impact of culture on EV adoption through its role in innovative and environmentally conscious behaviour.

To-date China is the largest market for EVs and vast number of research studies were conducted there to determine factors influencing consumer behaviour while purchasing new cars. Ye et al. [43] developed an integrated approach to jointly study three psychological attributes (attitude, subjective norms, and perceived behavioural control) and four policy attributes (purchase subsidies, license plate control, preferential usage, and preferential driving) influencing consumers' EV purchase intention. Research was conducted in 2019 in China on 1087 respondents. They found that these psychological attributes can increase consumers' EV purchase intention, even without government action (e.g., purchase subsidies). What's more, the lack of psychological attributes causes a decline in interest in buying EV, even with government subsidies [43].

Li et al., on a sample of 2851 respondents from the US, analysed how factors like demographics, socioeconomic status, driving patterns, and attitudes have an influence on alternative-fuel vehicles purchases using on the maximum-likelihood estimation method. General findings were that flexible-fuel or hybrid-electric vehicle consumers were characterised by: concerns about the cost of gasoline, concerns of the effect of oil imports on national security, and concerns about environmental impacts from cars. Their more detailed research with differentiation by vehicle type shows that longer formal education time has a more positive impact on the decision of buying a flexible-fuel vehicle than a hybrid-electric vehicle [44]. However, this is not surprising, given that more highly educated people tend to have higher incomes and can therefore more easily consider buying these more expensive vehicles.

With the use of Structural Equation Modelling, Krishnan and Koshy [16] evaluated the influence of various attitudinal factors on EV purchase intention of people in India. They revealed that perceived benefits, social influence, price acceptance, performance, technological consciousness, and marketing have positive effects on EV purchase intention [16]. Those findings were confirmed by Gurudath and Rani who conducted research on the factors influencing the decision to buy an electric vehicle on 125 people from Bengaluru (India). The results show that the following factors are very important in electric cars for the respondents: Service Warranty, Price, Safety, Life Span, Speed and other important factors like: Test Ride, Low noise, Trend, Delivery Time, Ability to Upgrade. Other findings from the study are that highly satisfying factors in electric cars are: Environment Friendliness, New Technology, and somewhat satisfying factors include Resale Value, Charging and Vehicle Capacity [45].

In the years to come, especially after Russia's aggression on Ukraine that resulted in serious concerns about imported petroleum security, the speed of up-take of electric vehicles may increase. However, this would require some support (including financial incentives and huge infrastructure investments). To the authors' best knowledge, there is a visible lack of extensive studies investigating the role of state and international regulators in EV diffusion. Given that the EU has adapted the Fitfor55 package that indicates electric mobility as a pillar for transport decarbonization (and simultaneously, the member states on their respective national levels), the impact of legislative changes on EVs adoption will be massive. However, the authors managed to find some papers dealing with the impact of regulatory issues. Some cities (in China for example) adapted license plate control policy as a tool to mitigate pollution in urban areas, and a 2019 study reported this policy to be more influential for Chinese consumers than a purchasing subsidy [46]. Tu and Yang [19] deliver additional recommendations on the role of government and car manufacturers who should consider increasing the publicity of EVs and introduce more attractive battery and charging schemes [19]. As underlined by Bobeth and Kastner [47], broader political support schemes are also needed to foster EVs adoption [47].

Apart from information campaigns postulated by the latter, the efficiency of subsidizing EV purchase policy should be of great research interest. A 2018 study in California (the state that accounted for 40% of EV purchase in the US and 10% of global EV purchase in 2018) estimated three crucial parameters of subsidizing policy: the rate of subsidy pass-through for the program, the impact on EV adoption, and the elasticity of demand for EVs among low- to middle-income customers. Muehlegger and Rapson estimated the demand elasticity between −3.2 and −3.4, to be interpreted that a subsidy decreasing the price of an EV by 10% has a potential to increase demand for EV by 32–34%. Even if this observation is remarkably promising at first glance, one should keep in mind the small baseline quantity, resulting in moderate increase of purchased EVs [48]. Nevertheless, these purchase subsidies may play a very important role in bringing low- and moderate-income people into the EV world. The case of Italy suggests that monetary incentives are the most effective measure for electric car promulgation. In that country, described by Danielis et al. [49] as "a country with limited but growing electric car uptake" subsidies appeared to have greater impact on consumers' purchase decisions than technological improvements. Research on electromobility development in Poland indicates that Polish consumers still perceive electric cars as expensive. According to Lewicki et al. [50], this implies the need for more active government action to support the demand side.

There are still some technological issues to be solved or clarified in coming years, and these solutions will be of great importance for future EV users and buyers. For instance, the time of charging, raised today so often by EV opponents, may be solved in various ways, including implementation of extra fast chargers or battery-swapping points. The unsuccessful attempt of Tesla to implement battery-swapping technology in 2013 [22] proved that American e-car drivers perceived faster (and free of charge) charging stations as a more compelling solution [51]. Meanwhile, as battery swapping services are promoted by the Chinese government, this model is likely to increase future electric vehicles adoptions [52].

The technological challenges are even more complex in places (like Poland) where most EVs are charged by electricity produced from coal (in 2021, over 75% of Polish-produced electricity was based on either hard or lower-grade brown coal [53]). So, while EVs are locally zero-emission (which is good for the places in which they're used), the overall carbon footprint is still substantial (i.e., the negative externality accrues to the coal power plant's location, as well as to the globe at large). Petrauskienė et al. [54] investigated assessment of BEV's performance with different electricity mix scenarios, built with the aid of scientific modelling for the years 2015–2050 for Lithuania.

Thus, a broader and more holistic green transformation of energy sources is crucial in this context. Polish consumers have recently achieved an incredible progress in becoming "*prosumers*" (i.e., people who produce energy at home using mainly photovoltaics (PV), consume the produced energy and add the surplus to a power grid). As of January 2022, Poland's installed PV power capacity is 8.1 GW, and PV has the biggest share (47%) among all green energy sources in Poland [55]. However, due to some technological constraints the future development of PV in Poland is likely to be slower. This issue will be detailed in Section 5 of this study.

Because an EV is still more expensive than an ICE car of a comparable size and standard of equipment, it may be assumed that in poorer EU countries such as Poland, EVs will be purchased by well-offs who pay more attention to their socio-economic status indicators. The symbolic motivations of this group may be more important than rational factors: the range and price of a car being less important than the message announced by it. Research in Portugal supports this claim: the probability of purchasing an EV is bigger in the higher-priced car segment. In the case of lower or middle car markets, the cost argument prevails and consumers prefer to buy conventional engine cars [56]. This observation suggests that, particularly in developing countries, EV purchase willingness of the well-off is driven more by "virtue-signalling" or "affluence-signalling" than by rational expectations. At the same time, the large remaining cohort of potential EV buyers is more limited by financial constraints. Rezvani et al. [26] also underline the need to explore the symbolic meanings attached to EVs in diverse cultures, as symbolic meaning is context-dependent.

The growing popularity of electric vehicles in Poland, despite unfavourable residual value data and a limited subsidy system (as indicated in Section 2.2), suggests that non-economic factors may be more important to consumers. This assertion is the foundation of the Hypothesis H1.

Electric car sharing has recently become a more popular and frequent scheme in urban areas, even if implemented with some substantial difficulties [22]. However, its growing popularity in various cities around the world results in more drivers who have already experienced driving an electric car. This provokes another research question—to which extent does previous experience with using an electric car result in growing readiness to buy an EV? Is there any positive correlation between EV trial and consumer response in a car showroom? The main objective of the research is to develop a robust predictive model using advanced machine learning methods. This also has a practical dimension, as such a model would allow automating the identification of customers buying electric vehicles and tailoring manufacturers' products to their customers' preferences and views on green solutions.

Consequently, based on literature review, the following research hypotheses were formulated:

Hypotheses 1 (H1). *In Poland personal values and beliefs play a more important role in EV purchase willingness (are significant predictors) than EV features such as range or price.*

Hypotheses 1 (H2). *Previous experience with electric car sharing has a positive impact on EV purchase decision: drivers who have already driven a shared EV are more likely to buy an EV in the near future.*

Hypotheses 1 (H3). *There are independent variables that, using machine learning methods such as Random Forest, will predict willingness to purchase an electric vehicle for personal use.*

2.2. Polish Government Subsidies

The Polish government adopted The National Policy Framework for the Development of Alternative Fuel Infrastructure in 2017. This framework implemented the EU Directive 2014/94/EU on the development of alternative fuel infrastructure [57]. Consequently, in 2018 the Ministry of Energy announced "Electromobility Development Plan in Poland 'Energy for the Future'" [58]. The subsidy scheme described below is part of a package aimed at supporting the development of electromobility in Poland.

In Poland, the electric car market is still at a very early stage of development. However, the COVID19 outbreak did not slow it down: as Rokicki et al. observed, the dynamics of introducing electric cars into use increased in 2021 in all EU countries, including Poland [18]. In 2021, an electric vehicle subsidy scheme called "My EV" ("Mój Elektryk" in Polish) was announced to promote zero-emission mobility. The main characteristics of this program are provided in Table 1.

Table 1. Details of "My EV" scheme for individual buyers, launched by the Polish government in 2021.

Feature	Data	Comments
Period of availability	1 May 2020–31 December 2025	Cars must be registered before 31 December 2025
Available amount of subsidy	18,750 PLN [1]/27,000 PLN [2]	Bigger subsidy for families with 3 and more children
Limit of car price	225,000 PLN [3]	No limit for families with 3 and more children
Eligible cars	EV, hydrogen	Around 37 models available in 2022, varying from Dacia Spring to Tesla 3 or Ford Mustang Mach-e
Weakness	Consumer must pay the whole price and then apply for a subsidy	Requires covering the whole cost initially

[1] Exchange rate (22 March 2022): 1 EURO = 4.7460 PLN; 1 USD = 4.2982 PLN. [2] Around 3950 EURO/5689 EURO or 4362 USD/6281 USD. [3] Around 47,408 EURO/52,347 USD. Source: own study, based on the program details [59].

At the very beginning there were only a few cars eligible for the subsidy [60]. With the widening of electric models available on the market, there are now around 37 models that could be co-financed by "My EV" scheme. The vast array of offers could account for increased dynamics of EV new registrations in Poland during the COVID-19 pandemic. However, these dynamics may be difficult to sustain in the years to come as continuous difficulties with supply chains and market shortages (especially regarding electronic components, crucial for the modern automotive industry) are still observed. Prolongation of the subsidy scheme beyond 2025 is likely to happen.

The authors of this study share the view of Sendek-Matysiak and Grys [61] that the system of supporting demand for electric cars in Poland is insufficient. The scope of required changes includes subsidies for EVs purchase regardless of their price, and tax relief defined as a significant reduction in the price of the car immediately at the time of purchase.

3. Materials and Methods

3.1. Recruitment of Participants and Study Procedure

This paper is a result of a larger project initiated in connection with the study of e-mobility in Poland (the project was carried out between 2019 and 2021). The research presented in this paper focuses on predicting the likelihood of purchasing electric cars by individuals. For this purpose, the authors set the following research hypotheses:

Hypotheses 1 (H1). *In Poland personal values and beliefs play a more important role in EV purchase willingness (are significant predictors) than EV features such as range or price.*

Hypotheses 1 (H2). *Previous experience with electric car sharing has a positive impact on EV purchase decision: drivers who have already driven a shared EV are more likely to buy an EV in the near future.*

Hypotheses 1 (H3). *There are independent variables that, using machine learning methods such as Random Forest, will predict willingness to purchase an electric vehicle for personal use.*

Choosing an adequate method to predict consumer behaviour in terms of propensity to purchase electric vehicles and evaluating the importance of different features is crucial to evaluate the classification process. Desk research was used to verify Hypothesis H1. On the other hand, linear regression and log-log regression models were used to test Hypothesis H2.

Then, to verify Hypothesis H3, an ensemble learning technique was applied by testing four popular algorithms. A Random Forest (RF) ensemble learning technique was chosen as the classifier because it can provide excellent classification performance in an efficient way and evaluate the importance of input features. Literature review revealed that no such advanced econometric modelling has been applied in the literature so far. In the literature, statistical methods used to evaluate social and economic factors to-date include: simple descriptive statistics [32], joint model estimation [30], application of discrete choice mode using adaptive Lasso methodology, binomial logit regression and ordered logit regression [34], and cross-tabulation analysis [38].

The empirical material used in this study was collected between January 2021 and August 2021 to describe the preferences of urban residents regarding e-mobility. An online survey questionnaire was used. The survey was developed using Survio software. Respondents were able to access the survey questionnaire via a link. The invitation to participate in the survey was posted on social media (e.g., the project's Twitter, FB and LinkedIn) on the university websites and sent from the email box of the university dean's office. The authors also used the snowball method [62,63], which involves non-random sampling and recruitment of participants by other participants to quickly increase the size of the research sample. This also allowed to reach respondents in the absence of a census. The authors are aware of the disadvantages of this method in terms of the representativeness of the research sample, but due to the nature of the study, this did not negatively affect the results. The criterion for inclusion in the research sample was age (over 18 years) and residing in Poland.

The survey consisted of 31 questions of closed and semi-closed type. Question 1 asked about a license to drive passenger cars. Questions 2–5 and 7–10 were metric questions. They were designed to elicit responses regarding the socio-demographic characteristics of the respondent such as: (1) gender, (2) age, (3) place of residence, (4) type of housing in the place of residence, (5) education, occupational status (working, retired, etc.), (6) sector of work, and (7) financial situation. Question 6 asked about the ability to charge an electric car at a residence. Questions 11–31 addressed, among other things, the modes of transportation used by respondents and the frequency, the type of propulsion system used for EVs, car sharing, factors that determine EV purchase, etc.

3.2. Study Participants

The research group (Table 2) included 198 residents of cities with a population of more than 50,000 (42.93% of them were men, 57.07% of them were women, 1.52% of them were non-binary persons), aged above 18 (the mean age was 33 years). The majority of respondents are from urban areas of more than 500,000 population (52.02%), of which 24.24% (54 respondents) are female and 24.24% (48 respondents) are male.

The research sample does not reflect the characteristics of the Polish population: better educated and wealthier people are overrepresented among the survey respondents. The predominance of women in the research sample is also apparent, as are student/unemployed respondents. For those reasons, the research presented here has some limitations, which are elaborated further in Section 5. However, the purpose of the survey conducted (data set in Table 2) among Polish respondents was not to obtain a representative sample. Instead, the purpose of the survey was to obtain as many respondents as possible who are characterized by different levels of interest in purchasing electric vehicles by 2024.

3.3. Research Tools

A survey examining respondents' preferences for purchasing an electric car and a sociodemographic metric were used to measure the variables included in the presented portion of the study.

First, a machine learning (ML) model was developed to predict willingness to purchase an electric car. The data for analysis was prepared using a method that involved removing variables with a high missing value coefficient and partially removing the effects of imbalance in the resulting set (oversampling). This allowed the training set to be trained to remove the effects of the imbalance. In this way, model estimation was possible.

Table 2. Selected socio-economic characteristics of the sample N (N = 198).

Category	Variable	N	%
gender	male	85	42.93
	female	110	55.56
	nonbinary	3	1.52
age	18–34	105	53.03
	35–44	56	28.28
	45–59	26	13.13
	$\leq$60	11	5.56
population of respondent's place of residence	Countryside to 100 k *	62	31.31
	100–500 k *	33	16.67
	more than 500 k *	103	52.02
type of building that respondent lives in?	single-family house/terraced house/semi-detached house	99	50.00
	multi-family building	99	50.00
the highest degree or level of school	none/elementary school/vocational school	31	15.66
	high school degree	115	58.08
	University/college degree/Doctoral degree	51	25.76
employment status	student/Unemployed	52	26.25
	employed/Self-employed	116	58.59
	retired/pensioner/Rentier (a person of leisure)/other	10	15.15
subjective assessment of respondent's financial situation	Sometimes, we are not able to pay for costs of living (rent, utilities, etc.)	8	4.04
	We earn enough to cover the costs of living, and from time to time we can either save money or afford extra expenses.	96	48.48
	Every month we can afford extra expenses, and we can regularly save part of our income	94	47.47

* or a dormitory own/ suburbs close to the town of a given size.

The twelve steps of the statistical part of the research procedure are shown in Figure 3. In the next step, logistic and linear regression models were performed. This allowed us to predict the reasons for purchasing an electric car based on factors such as: (1) age, (2) gender, (3) education, and (4) place of residence. In the last step with χ^2 test of independence, the research hypothesis was tested. The global significance level was $\alpha = 0.05$.

3.4. Data Analysis

Based on the literature review, the authors predicted that in countries with low levels of EV uptake (like Poland), it is the more affluent consumer groups that become EV early adopters. Their purchase decisions are often driven by non-economic factors (e.g., status signalling), without performing a financial profitability calculation (including total cost of ownership or residual value of a car). This is because the influence of values and beliefs of such consumers is greater, as well as the behaviours observed years ago by Thorstein Veblen (demonstration effect). This prediction was the basis for the formulation of the first hypothesis.

Due to the adoption of such an approach, the authors distinguished several factors to be included in the study, which described the values adhered to by the respondents. Furthermore, based on Hofstede's concept (the influence of the cultural dimension: masculinity vs. femininity), the authors attempted to determine whether the gender of the respondent would influence purchase decisions. Value-based factors were contrasted with other rationales for purchasing an EV (e.g., place of residence, access to a car charger). In addition, due to the authors' previous findings that experience with EV use can influence willingness to purchase an EV, the authors wanted to verify whether previous experience with electric car sharing would have a similar impact in the case of Poland.

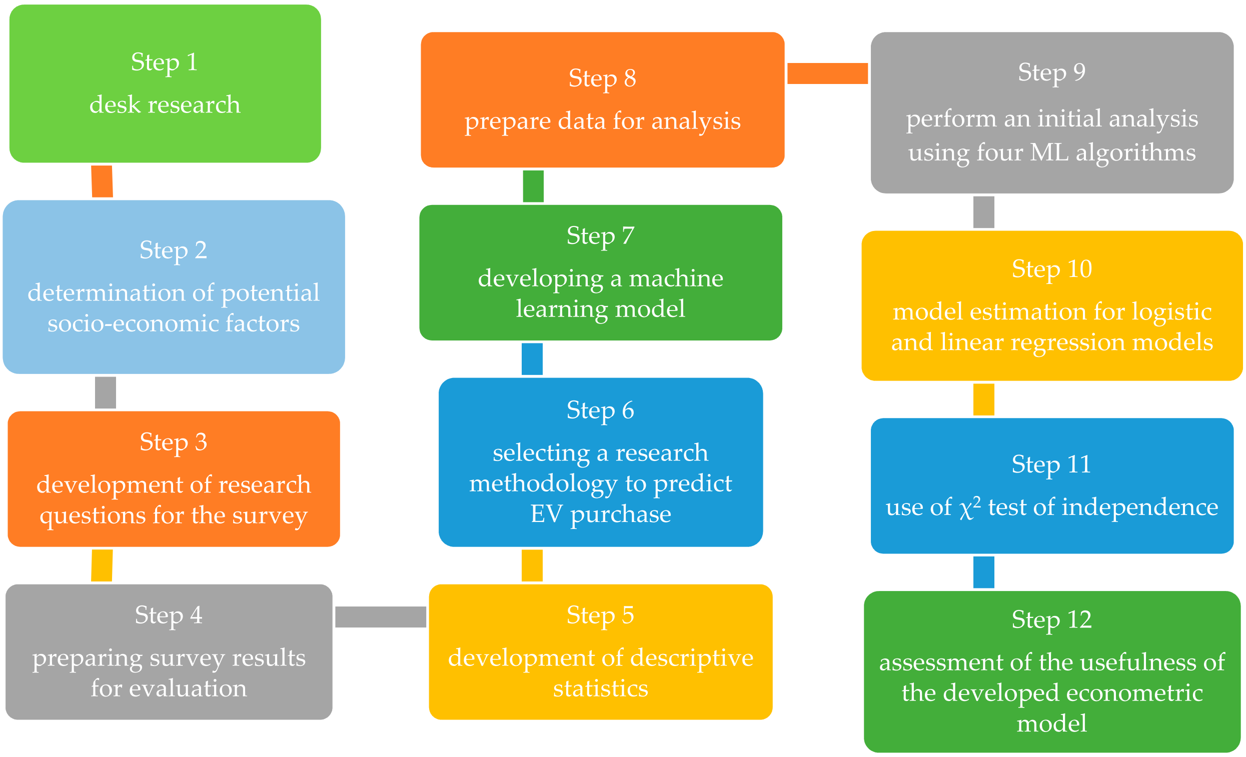


Figure 3. Multi-step research approach.

ML was conducted to answer Hypothesis H1 regarding the evaluation of the influence of personal values and beliefs have on the propensity to purchase electric vehicles.

The following factors were specified to verify the research Hypotheses H2 and H3:

(1) social: gender, age, place of residence, type of housing
(2) economic: access to a charger, subjective assessment of material situation, type of propulsion of the car used.

These variables were used for the logistic model and linear regression.

The R programming language and RStudio software [64] were used to perform the analyses and statistical calculations. Three packages: tidyverse [65], caret [66], and psych [67], were also imported to provide additional tools for the study.

4. Results

4.1. Machine Learning—An Algorithm for Predicting Electric Car Purchase Readiness

In order to predict the purchase of an electric car, machine learning (ML) techniques were used to develop a statistical model. The data extracted from the questionnaire was used for this purpose. First, variables (black dots in Figure 4) with more than 20% missing values (values below the red line in Figure 4) were removed from the dataset. The percentage of missing values is shown in Figure 4. The red line shows the 20% measurement cutoff value of the variables. Random Forest (RF) methodology is explained in detail in the literature [68–70].

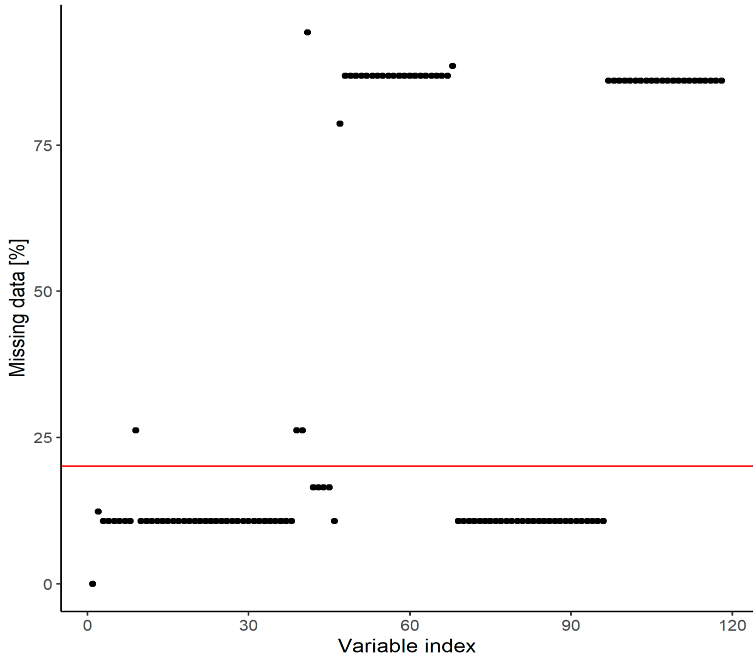


Figure 4. Percentage of missing values for each variable in the data set.

The survey also asked: Are you planning to buy an electric car by the end of 2024? Possible responses to the question about willingness to purchase an electric car were: (1) Yes, (2) No, (3) Hard to say. The following was taken as the explanatory variable (1): I plan to purchase an electric car by the end of 2024. Given this, all responses from group (3) were removed from the dataset. The other two classes were highly unbalanced, so the oversampling method was used. Then, the dataset was divided into a training (70%) and a test dataset (30%).

To develop an algorithm to predict of the readiness to purchase a private electric car, the algorithm with the best initial performance was used. For this purpose, a preliminary analysis was conducted using four popular machine learning (ML) algorithms. The following algorithms for the study were used:

(1) classification and regression trees (cart),
(2) k-nearest neighbour (knn),
(3) support vector machine (svm),
(4) random forest (rf).

The quality of the models was evaluated using measures of accuracy and kappa. All algorithms were run using 10-fold cross-validation. The Random Forest algorithm achieved the best performance, while the k-nearest neighbour algorithm achieved the lowest performance. Performance comparisons are shown in Figure 5.

The Random Forest algorithm obtained the best results with a mean accuracy of 98.67% and κ of 96.00%. Therefore, the Random Forest algorithm was selected for further analysis (Table 3).

The model was then tuned using the value of the mtry parameter (i.e., the number of variables randomly sampled as candidates at each split). The accuracy measures that depend on the value of the mtry parameter are shown in Figure 6.

The optimal value of the mtry parameter (number of variables randomly sampled as candidates at each split.) was 8. Finally, the model was fitted and its accuracy was evaluated. The confusion matrices on the training and test data sets are shown in Tables 4 and 5.

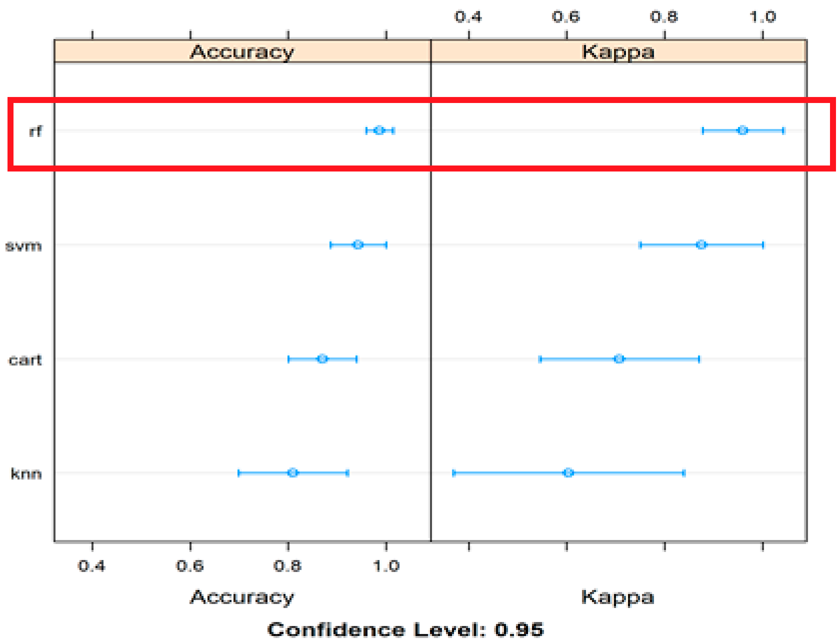


Figure 5. Comparison of different machine learning algorithms; rf—Random Forest, svm—Support Vector Machine, cart—classification and regression trees, knn—k-nearest neighbour.

Table 3. Results of accuracy and kappa values for algorithms: cart, knn, svm, rf.

Accuracy							
Models	**Min**	**1st Qu**	**MD**	**Mean**	**3rd Qu**	**Max**	**Na's**
cart	0.5000000	0.6666667	1	0.8700000	1	1	0
knn	0.5000000	0.6666667	1	0.8300000	1	1	0
svm	0.5000000	1.0000000	1	0.9433333	1	1	0
rf	0.6666667	1.0000000	1	0.9866667	1	1	0
Kappa							
cart	0	0.4	1	0.708	1	1	0
knn	0	0.4	1	0.644	1	1	0
svm	0	1.0	1	0.876	1	1	0
rf	0	1.0	1	0.960	1	1	0

Table 4. Training dataset—purchase of EV car—prediction and observation.

Training Dataset—Purchase of EV Car		**Prediction**	
		Yes	**No**
Observation	Yes	38	0
	No	0	38

Note: accuracy = 100.00%, 95% CI = [95.26–100.00%], specificity = 100.00%, sensitivity = 100.00%. Source: own study.

Table 5. Confusion matrix and model quality measures; test dataset.

Test Data Set—Prediction of Electric Car Purchase		**Prediction**	
		Yes	**No**
Observation	Yes	15	0
	No	1	16

Note: accuracy = 96.88%, 95% CI = [83.78–99.92%], specificity = 100.00%, sensitivity = 93.75%.

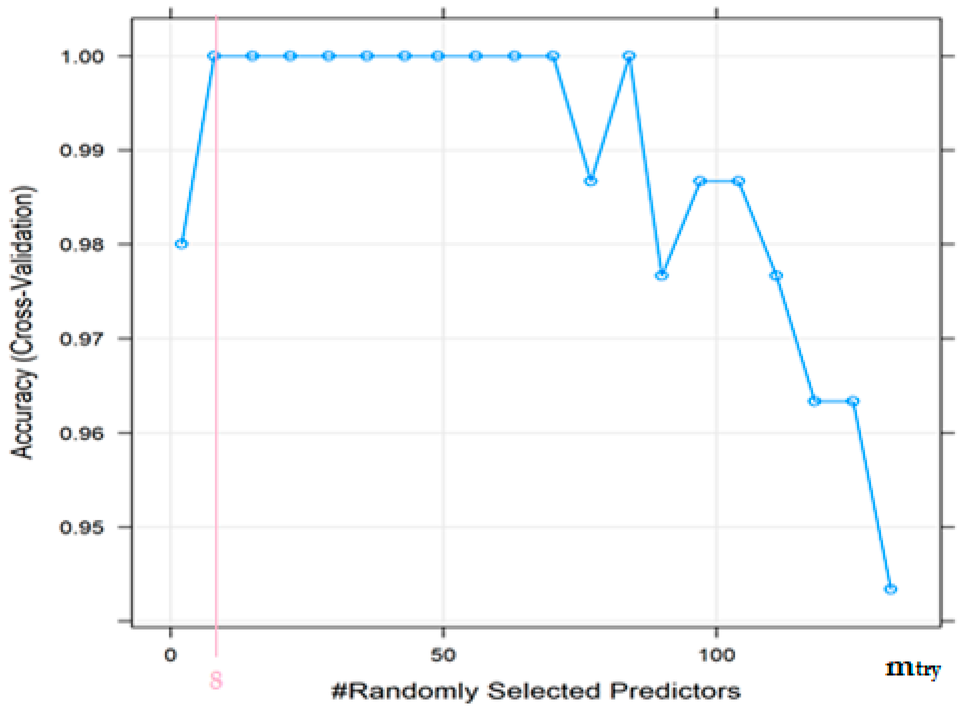
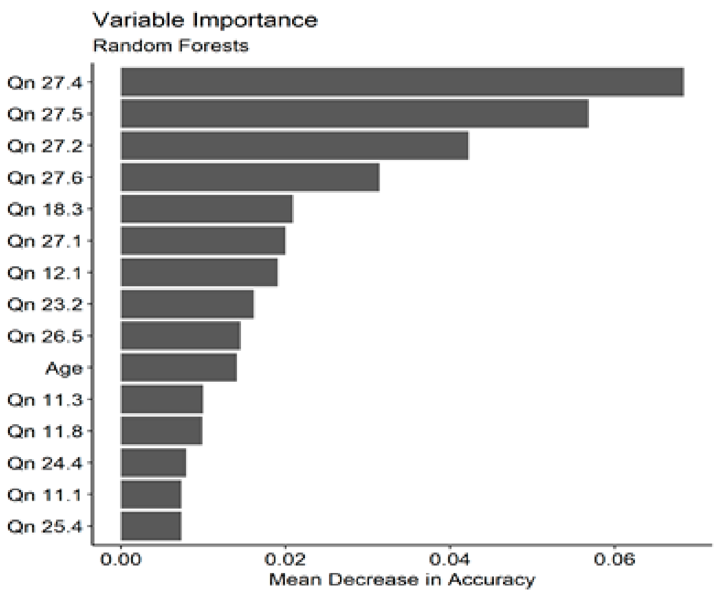


Figure 6. The accuracy of the Random Forest model as a function of the value of the mtry parameter.

Detailed accuracy and kappa values for the four algorithms tested are shown in Table 3.

The model fit was very good. Except for the test and training sets, the accuracy did not differ significantly, so no overfitting occurred. The selected parameters were then optimized to improve the performance of the algorithm. Fourteen variables with the highest predictive value in the model were plotted. This is shown in Figure 7. The greater the value of "mean Decrease in accuracy" (*x*-axis) is, the greater is the influence of the variable under study on the prediction of EV purchase intention.



Q_n—number of question.

Figure 7. Relative importance of variables in the final Random Forest model.

In turn, a description of the variables used in the study is presented in Table 6.

Table 6. Description of the relative importance of the variables in the final Random Forest model with variable importance.

Question [Qn]	Variable Name	Variable Importance
Qn. 27	**Respondents' response to the statements**	
Qn. 27.4	Choosing an electric car is pointless due to the "dirty" energy sources in our country.	**1**
Qn. 27.5	In 10 years, electric cars will replace gasoline (petrol) and diesel cars	**2**
Qn. 27.2	I would be better off travelling in a more environmentally friendly way	**3**
Qn. 27.6	If my employer would organize a ride for a few people from home to work, using electric vans (e.g., vanpooling), I would use this option regularly.	**4**
Qn. 27.1	Using cars causes many environmental problems	**6**
Qn. 18	**Have you ever driven an alternatively powered car**	
Qn. 18.3	100% electric	**5**
Qn. 12	**What form of transportation was used most often before COVID-19 to accomplish life activities.**	
Qn. 12.1	Running errands	**7**
Qn. 23	**Respondent's preferred model of organizing electric car sharing**	
Qn. 23.2	Part of an integrated transport system in a city, available for a single charge (so called Mobility as a Service)	**8**
Qn. 26	**Respondents' assessment of additional billing options with the electric car sharing operator**	
Qn. 26.5	Bonus (5 free minutes) for connecting the car to the charging station	**9**
Qn. 3	**Age**	**10**
Qn. 11	**Frequency of respondent's choice of a particular mode of transportation for daily travel (to work, shopping, etc.) prior to COVID-19 pandemic**	
Qn. 11.3	Streetcar	**11**
Qn. 11.8	Own bike/scooter/scooter	**12**
Qn. 11.1	Private car (as passenger)	**14**
Qn. 24	**Respondent's preferred method of payment for electric car sharing services**	
Qn. 24.4	Car sharing available as part of a mobility subscription (for all urban and shared transport modes), i.e., a Mobility as a Service (MaAS) that bundles a whole package of mobility services within a single application and fee. The fee depends on the profile/basket of services defined by the user.	**13**
Qn. 25	**Respondents' preferred method of billing the electric car sharing operator**	
Qn. 25.4	Payments based on time of use and distance travelled	**15**

The greatest relative importance of the variables in the final Random Forest model for predicting the willingness to purchase an electric car is described from 1 (greatest variable influence on the model) to 14 (least variable influence on the model).

4.2. Determinants of Electric Vehicle Purchase

The basic characteristics of the respondents and their relationship with the willingness to purchase an electric car for personal use are presented in Table 7.

Table 7. Respondents' stated plans to purchase an electric car for personal use.

Questions	Value	Yes	N%	No	N%	No Sure	N%
Are you planning to buy an electric car by the end of 2024?	**total**	29	15%	106	54%	63	32%
Gender	female	16	8%	56	28%	38	19%
	male	11	6%	50	25%	24	12%
	nonbinary	2	1%	0	0%	1	1%
	total	**29**	**15%**	**106**	**54%**	**63**	**32%**
Type of building that you living?	single-family house/terraced house/semi-detached house	18	9%	47	24%	34	17%
	multi-family building	11	6%	59	30%	29	15%
	total	**29**	**15%**	**106**	**54%**	**63**	**32%**
Age	18–34	9	5%	63	32%	33	17%
	35–44	13	7%	25	13%	18	9%
	45–59	6	3%	12	6%	8	4%
	<60	1	1%	6	3%	4	2%
	total	**29**	**15%**	**106**	**54%**	**63**	**32%**
The highest degree or level of school	none/elementary school vocational school	6	3%	17	9%	8	4%
	high school degree	13	7%	65	33%	38	19%
	University/college degree/Doctoral degree	10	5%	24	12%	17	9%
	total	29	15%	106	54%	63	32%
Place of residence	countryside to 100 k *	11	6%	32	16%	19	10%
	100 k–500 k *	5	3%	14	7%	14	7%
	more than 500 k *	13	7%	60	30%	30	15%
	total	29	15%	106	54%	63	32%
Subjective assessment of your financial situation	we are usually unable to cover basic costs of living/sometimes, we are not able to pay for costs of living	2	1%	2	1%	4	2%
	we earn enough to cover the costs of living, and from time to time we can either save money or afford extra expenses.	12	6%	52	26%	31	16%
	every month we can afford extra expenses, and we can regularly save part of our income	16	8%	51	26%	28	14%
	total	**30**	**15%**	**105**	**53%**	**63**	**32%**

* k—means a thousand.

The results obtained (Table 7) indicate that when it comes to planning a purchase of an electric car, only 15% of the respondents are planning such a purchase by 2024 and 32% have no opinion yet. As many as 54% of respondents (28% male and 25% female) responded that they are definitely not planning to purchase an electric car by 2024.

Among residents of multi-family buildings, 30% are definitely not planning to buy an electric car, and 15% have no opinion in this regard. In contrast, most 35–44 year olds plan to purchase an electric car, while as many as 32% of 18–34 year olds definitely do not plan such a purchase by 2024.

Among those living in cities over 500 K, as many as 30% do not have any plans to purchase an electric car, with 15% having yet to make a decision in this regard. Interestingly, as many as 52% of respondents describing their material situation as good (26%) and very good (26%) definitely do not plan to purchase an electric car by 2024, and only 14% declare their intention for such a purchase.

In order to further specify the determinants of electric vehicle purchase by individuals, logistic and linear regression analyses were conducted. This allowed us to determine whether factors such as gender, age, education, and/or place of residence (location) differentiate individuals' reasons for purchasing an electric vehicle. Coefficients of significance and r^2 were used as qualitative measures.

Questions 29 and 31 are nominal dichotomous variables that were answered 'yes' or 'no'. To assess the effect of independent variables on nominal variables, three models were tested: (1) age + gender, (2) education + gender, (3) location + gender. Ten linear models were shown to be statistically significant. Variables highlighted in yellow were found to be statistically significant, meaning that they are relevant to preferences (Table 8).

Table 8. Logistic regression results for the question about the decision to buy an electric car (for questions 29 and 31).

Dependent Variable	Independent Variables	Test χ^2	p (Probability Level)	Precision
Qn 29.1. Operating costs	Age + gender	2.59	0.274	0.67
	Education + gender	1.84	0.399	0.67
	Location + gender	1.78	0.410	0.67
Qn. 29.2. Ecology	Age + gender	4.01	0.134	0.80
	Education + gender	10.81	0.005	0.87
	Location + gender	2.66	0.264	0.80
Qn 29.3. Cost-offsets and benefits *	Age + gender	13.55	0.001	0.87
	Education + gender	11.74	0.003	0.87
	Location + gender	8.05	0.018	0.80
Q 29.4. Advantages advantages of electric propulsion **	Age + gender	5.03	0.081	0.73
	Education + gender	2.96	0.228	0.73
	Location + gender	2.84	0.242	0.73
Qn 29.5. Prestige/fashion	Age + gender	7.35	0.025	1.00
	Education + gender	7.35	0.025	1.00
	Location + gender	7.35	0.025	1.00
Qn 31.1. Purchase cost/price	Age + gender	4.51	0.105	0.87
	Education + gender	2.32	0.314	0.80
	Location + gender	2.61	0.271	0.80
Qn 31.2. Battery range/capacity	Age + gender	7.35	0.025	1.00
	Education + gender	7.35	0.025	1.00
	Location + gender	7.35	0.025	1.00
Qn 31.3. Appearance and design (color, aesthetics)	Age + gender	0.86	0.650	0.80
	Education + gender	0.69	0.709	0.80
	Location + gender	3.13	0.209	0.80
Qn 31.4. Environmental friendliness of the car	Age + gender	1.77	0.413	0.67
	Education + gender	3.22	0.200	0.80
	Location + gender	1.84	0.399	0.67
Qn 31.5. Equipment	Age + gender	1.57	0.455	0.80
	Education + gender	0.12	0.940	0.60
	Location + gender	0.06	0.969	0.60
Qn 31.6. Power, performance	Age + gender	0.46	0.795	0.53
	Education + gender	0.14	0.935	0.60
	Location + gender	1.94	0.379	0.73
Qn 31.7. Vehicle make ***	Age + gender	1.07	0.584	0.80
	Education + gender	3.56	0.168	0.67
	Location + gender	5.47	0.065	0.73
Qn 31.8. Segment/class of car	Age + gender	1.60	0.448	0.80
	Education + gender	0.19	0.910	0.73
	Location + gender	2.96	0.228	0.80
Qn. 31.9 Possibility to take advantage of government subsidies	Age + gender	0.29	0.867	0.60
	Education + gender	4.26	0.119	0.73
	Location + gender	1.17	0.556	0.67

* Abatements and privileges (free parking, ability to drive in bus lanes, purchase subsidies, etc.). ** Advantages of electric drive (quietness, acceleration, etc.). *** Vehicle brand (prestige, guarantee of quality).

Responses to questions 30 were responses assigned according to a scale from 1–4. The results are presented in Table 9.

Table 9. Factors adversely affecting EV purchase decisions.

Dependent Variable	Which Factor Argues Most Strongly against an Electric Car Purchase Decision?							
	Rating Scale							
	1		2		3		4	
	N	%	N	%	N	%	N	%
Qn. 30.1. Price	152	77%	41	21%	4	2%	1	1%
Qn 30.2. Lack of a sufficiently developed charging infrastructure	29	15%	50	25%	34	17%	85	43%
Qn 30.3. Too short-range	52	26%	89	45%	39	20%	18	9%
Qn 30.4. Charging time too long	34	17%	3	2%	34	17%	127	64%
Qn 30.5. No suitable car offer	4	2%	9	5%	51	26%	134	68%

where: 1—the biggest disadvantage, the 4—the least important disadvantage.

In the Ecology domain (Qn 29.2), independent variables such as education + gender or location + gender do influence the decision to purchase an electric car. In the area of Cost-offeset and benefits (Qn 29.3), independent variables such as age + gender, education + gender, and location + gender do influence the decision to purchase an electric car. In the Prestige/fashion area (Qn 29.5), independent variables such as age + gender, education + gender, and location + gender do influence the decision to purchase an electric car. In the area of Battery range/capacity (Qn 31.2), independent variables such as age + gender, education + gender, and location + gender do influence the decision to purchase an electric car.

The logistic regression model for question Q 29.5 and Qn 31.2 demonstrates 100% explanation of the effect of the independent variables by the explained nominal variable. For the other variables (Qn 29.2 and Qn 29.3), the accuracy of the model was between 0.80 and 0.87.

In other areas (Qn. 29.1, partly Qn.29.2, Qn. 29.4, Qn 31.1, Qn 31.3–Qn. 31.9) independent variables such as age + gender, education + gender and location + gender do not influence the decision to purchase an electric car. Linear regression models showed a lack of statistical significance.

In response to the question Qn 31 (Table 9: Which factor argues most strongly against an electric car purchase decision?), as many as 77% of respondents indicate price and too short a range (26%). On the other hand, the least important factors influencing the decision against EV purchase are: "lack of suitable car offer" (68%) and "charging time too long" (64%).

In contrast, the linear regression results indicate that the independent variables: (1) age + gender, (2) education + gender, and (3) location + gender are not statistically significant in explaining discouraging effects on electric vehicle purchase decisions. None of the models tested showed statistical significance (Table 10).

Table 10. Linear regression results for factors that least influence electric vehicle purchase abandonment (for question 30).

Dependent Variable	Independent Variables	F *	P *	$R^2_{adj.}$ *
Qn. 30.1. price	Age + gender	0.45	0.649	−0.09
	Education + gender	0.45	0.649	−0.09
	Location + gender	2.37	0.136	0.16
Qn 30.2. Lack of a sufficiently developed charging infrastructure	Age + gender	0.24	0.787	−0.12
	Education + gender	0.40	0.680	−0.09
	Location + gender	0.15	0.862	−0.14
Qn 30.2. Too short-range	Age + gender	2.02	0.175	0.13
	Education + gender	1.24	0.324	0.03
	Location + gender	2.94	0.092	0.22
Qn 30.3 Charging time too long	Age + gender	0.10	0.905	−0.15
	Education + gender	0.15	0.861	−0.14
	Location + gender	1.24	0.323	0.03
Qn 30.4 No suitable car offer	Age + gender	2.64	0.112	0.19
	Education + gender	0.08	0.923	−0.15
	Location + gender	0.18	0.838	−0.13

* F—value of the statistic, *p*—probability level, R^2_{adj}.—adjusted R-square. Ten linear models were shown to be statistically significant.

4.3. Car-Sharing Use and Willingness to Purchase an Electric Car

A χ^2 independence test was used to test whether there was a significant relationship between past car-sharing use and willingness to purchase an electric car, and the results are presented in Table 11.

Table 11. Car-sharing use according to willingness to purchase an electric car.

Have You Ever Used Car Sharing?	Parameter	Are You Planning to Purchase an Electric Car?	
		No	Yes
No	*n*	42	7
	%	85.71	14.29
Yes	*n*	13	10
	%	56.52	43.48
$\chi^2(1) = 1.21$; $p = 0.271$; $V = 0.16$			

The test was not statistically significant, which means that there is no relationship between the former usage of car-sharing services and the desire to purchase an EV.

5. Discussion

Based on the research conducted, it can be concluded that there are few socioeconomic factors that can be used to predict consumer behaviour in terms of willingness to purchase an electric car. These are: age, gender, place of residence and education. For this purpose, Random Forest proved to be the most accurate method (the other methods—cart, k-nearest neighbour, and support vector machine—were less accurate). This validated research Hypothesis H3: There are independent variables that, using machine learning methods such as Random Forest, will predict willingness to purchase an electric vehicle for personal use.

The research shows that the person who is the most likely to buy an EV by 2024 is characterised by the following qualities: female, aged 35–44, employed or self-employed and living in a city over 500 K. Conversely, the person least likely to plan to buy an EV by 2024 is: male, aged 18–34, working or self-employed and living in a city over 500 K. The study by Novotny et al. [42] also proved that masculinity has a significant negative impact on BEV sales. This is consistent with the results of the previously-cited German study [41], which found that residents of large cities who were more likely to be assigned a green identity (e.g., working men), were not as willing to switch to zero-emission cars. That observation is in accordance with Tindall et al. [67] who discerned that women, on average, are much more likely to be environmentally friendly in their private sphere—when it comes to purchasing decisions, separating waste at home, or limiting the use of a car for the sake of clean air [67]. According to the cited authors, this is due to existing societal beliefs that pro-environmental products and behaviours are considered feminine and men do not want to be associated with them because they are most likely afraid of losing their gender identity. They are more likely to take environmental action if it validates their masculinity. This may be an important clue for companies involved in creating and promoting environmental products and attitudes [67].

In the light of this finding, EV manufacturers should advocate environmental protection and green life issues to increase consumers' cognition and preference for EVs. Targeted information and education campaigns on the incentives for using EVs and introducing more attractive battery and charging systems are needed. This recommendation is in line with postulates of Schuitema et al. [39]. As Machová et al. stated [68], informing and educating consumers plays a crucial role in influencing them to purchase environmentally friendly products.

The findings of the "New Mobility Barometer" study [12] noted that considering an EV purchase while looking for a new car does not necessarily translate into a decision to buy one. In contrast, the authors did not confirm the findings of the UK study [40] that EV purchase intention increases among younger people who are students or unemployed.

The H2 hypothesis could not be confirmed: the study did not prove that previous experience with electric car sharing has a positive impact on EV purchase decision. These results are consistent with the earlier study by Jensen et al. [35], which found that individual preferences of consumers who experienced electric vehicle driving during a three-month trial period did not translate into a purchase decision.

It was found that the factors that stimulate the decision to purchase an electric car to the highest extent are: (1) Purchase cost/price, (2) Appearance and design (colour, aesthetics), (3) Car segment/class, (4) Equipment, (5) Electric drive advantages. In this case, these decisions are differentiated by factors such as age, gender, education, and place of residence. According to the latest "New Mobility Barometer" report, Poles will be willing to buy an EV if it is 22% cheaper [12]. Upfront cost of EV was confirmed to be a strongly influential factor in several studies [69–73]. This underscores that the price of EVs is a key factor in the choice of the average consumer and, consequently, that subsidy schemes will play an important role in strengthening the demand side in coming years.

The factors that are less influential in the decision not to purchase an electric vehicle were identified as (1) Operating costs, (2) Cost-offsets and benefits, (3) Advantages of electric propulsion. The impact of these factors is differentiated by factors such as age, gender, education and place of residence. This is particularly important from the point of view of shaping information policy both at the level of government administration and companies involved in promoting pro-environmental solutions. Conversely, regression models used by Brase [2] indicated that predictors of vehicle choices concerns were about the performance and range of EVs, EV prevalence in general, and beliefs about what message different car types brought about their owners and the owners' values.

On the other hand, the results of the study indicate that some factors regarding the purchase of an electric vehicle are statistically significant and may predict consumers' decision to purchase an electric vehicle. These are the following factors or beliefs/attitudes of the respondents: (1) positive green attitude, (2) cost-offsets and benefits (3) prestige/mode, and (4) range/battery capacity. In this case, independent variables such as age + gender, education + gender, location + gender were significant. Similar results on battery life were obtained by Gurudath and Rani [45] on a sample of 126 respondents from India.

Although the relationship between previous use of car-sharing services and willingness to purchase an electric car was not confirmed, factors such as age, education and financial situation will influence the decision to purchase an electric car. It is likely that the decision to purchase an electric car is also influenced by the general trend of using green modes of transportation and the need to care for the environment.

The research showed that as many as 77% of the respondents indicated that the price of an electric car is the factor that most strongly argues against the decision to purchase one. A similar result was obtained in the other studies (cf. [13,74]). This leads to a political recommendation that a suitable and efficient subsidy system, inclusive for the less well-off, is needed if governments expect to achieve a massive shift towards zero-emission individual mobility. This advice is consistent with the recommendations of other authors, previously cited in this article [57,61]. Evidence from Norway, a global forerunner in the field of electromobility and the BEV market share, shows that strong incentives for promoting purchase and ownership of BEVs are essential. Findings by Bjerkan et al. [75] clearly support the significance of incentives for reducing purchase costs (e.g.,: exemption from VAT and purchase taxes).

Too short EV range was second important obstacle for potential EV buyers (26% of respondents). On the other hand, "lack of suitable car offer" and "charging time too long" were considered the least important factors (68% of respondents).

The results obtained by the authors using the Random Forest model allow us to conclude that the most important consumer beliefs/claims supporting or discouraging plans to purchase an electric car by 2024 are the following:

(1) It makes no sense to choose an electric car because of the "dirty" energy sources in our country.
(2) In 10 years, electric cars will replace gasoline and diesel cars.
(3) It would be better if I travelled in a more environmentally friendly way.
(4) If my employer arranged rides for several people from home to work using electric vans (e.g., vanpooling), I would use this option regularly.

Therefore, using a Random Forest algorithm can help automate the identification of customers buying electric vehicles and tailor manufacturers' products to their customers' preferences and views on green solutions.

The results of this study regarding the belief in the environmental impact of EVs (3) as a determinant of purchase intention are in line with a study conducted in Norway [38].

Successful EV promulgation and making them truly zero-emission (not just locally) requires complex multidimensional public policy, including efficient support for future expansion of micro-installation of solar and wind systems. The photovoltaic boom that happened in Poland in the period of 2015–2021 (Poland then led the European Union in terms of the growth rate of photovoltaic power [76]) was possible because of (1) available grants decreasing investment costs within the "My Electricity" program (owners of single-family house were mostly targeted by the grants), (2) income tax reductions, and (3) favourable and "prosumer"-friendly billing mechanism (i.e., net-metering system).

As regards the latter: power grid operator serves as a virtual energy storage for individual producers at a cost of 20/30% of energy surplus added to the grid (20% for on-grid PV installation up to 10 kWp; 30% for the bigger ones). Net metering allows solar energy systems owners to export surplus power to the grid and reduce their future electric bills. As the authors already mentioned, the power installed in PV in Poland rocketed in last few years. Unfortunately, the backward power grid system appeared to be technologically inefficient—it could not storage the whole energy added by PV. Technical challenges surrounding on-grid energy storage resulted in a regulatory change (beginning in April 2022) shifting from net metering towards net-billing.

According to initial estimate, the new system will be less favourable for new on-grid solar energy system owners. Moreover, current grant system is addressed mainly to private owners of single-family houses, terraced houses or semi-detached houses. Taking into account that the majority of inhabitants in urban areas live in multi-family buildings, this group is excluded from this system. Therefore, lack of charging stations available for majority of city dwellers in their residences may be one of brakes for EV readiness in urban areas.

One promising direction linking "prosumer" energy storage and EVs is a solution based on the 'vehicle-to-grid' concept (V2G). This is a technology that makes good use of EVs to balance electricity demand in the power system [77]. To-date there are only a few cars with this feature available, but enhanced, collaborative efforts of the automotive industry, power grid companies, and regulators could be beneficial and effective in a relatively short term.

These changes, and many others needed to accelerate EV uptake, will require some support at the EU, national and regional levels, and local levels, particularly in terms of developing and implementing appropriate financial incentive policies and large investments in infrastructure. As Bobeth and Kastner pointed out, broader policy support programs are also needed for the uptake of electric vehicles [47].

This also requires amendment of the Fitfor55 package adopted by the European Union, which identifies electric mobility as a pillar of transport decarbonization. This amendment should concern more rapid implementation of legislative changes and an increase in financial outlays, which would have an enormous impact on the development of electromobility. At the same time, the authors point out that there is also a lack of extensive research on the impact and role of state and international regulatory bodies in the deployment of electric vehicles. Local policies to support EVs may also need to be explored.

Based on the findings, we the authors recommend authorities consider the following actions at the local level.

Future research is required in the field of developing efficient business models for housing cooperatives willing to equip their buildings in charging stations and PV systems. Since Polish law currently does not oblige the existing housing communities to invest in e-mobility, demonstrating their economic rationality would help to drive such legal policy changes. Transforming housing communities into lower- and greener-energy, and supporting e-mobility, requires the development of modern management tools (business models) and legal solutions in the field of the use of renewable energy sources, ensuring the profitability of this process.

6. Conclusions

This paper reviews and analyses the socio-economic dynamics of green revolution in private transportation and extends previous knowledge on sustainable mobility development in Poland. This article highlights a number of opportunities and challenges for successful promulgation of private EVs in urban areas.

In the presented research, an ensemble machine learning technique using Random Forest (RF) was applied, which is an innovative approach for this type of research. As confirmed by the results from the literature review, this type of advanced econometric modeling has not been used in the literature before.

The proposed Random Forest approach enables the prediction of consumer behaviour in terms of their propensity to purchase an electric car. It may be particularly helpful in detecting which customers are more likely to purchase an electric car. This algorithm will also help the automotive industry to operate effectively in the private electric car segment. It will help in recommending suitable products and services and predicting customer satisfaction.

The findings indicate that it is particularly important to carry out long-term information campaigns at the national and regional levels to demonstrate the advantages of electric automotive vehicles, e.g., in terms of their efficiency, technological awareness, and positive environmental impact. These conclusions are consistent with the results of the studies cited earlier [15,44,45].

In view of the research results presented herein and taking into account the current watershed moment (Russia's aggression against Ukraine driving renewed efforts for nations to become independent from fossil fuels imported from Russia, it may be expected that EV promulgation will accelerate. This will require more effective approaches on the part of EV manufacturers to more effectively move public opinion regarding the value of EV purchases for individuals as well as for society as a whole. This paper's findings demonstrate important potential target areas for those efforts.

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Abbreviations

BEV	Battery Electric Vehicle
HEV	Hybrid Electric Vehicles
ICEV	Internal Combustion Engine Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
EV	Electric vehicle
V2G	'Vehicle-to-grid' concept

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Article

Determinants of Managerial Competences Transformation in the Polish Energy Industry

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Abstract: Different technological, socio-economic, geopolitical, and demographic factors have a significant influence on labor markets. Currently, due to COVID-19, the global economy is in a challenging situation, and millions of people from different countries have lost their jobs. The employee's mental health and well-being are in risk conditions. In the coming years, the Polish energy sector will face several transformations. Emerging technologies are intended to deal with the problems in energy management. One of the main industry forces is human capital, people who will be able to project and manage the innovative technologies. Thus, this paper examines the determinants of managerial competences transformation in the energy industry from the labor market perspective. The paper fulfills the research gap in the energy manager profession's transformation in Poland. The aim of the paper was to present the current state of the energy manager profession in Poland. Two methodological approaches were used: the theoretical and practical approaches. Descriptive statistics are provided to present the labor market research results. The findings of the research can contribute to the literature and practice by applying them in the process of developing energy manager competency models, as well as in education programs and training courses for enterprises and universities.

Keywords: energy manager; competences; labor market; energy industry; COVID-19

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1. Introduction

Current technological, socio-economic, geopolitical, and demographic developments and their interconnections will generate new categories of jobs and professions in the near future [1]. On the other hand, at the same time, they partly or wholly could displace current occupations [1]. They will change the skills and even skills groups required in both old and new professions in many industries, and will transform workplaces, involving management and regulatory challenges [1]. By introducing the new skills and competences, organizations will be able to reduce the current skills gaps [2]. According to the World Economic Forum Report 2020, the skills gap rate in the energy labor market was 70.6% in 2020 [2].

The COVID-19 pandemic has strongly affected the economic life and the labor markets around the world [3]. "*The lock-down and other health-related measures implied a slowdown of the business activity*" [3]. The consequences may be considerable for the labor markets, among others: people may have lost their jobs, the absences from work have been increased, new workplaces could have been cancelled or frozen, unemployed people may temporary abandon from job search for family reasons, and employed staff may have reduced their working hours or even stopped working for a time [3].

According to Eurostat data, "*the EU employment rate (for people aged 20 to 64) went down from 73.1% in 2019 to 72.4% in 2020*". "*At EU level, between 2019 and 2020, the share of employed people usually working from home greatly increased from 5.4% to 12.3%. From 2019 to 2020, the largest declines in terms of temporary contracts in total employment were recorded in Poland (−2.7 percentage points), Croatia (−2.5 percentage points) and Portugal (−2.4 percentage points)*" [3]. On the other hand, the number of job vacancies in March of 2020 went down in EU to 1.6%. Currently, it has increased, and is at a 2.1% level, as before the pandemic [3].

ILO Monitor also has provided a description of the continuing and devastating impacts of the pandemic on labor markets since early 2020, and the massive disruptions in the labor market that persisted into the fourth quarter of 2020 [4].

According to research by the World Bank and other several sources, the economic crisis caused by the COVID-19 pandemic severely reduced mobility and economic activity [5–12]. In 2021, the World Bank estimated the crisis' impact on labor markets in 39 countries from April to July 2020. The research results revealed that "*34% of respondents reported stopping work*", "*20% of wage workers reported lack of payment for work performed*", "*9% reported job changes due to the pandemic*" and "*62% reported income loss in their household*" [5] (pp. 3–4).

On the other hand, the crisis has accelerated the use of digital technologies. "*This crisis like no other can be an opportunity to leverage digital solutions to set up more permanent mechanisms to expand social protection and to provide vulnerable individuals or firms with adequate incentives to join a national register as a step toward formalization*" [13] (p. 3). Other tools can include a combination of support to small and medium-sized enterprises, as well as tax policies and administration measures [13].

The changes involved in environmental events have been widely discussed by many authorities. The German Committee on Sustainable Development for Future Earth highlighted the significance of climate change and the transformation of the energy industry during its 2021 Summit [14,15]. Thus, it was also proved that the environmental changes have an impact on energy labor markets. The new recommendations are required to achieve sustainability between labor productivity and environmental protection [16,17].

One of the most important feedbacks to global changes are green initiatives towards sustainability development such as green finance [18], green city [19], and green information processes [20] and systems [21].

Likewise, a significant role in energy industry development is played by emerging technologies. Energy executives pointed out that for them, the biggest opportunity was in using innovative cognitive solutions to deliver attractive energy savings and measure business benefits [22–25].

The Deloitte company noticed the role of cognitive technologies in the oil and gas sector [22]. IBM executives argued that cognitive IoT creates insufficient opportunities for the gas and oil industry [23]. According to the IBM Institute for Business Value Research, in 2016, "*94% of oil and gas executives familiar with cognitive computing believe that it will play a disruptive role in the oil and gas industry*" [24]. A report from the McKinsey Global Institute highlighted how jobs based on human skills will be affected by artificial intelligence (AI) and automation in the future [26]. The Accenture company, in its "*Future skills pilot*", stated that artificial intelligence will force organizations to create more job pathways [27]. Millions of jobs may be changed by using machines by 2025. Millions of new roles may emerge by 2025 due these changes [27]. Moreover, according to the International Monetary Fund, "*the labor market regulations can be simplified to ensure greater flexibility and facilitate informal workers' entry into formal employment*". "*Digital platforms, including government-to-person mobile transfers, can support new policies generation and contribute to inclusive growth*" [28].

As in many countries of the world, the Polish economy is facing post-COVID environmental and demographic challenges in the years ahead. The research of Długosz, based on opinions of more than 1000 respondents, revealed the negative impact of COVID-19 on society in Poland [29].

The significant transformation is also waiting for the energy industry. According to a McKinsey report, "*the Polish energy sector needs to close its 48% productivity gap with the EU-15*" [30]. Furthermore, according to a United Nations report, in Poland, self-sufficiency in 2021 was defined at the 58.7% level. Renewable energy share is only 11.4 percent at the moment [30]. These indexes are planned to be improved by transformation of the energy industry [31]. The importance of research on the determinants of decarbonization and sustainable energy development in terms of green European and global governance has been highlighted by experts in the Polish energy industry [32].

Transformations in the energy sector have an impact on the structure of employment. Several problems were identified by researchers; for example, the problem of ensuring a sufficient number of employees with the appropriate competences. Moreover, it should be noted that the population of people working in the power industry is clearly older than the total number of people working. In the near future, the energy industry will have to cope with the wave of retirement departures. These changes involve the need to plan and implement the new competency models for energy enterprises [33].

Since the role of a modern university is to support the labor markets, its new mission can be defined as "*effectively linking universities with users of knowledge and establishing the university as an important economic actor*" [34]. Universities should offer new education programs, both at the graduate and postgraduate levels, adapted to current energy market requirements.

Above all, in the literature on energy sector, there is a research gap in the influence of the emerging situation of the energy manager's profession transformation in Poland. Moreover, there is a lack of scientific research on the current skills and abilities of energy managers in Poland.

This paper presents the continuation of research conducted in 2020 [35]. However, this time it is focused on the main directions of the transformation of the energy manager profession, highlighting the differences in skills demanded and weak points of the labor market in Poland.

The purpose of the paper is to identify the main directions and determinants of this profession transformation, with special attention paid to the impact of emerging technologies and emerging concepts.

The research tested the hypothesis that the transformation of the energy industry involves the need to modify the skills and competences of energy managers in Poland to prepare them for the implementation of the low-emission transformation plan by 2040. To this purpose, a comparison of was made of the two models: the global energy manager skills model, and the Polish energy manager skills model.

To analyze the main aspects of the transformation of the energy manager profession in Poland, a hybrid research approach based on a literature study and a labor market analysis was used (Figure 1). The approach was adapted from previous research [35] and extended to add the new tasks. In particular, the determinants involved changes in energy management and the energy manager profession in Poland were identified. Moreover, the current skills of energy managers were identified and compared to a global energy manager skills model created in 2020 [35]. The differences in skills and competences required were described and highlighted.

This paper consists of five main parts. In the Introduction, the implications, research methodology, and research framework are presented and described. After the Introduction, a literature study outlining the core directions and determinants of the energy manager profession's transformation is reported. The literature study is followed by a labor market study, and a discussion of the results and limitations of this research. Finally, conclusions and the future research perspectives are discussed.

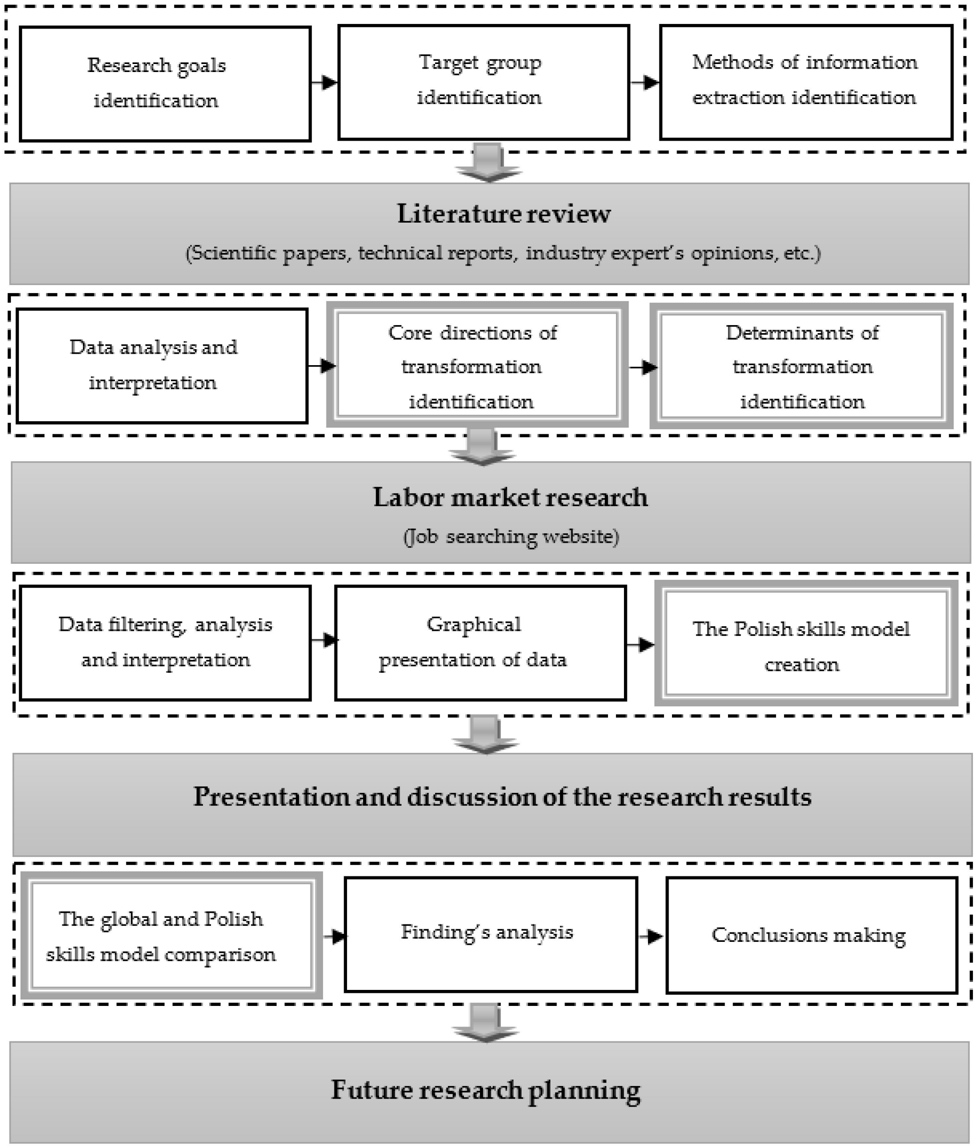


Figure 1. The research framework.

2. Literature Review

According to Gita Bhatt, the pandemic accelerated the digital future, and digitalization is coming at us faster than ever before. It will transform the economic and social spheres [36]. The pandemic has also accelerated the process of substituting machines for workers [37].

There are different opinions: some argue that automation is the price humans pay for prosperity, and new technologies will increase productivity and incomes; and on the other hand, they can dislocate some workers and disrupt existing businesses and industries [38].

Current changes in emerging technologies were influenced by several enablers.

The first are mobile technologies and the Internet, connecting individuals and enterprises with information and providers of financial services [39]. People have become more mobile with political and cultural globalization, the development of Internet and information technologies, and possibilities of fast and cheap transport. For employers, this means that employees are easier to lose, but easier to find as well. In 2021, in line with current trends, the Workplaceless Remote Work Competency Model was created. In this framework of new essential competencies needed to succeed in remote work were described [40]. This model provides a holistic view of the competencies (attitudes, behaviors, knowledge, and skills) needed in distributed workers, team members, leaders, and executives. According to the model, a new remote leader should have knowledge of change management, performance management, conflict management, team culture, communication management, remote leadership tools, stakeholder management, resource management, and innovations [40]. The model also suggests changes in ways of communication and highlights the necessity of employees' skills correction.

A second enabler is the storage and processing of large amounts of data [39].

Finally, technologies such as cloud computing, artificial intelligence and cognitive technologies, distributed ledger technology, and biometric technologies have a significant influence. Moreover, "*at the core of all these innovations is the ability to gather information and reach users at a very low cost*" [39].

J. Kubicka argued that from the perspective of entrepreneurship and the labor market, re-skilling of mining sector employees is not an easy task and will not become one; however, by providing for professional cooperation between experts, enterprises, temporary employment agents, head-hunters, and other stakeholders, such a change can be introduced as a fair transformation [41].

It is necessary to make up for deficiencies in the labor market by competing for talents and the most competent employees, even from other countries, which is a long-lasting and difficult process in view of cultural differences [41].

With the noticeable climate change, society has noticed the occurring threats, and there is a growing anxiety about life quality [41].

According to the World Economic Forum, the current drivers of change for the energy industry are new energy supplies and technologies, the changing nature of work, flexible work, climate change, natural resources, and geopolitical volatility [2].

The pandemic has significantly affected the way of life in many countries.

Drawing on degrowth literature, in the paper "*Coronavirus: Impact on the labor market*", the authors noticed the difference in COVID-19′s impact on different groups of people, especially work losses among men and women, and workers from different age and ethnic groups [42].

According to Statistics Poland, in the first quarter of 2020, the number of job vacancies decreased from about 150,000 in Q2 and Q3 of 2019 to 78,000. In first quarter of 2021, the number of offers increased to about 110,000 [43].

Moreover, in the first quarter of 2021, 70,200 thousand jobs were liquidated, 41.5% fewer than in the first quarter of 2020. It should be noted, however, that the number of job cuts related to the spread of COVID-19 accounted for nearly 24% of all job losses. Job losses due to the spread of COVID-19 occurred mainly in the private sector [43].

It was found that 14.2% of the total number of employed persons in Poland worked remotely on 31 March 2021 due to the pandemic situation [43]. This was 3.2 percentage points more than at the end of March 2020 [43]. It was about 20% in the electricity, gas, steam, and air sectors [43].

According to Dolot, some temporary solutions will remain popular after the restrictions are removed; for example, remote work and more frequent use of digital technologies [44]. This, in turn, may contribute to permanent changes in the ways in which work is performed, as well as the creation of new jobs.

Summarizing the above, the latest labor market developments caused by the pandemic are continuing workplace closures, working-hour losses, and decreases in labor income. Many authors have proved the impact of COVID-19 on the Polish energy industry.

In the work of Nagaj and Korpysa, the authors studied the impact of COVID-19 on the level of energy poverty in Poland [45]. Thus, "the authors *proved that "COVID-19 has contributed to the intensification of energy poverty in Poland*". In [46], Kordel and Wolniak studied the impact of COVID-19 on technology entrepreneurship and the performance of enterprises.

Moreover, Rybak and Rybak studied the impact of the COVID-19 pandemic on gaseous and solid air pollutant concentrations and emissions in Poland [47]. Bielecki et al. studied the impact of the COVID-19 pandemic on electricity use by residential users [48].

In the work of Czech and Wielechowski, the authors studied the alternative energy sector's COVID-19 resistance in comparison to that of the conventional energy sector [49].

In the work of Dmytrów, Landmesser, and Bieszk-Stolorz, the authors studied the connections between COVID-19 and energy commodity prices. Their analysis revealed that "*the alternative energy sector, represented by the MSCI Global Alternative Energy Index, is more resistant to COVID-19 than the conventional energy sector*" [50].

Other determinants of changes in the energy sector in different countries were described in [35,51–55].

Transformations of the electricity and gas market forced changes in the employment structure in the Polish energy sector [33]. Market mechanisms forced the energy sector to select suitably qualified personnel. The most sought-after employees in the energy sector included sales, customer service, and call center specialists. In the energy sector, the problem may be to ensure a sufficient number of employees with the appropriate competences [33]. Moreover, the demand for new competences is unlikely to increase employment, but on the contrary—employment in the energy sector will gradually decrease, mainly due to technological restructuring, which in turn will force organizational restructuring, especially at state-owned energy companies [33].

The role of digital technologies for the energy industry has been described by many authors [56–66].

The technological transformation also became a reality in Poland. Tobias Kurth argued that technologies are needed that can provide accurate measurements, control, and regulation of energy production, and at the same time can consider forecasts in real time. This would involve massive amounts of data: once, one recipient was one data point, and so was one power plant. According to Kurth, in the last phase of transformation; i.e., from 2030, companies will have systems that are fully intelligent and maximally efficient [67].

In recent years, PKP Energetyka—one of the Polish energy industry leaders—has been undergoing a digital evolution from Company 3.0 to Company 4.0 (in reference to the idea of Industry 4.0) [68]. The vision of PKP Energetyka 4.0 is based on using the Internet of Things, data analysis (big data), robotization, and automation, as well as artificial intelligence. The newly created Digital Competence Center (Center of Excellence), is responsible for process improvement using the latest digital technologies, such as robot process automation (RPA). The company implemented emerging technologies; in particular, SAP systems; SAP ISU billing systems; iValua procurement management system or IBM Maximo; Planer, e-Tabor, and SAP HR resource management systems; SAP Fiori; Scada; GIS; and hybrid cloud [68].

Moreover, Enea Operator, another market leader, constantly increases the security of distribution networks through IT-related issues and the pursuit of a smart grid [69]. For Enea Operator, investing in electromobility and modern network solutions has become one of the most important elements of creating the company's future business model [70].

When analyzing the data of the UN report, it could be argued that Poland's situation is comparable to that of some EU countries; its self-sufficiency rate currently oscillates around 59%. The share of renewable energy, on the other hand, is around 11% [71].

As officials estimate in the document "*Poland's Energy Policy 2040*", nuclear power plants in Poland can provide 25,000–38,000 new jobs [72]. "*The expansion of the generation and grid infrastructure will lead to the creation of an almost new power system by 2040, largely based on zero-emission sources*" [72]. "*Poland will strive to be able to cover the demand for power with its own resources. Domestic coal resources will remain an important element of Poland's energy security, but the increase in demand will be covered by sources other than conventional coal capacities*" [72]. The goals of PEP2040 are "*energy security, competitiveness, improvement of the energy efficiency of the economy, and reduction of environmental impact*" [72]. On the other hand, one of the sustainable development goals is to provide jobs for the urban regions that were most affected by the decarbonization process.

According to research in 2019 and 2020, about 90% of companies in the energy sector have planned to employ new workers. Moreover, only 46% of companies declared that they have enough competencies to reach the goals, and 51% declared that they have partial competency sources [73].

According to a 2020 report by Hays, executive salaries in the energy sector in Poland are attractive enough, and vary from PLN 10,000 to 40,000 [73]. For example, the salary of the director of the photovoltaic department varies from PLN 20,000 to 28,000 [73]. The high rates create the perspectives for future sustainable employment.

For years, the energy sector in Poland was dominated primarily by employees with secondary and basic vocational educations [33]. Although there was no one dominant professional group in the power industry, technical specialist professions were relatively important here, as knowledge of the industry and practical skills are of key importance [33]. Recently, the situation changed, and more job offers for management staff have appeared. Green jobs will replace jobs related to the conventional sector. In addition to avoiding health costs and environmental risks, low-carbon modernization offers the opportunity to stimulate innovation and the emergence of highly productive jobs.

At present, the most dynamically developed sector in Poland is the photovoltaic sector [74]. Limited potential for performance may make it difficult to find specialists experienced in these technologies [74].

The key shortcomings of the labor market in Poland that hinder its green transformation include its general inflexibility, shortages of adequate skills among employees, new efficiency strategies and policies, and local diversification of economic potential [75,76].

As pointed out in the article "*Addressing climate change in a post-pandemic world*", the fight against climate change cannot be stopped. According to scientists, climate change may contribute to further pandemics. Rising temperatures can, for example, create conditions for the spread of certain infectious diseases [77].

Faced by new technologies and new management concepts, the role of energy managers is undergoing continuous transformations. In the 1970s, they were perceived as a "*fire fighter*" [78]. While the energy analysis and valuation methods have been changed, new concepts, policies, and energy-management programs were created [79,80].

Today, despite that a common definition of the energy manager profession does not exist, some works described the skills and competences required for this profession. As commonly described, an energy manager should have technical skills, as well as expertise in management, financing, communication, and public policy [81]; and in different cultures/subcultures [80,82] and systems [83]. Looking forward, to raise the professional standards and to award special recognition to persons who have demonstrated a high level of competence and ethical standards for energy management, certification programs were created.

Thus, it is important to study the current demand in energy labor markets and anticipate changes in the competency needs of future employees in advance. In this situation, the role of enterprises in the energy industry is to develop requirements and define qualifications. The role of universities is to prepare students to work in all green positions in the industry. It is also necessary to adapt the curricula to market requirements. "*This represents a new mission of university which can be defined as: effectively linking universities with users of knowledge and establishing the university as an important economic actor in future energy industry*" [34].

Despite rapid labor market transformations in many countries, still there is a lack of scientific papers describing the challenges of the energy manager profession's transformation [35]. To this purpose based on sources [84–90], the holistic energy manager skills model was created in 2020. The following parts of this article will present the results of this model's adoption by the Polish labor market, as well as discussion of the most important results, and conclusions.

3. Materials and Methods

This research was planned as a continuation of the labor market study conducted in 2020 and presented in [35]. The first part of the research was conducted in July−August of 2020 [35]. The second stage of the research was conducted in May−August 2021. The research was structured as follows.

Firstly, the employment in Poland was studied by using data from the two most popular job-search websites. Data filtering, analysis, interpretation, and graphical presentation were used. For these purposes, the most popular worldwide job-search websites (according to the worldwide rankings) using a Google search were selected. The following selection criteria were used: (1) the largest number of current energy executive published job posts; (2) clustering by industry (an already-defined separate "*Energy*" job group for the energy sector should have appeared); and (3) "*advanced search*" options. Consequently, the indeed.pl and pracuj.pl job-search websites were chosen. The jobs were browsed for the "*Energy*" job group on indeed.pl [91] and for "*energetyka*" on Pracuj.pl [92].

About 2000 job posts were processed. The following data were extracted: the average number of job offers by region, by place of work, by company, by emerging concepts, by position level, by contract type, and by industry category. The amount of demand for energy manager positions reflected the influence of different concepts of energy management among countries. The results are presented in Figures 2–8.

In line with worldwide tendencies, the most focus was placed on the study of employment in the renewable energies group. Thus, in the next stage the employment in EU countries was analyzed based on most recent data from [93,94]. From a methodological point of view, employment data were presented for each renewable energy source (RES), which refers to gross employment; i.e., not considering developments in nonrenewable energy sectors or reduced expenditure in other sectors. In this research, the data included both direct and indirect employment (Table A1). Direct employment included RES equipment manufacturing, RES plant construction, engineering and management, operation and maintenance, biomass supply, and exploitation. Indirect employment refers to secondary activities, such as transport and other services [80,93].

At the final stage of labor market research, the current skills requirements according to the skills model from [35] were checked for Poland. The differences, opportunities, and future directions were defined while taking into consideration the social and economic effects of the pandemic [95].

Based on the main labor market research findings, the determinants of the energy manager profession's transformation were identified.

4. Results

First, the data on the spatial distribution of job offers were extracted by using the Indeed website. The greatest number of vacant job posts in the energy sector was found in Warsaw and the surrounding region—44% (Figure 2).

All the jobs were divided by workplace, remote, and remote due to COVID-19; 15% of jobs were offered as remote, and 8% of them for COVID-19 reasons (Figure 3).

After that, the average number of job offers in the Polish energy industry by companies was determined. The largest number of offers were submitted by the Accenture company, the Bosch group, Votum Energy, PKP Energetyka, TE Connectivity, and Schneider during the research period. Figure 4 presents the names of the companies that had the largest numbers of job offers.

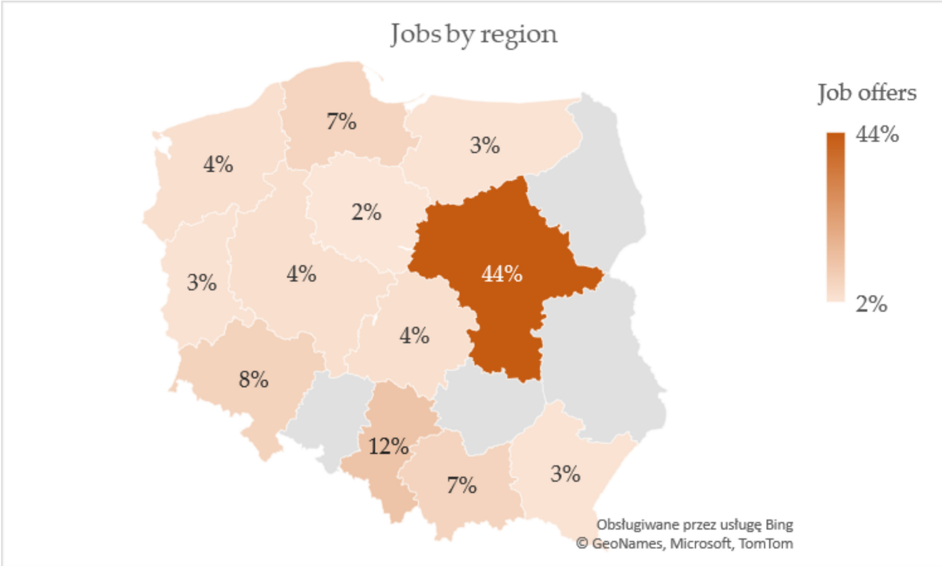


Figure 2. The map of spatial distribution of job offers in the Polish labor market. Source: author's preparation based on the data from https://pl.indeed.com/ (accessed on 7 August 2021).

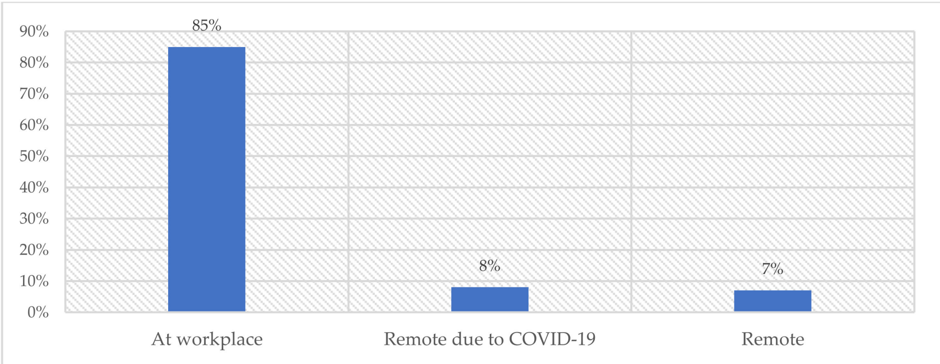


Figure 3. The percentage of job offers grouped by the method of doing the work. Source: author's preparation based on data from https://pl.indeed.com/ (accessed on 7 August 2021).

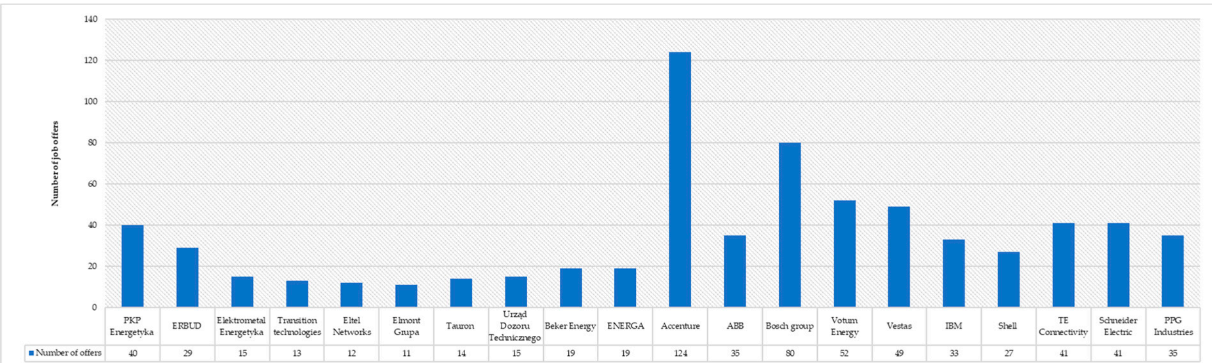
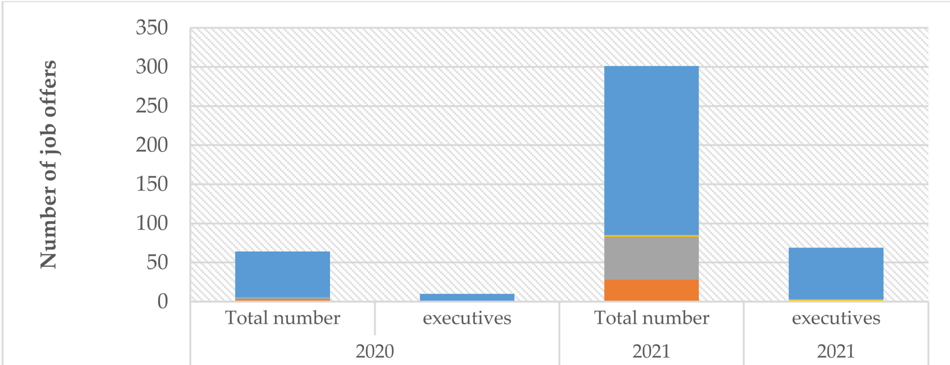


Figure 4. The average number of jobs offers in the Polish energy industry by company. Source: author's preparation based on data from https://pl.indeed.com/ and https://www.pracuj.pl/ job-search websites (accessed on 7 August 2021).

In the next step, the impact of emerging concepts was studied in 2021 and compared with the results from 2020 (Figure 5). The research revealed a significant increase in the number of job offers, especially for executives.



	Total number 2020	executives 2020	Total number 2021	executives 2021
Sustainability	58	10	216	66
Smart City	0	0	2	2
Big Data	3	0	55	0
AI	3	0	28	1

Figure 5. The average number of job offers in the energy sector in Poland impacted by emerging concepts: the total number and the number of job posts for executives in July–August of 2020 and July–August of 2021. Source: author's preparation based on data from https://pl.indeed.com/ (accessed on 7 August 2021).

The research also revealed that the sustainability development concept had the greatest influence on energy manager competences. Competences in big data and AI were required for specialist positions in 2020, as well as in 2021. Once, two offers requiring smart city concept knowledge were found, and one with knowledge in artificial intelligence. Thus, this skills category remained generally without significant changes.

Furthermore, according to the Indeed website data, employers were looking for specialists (75% of job offers), and the share of job offers for energy executives was 18% during the research period (Figure 6).

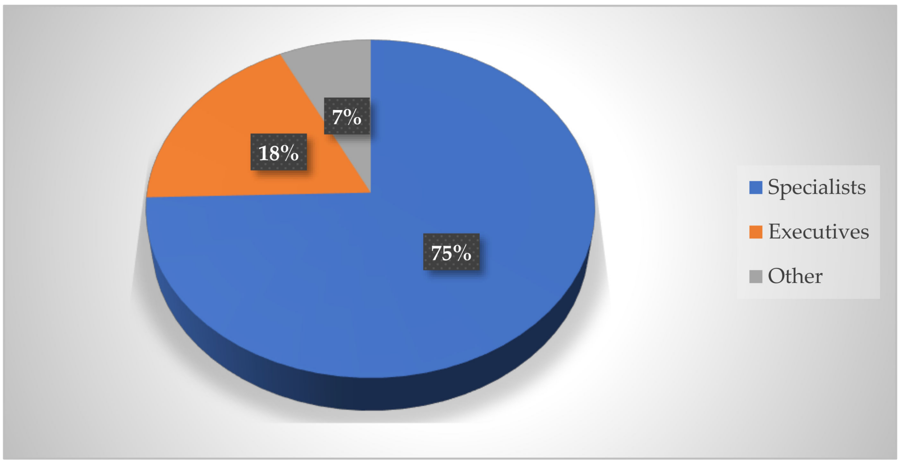


Figure 6. Job-offer classification according to position levels. Source: author's preparation based on data from the https://www.pracuj.pl/ job-search websites (accessed on 7 August 2021).

When analyzing the job contract types, it was found that the most preferred types were an employment contract and a B2B contract (Figure 7). It should be noticed that many employers offered the possibility to choose the appropriate type.

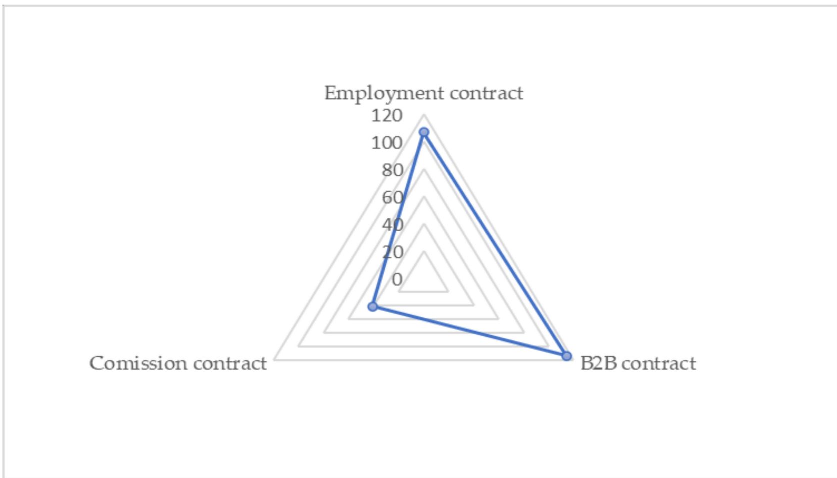


Figure 7. The average number of job offers for energy managers by contract type. Source: author's preparation based on data from https://www.pracuj.pl/ job-search websites (accessed on 7 August 2021).

After the contract type analysis, the number of job offers according to energy type was calculated. In Figure 8, the percentage of job offers is presented as classified by the search engine.

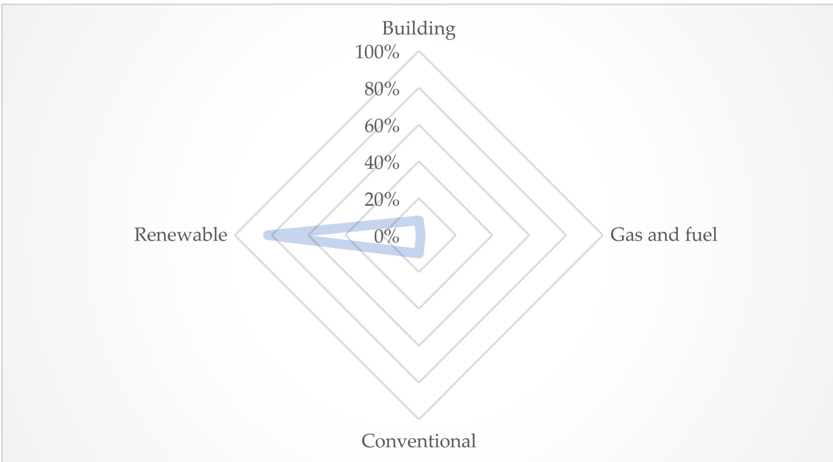


Figure 8. The number of job offers in Poland by industry category. Source: author's preparation based on data from https://www.pracuj.pl/ job-search websites (accessed on 7 August 2021).

As shown in Figure 8, the job offers were predominantly posted in the renewable energies sector (more than 60%). Due to this fact, employment in the renewable energies sector was subjected to more in-depth research. Consequently, the place and position of Poland in the rankings among other European countries and the United Kingdom were identified (Table A1).

According to EurObservER's data, the greatest employment in renewable energies was noticed in Germany, France, Italy, Spain, and the United Kingdom (Figure 9). The Polish employment share varied, from the largest in biofuels to the smallest in hydro power among the 28 countries (Figure 10).

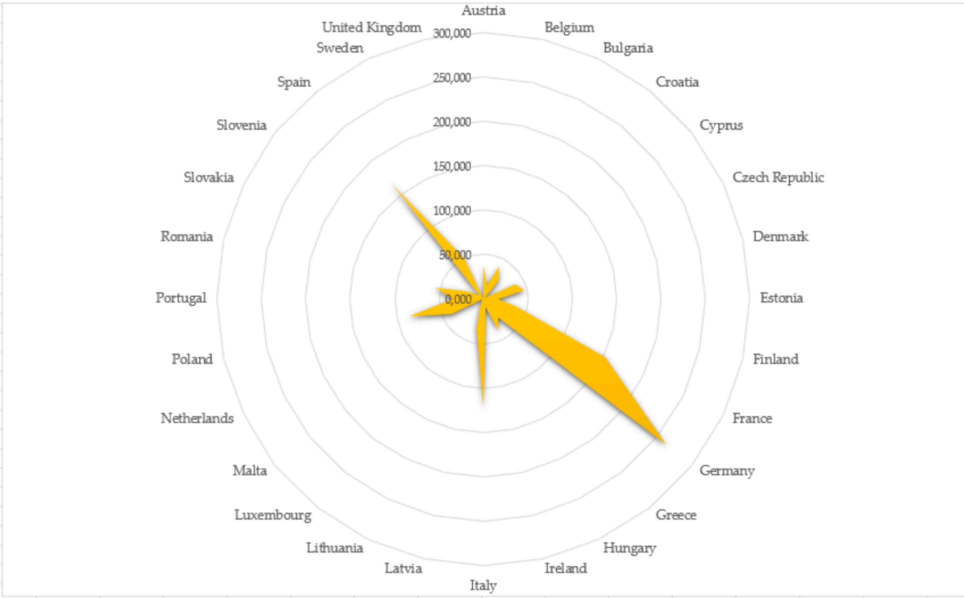


Figure 9. The state of employment in renewable energies in the European Union and United Kingdom. Source: author's preparation based on data from on https://www.eurobserv-er.org/online-database (accessed on 1 August 2021).

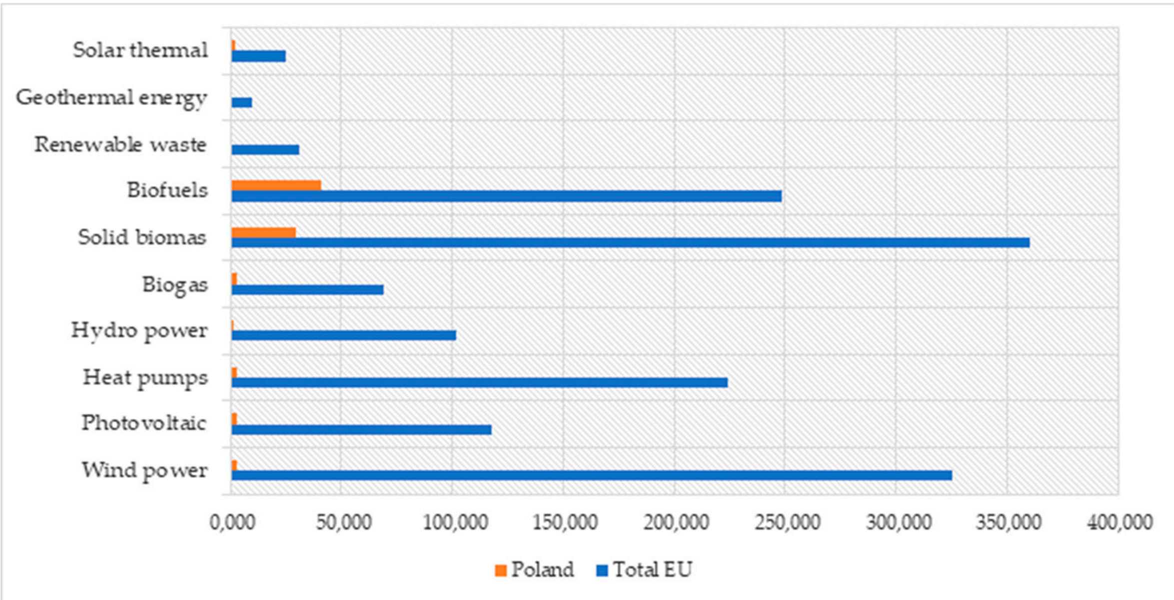


Figure 10. The comparison of employment levels in renewable energies between Poland and the European Union and UK (EU). Source: author's preparation based on data from https://www.eurobserv-er.org/online-database. (accessed on 1 August 2021).

The comparison of employment levels in renewable energies between Poland and the European Union and United Kingdom created the possibility to identify the rank position, calculated based on the percentage share of total employment (Figure 11).

Poland's position varied from 1 to 18. The ranking only had an informative character. To define the real position relative to other countries, more labor market characteristics should be analyzed while taking into account population, employment, and other indices.

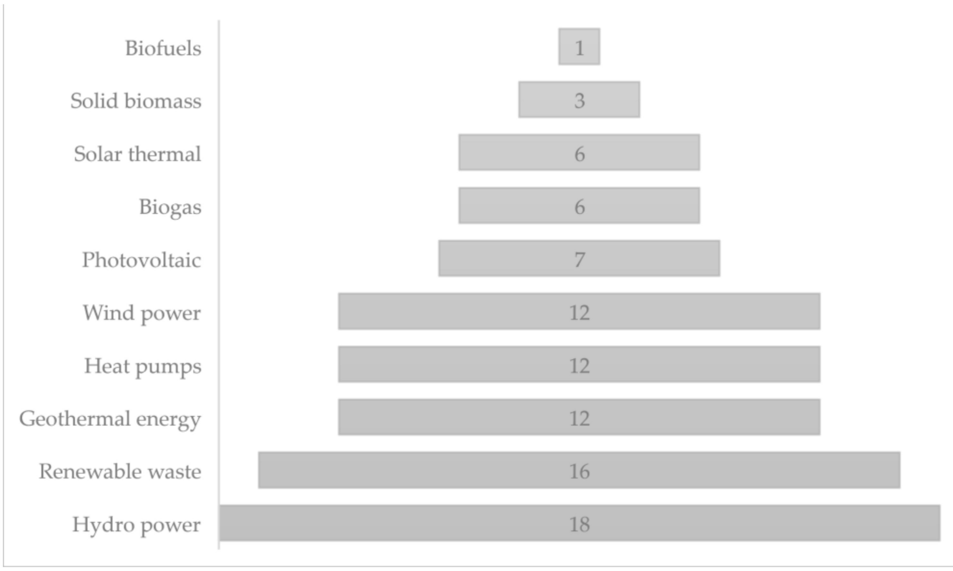


Figure 11. The Polish position in employment in renewable energies among EU countries and the UK in renewable energy production. Source: author's preparation based on data from https://www.eurobserv-er.org/online-database. (accessed on 1 August 2021).

5. Discussion

The research revealed the main determinants of the energy manager profession's transformation.

(1) First, COVID-19 had a significant influence. During the research period, the impact was significant enough in many European countries.

The common influence of the pandemic on widespread remote working was noticed by many experts [2,3,38,43].

According to the World Economic Forum 2020 report, the impact of COVID-19 on companies' strategies in the energy industry and the share of companies surveyed looking to adopt this strategy as a result of COVID-19 contained the following perspectives [2]:

- Accelerate the digitalization of work processes—91.5%;
- Provide more opportunities to work remotely—86.4%;
- Accelerate automation of tasks—57.6%;
- Accelerate the digitalization of upskilling/reskilling—54.2%;
- Accelerate the implementation of upskilling/reskilling programs—44.1%.

Additionally, the following remote work levels with the related job positions were identified based on the labor market study: high (remote), average (hybrid), and low (at workplace) (Figure 12).

(2) Second, the demographic changes had a great impact on the energy industry in Poland, including an aging population, and an increase in population density in large urban agglomerations.
(3) Third, environmental changes such as climate change, global warming and extreme natural events and hazards, natural resources changes, discovery of new energy sources, and biologic environmental changes (pandemics, etc.). Environmental changes contributed to the emergence of changes in regulations and policies.
(4) The emerging technologies such as big data, cloud computing, the IoT, artificial intelligence, and machine learning had an influence on the infrastructure transformation of Polish market-leading suppliers. Distributed ledger technology and biometric technologies also had a significant influence on:
    - New technological solutions and innovations in the energy industry, renewable energies;

- Digital technologies: communication technologies, cloud computing, the IoT, edge computing, big data, artificial intelligence, cognitive systems, blockchain, business process automation, etc.;
- Changes in transportation.

(5) Society noticed the occurring threats and risks, and there was a growing anxiety about life quality. Furthermore, the core socio-economic determinants are:
- Large-scale economic (e.g., Brexit) and social events;
- Changes in methods of business communication;
- New energy suppliers;
- Labor market changes in work and employment conditions, and those caused by the pandemic, such as: continuing workplace closures, working-hour losses and decreases in labor income, and allocation in large agglomerations;
- Conceptual changes—the new concepts also had an impact on changes in the labor markets. The concepts such as sustainable development, smart cities, and smart organization influenced the creation of new technologies such as smart grids, smart metering systems, etc.

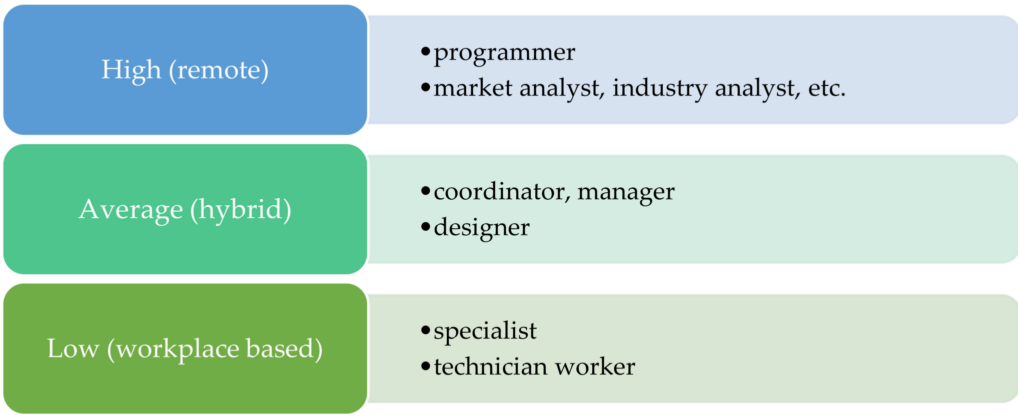


Figure 12. A diagram of remote work levels in the energy industry with associated job positions.

Due to globalization, cultural changes are occurring in organizations. Multicultural environments have been established in the energy sector, with the English language the most required by employees.

All the above-mentioned determinants involved changes in energy management and the energy manager profession. They became more "*green: more digitalized, better communicated, more remote, more multicultural, more diversified, more policy based—and, in consequence, more sustainable*".

The framework of core directions of changes and determinants of transformation of the energy manager profession is presented in Figure 13.

Applying the previously created holistic skills model [35] for Poland, several differences were found (Figure 14).

The significant difference between Poland and the EU countries was noticed in the following groups of skills for energy managers: management knowledge, IT skills, emerging-concept knowledge, and finance knowledge. So, the requirements for energy managers in Poland currently are lower than in other countries in the following areas: IT, finance, management, and emerging concepts.

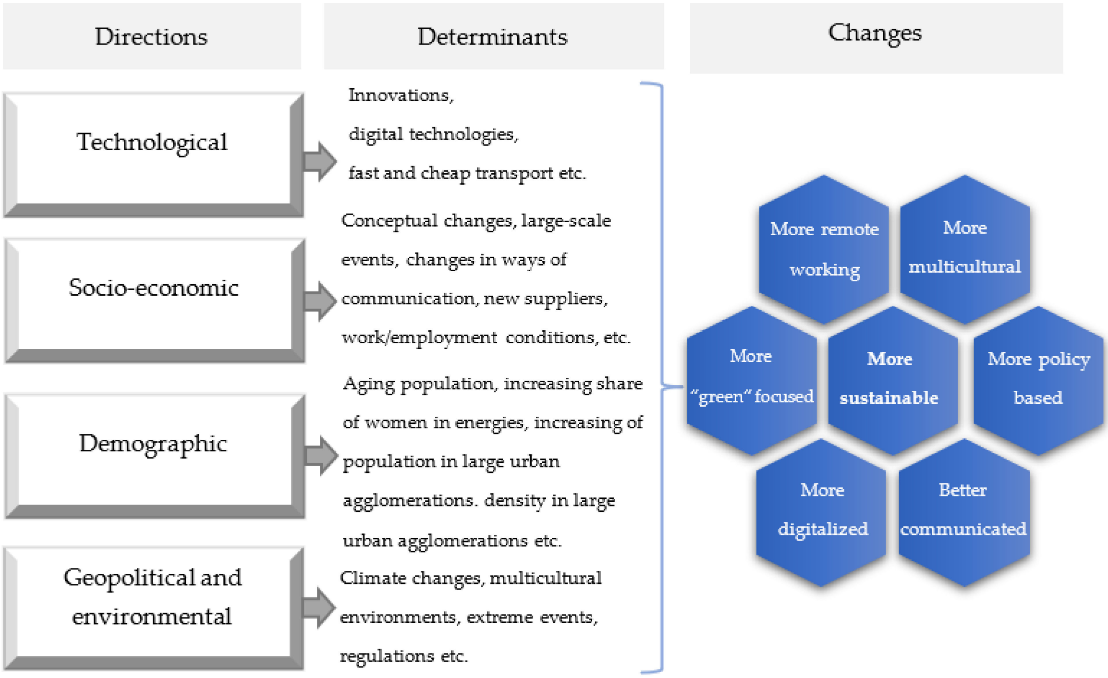


Figure 13. The core determinants of the energy manager profession's transformation.

The convergence of information technologies creates new concepts involved in the energy sector's day-to-day operations, such as sustainable smart production, smart meter measurement, smart grids, and many others that are actually commonly used in other countries. The knowledge of these and more modern concepts has become an important condition of energy manager employment, but still is not in demand in Poland.

A significant number of job positions was offered in the Mazovian region. However, taking into consideration that most power is generated by the West-Pomeranian Voivodeship [96,97] and that the transformation perspective in renewable energy sector is the exceptionally optimistic for this region and the Pomeranian Voivodeship, the new opportunities and challenges will occur in different economic spheres, as well as in education.

New-concept skills, as well as IT skills, according to experts' opinions, will be in demand in the near future. Currently, there is also a lack of complete education offers for the energy manager profession. The existing education programs are mainly based on technical skills. However, the labor market analysis showed that these programs should be supplemented first of all with managerial and information technology competences.

To sum up, the following findings were defined:

1. The energy sector in Poland currently is undergoing significant transformations. The determinants of transformations identified for Poland were in line with core global directions identified in the result of the literature review.
2. Currently, companies in Poland are looking for qualified energy managers. However, the requirements are lower than the global requirements in comparison with model created in 2020.
3. Due to the COVID-19 situation, many companies' employees are conducting their work remotely. After analyzing the remote work levels in the energy industry, a diagram with job positions was created. The further transformation could lead to extending the practice of remote work.
4. Currently, most of the job offers are in the renewable energies sector, with a predominance of photovoltaics.
5. The multicultural nature of the energy sector involves the need for advanced English language knowledge.

6. Currently, most job offers are concentrated in the Mazovian region. This situation could change with the market and suppliers offering transformations, together with the implementation of the Polish energy policy by 2040.
7. The research also revealed that several emerging concepts had an impact on energy manager competences. The sustainability development concept had the greatest influence on energy manager competences; conversely, competences in big data, smart technologies, and AI were required only by selected companies.

From the above, it can be concluded that the transformation of the energy industry involves the need to modify the skills and competences of energy managers in Poland to prepare them for the implementation of the low-emission transformation plan by 2040.

Figure 14. The current energy manager skills model for Poland. The skills groups with comparatively lower requirements are presented in the dotted boxes. Source: author's preparation based on [35].

6. Conclusions

The energy industry in Poland and around the world is currently undergoing significant transformations. One of the main sustainable development purposes is to provide new development opportunities for regions and communities negatively affected by the low-carbon energy transition by providing new jobs [74].

Therefore, the choice of a career in this industry now could be very promising for young people.

Actions taken in the next decade will be crucial in the decarbonization process, and investments in climate-resilient infrastructure and the transition to a low-carbon economy can create new jobs in the short term while increasing economic and environmental resilience [72]. "*The expansion of the generation and grid infrastructure will lead to the creation of an almost new power system by 2050, largely based on zero-emission sources*" [98].

The labor market research revealed that at the moment, managers must have a basic education in energy, but this education could be supplemented with additional programs and courses; for example, postgraduate programs.

The profession has become more green, more digitalized, better communicated, more remote, more multicultural, more diversified, and more policy based, and as a result, more sustainable.

The main contribution of this paper was the identification of the determinants that influence the energy manager profession in Poland and the current energy manager skill model, which reflects the current skills requirements in Poland. It could be used in the process of developing energy manager competency models in enterprises. It also can be applied as the basis for further elaboration of education programs and training courses.

The core theoretical contribution was the discovery of the core directions that currently drive the transformations of the energy sector.

Drawing from the carrier's general development conditions in the literature and the tendencies in emerging-technology analysis, a new consideration of the impact of determinants of the energy manager profession's development in Poland have been presented.

This article contributes to the management of professions by suggesting a framework for analyzing skills as fundamental to energy management. Empirically, the article builds on fieldwork observations and current labor market job-post analysis.

The analysis showed that energy managers' professional role is undergoing significant transformations, since the renewable sources reuse conventional ones. These changes involve the transformations of employee skills and competences, which should be continuously monitored and adapted to labor market requirements.

The comparison of the global holistic skills model and the Polish skills model outlined the lower-level requirement zones, which could be changed in the near future, together with the energy strategy and policy changes. While companies from the countries with greater shares of renewable sources have more advanced requirements related to emerging technologies and concepts, it could be expected that the situation in Poland will also change in near future. Several seedlings are already becoming noticeable.

On the other hand, universities should be prepared to ensure the appropriate high level of education to create a new generation of qualified energy managers. In such conditions, the skills models use the exceptional importance to ensure the successful relationship between companies and education sector.

The limitation of the research was that it was conducted based on a literature review and job-search websites, and excluded employer and employee opinions. Therefore, future research could be focused on the study of the opinions of a company's managing staff and employees by using the questionnaire method. This would provide the opportunity to include the missing part, and to obtain a holistic view of the situation from three perspectives: EU statistics, job-search websites, and the enterprises.

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Informed Consent Statement: Not applicable.

Data Availability Statement: All the data available from sources mentioned in the references.

Conflicts of Interest: The author declares no conflict of interest.

Appendix A

Table A1. Employment in the renewable energies sector among EU countries and the UK. Source: https://www.eurobserv-er.org (accessed on 1 August 2021).

	Wind Power		Photovoltaic		Heat Pumps		Hydro Power		Biogas		Solid Biomass		Biofuels		Renewable Waste		Geothermal Energy		Solar Thermal		Total	
YEAR	**2017**	**2018**	**2017**	**2018**	**2017**	**2018**	**2017**	**2018**	**2017**	**2018**	**2017**	**2018**	**2017**	**2018**	**2017**	**2018**	**2017**	**2018**	**2017**	**2018**	**2017**	**2018**
Austria	2000	2500	1600	1900	1300	1700	4200	17,300	400	400	8700	10,100	2000	2100	1600	200	100	400	2600	1800	23,500	38,400
Belgium	5500	7400	3000	1700	1400	2900	400	400	500	400	2000	1500	1500	1100	3200	600	200	100	100	100	17,800	16,200
Bulgaria	500	500	600	600	700	600	2300	2300	600	1000	8700	27,000	7700	7500	100	100	200	200	1500	1300	22,700	41,100
Croatia	1100	1100	100	400	100	100	1400	2100	800	2200	14,400	16,700	2000	2500	100	100	100	100	200	200	20,300	25,500
Cyprus	200	100	500	200	100	100	100	100	100	100	100	300	100	100	100	100	100	100	100	300	1500	1500
Czech Republic	900	1300	1300	1900	2600	5300	1500	1300	4500	4100	12,300	16,700	8400	8000	700	200	100	100	600	200	32,500	39,100
Denmark	34,200	35,400	1100	1600	1500	2700	100	100	700	600	10,500	5300	700	700	600	600	600	100	1300	500	50,200	47,600
Estonia	1200	400	100	500	1700	1800	100	100	100	100	8000	12,200	700	500	100	500	100	100	100	100	12,200	16,300
Finland	4100	700	700	1200	4700	5500	1200	1300	600	500	26,800	23,700	1600	2600	400	1200	100	100	100	100	40,300	36,900
France	18,500	15,700	9300	15,000	36,200	41,200	9900	10,500	2400	4200	33,900	31,100	24,400	29,100	2600	2100	2500	900	1400	1800	140,700	151,600
Germany	140,800	106,200	29,300	41,900	9300	15,700	4600	7600	35,000	30,800	44,900	35,400	15,500	14,500	6300	7600	500	300	7200	3700	290,700	263,700
Greece	3100	5100	1300	1800	1200	1500	2000	2400	1300	800	2600	2400	11,500	10,900	100	100	100	100	1700	1800	25,200	26,900
Hungary	800	900	1300	4500	400	800	100	100	600	700	13,300	11,800	18,200	18,000	400	400	700	700	200	200	36,000	38,100
Ireland	6500	4500	100	200	300	400	300	300	200	200	1200	1100	200	200	700	1600	100	100	200	100	9700	8700
Italy	7500	8100	11,200	11,400	41,300	37,600	10,800	17,300	8100	8400	35,800	24,400	9000	8500	2500	2400	3100	2200	1400	1100	129,900	121,400
Latvia	100	200	100	100	100	100	1000	3300	900	800	20,700	24,400	4000	4900	100	100	100	100	100	100	27,200	34,100
Lithuania	500	500	100	100	300	100	700	600	700	300	3600	2700	4500	6100	100	100	100	100	100	100	10,700	10,700
Luxembourg	100	100	100	100	100	100	500	500	100	100	100	100	100	100	100	100	100	100	100	100	1400	1400
Malta	100	100	300	200	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	1200	1100
Netherlands	5800	6800	6000	14,300	6800	8000	100	100	700	700	4800	3300	2800	2400	1500	3400	100	800	100	100	28,700	39,900
Poland	8000	3000	1100	3100	3000	2600	1100	1000	2300	2700	25,900	29,600	31,400	41,200	700	200	100	200	2200	2200	73,900	85,800
Portugal	3100	2600	1500	1600	13,800	13,900	4200	7700	700	700	8000	7100	400	300	500	500	400	400	500	500	33,100	35,300
Romania	2100	2200	900	1100	200	300	3400	3300	300	300	11,400	6800	34,300	40,000	100	100	200	1100	100	100	53,000	55,300
Slovakia	100	100	200	200	200	2400	1200	1200	500	1100	9000	11,300	3800	4000	100	100	700	400	100	100	15,900	20,900

Table A1. *Cont.*

Slovenia	100	100	100	100	900	400	800	2000	100	100	1500	1800	500	100	100	100	100	300	100	100	4300	5100
Spain	37,200	32,300	5500	2200	56,600	68,700	11,200	12,300	1600	1200	20,800	18,300	26,600	23,200	1100	600	100	100	8400	8200	168,800	167,100
Sweden	2700	4600	500	1100	5100	7800	4700	4300	100	100	20,700	18,900	8300	10,900	800	3400	100	100	100	100	43,100	51,300
United Kingdom	69,900	82,800	12,900	8600	1700	2100	2300	2500	8400	6100	15,000	16,500	10,100	8600	10,800	4400	100	100	200	200	131,400	131,900
Total EU	356,700	325,300	90,800	117,600	191,700	224,500	70,700	102,100	72,400	68,800	36,4800	360,600	230,400	248,200	35,600	31,000	10,900	9500	30,900	25,300	1,445,900	15,12,900

Table A2. Descriptive statistics.

	N	Missing	Mean	SE	Median	Mode	Sum	SD	Variance	IQR	Range	Minimum	Maximum	Skewness	SE	Kurtosis	SE	W	*p*
Wind power	30	0	21,754	11,375	2350	100	652,618	62,304	3.88 × 109	6750	325,200	100	325,300	4.37	0.427	20.8	0.833	0.384	<0.001
Photovoltaic	30	0	7907	4069	1600	100 [a]	237,218	22,287	4.97 × 108	2625	117,500	100	117,600	4.51	0.427	21.8	0.833	0.373	<0.001
Heat pumps	30	0	15,034	7740	2059	100	451,018	42,394	1.8 × 109	6825	224,400	100	224,500	4.52	0.427	22.1	0.833	0.381	<0.001
Hydropower	30	0	6874	3401	2009	100	206,218	18,626	3.47 × 108	3625	102,000	100	102,100	4.93	0.427	25.7	0.833	0.359	<0.001
Biogas	30	0	4654	2444	700	100	139,618	13,389	1.79 × 108	1855	68,700	100	68,800	4.31	0.427	19.6	0.833	0.365	<0.001
Solid biomass	30	0	24,107	11,763	11,550	100 [a]	723,218	64,427	4.15 × 109	20,025	360,500	100	360,600	5.24	0.427	28.2	0.833	0.312	<0.001
Biofuels	30	0	16,614	8246	4450	100	498,418	45,163	2.04 × 109	10,100	248,100	100	248,200	4.97	0.427	26	0.833	0.356	<0.001
Renewable waste	30	0	2134	1042	450	100	64,018	5708	3.26 × 107	1814	30,900	100	31,000	4.79	0.427	24.5	0.833	0.373	<0.001
Geothermal	30	0	701	319	100	100	21,018	1747	3.05 × 106	300	9400	100	9500	4.74	0.427	24	0.833	0.37	<0.001
Solar thermal	30	0	1754	865	200	100	52,618	4738	2.25 × 107	1575	25,200	100	25,300	4,60	0.427	22,7	0.833	0.376	<0.001

[a]: More than one mode exists, only the first is reported.

Table A3. Pearson's, Spearman's correlation matrix and Kendall's Tau correlation matrix.

		Wind Power	Photovoltaic	Heat Pumps	Hydropower	Biogas	Solid Biomass	Biofuels	Renewable Waste	Geothermal	Solar Thermal
Wind power	Pearson's r	—									
	p-value	—									
	95% CI Upper	—									
	95% CI Lower	—									
	Spearman's rho	—									
	p-value	—									
	Kendall's Tau B	—									
	p-value	—									
	N	—									
Photovoltaic	Pearson's r	0.965 ***	—								
	p-value	<0.001	—								
	95% CI Upper	0.984	—								
	95% CI Lower	0.928	—								
	Spearman's rho	0.802 ***	—								
	p-value	<0.001	—								
	Kendall's Tau B	0.628 ***	—								
	p-value	<0.001	—								
	N	30	—								
Heat pumps	Pearson's r	0.894 ***	0.909 ***	—							
	p-value	<0.001	<0.001	—							
	95% CI Upper	0.949	0.956	—							
	95% CI Lower	0.788	0.816	—							
	Spearman's rho	0.735 ***	0.777 ***	—							
	p-value	<0.001	<0.001	—							
	Kendall's Tau B	0.562 ***	0.591 ***	—							
	p-value	<0.001	<0.001	—							
	N	30	30	—							
Hydropower	Pearson's r	0.908 ***	0.928 ***	0.964 ***	—						
	p-value	<0.001	<0.001	<0.001	—						
	95% CI Upper	0.956	0.966	0.983	—						
	95% CI Lower	0.815	0.853	0.925	—						
	Spearman's rho	0.462 *	0.402 *	0.464 **	—						
	p-value	0.01	0.028	0.01	—						
	Kendall's Tau B	0.345 **	0.294 *	0.344 **	—						
	p-value	0.009	0.027	0.009	—						
	N	30	30	30	—						

Table A3. *Cont.*

		Wind Power	Photovoltaic	Heat Pumps	Hydropower	Biogas	Solid Biomass	Biofuels	Renewable Waste	Geothermal	Solar Thermal
Biogas	Pearson's r	0.965 ***	0.986 ***	0.879 ***	0.907 ***	—					
	p-value	<0.001	<0.001	<0.001	<0.001	—					
	95% CI Upper	0.984	0.993	0.941	0.955	—					
	95% CI Lower	0.928	0.971	0.76	0.812	—					
	Spearman's rho	0.579 ***	0.716 ***	0.558 **	0.536 **	—					
	p-value	<0.001	<0.001	0.001	0.002	—					
	Kendall's Tau B	0.442 ***	0.573 ***	0.42 **	0.385 **	—					
	p-value	<0.001	<0.001	0.002	0.004	—					
	N	30	30	30	30	—					
Solid biomass	Pearson's r	0.932 ***	0.948 ***	0.945 ***	0.97 ***	0.931 ***	—				
	p-value	<0.001	<0.001	<0.001	<0.001	<0.001	—				
	95% CI Upper	0.968	0.975	0.974	0.986	0.967	—				
	95% CI Lower	0.862	0.892	0.886	0.937	0.858	—				
	Spearman's rho	0.417 *	0.525 **	0.562 **	0.598 ***	0.699 ***	—				
	p-value	0.022	0.003	0.001	<0.001	<0.001	—				
	Kendall's Tau B	0.29 *	0.392 **	0.43 **	0.438 ***	0.549 ***	—				
	p-value	0.026	0.003	0.001	<0.001	<0.001	—				
	N	30	30	30	30	30	—				
Biofuels	Pearson's r	0.905 ***	0.92 ***	0.935 ***	0.948 ***	0.895 ***	0.975 ***	—			
	p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	—			
	95% CI Upper	0.954	0.962	0.969	0.975	0.949	0.988	—			
	95% CI Lower	0.808	0.838	0.867	0.894	0.789	0.948	—			
	Spearman's rho	0.539 **	0.622 ***	0.464 **	0.538 **	0.65 ***	0.74 ***	—			
	p-value	0.002	<0.001	0.01	0.002	<0.001	<0.001	—			
	Kendall's Tau B	0.383 **	0.465 ***	0.347 **	0.414 **	0.511 ***	0.572 ***	—			
	p-value	0.003	<0.001	0.008	0.002	<0.001	<0.001	—			
	N	30	30	30	30	30	30	—			
Renewable waste	Pearson's r	0.971 ***	0.981 ***	0.915 ***	0.939 ***	0.964 ***	0.962 ***	0.93 ***	—		
	p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	—		
	95% CI Upper	0.986	0.991	0.959	0.971	0.983	0.982	0.967	—		
	95% CI Lower	0.94	0.961	0.828	0.875	0.925	0.921	0.857	—		
	Spearman's rho	0.784 ***	0.744 ***	0.784 ***	0.292	0.428 *	0.403 *	0.312	—		
	p-value	<0.001	<0.001	<0.001	0.118	0.018	0.027	0.093	—		
	Kendall's Tau B	0.629 ***	0.584 ***	0.626 ***	0.203	0.339 *	0.304 *	0.248	—		
	p-value	<0.001	<0.001	<0.001	0.14	0.014	0.025	0.069	—		
	N	30	30	30	30	30	30	30	—		

Table A3. *Cont.*

		Wind Power		Photovoltaic		Heat Pumps		Hydropower		Biogas		Solid Biomass		Biofuels		Renewable Waste		Geothermal		Solar Thermal
Geothermal	Pearson's r	0.865	***	0.909	***	0.918	***	0.952	***	0.879	***	0.942	***	0.936	***	0.927	***	—		
	p-value	<0.001		<0.001		<0.001		<0.001		<0.001		<0.001		<0.001		<0.001		—		
	95% CI Upper	0.934		0.956		0.96		0.977		0.941		0.972		0.969		0.965		—		
	95% CI Lower	0.733		0.816		0.833		0.9		0.759		0.88		0.868		0.851		—		
	Spearman's rho	0.233		0.525	**	0.386	*	0.401	*	0.41	*	0.282		0.347		0.291		—		
	p-value	0.216		0.003		0.035		0.028		0.024		0.131		0.06		0.118		—		
	Kendall's Tau B	0.171		0.413	**	0.302	*	0.325	*	0.324	*	0.216		0.272		0.233		—		
	p-value	0.227		0.004		0.033		0.022		0.023		0.124		0.054		0.114		—		
	N	30		30		30		30		30		30		30		30		—		
Solar thermal	Pearson's r	0.916	***	0.913	***	0.971	***	0.953	***	0.899	***	0.946	***	0.943	***	0.917	***	0.9	***	—
	p-value	<0.001		<0.001		<0.001		<0.001		<0.001		<0.001		<0.001		<0.001		<0.001		—
	95% CI Upper	0.96		0.958		0.986		0.978		0.951		0.974		0.973		0.96		0.952		—
	95% CI Lower	0.83		0.824		0.939		0.903		0.796		0.888		0.883		0.832		0.798		—
	Spearman's rho	0.554	**	0.676	***	0.477	**	0.528	**	0.68	***	0.474	**	0.478	**	0.319		0.374	*	—
	p-value	0.001		<0.001		0.008		0.003		<0.001		0.008		0.007		0.085		0.042		—
	Kendall's Tau B	0.433	**	0.547	***	0.383	**	0.392	**	0.53	***	0.367	**	0.376	**	0.256		0.302	*	—
	p-value	0.002		<0.001		0.006		0.005		<0.001		0.008		0.007		0.077		0.044		—
	N	30		30		30		30		30		30		30		30		30		—

Note. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table A4. Scale reliability statistics.

	Mean	sd	Cronbach's α	McDonald's ω
scale	10,153	27,304	0.918	0.993

Table A5. Item reliability statistics.

	Mean	sd	Item-Rest Correlation	Cronbach's α	McDonald's ω
Wind power	21,754	62,304	0.945	0.901	0.992
Photovoltaic	7907	22,287	0.968	0.903	0.992
Heat pumps	15,034	42,394	0.947	0.983	0.992
Hydropower	6874	18,626	0.969	0.907	0.992
Biogas	4654	13,389	0.953	0.913	0.992
Solid biomass	24,107	64,427	0.980	0.900	0.991
Biofuels	16,614	45,163	0.961	0.892	0.992
Renewable waste	2134	5708	0.978	0.922	0.992
Geothermal	701	1747	0.940	0.927	0.993
Solar thermal	1754	4738	0.964	0.923	0.992

Table A6. Component loadings.

	Component	Uniqueness
Wind power	0.962	0.0745
Photovoltaic	0.976	0.0470
Heat pumps	0.963	0.0732
Hydropower	0.977	0.0451
Biogas	0.960	0.0781
Solid biomass	0.986	0.0287
Biofuels	0.969	0.0615
Renewable waste	0.981	0.0374
Geothermal	0.952	0.0937
Solar thermal	0.966	0.0676

Table A7. Factor loadings.

	Factor	Uniqueness
Wind power	0.957	0.0845
Photovoltaic	0.974	0.0505
Heat pumps	0.958	0.0830
Hydropower	0.976	0.0481
Biogas	0.954	0.0890
Solid biomass	0.986	0.0275
Biofuels	0.965	0.0686
Renewable waste	0.981	0.0385
Geothermal	0.944	0.1081
Solar thermal	0.961	0.0761

Table A8. KMO Measure of Sampling Adequacy.

	MSA
Wind power	0.887
Photovoltaic	0.860
Heat pumps	0.910
Hydropower	0.932
Biogas	0.855
Solid biomass	0.879
Biofuels	0.873
Renewable waste	0.859
Geothermal	0.902
Solar thermal	0.919

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Article

Impacts of COVID-19 on Energy Expenditures of Local Self-Government Units in Poland

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Abstract: Measures taken by the public administration to prevent the spread of the COVID-19 pandemic have led to drastic consequences for the economy. The full identification of its effects is hindered due to the delay in publishing the results of public statistics. The use of financial reports prepared by self-government authorities of all municipalities in Poland made it possible to obtain preemptive information in relation to the public statistics regarding the impact of COVID-19-related limitations on the energy expenditures incurred by local government units (LGUs), as well as an assessment of to what extent the LGUs had rationalized the energy consumption. By contrast, data from reports of energy companies made it possible to determine the impact of restrictions arising from the pandemic on the amount of energy sold and revenues from sales made by these companies. The analyses use indexes of the dynamics of changes in energy prices as well as indexes of the dynamics of changes in energy expenditures incurred by LGUs. Additionally, distributions of these indexes for the populations of municipalities are analyzed. To assess the effect of economic activity on energy expenditures incurred by LGUs, classification trees are utilized. It is established that the total production and sales of energy in Poland, in volume, in each quarter of 2020 were lower than in the corresponding period of the preceding year. However, as a result of an increase in energy prices by approximately 25%, the sales of electric power generating companies, in amounts, were higher in 2020 than in 2019. The increase in energy prices was also a cause of slightly increased total expenditures for purchasing energy in LGUs in Poland, which increased by 2.15% in 2020 compared to 2019. However, a substantial diversity in expenditure indexes was observed. That concerned both total expenditures and expenditures within individual sections of the budgets of municipalities.

Keywords: COVID-19; self-government units; energy consumption; energy consumption; monitoring; energy consumption effectiveness

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1. Introduction

The emergence of COVID-19 forced the public authorities of countries worldwide to put into action measures to mitigate the negative impacts of the spread of the virus [1–4]. To contain the spread of the infection, governments have introduced a series of social distancing measures, along with lockdowns and shutting down businesses. The wide use of containment measures by the public administrations of almost all countries has had far-reaching consequences for the global economy [5,6]. In many regions of the world, a significant decline in economic activity has been reported [7].

Understanding the effects of governments' actions on the economy and international trade would be helpful in defining an adequate economic policy framework, which would additionally limit the negative effects of restrictions on the economy [5].

Common policies of public authorities have caused chain reactions in economic systems. Due to diminishing production and reduced demand in certain product groups, governments' interventions have had a significant impact both on the national economy and on international trade.

Referring to the model-based estimates, Guan et al. [8] suggest that, depending upon the scale of the implementation of containment measures, the global industry's value added may have fallen by 25–40%. Publications suggest significant variations in the consequences of government-led countermeasures [9,10]. There are also significant sectoral and geographic discrepancies in the governments' actions impacts on economic activity. The largest drops in production, up to 12%, were experienced by the manufacturing sectors. The negative effects of the lockdown diminish over time. However, Fezzi and Fanghella [10] estimated that the few weeks of the most severe lockdown reduced the corresponding Italian GDP by roughly 30%.

Results of some studies show meaningful trade losses, particularly in China, Western Europe, and the Middle East [11]. From a major perspective, the collapse of international trade was the aftermath of disrupted supply chains [8,11].

Quantifying the effects of various mitigation measures on the economy is essential for the formulation of effective policy responses. However, an assessment of the degree of disruption caused to the global economy by mitigating measures is difficult due to the following reasons:

- Traditional macroeconomic indicators are usually published with a significant delay;
- The aggregate nature of traditional macroeconomic indicators makes it difficult to isolate the impact of various mechanisms of influence;
- The limited availability of macroeconomic indicators for countries with a low level of development makes it difficult to assess the economic effects of turbulence in the global economy.

Owing to the fact that official statistics are published with a delay (at least a few months), there is a need to estimate the causal short-run impacts of COVID-19 on the economy. Discernment, in this regard, can be used for shaping the possible future lockdown and economic policy.

Having the right real-time indicators of economic activity can be helpful in the impact assessment phase of individual policies on the economy. Additionally, adequate allocation of funds to the hardest hit sectors of the economy can support efforts aimed at stimulating economic recovery.

In response to the demand from decision makers for up-to-date information, some authors are trying to develop methods of analysis that will make it possible to assess the effects of implemented restrictions with a relatively short delay. For example, to assess the global maritime trade losses during the first months of the pandemic, Verschuur, Koks, and Hall, formed a high-frequency index of economic activity based on empirical vessel tracking data [11]. The authors used high-frequency data representing information related to vessel tracking data to estimate the global trade disturbances. The impact of governments' interventions on maritime exports served as a proxy of economic activity. The research showed that during the eight months of 2020, global maritime trade was reduced by 7.0–9.6%, which is equal to 412 billion USD in value losses. In addition to the relationship between the level of activity of economic sectors and the intensity of trade, the authors unexpectedly identified the negative impact of pandemic-related school closures and public transport restrictions on country-wide exports.

An increasing number of authors are using high-frequency data to track the economic impact of remedial programs created by public authorities to help prevent the spread of the pandemic. Such research is carried out both on a national and global scale. To track the impact of pandemic evolution on economic and social systems, the growing body of literature increasingly refers to such data sources as follows:

- Degree of human mobility [12–14];
- Air pollution indicators [5,15,16];
- Night-time light intensity [17–19];
- Level of electricity consumption [9,10,17,20,21].

From the perspective of this study, studies that use data on electricity consumption to assess the effects of the restrictions introduced are the most important reference points.

The findings on the long-run relationship indicate that a sufficiently large supply of electricity can ensure a higher level of economic growth [20].

An assessment of the costs and benefits of various mitigation measures for the economy and international trade is essential for effective countermeasures in the process of shaping appropriate economic policies. Various authors emphasize that the goal of effective policies is to find a compromise between inhibiting the spread of the epidemic and reducing the negative effects of the applied restrictions [5,7,9].

In recent years, up to 2019, the Polish economy had been developing steadily. The increase in gross domestic product amounted to 1.1% in 2013, 3.4% in 2014, 4.2% in 2015, 3.1% in 2016, 4.8% in 2017, 5.4% in 2018, and 4.5% in 2019 [22]. Observation of the listed increases showed that the trend continued in subsequent years. Unfortunately, in 2020, Poland, as the rest of the world, was affected by the COVID–19 pandemic. One of the effects of this pandemic was a sudden economic downturn, evidenced by a 2.7% decline in the Polish GDP in 2020, compared to the preceding year [23].

The COVID-19 pandemic made it necessary for public authorities to undertake a series of actions. In Poland, one of them was the introduction (on 2 March 2020) of the Act on specific solutions related to the preventing, counteracting, and combating of COVID-19 and other infectious diseases and crisis situations caused by them [24]. That act allowed employers to order their employees to work from home. It also made it possible to provisionally reduce the determined extent of entrepreneurs' activities and introduced the obligation to be subjected to quarantine.

In a regulation issued on 20 March 2020, the Minister of Health declared a state of pandemic within the territory of Poland [25]. Rail transport of passengers related to crossing the Polish border was suspended by that regulation, as was the activity of restaurants (except takeaway sales), organizing events, congresses, etc., activities connected with all collective forms of culture and entertainment, sports and recreational activities, and the activities of libraries and spas. It was also possible to reduce the activities of public administration units solely to the tasks indispensable for providing help to citizens. It was also allowed to carry out tasks without direct client service. Restrictions were also introduced in schools and universities. In the period from March 2020 to June 2021, teaching was conducted remotely.

The introduced restrictions had an impact on the functioning of LGUs. Restricting their activities ought to reduce energy consumption in many areas and, by extension, lower the costs incurred for this purpose. The aim of this study is to determine the effect of restrictions arising from the pandemic on the amount of energy sold and revenues from the sale of energy companies, as well as to examine to what degree LGUs have rationalized energy consumption under restricted activities and how this has been reflected in the costs incurred by them.

2. Materials and Methods

The study covered two areas. The energy market in Poland was the first. The study focused on the activities of energy companies. The volume of sales of electric and thermal energy in 2019 and 2020 as well as average sale prices of electric energy in individual quarters were analyzed. Revenues and financial results of these companies were also analyzed. The study covered Polish listed companies in the energy sector. The Warsaw Stock Exchange qualifies 9 companies for the energy sector. These companies are the following: Elektrociepłownia Będzin S.A., ENEA S.A., ENERGA S.A., PGE Polska Grupa Energetyczna S.A., Polenergia S.A., TAURON Polska Energia S.A., Zespół Elektrociepłowni

Wrocławskich KOGENERACJA S.A. and Zespół Elektrowni Pątnów-Adamów-Konin S.A. and ML System S.A. The last company was not taken into account in the analysis since it does not deal with the production and distribution of energy but with the assembly of renewable energy installations, e.g., photovoltaics. All of the analyzed companies form corporate groups. They are obliged to publish annual, semi-annual, and quarterly consolidated reports. The analysis took into account consolidated reports, which are prepared every quarter and include the dominant entity as well as other companies from the corporate group. Stock reports of the companies constituted the source of data [26]. The data on energy sales come from the website of the Energy Regulatory Office [27].

Energy expenditures of municipal governments were the second study area. The study was based on financial data coming from all municipal government units in Poland. The data were obtained from Rb-28S budgetary reports, made available by the Ministry of Finance. Reports for the last quarter of 2019 and 2020 were used in the analysis. The report for the last quarter contains data on budgetary expenditures of municipalities for the entire fiscal year. The RB28S report is made in accordance with the municipality's budget. Sections are the fundamental elements of the budget classification. Sections are divided into subsections, and they specify the type of activity. Expenditure groups within individual sections are indicated by an appropriate numeric code called an article. Data specified by Article 426—"purchase of energy"—are the subject of the analysis. This article includes expenditures for the supply of electric, thermal, and other energy as well as gas and water.

To determine the share of expenditures for water within individual sections, computations were made based on the data obtained from several selected municipalities. The results are shown in Table 1.

Table 1. Share of water consumption costs in costs within Article 426.

Section of the Budget Classification	Share of Water Cost in 2019 [%]	Share of Water Cost in 2019 [%]	Ratio of Water Consumption Cost 2020/2019
70005 Housing economy	15.67	11.94	1.01
75023 Public administration	3.56	1.53	1.01
80101 Education and upbringing—schools	3.18	2.60	0.90
80104 Education and upbringing—kindergartens	3.55	1.51	0.44
90015 Lighting of streets, roads and squares	0.00	1.51	

Source: Own calculations based on data from municipalities.

In the analyzed sections, the percent share of water costs in the costs within Article 426 is low. The highest was recorded under the 'Housing economy' section. It is the consumption associated with people inhabiting municipal amenity buildings.

Table 2 shows expenditures within individual sections of Article 426 for the years 2019 and 2020. Sections are arranged in order of the highest energy expenditure.

The first five sections were selected for the analysis, on account of their large share of energy consumption costs (87% of total expenses). From individual sections, sections with the largest share of energy expenditures were selected for the analysis, as presented in Table 3.

Table 2. Budgetary expenditures of municipalities in Poland in 2019 and 2020 for Article 426 according to sections.

Section No.	Section Name	Expenditure in 2019 PLN	Expenditure in 2020 PLN	Share in Total Expenditure in 2019 in %	Share in Total Expenditure in 2020 in %
801	Education and upbringing	1,613,339,028	1,520,746,092	34.56	31.90
900	Municipal economy and environmental protection	1,103,893,587	1,241,630,291	23.65	26.04
700	Housing economy	830,763,739	847,365,555	17.80	17.77
926	Physical culture	298,264,259	288,897,533	6.39	6.06
750	Public administration	214,276,715	230,827,369	4.59	4.84
400	Producing and supplying electrical energy, gas, and water	114,412,978	120,508,002	2.45	2.53
852	Social service	111,177,352	116,729,787	2.38	2.45
754	Public safety and fire protection	77,396,314	80,360,878	1.66	1.69
754	Public safety and fire protection	77,396,314	80,360,878	1.66	1.69
854	Educational care	64,698,698	62,672,552	1.39	1.31
855	Family	56,188,382	59,422,497	1.20	1.25
600	Transport and communication	45,521,812	51,994,857	0.98	1.10
010	Agriculture and hunting	44,356,870	50,354,824	0.95	1.06
921	Culture and protection of national heritage	38,859,244	38,351,447	0.83	0.80
710	Service activities	20,955,162	23,183,679	0.45	0.47
851	Health protection	9,425,502	9,093,862	0.20	0.19
925	Botanical and zoological gardens as well as natural areas and nature protected areas	8,664,896	9,100,020	0.19	0.19
853	Other tasks within social policy	7,996,895	8,360,348	0.17	0.18
630	Tourism	3,999,145	4,209,755	0.09	0.09
150	Industrial processing	1,328,286	1,458,911	0.03	0.03
500	Trade	1,060,926	1,452,383	0.02	0.03
720	Computer science	201,687	251,809	0.004	0.005
730	Higher education and research	199,630	228,442	0.004	0.005
751	Offices of supreme state authorities, control and protection of law and judiciary	190,788	121,744	0.004	0.00255
550	Hotels and restaurants	173,648	208,894	0.004	0.004
020	Forestry	152,238	185,902	0.003	0.004
755	Judicial system	127,054	111,779	0.003	0.002
050	Fishing	85,214	84,423	0.002	0.002
758	Various accruals	7018	0	0.0001	0.000
756	Income from legal persons, natural persons and other units without legal personality, and expenses related to its collection	3328	335	0.00007	0.00001
100	Mining and quarrying	580	581	0.00001	0.00001
	Total	4,667,720,975	4,767,914,550		

Source: Own calculations based on data from the Ministry of Finance [28].

Table 3. Sections selected for analysis.

Section No.	Section Name	Share of the Section in the Costs of the Section in 2020
80101	Primary schools	60.33%
80104	Kindergartens	116.73%
90015	Lighting of streets, squares and roads	88.51%
70005	Land and real estate management	56.89%
92604	Institutions of physical culture	45.95%
75023	Municipal offices	93.35%

Source: Own calculations based on data from the Ministry of Finance [28].

To extract interesting information from reports of energy companies, methods of cause-and-effect analysis were used, in particular the method of chain substitutions. [29,30]. Revenues from energy sales and the amount of energy sold were extracted from the company's report. Based on that, the average unit price of energy was established. Indexes were used to assess the changes in this price in the 2019–2020 period.

For the purpose of analyzing the expenditures of local government units, indexes were created. Those indexes describe dynamic changes in energy expenditures within individual sections and also changes in total energy expenditures incurred by respective municipalities. Population of municipalities described with a set of these indexes was then analyzed using average and dispersion measures [31]. Distribution of indexes is presented using a histogram.

To assess the effect of economic activity on energy expenditures incurred by LGUs, classification and regression trees were also utilized. A classification tree is a directed graph with a root and nodes in which conditions concerning variables are checked, and also branches with certain decision-making rules. Analysis using the classification tree algorithm involves finding a set of logical conditions for dividing a set of objects into possible homogeneous classes. The CART (Classification and Regression Trees) algorithm proposed by Breiman et al. is one of the most effective ones. It consists of considering all combinations of levels of independent diagnostic variables in order to find the best division. This division is performed recursively in the N-dimensional object space [32]. The advantage of using trees is that it is relatively simple to interpret the results, present them clearly, and obtain good results from predictions [33,34]. Some of the results were verified through individual interviews with financial services staff of individual municipalities.

3. Literature Review

The impact of the pandemic on energy consumption has been the subject of research by several research teams. Already in 2020, H.M. Alhajeri et al., when analyzing the case of Kuwait, examined the impact of the pandemic on energy demand. The study concluded that the pandemic had reduced energy demand in the first half of 2020, both in comparison with the planned amounts and compared to an analogous period in 2019 [35]. The same problem in Italy was addressed in the paper by E. Ghiani, M. Galici, M. Mureddu, and F. Pilo. They concluded that electricity consumption had decreased in Italy by 37% compared to the same period in the previous year [36]. Syksnelyte-Butkienie [37] concludes that energy demand decreased during the pandemic. Demand from households increased but declined in business and industry. In their paper, Abu-Rayash and Dincer analyzed energy demand [38]. The authors focused on the Canadian case study. They saw a significant decrease (14%) in energy demand in April 2020 compared to April 2019. The impact of COVID-19 restrictions on electric energy consumption in Europe was addressed in an article by A. Bahmanyar, A. Estebsari, and D. Ernst. They compared countries that had applied strict restrictions (Spain, Italy, Belgium, and Great Britain) to those where restrictions were more lenient (Netherlands and Sweden). Their analysis concluded that in countries with severe restrictions, energy consumption decreased on working days, whereas at weekends it remained at the same level as in the previous year, while in countries with light restrictions, energy consumption remained substantially unchanged, and in Sweden, it even increased [39]. In their paper, P. Mastropietro, P. Rodilla, and C. Batlle analyzed the impact of COVID-19 restrictions on the ability of households to pay energy bills. They concluded that the most vulnerable households needed financial assistance [40]. E. Bompard et al. focused their paper on the impact of the pandemic on the energy system in Europe. The authors concluded that energy demand fell by around 15% in countries where restrictions were the most severe. The impact of the pandemic on the energy and electrical systems depends on how long the pandemic will last and how it will affect the economy [41]. K. Dmytrów, J. Landmesser, and B. Bieszk-Stolorz focused their paper on the relationship between the pandemic and the prices of energy raw materials. They concluded that their prices initially dropped in 2020, only to rise later on. The prices of raw materials changed in a similar way [42]. A significant decrease in electric energy consumption in France and Spain between 15 March and 5 April 2020 compared to the same period in previous years was also observed by A. Navon, R. Machlev, and D. Carmon [43]. The impact of the pandemic on household electric energy consumption has been addressed by S. Bielecki et al. The authors point to an increase in household energy consumption during the day, due to the shift of work to the remote form [44]. In their paper, M. Malec, G. Kinelski, and M. Czarnecka analyzed the business customer demand for energy in Poland. They concluded that the first lockdown caused a fall in energy demand of about 15–23% and the second one of about 11% [45].

Due to the set research objectives, particular attention was paid to the sector of local government units. Pursuant to Article 3 of the European Charter on Local Self-government [46], “local self-government denotes the right and the ability of local authorities, within the limits of the law, to regulate and manage a substantial share of public affairs under their own responsibility and in the interests of the local population”. In Poland, local governments have become unquestionable landlords, jointly responsible for the living conditions of the population within a municipality and for its socio-economic development [47]. The importance of LGUs in the performance of public sector tasks is highlighted in scientific literature. Local government units of the public finance sector perform tasks in such sensitive areas as education, health protection, transport, road and technical infrastructure, support for people with disabilities, unemployment prevention, water supply and wastewater disposal, fire protection and public order [48]. The role of public finances in the country’s financial system is highlighted by S. Owsiak [49]. In Poland, this system is composed of the state budget, municipal budgets, district budgets, provincial government budgets, and special purpose state funds. The role of public finances in the new economic governance of the European Union was presented in the collective work edited by the same author [50]. The public finance system, due to its role, is a subject of great interest in the source literature. S. Owsiak focused his paper on general public finance rules [51]. The author provides various concepts of public finances. He mainly emphasizes the so-called Golden Rule of public finances, defining it in such a way that the source of funding provided for in the plan (budget) should be ensured [51]. Malinowska-Misiąg, Misiąg [52] focused their paper on the management of public finances. The main problems raised by these authors are the maximum permissible debt limits of public finance entities and the rules on public expenditure. Expenditures may be incurred for the purposes and at the rate laid down in the relevant resolution or plan. The principles of purposefulness and cost savings (obtaining the best results from a given expense and optimal choice of methods and measures to achieve the objectives pursued) apply in such a way as to enable the tasks to be carried out on time, in the amount and timing arising from the commitments previously entered into [52].

The crisis caused by the COVID-19 pandemic affected the budgets of local government units in 2020, but to a much lesser extent than had been feared. Total income increased by 9.5% to 304.9 bn PLN. Income growth was recorded in all types of LGUs. LGUs’ own income increased slightly less (by 7.8% to 146.4 billion zlotys), and their own basic income (i.e., excluding PIT and CIT) increased by 16.3% to 80.0 billion zlotys. Tax income from natural and legal persons dropped by 1.0%, to 66.4 billion zlotys. PIT proceeds, with a higher share (18.1%) of total income, decreased by 1.9%, and CIT proceeds managed to continue to grow (3.9%). Real estate tax income increased by 3.9% in 2020 [53]. The pessimistic forecasts of the first months of the pandemic had not come true (according to the BGK's study from June 2020, LGUs expected an 11% and 15% drop in PIT and CIT proceeds, respectively, and a 4% drop in real estate tax income [54]. The financing of LGUs involves several different sources of financial resources, i.e., grants, subventions, and own resources. Such a structure makes local government proceeds more stable over time while being less dependent on the current economic situation than if they were based on a single source of financing [55].

Governance in the public sector consists of harmonizing management measures to ensure that the objectives of public organizations are properly set, and that people can act efficiently [56]. General governance rules apply to public governance, taking into account social, economic, organizational, and management criteria [57]. Proceeding according to the rule of purposefulness and saving is directly linked to incurring costs. Information on the amount of costs incurred is essential for each organization because it reflects the quality of the organization's activities. Local government units are not profit-making but have public funds, which obliges them to operate in a rational manner, providing both savings and efficiency. That is why the issue of cost formation and rationalization is a key area of interest for management and society [58]. Any unnecessary expense should therefore be eliminated. An internal audit, among other things, helps to implement these proposals. The implementation of audit tasks should take into account the risks associated with COVID-19 [59]. According to Gonet, Suchodolski [60], crisis situations have a negative impact on the budgets of the state and local government units. Financial crises have a stronger impact on the state budget than cataclysms on the budgets of local government units. It is therefore very important to avoid unnecessary expenditure in the event of a cataclysm, even if it was originally planned in the budget.

The question of the reasonableness of the expenditure incurred is of interest to the audit authorities. In Poland, for example, the Supreme Audit Office carried out audits concerning the optimization of electric energy costs in the public finance sector [61]. The scope of this audit was limited to the issue of distribution fees, where many irregularities were found. The problem of adjusting the amount of energy consumed depending on demand is a more complex issue, but there are many possibilities for optimization. The problem was also recognized by the Energy Regulatory Office, which made the following recommendations: The current challenges for energy and climate policy, as well as the related increase in energy prices, require a search for the most effective means of managing not only its production, but also its informed and cost-effective use. Such measures are necessary to ensure energy efficiency, to safeguard the operation of the electricity system and to achieve climate objectives, but they can also benefit consumers in the form of lower electricity bills [62]. During the pandemic, local authorities in many countries have highlighted the need to optimize energy systems. The desired future sustainable urban energy system should be optimized to reduce the consumption of fossil energy while providing the required energy services to increase energy efficiency at competitive costs [63].

4. Results

4.1. Production and Sales of Energy in Poland in 2019–2020

In 2019 and 2020, there were significant differences in the amount of electric energy sold. Figure 1 presents data on the volume of electric energy sales in Poland in the individual quarters of 2019 and 2020. Changes can be attributed to the impact of the COVID-19 pandemic. The introduction of measures to reduce the spread of the epidemic has resulted in a very large reduction in activities in different sectors of the economy, which has translated into a reduction in energy consumption. Electric energy sales in 2020 decreased by around 8.3% compared to 2019.

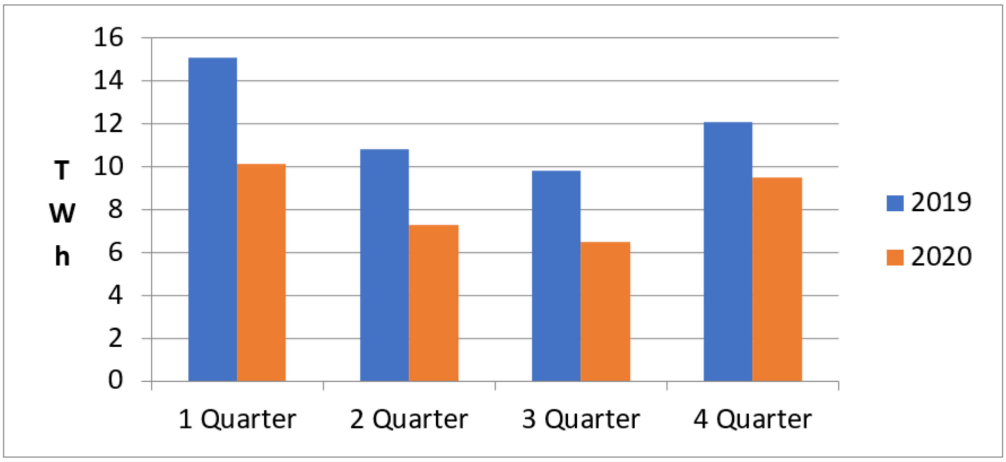

Figure 1. Volume of electric energy sales in the individual quarters of 2019 and 2020. Source: Authors' own elaboration based on the data from reports of said companies [27].

Figure 2 shows the value of revenue from energy sales for individual quarters of 2019 and 2020. The data show that despite a significant decrease in the amount of energy sold, sales revenues increased.

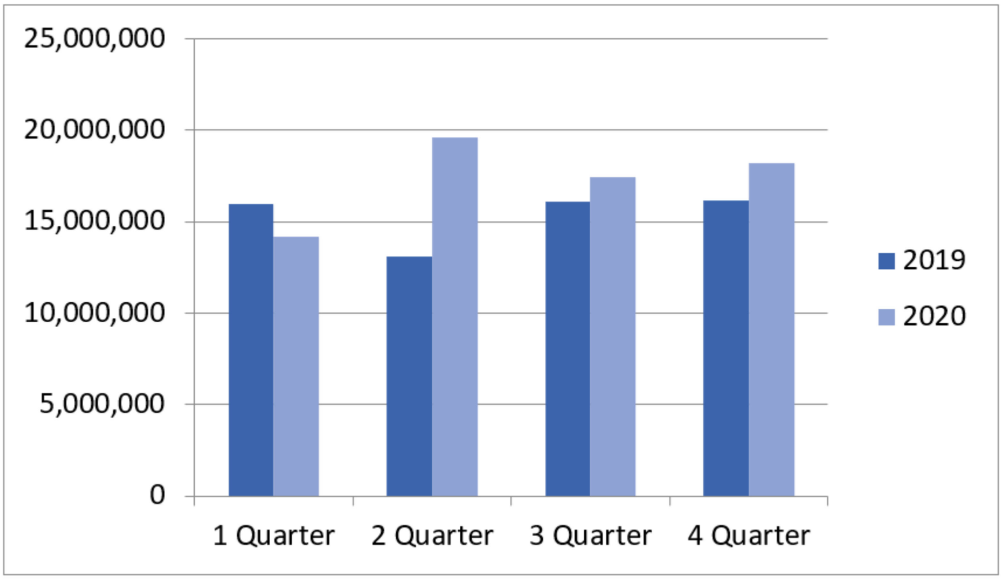

Figure 2. Electric energy sales in the individual quarters of 2019 and 2020. Source: Authors' own elaboration based on the data from reports of said companies [26].

The average quarterly price of electric energy not subject to public sales as calculated based on company report data is presented in Figure 3.

There is clearly a significant increase in electric energy prices in 2020 compared to the same period in 2019. In 2018, the Sejm of the Republic of Poland adopted an act amending the act on excise tax and certain other acts, commonly referred to as the 'current act' or the 'act on electricity prices'. It was intended to maintain electricity prices from the first half of 2018 until the end of 2019. After the expiry of the act on electricity prices (after 1 January 2020), electricity prices increased [64]. The compensation resulting from the price difference was paid to energy trading companies. The average total sales revenues of energy companies increased by 13.8% in 2020 compared to the previous year. On average, energy sales revenues of these companies represent 69.77% of total sales revenue, while energy sales revenues are largely dominated by electric energy (93.25%). On the other hand, in volume (MWh), electricity sales decreased in 2020 by an average of 7.65% compared to 2019. The average unit price of electricity increased on average by 24.61%, whereas thermal energy increased by 5.81%. Thus, the increase in revenues from sales, in amounts, was a result of the increase in prices. The financial performance of these companies is a negative phenomenon. Most of them (especially in 2020) suffer significant losses despite the rise in prices and the increase in sales revenue. Other conclusions can be drawn from the analysis of fuel companies. In the capital group of the Polish Oil Concern 'Orlen S.A.', sales in volume decreased significantly in 2020, while the unit price of fuel sales decreased, resulting in a decrease in revenues [26].

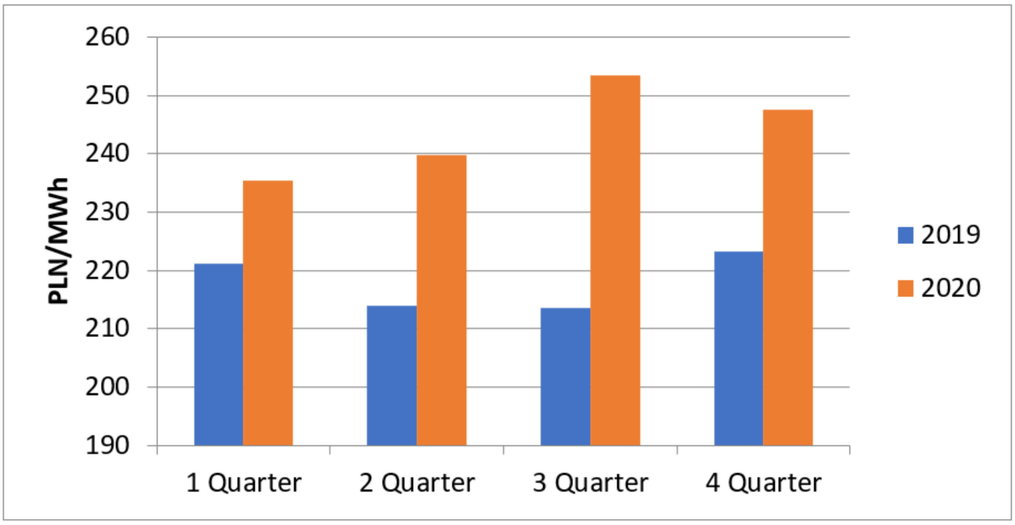

Figure 3. Electric energy sales prices for the individual quarters of 2019 and 2020. Source: Authors' own elaboration based on the data from reports of said companies [27].

4.2. Changes in Energy Expenditures Incurred by Local Government Units

The restrictions introduced to reduce the spread of SARS-CoV-2 have had a significant impact on the functioning of most entities in Poland. One of the sectors affected by the pandemic was the public administration sector. Energy consumption may, to some extent, be an indicator of economic activity in LGUs. Thus, the impact of the pandemic on energy expenditures in municipalities has been analyzed. According to the assumptions in the methodology, dynamic changes in energy expenditure incurred by local authorities within selected activities were analyzed.

4.2.1. Section 90015—Lighting of Streets, Squares, and Roads

Section 90015—lighting of streets, squares, and roads accounts for more than 88% of the energy expenditure for the whole of Section 900. It is characteristic since electricity is the only energy cost here. The index of lighting costs for 2020/2019 amounts to almost 1.247. This value coincides with the electricity unit price index obtained in the energy market analysis, which amounted to 1.246. The increase in lighting costs in 2020 can therefore be considered to be linked to the increase in electricity prices.

The mean index calculated for all municipalities in Poland is 1.175. It is characterized by substantial variability. The coefficient of variation amounts to 137.6%. Objects with the index between 1.1 and 1.2 constituted the largest group (21.07%) (Figure 4). In Section 90015, there are few cases with significant index increases or decreases. Increases are linked to the adoption of new lighting sections, and decreases are the result of ongoing modernization projects.

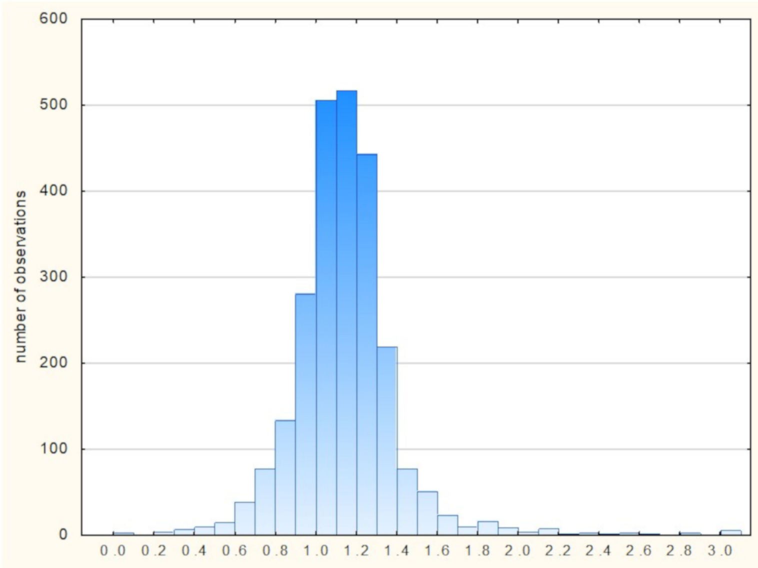

Figure 4. Histogram of the distribution of cost indices in Article 426 for Section 90015. Source: Authors' own calculations.

4.2.2. Section 80101—Primary Schools

Actions to reduce the spread of the pandemic were implemented, among other things, in education. Most educational facilities provided remote teaching, which involved the absence of students in these facilities. School buildings were used only to a limited extent. Overall, the amounts spent on energy in the education and upbringing section in 2020 decreased compared to 2019. Primary schools and kindergartens have the largest share of energy spending within Section 801.

An analysis of the change in expenditure under Article 426 'Purchase of energy' for Section 80101 shows an average slight increase in expenditure—an average index of 1.065. However, it is not due to an increase in energy consumption but to an increase in electricity prices. In addition, as a result of the transformation of the education system in 2020, Section 80101 included energy expenditure for facilities that had formerly been junior high school facilities. Despite this, almost half of the municipalities (49.31%) recorded a decrease in energy expenditure under this section (Figure 5). This indicates savings that stemmed from the COVID-19 pandemic restrictions.

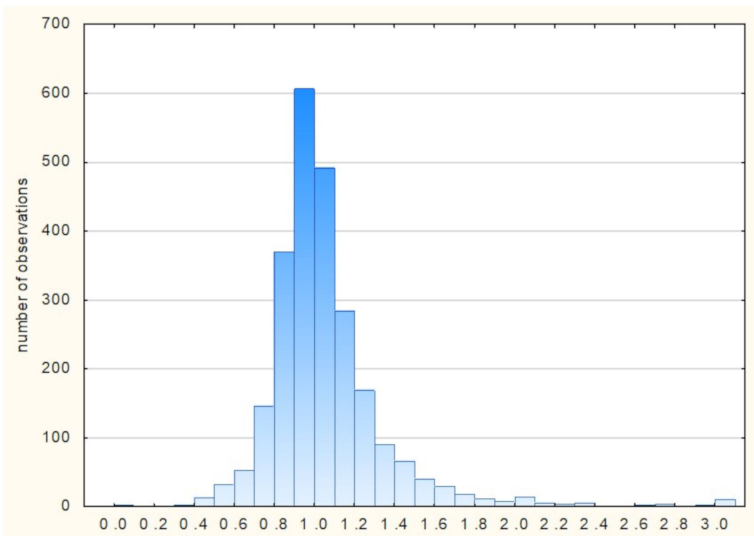

Figure 5. Histogram for the distribution of cost indices in Article 426 for Section 80101. Source. Authors' own calculations.

4.2.3. Section 80104—Kindergartens

The change in costs in Section 80104—Kindergartens in 2020 is small compared to 2019, as it is only about 3%. Taking into account the evolution of electricity prices, it can be concluded that the decrease in energy consumption is much higher. The average energy purchase cost index is 1.134, but it should be noted that for 62.13% of units, the index is less than one (Figure 6). However, the population of municipalities shows a large internal variation, as evidenced by the high standard deviation. A significant increase in energy costs was most often the result of the launch of new kindergartens; more than three times the increase in energy costs was observed in 31 municipalities. Despite the lower intensity of restrictions on the functioning of kindergartens than schools during the pandemic period, there is a noticeable drop in energy expenditure, which could be caused by actions to counter the spread of the SARS-CoV-2 virus.

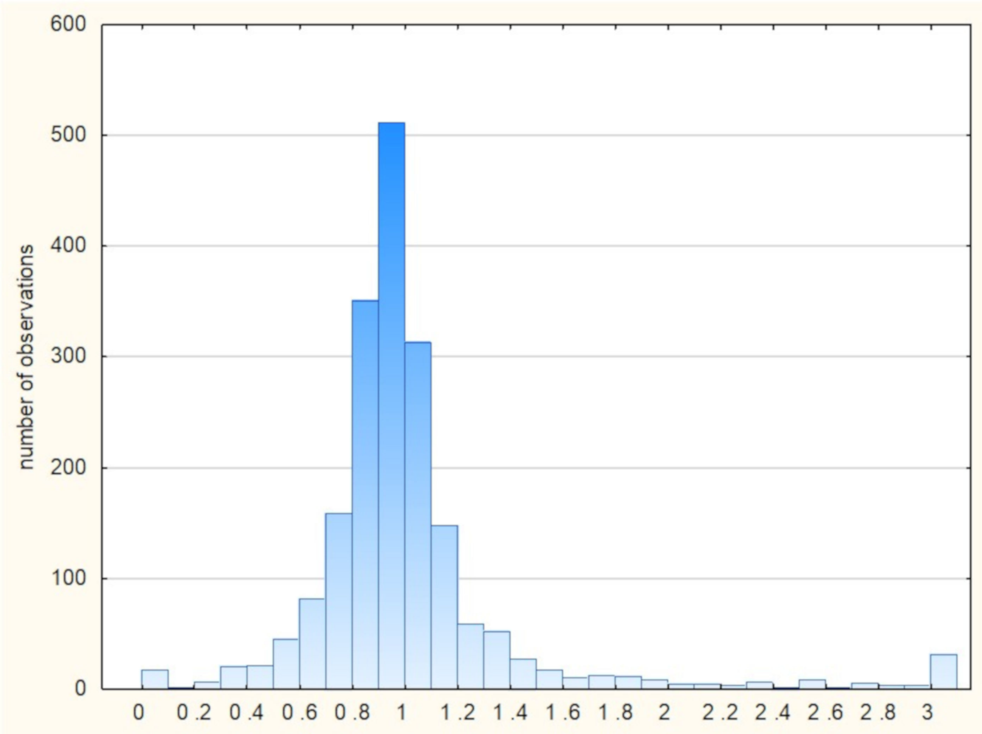

Figure 6. Histogram of the distribution of cost indices in Article 426 for Section 80104. Section 70005—Land and real estate management.

Under Section 700 (Housing economy), expenditure increased by almost 3.8%. Section 70005—Land and real estate management has the largest share of expenditure under this section. This section covers, among other things, expenditure on amenity housing. The total expenditure under this section increased by 3.5%, but the population of municipalities is highly differentiated in this respect (standard deviation of 6.21, coefficient of variation of 374%). The average cost index was 1.665, with 44.11% of units having an index lower than one (Figure 7). In the group in question, there are as many as 70 municipalities with an index above 3.0. The reason for this high cost increase is the opening of new amenity buildings. Electricity has little impact on the change in costs due to its low contribution to the consumption pattern. As a rule, the cost of electricity consumed by residents is not included in these expenditures as they have individual contracts with the electricity supplier.

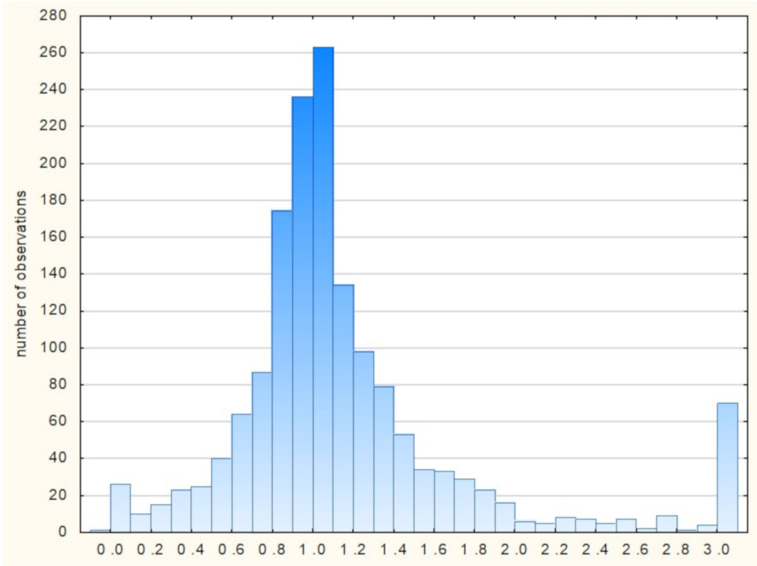

Figure 7. Histogram of the distribution of cost indices in Article 426 for Section 70005. Source: Authors' own calculations.

4.2.4. Section 92604—Institutions of Physical Culture

The costs under Article 426 for Section 926 were reduced by approximately 3.14%. Section 92604—Institutions of physical culture is the section with the highest share of energy costs in this section. This section includes expenditure on the operation of units engaged in the dissemination of physical culture. In municipalities, these units manage sports facilities. The average energy cost index under this section is lower than one (0.998), with as much as 70.59% of units spending less on energy in 2020 than in 2019 (Figure 8). Moderate variability is observed within the population of municipalities, and the coefficient of variation is 44.12%. Electricity contributes significantly to the costs of the physical cultural facilities. Increased energy tariffs did not reduce the costs proportionally to the reduction in consumption. The physical culture units were quite heavily affected by restrictions related to the containment of COVID-19. They were completely excluded from the operation during the period of the increase in the number of COVID-19 cases. Despite a total reduction in activity, energy costs did not fall proportionally to the scale of the reduction.

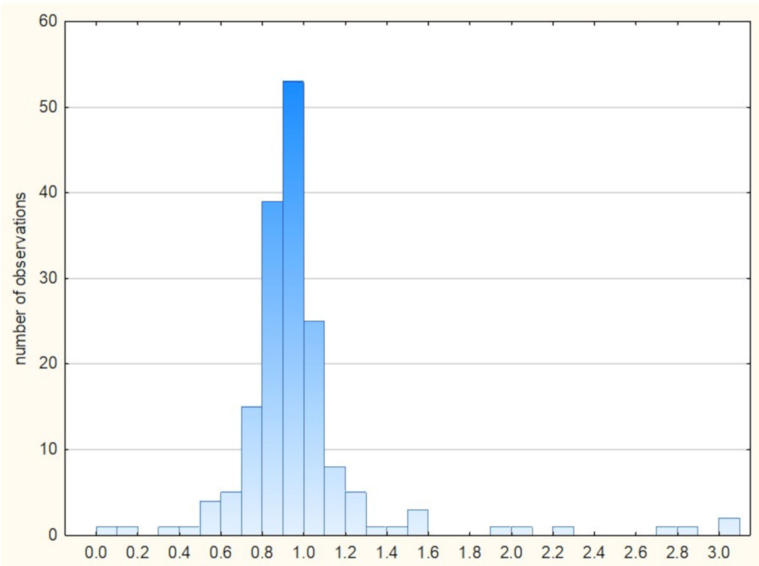

Figure 8. Histogram for distribution of cost indices of Article 426 for Section 92604. Source: Authors' own calculations.

4.2.5. Section 75023—Municipal Offices

Section 750 is fifth in the amount of energy expenditure. Its share of the total energy costs in 2020 was about 4.84%. Energy expenditure increased by around 7.72% in 2020 compared to 2019. Section 75023—Municipal offices (of cities and cities on the rights of the district) represents the largest share of the cost of Section 750. It accounts for almost 94% of the expenditure in this section. The total expenditure under Section 75023 increased by approximately 7.86%. The average index is 1.156, with a coefficient of variation of 112.38%, with expenditure indices below one appearing in approximately 17.18% of municipalities (Figure 9). These figures indicate the limited impact of the pandemic on energy consumption within Section 75023. Municipal offices were functioning during the pandemic period, while restrictions were only related to public access.

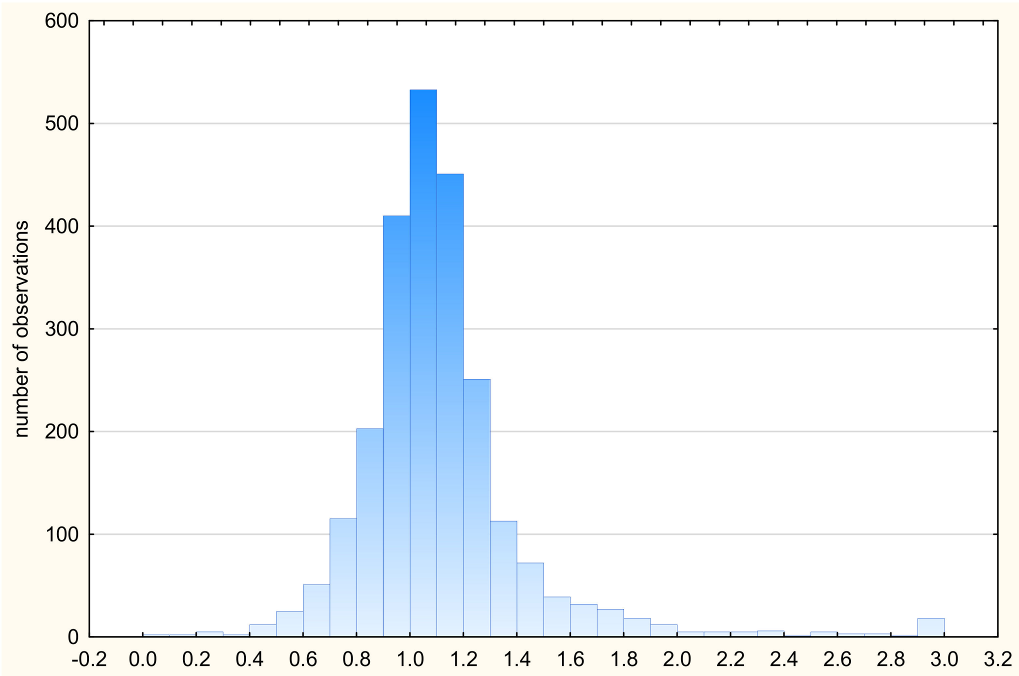

Figure 9. Histogram of the distribution of cost indices in Article 426 for Section 75023—Municipal offices. Source: Authors' own calculations.

Contact with the office staff was limited to phone contact or via electronic channels. Office visits were limited to the minimum necessary. Some employees were working remotely. This did not reduce energy consumption significantly.

4.2.6. Total Energy Expenditure in Municipalities

For each of the municipalities covered by the study, the rate of change in total energy expenditure in 2020 compared to 2019 was calculated. The distribution of this index is presented in Figure 10 in the form of a histogram. The average index is 1.038, with a coefficient of variation of 14.55%, a minimum of 0.523, and a maximum of 2.939. There was no change or reduction in energy expenditure in 39.90% of municipalities. The low coefficient of variation indicates the homogeneity of the collectivity of municipalities due to changes in energy expenditure. When analyzing expenditure within sections, outlier index values were observed, which do not appear when analyzing the total expenditure. This means that some significant changes within individual sections did not significantly affect the index value for the total expenditure.

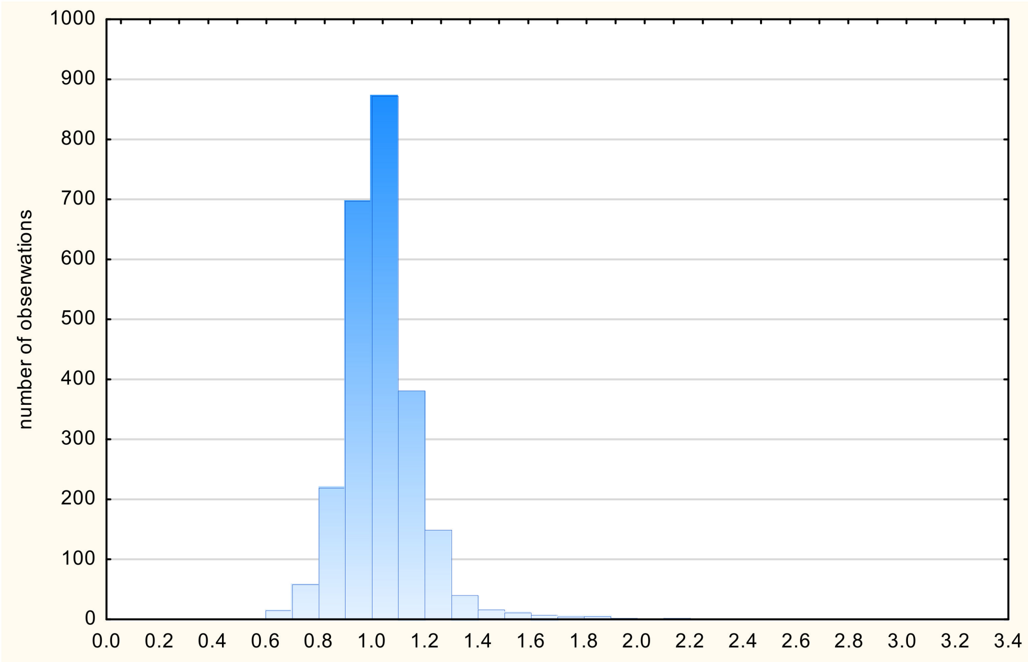

Figure 10. Histogram for distribution of cost indices of Article 426 for total expenditure within a municipality. Source: Authors' own calculations.

4.2.7. Analysis of Factors That Determine Changes in Energy Expenditure Using Classification and Regression Trees

Changes in the cost of electric energy for street lighting had the greatest impact on the changes in the total energy expenditure in municipalities. This is probably due to significant increases in the price of electric energy during the studied period (Figure 11). Section 90015 is characteristic because it exclusively contains expenses for electric energy. The other sections have both electric energy and other energy in their cost structure. Despite the increase in unit energy prices on the market, 218 municipalities recorded a decrease in lighting expenditure (an index below 0.862). The reasons for this are savings resulting from the decision of the municipal authorities to reduce budgetary expenditure. It was anticipated that restrictions to reduce the spread of the COVID-19 pandemic would have a negative impact on the income of municipalities' budgets. Some municipalities chose to temporarily turn off the street lighting when looking for savings. Another reason for reducing lighting costs was the modernization of light points by replacing lamps with less energy-intensive lamps. A larger amount of savings could have occurred in those municipalities where the unit price of energy in 2019–2020 did not change, as an energy supply contract was concluded for a period longer than the financial year.

Nearly 48% of municipalities were in the ID3 group, for which the average rate of increase in total energy costs is 1.105. All these municipalities have high indices of change in the cost of street lighting (above 1.140). A high aggregate change rate is the result of an increase in the price of electricity.

The dependency analysis used data describing the energy expenditure totals (a dependent variable) and a set of indexes for selected sections of the budget classification, thus obtaining 8621 objects. The first node is divided according to the index value criterion for each section, and the result is that the ID3 group is isolated, covering 25.58% of all objects with subindices greater than 1.19 (Figure 12). These are the objects with the highest increase in energy expenditure. The other objects form group ID2, which is divided into two child nodes according to the sub index value criterion at the level of 0.93. Among the index values under consideration, 44.15% represent more than 0.93 results, and 30.27% of the analyzed indices had values of less than 0.93. A characteristic group was extracted by dividing the ID4 node. It is group ID6, which includes objects for which the value of the expenditure index for street and square lighting is lower than or equal to 0.93. This means, in the face of rising prices for electric energy, switching off street lighting or implementing measures to reduce the amount of energy consumed. Another characteristic group is ID20, with objects from eight provinces that have a low average GDP per capita [65]. The average rate of total expenditure in this group is 0.98, so the very low incomes of these municipalities forced savings.

The analysis of the dependency of the light expenditure index on the location of the municipality indicates a significant variation of these indices (the coefficient of variation is 137.6%). The group of municipalities from the Mazowieckie Province, for which the highest average index (1.39) was recorded, is clearly different from the rest of the objects, and this group is not homogeneous, as indicated by the high standard deviation (4.48) (Figure 13). This variation is due to the adoption of new lighting sections, which results in a significant increase in the cost index of these municipalities.

The node which remained after the group of Mazowieckie municipalities was separated, including relatively homogeneous objects, the standard deviation remains at 0.286. There is no significant spatial differentiation of the indices. All other provinces apart from Mazowieckie have an average index at a similar level, with the lowest average values of these indices recorded in Świętokrzyskie (1.08) and Podkarpackie (1.10) provinces.

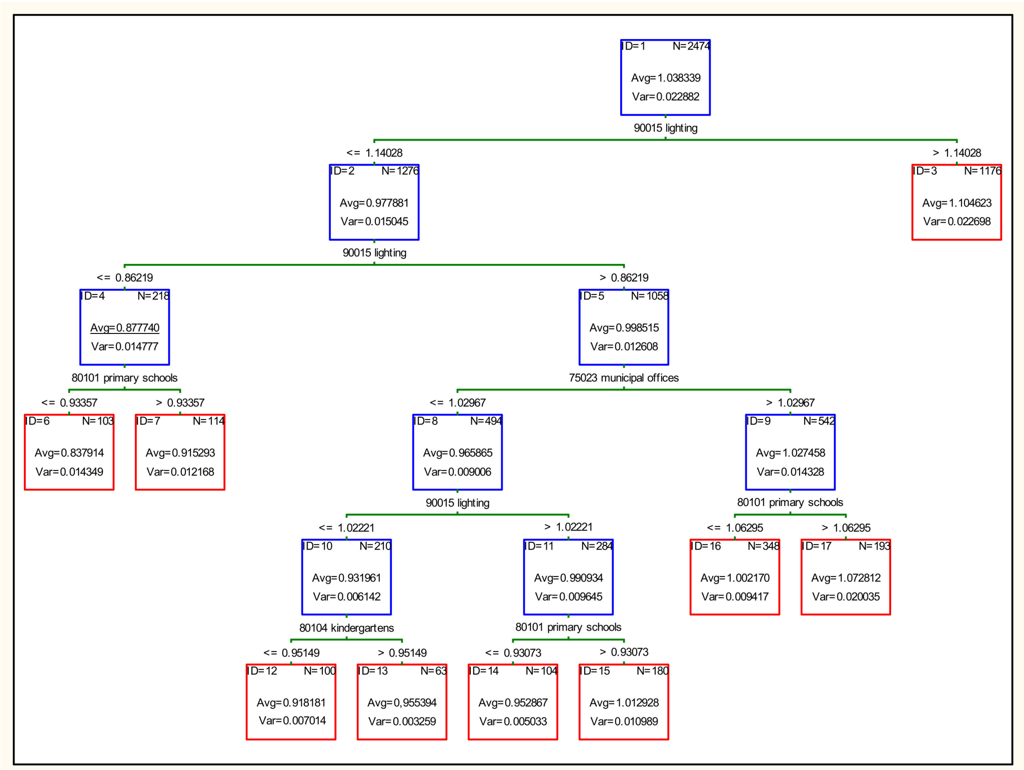

Figure 11. Regression tree describing the dependency of the indices of total energy expenditure on the index of changes in sections: 90015-Lighting of streets, squares and roads, 80101-Primary schools, 80104-Kindergartens, 70005-Land and real estate management, and 75023-Municipal offices. Source: Authors' own calculations.

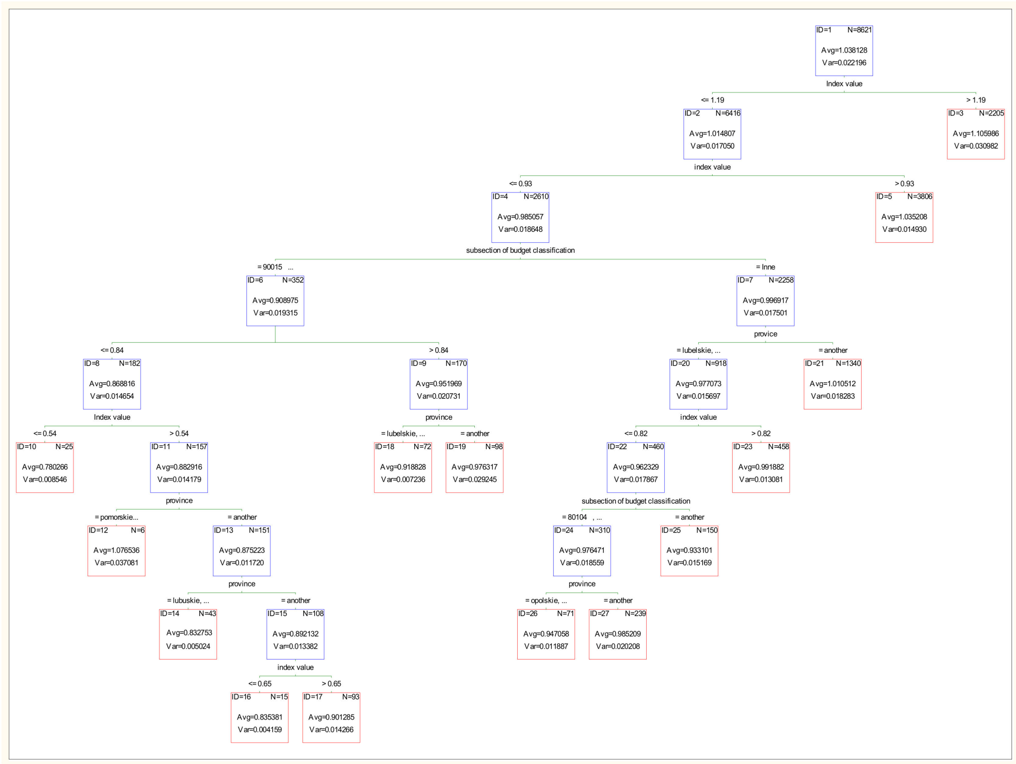

Figure 12. Regression tree describing the dependency of total energy expenditure indexes on the change indexes in the analyzed sections and locations. Source: Authors' own calculations.

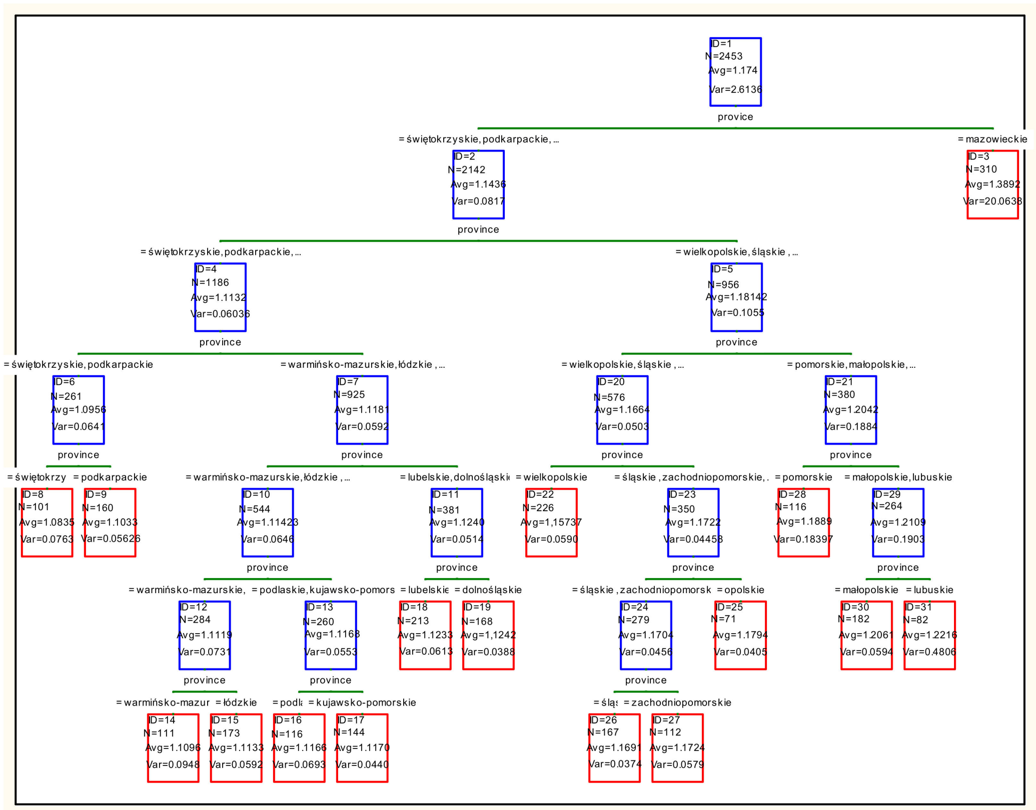

Figure 13. Regression tree describing the dependency of the lighting expenditure index on the location of the municipality. Source: Authors' own calculations.

5. Conclusions

5.1. Discussion and Policy Implications

The outbreak of the COVID-19 pandemic required an immediate and comprehensive response from governments. In the first place, governments had to put in place measures to contain the spread of the virus. Actions taken by public authorities based on lockdowns blocked economies and had far-reaching negative micro- and macroeconomic effects. Following the impending economic crisis, governments have been attempting to mitigate the impact of the economic crisis on the economic well-being of the population. Apart from the problem of population health and the need to control the economy, governments also had to reevaluate the principles on which the functioning of public management systems was based. In particular, the basic tasks of public administration fall under the provision and responsibility of public services [66]. When considering the state's contribution to counteracting the COVID-19 pandemic, the role of public administration in this respect cannot be overlooked [67].

Governments of all developed countries have taken steps to ensure the provision of essential services to citizens and businesses. In response to new circumstances, to maintain the continuity of the provision of services to citizens and enterprises, the public administration modified its activities, applied simplifications, and used alternative tools [68]. This led to the introduction of new administrative services and procedures but the suspension of others [69]. In all countries, public administration increasingly relies on IT solutions. In Poland, the public administration was forced to change the following areas of operational activity: internal organization, inter-institutional cooperation, customer service, and performing specific tasks commissioned by the government administration.

During the crisis caused by the pandemic, the provision of public services, such as education and health, was put to the test. To counteract the effects of the pandemic on a global scale, a number of measures have been taken to ensure the health security of citizens. In Poland, initial precautionary measures were recommended consisting of maintaining social distance and wearing protective masks and gloves. Due to the increasing number of infections in other countries, restrictions on the movement of people were introduced. As the number of infections increased, additional measures were taken, such as recommending that people stay at home. In Poland, the restrictions were instated on 20 March 2020.

One of the special effects of the economic slowdown resulting from the closing of the economy and limiting the activities of public institutions is the impact on energy consumption. As a result of the economic slowdown in the first quarter of 2020, the demand for energy in the global economy decreased by 3.8% compared to the corresponding quarter of 2019 [70,71]. The magnitude of changes in energy consumption varied significantly between countries and time periods. For example, Bompart et al. reported that compared to 2019, in 2020 in France and Spain, the demand for energy decreased by 15% [41]. According to Abu-Rayash and Dincer, during this period, Canada's energy consumption decreased by 14% [38]. Similar trends were recorded in Poland where, in annual terms, sales of electricity in quantitative terms decreased in 2020 compared to the previous year by approximately 8.3% [27].

Despite the negative impact of the decline in economic activity as a result of lockdowns during the pandemic, the reduction in energy consumption and the accompanying increase in energy efficiency is an opportunity to reduce CO_2 emissions [72]. The significant contribution of the energy sector to the generation of the carbon footprint was emphasized, for example, by Buenano et al. [73] and Percebois and Pommeret [74]. This problem is of particular importance in Poland, where electricity is generated predominantly on the basis of coal, and the production of electricity causes the emission of 758 g of CO_2 for every 1 kWh of electricity produced in power plants and combined heat and power plants [75]. Hence, the decrease in electricity sales in the period under consideration resulted in a reduction of CO_2 emissions by 3 MT.

The economy has suffered greatly as a result of the restrictions connected with the epidemic. The most affected sectors include transport, tourism, gastronomy, and the hotel industry. Nevertheless, the effects of the introduced restrictions have also affected cultural institutions, such as cinemas, theaters, philharmonics, museums, and art galleries. During the pandemic, educational institutions and universities were closed, and many institutions switched to working remotely. The education sector reacted to the challenges related to the limitations in interpersonal contact by relatively quickly incorporating technological progress in teaching [76]. The academic community has rapidly migrated from an interactive face-to-face learning system to remote learning using a digital environment [77,78]. Including information technology into the teaching process was particularly challenging for the younger primary school students, but also for university students. To take part in classes, participants in the teaching process had to adapt to sometimes asynchronous audiovisual sessions without any interaction. Compared to the period before 2020, the education system has undergone far-reaching changes. Its evolution continues, and the academic community has become resistant to dynamic changes in the environment and has improved its adaptation skills [79].

The pandemic and the manner in which its effects were counteracted by public institutions have had wide economic repercussions, both for the population and students, and due to the change in the forms of operation for educational institutions. The impact of the pandemic and related lockdowns on energy use by the education sector has been studied relatively extensively. These studies have led to the general conclusion that the energy consumption of the education sector has decreased as a result of the COVID-19 pandemic.

The study by Samuel et al., carried out in South African primary and secondary schools, led to the conclusion that energy consumption decreased by 30% to 40% [80]. Electric lighting plays an important role in educational institutions. Research conducted in the USA has shown that electric lighting is responsible for about 14% of energy consumption in schools [81]. Research that quantifies the impact of the COVID-19 pandemic on energy consumption in educational institutions is an important source of information at the stage of creating plans to restore these institutions to their full operating condition.

Changes in the form of university functioning have had an ambiguous impact on the level of energy consumption—including electricity. In general, except in Europe, where declines of 10% to 40% have been recorded [81], in other regions of the globe, closing universities and switching to remote education have not had a major impact on the amount of electricity consumed [82,83]. In some universities in various parts of the world, energy consumption fell by more than 10% after the closure of university buildings. This was the result of closing university buildings as well as reducing the use of air conditioning systems [38,82]. The study conducted by Birch et al. reports a significant reduction in electricity demand in European universities due to the decommissioning of various buildings and laboratories, which reduces energy costs [84]. For example, at the University of Almeria in Spain, energy consumption has been reduced most in library buildings and least in research facilities [81]. The demand for electricity in extracurricular spaces (student dormitories) in some states in the US, as a result of their closure, has decreased by up to 40% [85].

The analysis of the expenditure of local self-government units on energy carried out by the authors of the study showed a significant impact of the pandemic on the amount of energy consumption in the studied entities. The reduced energy consumption resulted directly from the reduction of activity in many sectors of the economy. In 2020, there was also a significant increase in energy prices in Poland—the average price of electricity increased by approximately 24%. Despite such significant growth, companies from the energy sector recorded losses, which can be treated as an announcement of further increases in energy prices in Poland.

Expenditure on energy represents one of the main budget lines of local self-government units. The scope of changes in energy consumption in individual units has been diversified. Hence, estimating the impact of restrictions on the activities of entities managed by local self-government units on the change in energy expenditure has potentially wide implications. In particular, energy consumption rationalization programs can be very effective in improving the financial condition of municipalities. There are ready-made solutions that can be implemented in local self-government units. A number of examples of good practices in terms of energy efficiency and the use of renewable energy sources were presented as part of the cooperation project "Polish-Norwegian cooperation platform for climate and energy conservation". One of the partners of this project was the local self-government of the City of Częstochowa, where was implemented the system enabling the ongoing control of the effectiveness of media use and the correctness of settlements. As a result of the implemented rationalization measures, real savings due to the reduction of utility consumption amounted to approximately PLN 27 million. The total consumption of fuels and energy in 2014 for a group of 118 educational facilities, covered by detailed monitoring and reporting, was lower by 38.5%, and CO_2 emissions decreased by 36.9%, while the total consumption of water decreased by 37.9% (compared to 2003).

Saving (unused) energy is the cleanest method of reducing the emission of harmful substances without negative ecological effects, and the improvement of energy efficiency is the most effective way to reduce the cost of energy consumption [86]. Energy consumption rationalization activities may have positive effects both at the level of a single organization and when implemented on a wider scale, may contribute to an increase in the competitiveness of a given country's economy in the global market [87].

It is estimated that currently, buildings use 80% more energy than they would if they were all equipped with modern technologies and smart building solutions. Appropriate management of energy consumption and its ongoing control could bring savings in this respect, even up to 20% [88]. From this perspective, there is a surprisingly low level of implementation of energy management systems in Poland.

The benefits of implementing the energy management system are the reduction of its consumption and thus the reduction of the costs of current operations of the entities under consideration, as well as the reduction of the negative impact on the environment, among others, as a result of the reduction of greenhouse gas emissions [86]. The most widely used are energy management systems based on ISO 50001. According to estimated data, energy savings, thanks to their implementation, may reach even several dozen percent [89].

In Poland, public funds are available for municipalities for measures aimed at improving energy efficiency, saving energy and reducing CO2 and other pollutants' emissions into the environment. In addition to public funds, private funds are also available. Especially promising is the ESCO formula, where the partner—usually a company—proposes the scope of rationalization and implements the project, financing it from its own resources. Payment for completed tasks is made in installments from the savings generated by the project.

The issues raised in the study are important due to the potential for considerable savings in financial resources and promising outlooks for limiting the negative impact on the natural environment. Expanding and propagating knowledge in that scope is part of the sustainable development strategy.

The research conducted also has some limitations. Although reference was made to data describing all LGUs in Poland, the statistical data refers to financial information reflecting energy expenditures. The authors did not have information about the amount of energy consumed—such databases are not available. This limits the possibility of conducting an in-depth analysis of energy consumption within individual sections of the budget classification. Additionally, significant changes in energy prices took place in the analyzed period. This made estimations and drawing conclusions difficult.

5.2. Conclusions and Implication for Future Research

1. Total production and sales of energy in Poland, in volume, in each quarter of 2020 were lower than in the corresponding period of the preceding year;
2. Electricity prices in 2020 increased by around 25% compared to 2019;
3. Thanks to the price increase, the sales of energy from electricity producing companies in 2020 were higher than in 2019;

4. In 2020, there were large cumulative losses in the analyzed corporate groups of energy companies. This may result in an increase in energy prices in Poland in the future;
5. Total expenditure under Article 426 'Purchase of energy' in self-government units in Poland in 2020 increased by 2.15% compared to 2019. However, different municipalities had different levels of change;
6. The cost of purchasing energy by municipalities was influenced by the increase in electricity prices. Taking into account the rising electricity prices, it is appropriate to conclude that energy consumption in self-government units in Poland during the COVID-19 pandemic has decreased;
7. The increase in lighting costs in 2020 is linked to the increase in electricity prices. Despite the increase in unit energy prices on the market, 218 municipalities recorded a decrease in lighting expenditure (an index below 0.862). One of the reasons for the savings is the decision of the municipal authorities to limit the lighting time required to reduce budgetary expenditure;
8. Energy costs spent under the education and upbringing section have decreased; However, the decline is not adequate to reduce the activity in schools and kindergartens;
9. The effects of the increased costs of purchasing electricity by LGUs in 2020 were mitigated by reduced energy consumption within certain sections where COVID-19 business restrictions were introduced;
10. Savings in the education and upbringing—primary schools, kindergartens, as well as in physical culture—physical culture institutions divisions reduced the spending of local government units on energy during the COVID-19 pandemic. Despite a total reduction in activity, energy costs have not fallen in proportion to the scale of the reduction in economic activity;
11. There was no significant reduction in energy consumption in Section 75023—Municipal offices. Municipal offices were functioning during the pandemic period; restrictions were only related to public access.
12. The imbalance in the cost of energy consumption in the restricted areas associated with preventing the spread of COVID-19 is due to the different technical possibilities of controlling energy systems and the quality of management. In some self-government units, despite operating restrictions, there were no corresponding savings in energy expenditure. In these units, it is desirable to analyze the reasons for this state of affairs. As a result of this analysis, a unit should be given recommendations for the solutions necessary to implement in order to improve energy efficiency.

The issue of managing energy consumption in local self-government units requires in-depth research. It is particularly important to diagnose the current state in this regard, which may be the basis for recommending solutions leading to a reduction in energy consumption. This would directly save money and reduce the negative impact on the environment.

It would be very useful to analyze the energy consumption of individual local self-government units with the use of indicator data, allowing for the rating of the status of energy consumption. The estimated indicators could be used by the management of LGUs to diagnose the condition of energy systems and plan the direction of their development. Based on the estimates of the indicators, it would also be possible to compare the efficiency of energy consumption demand between individual LGUs.

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Sustainability Development: Assessment of Selected Indicators of Sustainable Energy Development in Poland and in Selected EU Member States Prior to COVID-19 and Following the Third Wave of COVID-19

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Abstract: An important question in the literature on climate change and sustainable development is the relationship between countries' economic growth, household electricity consumption and greenhouse gas emissions. Despite the ongoing COVID-19 pandemic and related economic restrictions, sustainable economic growth remains at the forefront of the global development agenda. However, given the strong relationship between the ever increasing electricity consumption and greenhouse gas CO_2 emissions, an increasing number of scientists have been questioning the feasibility of the planned emission reduction. In my research, I strove to determine whether there exists a relationship between the change in the structure of electricity consumption of households in selected EU Member States (15 countries), the impact of innovation, changes in electricity prices and economic growth, and CO_2 emissions in 2007–2019, prior to the outbreak of the COVID-19 pandemic, and following its third wave (2021). The aim of the article is to propose a synthetic index to assess the degree of sustainable energy development (SISED) in selected EU countries. Multiobjective decision analysis (MODA) was applied in order to assess the sustainable energy development of the selected European countries. Research findings may contribute to both literature and practice if they are applied by individual EU countries in the process of formulating directions aimed at achieving sustainable energy development.

Keywords: COVID-19; sustainable energy development; households

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1. Introduction

All human activity, including economic activity, ought to avoid irreversible damage to the environment and nature through using renewable natural resources in a sustainable manner. However, achieving this goal requires far-reaching, structural changes in the way our cities and entire economies function [1].

The twenty-first century is, undoubtedly, the century of urban spaces. There has been a rapid development of cities, which for an increasing number of people perform vital functions and become centers of numerous economic activities.The United Nations Department of Economic and Social Affairs predicts that the world population will reach 9.7 billion by 2050, 2 billion more than today. By 2050, approx. 70% of the world's population will live in cities, compared to 50% today [2]. Europe is one of the most urbanized continents, with more than 2/3 of the population living in cities [2]. According to the IESE Cities in Motion Index 2020, the world's smartest cities are London, New York and Paris. However, smart does not mean sustainable. The example of Paris, in particular, shows the scale of efforts that city authorities will need to undertake in terms of ecological action, including climate change. For example, in the center of Paris, congested by car transport, CO_2 levels during the rush hour exceed twofold the limit set by the WHO [3].

Countries and cities, therefore, play a vital role in attaining the sustainability objective and in preventing a climate catastrophe: they are the source of problems but, owing to their culture of innovation, also of solutions. The EU is also motivated by the idea of the European Green Deal, which sets the ambitious goal of turning Europe into a climate-neutral continent by 2050.

This is why almost all EU funds, including the Reconstruction Fund (which is to counteract the effects of the pandemic) are attributed to projects which guarantee that over 30 percent of funding will be spent on projects aimed at achieving climate neutrality. The scale and complexity of challenges faced by countries (as socio-economic organisms) and city authorities mean that no single concept recognized in the literature and practice of management for assessing sustainable energy development is sufficient.

Our use of energy is the very basis of the functioning of economies. The development of humanity and the economic world has always been related to the use of energy. This is why energy is one of the factors of sustainable development. The relationship between energy and sustainability can be both positive as well as negative. On the one hand, it enables technological development, which contributes to the improvement of living conditions [4–7]. On the other hand, the use of energy, e.g., for the production of goods, may cause environmental pollution [8–10].

Currently, energy is generated mainly from fossil fuels. However, this method of production is harmful to the environment and causes the emission of harmful substances to the atmosphere (greenhouse gases). According to the World Economic Forum, the current changes in the energy sector are related, inter alia, to the emergence of new technologies, to climate change, and dwindling natural resources [11].

Given the ongoing climate changes, it necessary to move towards economies that are as climate neutral as possible. One of the pillars of such transformation is the improved energy efficiency of the processes of production, transmission and use of energy; they all form part of a sustainable energy policy. An important question in the literature on climate change and sustainable development is, therefore, the relationship between countries' economic growth, household electricity consumption and CO_2. Despite the ongoing COVID-19 pandemic and all related economic restrictions, sustainable economic growth remains a major global concern, as the current global amount of CO_2 emissions is causing an increasing number of scientists to question the feasibility of the planned emission reduction.

Research on sustainable energy development and its level has been conducted for many years. However, no studies exist that would assess the level of sustainable energy development in the European Union Member States over the period of 2007–2021, with an examination of these relationships in the period following the third wave of the pandemic, using simplified indicators. This research gap is filled by the presented study.

The aim of the article is to propose a synthetic index to assess the degree of sustainable energy development (SISED) in selected EU countries. Two main dimensions have been selected for this purpose: (1) Economic Indices and (2) Energy and Climate. Data from 15 countries, i.e., Austria, Denmark, Finland, France, Greece, Spain, the Netherlands, Ireland, Germany, Norway, Poland, Portugal, Sweden, Great Britain and Italy has been analyzed.

My research was to allow us to determine the existence of a relationship between the change in the structure of electricity consumption in EU households, the impact of innovation, changes in electricity prices and economic growth, and CO_2 emissions in 2007–2019, i.e., before the outbreak of the COVID-19 pandemic, and following its third wave (January 2020–September 2021). In order to assess the energy sustainability of the chosen European countries, the multiobjective decision analysis (MODA) was applied. Detailed information is presented in Section 3. Materials and Methods.

2. Literature Review

2.1. Sustainable Energy in EU

With the deteriorating environment and dwindling natural resources, the European Union has begun to take action to transform economies and counteract climate change.

At the same time, Europe's overarching goal is sustainable development, as indicated in Article 2 of the Lisbon Treaty [12]. According to this concept, one of the most important goals is [13–19]: (1) creating a stable environment, (2) achieving sustainable consumption and production (3) minimizing poverty.

The European Union is a key actor in the global climate policy and is the creator of comprehensive regulatory standards in the area of climate protection and the reduction of CO_2 emissions. The EU Emissions Trading Scheme (EU ETS), created in 2005, is the world's largest international trading system for CO_2 emissions. The system is a key element of the European Union's climate policy and an essential tool for reducing greenhouse gas emissions.

In 2008, the European Parliament and the Council of the EU approved the energy and climate package which sets targets for combating climate change until 2020. It focuses on three key objectives (the 3 × 20% package): (1) reducing greenhouse gas emissions, (2) promoting the use of energy from renewable sources, and (3) increasing the energy efficiency of the European Union. Subsequently, on 24 October 2014, climate and energy policies to be pursued until 2030 were agreed upon. They obliged member countries to reduce emissions in total by at least 40% by 2030 compared to 1990. In addition, the European Council approved four targets for the entire European Union in the 2030 perspective. They were revised in 2018 and, in 2020, they stated as follows:

(1) a reduction in greenhouse gas emissions by at least 55% compared to the 1990 level;
(2) 32% as the minimum share of energy from renewable sources in gross final energy consumption;
(3) increase in energy efficiency by 32.5%;
(4) completion of the EU internal energy market.

Increasing energy efficiency by lowering primary energy consumption and reducing energy imports has been identified as one of the main means of action. Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC, indicated that It helps to reduce greenhouse gas emissions in a cost-effective manner and, thereby, to has indicated that it is possible to reduce greenhouse gas emissions by contributing to halting climate change. The transition towards a more energy-efficient economy will also increase access to innovative technological solutions, enhance the competitiveness of European industry. It will also contribute to stimulating economic growth and creating new jobs related to energy efficiency. In addition, in November 2016, the European Commission presented the "Clean Energy for All Europeans" package, also known as the Winter Package. It sets EU targets for a global and comprehensive transition towards low-carbon economy in an attempt to mitigate climate change.

On 11 December 2019, the European Commission presented the European Green Deal (EGD). It aims to transform the European Union into a fair and prosperous political society. This strategy includes actions to, among other things: (1) enable prevention of climate change, (2) eliminate pollution, (3) protect and restore biodiversity, (4) transition to a circular economy. The EGD aims to reduce net greenhouse gas emissions to zero and minimize the relationship between economic growth and resources. The European Union is set to be the first climate-neutral continent by 2050.

Sustainable energy development of countries and regions is a broad area of scientific research [20–22]. On the other hand, few empirical and theoretical articles have been devoted to the methods of defining Sustainability Development indicators. It is possible by providing all citizens with access to "clean" energy that will be produced from renewable energy sources (RES) [23]. This has given rise to the question about how the Suitability Energy Development indicator can be measured. One such tool is the Energy Indicators for Sustainable Development (EISD) [24]. It is the result of activities carried out by the IAEA in cooperation with UNDESA, IEA, the Statistical Office of the European Communities (Eurostat) and the European Environment Agency (EEA).

This problem is indicated by M. T. García-Álvarez, B. Moreno and I. Soaresz from 2016 [25]. They proposed the Synthetic Index of Energy Sustainable Development for EU-15. It was calculated on the basis of three indicators: Security of Energy Supply, Competitive Energy Market dimension, and Environmental Protection indicators, which were then aggregated into a synthetic index. Denmark, the Netherlands, France, Portugal and the United Kingdom scored best, while Spain, Ireland, Greece, Belgium and Luxembourg-worst. They clearly showed the need for new and more effective actions, as well as better coordination of energy policies at national and EU level. Ingunn Gunnarsdottir et al. [26] provided an overview of indicators for assessing energy sustainability. They conducted an analysis and evaluation of established indicator sets for sustainable energy development (SED). A total of 57 sets of indicators were analysed to monitor progress in energy sustainability or only selected aspects of it., were described. It transpired that, with the exception of one, all indicator sets were deficient in some aspect, in particular due to the lack of transparency, lack of consideration of links between indicators, an unbalanced picture they presented, and lack of stakeholder engagement in the process of indicator development. Energy Indicators for Sustainable Development, jointly developed by many international agencies, were identified as one complete indicator. However, several flaws were found in this set. These indicators (EISD) can be used for an initial assessment and should then be adapted to the context being analyzed to ensure their usefulness. It is indicated that stakeholder participation should also be enhanced in the process of refining these indicators, ensuring a trade-off between the three dimensions. However, the experiences of many countries indicate that the EISD does not sufficiently capture the specificities of all countries, especially those with unique energy mixes e.g., the Baltic States [27] or Iceland [28]. The EISD indicators require a very large number of indicators, which causes a problem in its analysis, making it impractical and difficult to interpret [29]. In addition, EISD indicators are not aggregated, which makes them multidimensional and difficult to verify [30].

Streimikiene D., Ciegis R. and Grundey D. [28] present the use of EISD to analyze trends, set energy policy goals and monitor these goals. On their basis, recommendations for the development of sustainable energy policy in the Baltic states with the use of this indicator approach were presented. It was designed to provide information on current energy trends. Its purpose is to assist decision makers at the national level and to enable the assessment of the effectiveness of energy policy in terms of actions for sustainable development.

A method of assessing the level of energy and climate sustainability was proposed by M. Tutak, J. Brodny and P. Bindzar [30]. The assessment of indicators monitoring the implementation of Sustainable Development Goals was carried out using data from the European Statistical Office (Eurostat) for the period 2009–2018. The analysis was conducted for 27 countries, based on 14 indicators. These indicators are divided into stimulants (e.g., final energy consumption), and destimulants (e.g., greenhouse gas emissions, tons per capita, electricity prices by type of user).

2.2. COVID-19 and Sustainable Energy

The impact of the COVID-19 pandemic on energy sustainability is not insignificant. The pandemic caused a global health [31,32], social and economic [33–36] crisis. It also strongly affected real estate markets and changed the role played by housing [37–55]. Many other interesting publications in this field can be found. However, in my research, I focused on estimating the impact of COVID-19 on energy sustainability. Many researchers have attempted to estimate the impact of COVID-19 on the energy sector [56–68], inter alia in the context of the energy crisis and the increase in electricity demand [69–71].

For example, the impact of COVID-19 on the level of energy poverty in Poland was studied [72]. COVID-19 was shown to exacerbate energy poverty in Poland. The impact of the COVID-19 pandemic on electricity consumption by residential consumers was also demonstrated [73]. On average, the energy consumption of residential customers increased. Nevertheless, the peak power for these facilities during lockdown remained virtually unchanged compared to pre-pandemic values.

COVID-19 also had a not insignificant impact on stock indices associated with the alternative and the conventional energy sector [74]. It was indicated that the energy sector, as measured by the Global Alternative Energy Index (MSCI), is more resilient to COVID-19 than the conventional energy sector.

3. Materials and Methods

In order to achieve the aim of my research, I formulated the following research hypotheses:

- H1: There is a relationship between household electricity price, economic growth and innovation expenditures and CO_2 emissions between 2007 and 2021.
- H2: There is a relationship between GDP per capita, innovation expenditure, CO_2 emissions and electricity consumption (renewable and black energy–fossil fuels).
- H3: There is a relationship between energy prices, GDP per capita and renewable energy consumption before the COVID-19 outbreak (i.e., before 2019) and following the 3rd wave in 2021.

The structure of energy production was defined according to several groups described in Figure 1. Electricity production data has been aggregated into six generation types. Data was collected using EUROSTAT sources, from Embrer's website and from national sources.

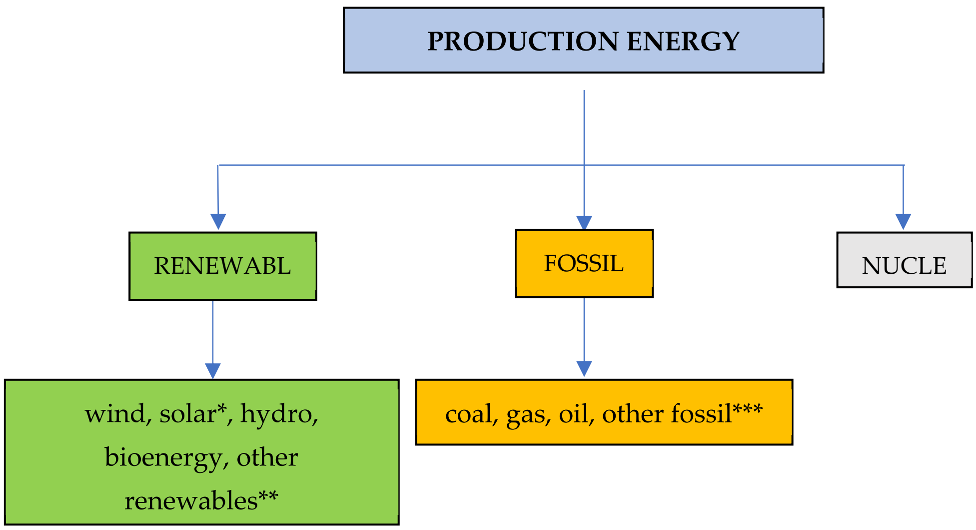

Figure 1. Structure of energy production. * The "solar" group includes all sources, including solar farms, photovoltaic cells and distributed generation. ** The "other renewables" group includes geothermal, tidal and wave power generation. *** The "other fossil" group includes sources that use raw materials: oil, petroleum products and industrial gases.

In this paper, selected indicators are comprehensively analyzed with a special focus on the impact of the pandemic on sustainable energy development. To obtain the information required for this study, I started by searching for data from recognized scientific databases such as Google Scholar, Web of Science, Scopus, journal pages (MDPI, Elsevier, Springer, etc.); the following were used as titles, abstracts and keywords in the query: sustainable energy development, households, energy price, production energy, renewables, COVID-19. At this stage, I collected relevant studies. Then, based on eligibility criteria and their availability, I identified the knowledge of indicators for energy sustainability assessment within 15 years. This allowed for a global understanding of problems associated with development. The analysis was conducted for 15 European countries. Each country is described by 9 indicators, which are also indicators of energy-climate sustainability.

In the next step, in order to create of synthetic index to assess the degree of sustainable energy development (SISED), the following data was collected [75–82]:

(1) electricity price for household consumers [MWh],
(2) GDP,
(3) CO_2 emissions,
(4) population,
(5) investment in innovation (R&D),
(6) the country's total energy production (black and renewable),
(7) production of renewable energy,
(8) production of black energy (fossil fuels).

Electricity price data was determined as follows:

- time frequency: average annual electricity price,
- consumption: Band DC: 2500 kWh < Consumption < 5000 kWh,
- taxes: excluding taxes and levies,
- currency: Euro.

As some data from 2021 is missing, it were determined using the linear approximation method. For this purpose, data from 60 months between January 2015 and December 2020 was taken into consideration.

In order to determine the impact of the analyzed factors, the structures of electricity consumption of households, innovation expenditure, changes in electricity prices and economic growth with the level of CO_2 emissions between individual European Union (EU) countries were compared using the multiobjective decision analysis (MODA) with the single attribute value function (SAVF). These methods were chosen because of some very complex issues involving multiple criteria and multiple parties that can be profoundly affected by the outcomes of decision. Multi-Objective Decision Analysis (MODA) is the decision-making process when there are very complex issues, including many criteria and many pages that can be profoundly influenced by decision outcomes. This will allow consideration and weighing of factors and tradeoffs when evaluating each alternative (in this case, quarterbacks entering the draft). The groups then discuss the combined group results to help make a decision about the recommendation. The MODA analysis I conducted consisted of ten steps, which are shown in Figure 2. These are the various stages of the research.

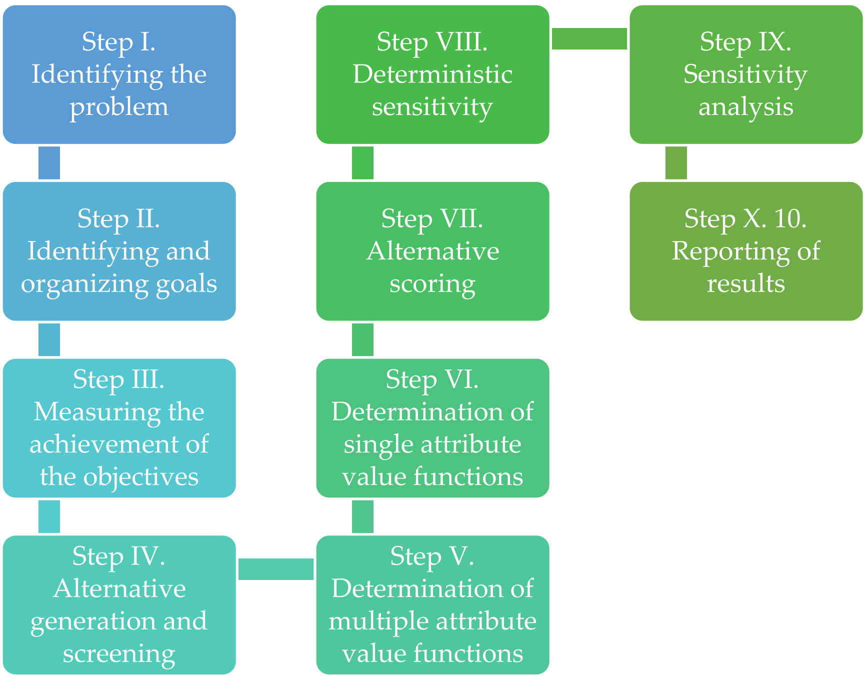

Figure 2. Ten steps of the MODA analysis.

Step I–III concerns discussing and agreeing the assessment factors. Step IV–VI concerns determining the relative importance of each factor and assigning appropriate weights to it. Step VII deals with determining the route options to be assessed. Step VIII–IX is the evaluation of each route option for each weighted factor. Step X is to discuss the results and make a decision.

Single-value attribute functions (SAVFs) are used to calculate scores for individual criteria based on raw data. The three types of SAVFs are exponential, linear, and categorical. SAVF values can be increasing or decreasing.

In order to assess the energetic sustainability of the selected European countries, the multiobjective decision analysis (MODA) was used. The analyzed data covers the period:

(1) from 2007 to 2019-before the outbreak of the COVID-19 pandemic,
(2) after the third wave COVID-19 (April 2021–September 2021).

The choice of the research period was not accidental. I focused on the third wave, because only after this period could I observe changes in the area of sustainable energy development compared to the period before the pandemic, and whether the closure of economies had an impact on this area. After the first wave of the pandemic, it has not yet been possible to conclude on its impact on energy sustainability compared to the pre-pandemic period.

The assessment of sustainable energy and climate development in the selected of EU countries was carried out in two dimensions (areas): (1) energy and climate, and (2) economic indices. These are some of the key areas for the assessment of the sustainable energy development.

All calculations were performed using the R programming language and RStudio IDE. Obtaining additional functionality of the program was possible by using additional packages, i.e., tidyverse, Cairo, Decision Analysis and rworldmap.

4. Results

4.1. Preliminary Analysis

To determine the changes from 2007 to 2019 and 2019 to 2021 in the values of the 9 indicators of energy sustainability, I conducted a comparative analysis. The results of the analysis are presented in Figure 3. 2007 has been adopted as the base year. This means that the changes of indicators (in percentage terms) have been calculated in relation to 2007. To have the first insight into the obtained data, a preliminary analysis was performed. This analysis involved standardizing the variables and developing one common scale, which was then plotted on a graph. To normalize the data, in the first step, relative percentages for 2021 were calculated. This allowed us to show the values of the variables for a relative increase or decrease. Next, all variables were plotted using a line plot. The results of the analysis are presented in the Figure 3.

Analysing the percentage changes of the studied indicators in each country (Figure 2), one will notice significant differences in this process. In terms of the use of black energy, the greatest progress was achieved by Denmark, which reduced this consumption by more than 79.43% in the examined period. The most insignificant changes in black energy consumption were achieved by Poland (−4.59%) and the Netherlands (−6.20%).

The greatest increase in electricity prices for households was observed in Greece (change of +44.89%), Finland (+38.25%) and France (+37.66%), while the smallest in Denmark (+1.27%). Interestingly, in Sweden the energy price for households decreased by −43.97% and in Poland by −13.84%.

In relation to the indicator of CO_2 emission, the greatest reduction was achieved by Greece (−36.64), Denmark (−36.6%) and Finland (−32.95%), while in Poland the reduction was only −1.53%.

With regard to the indicator of the amount of renewable energy sources in the total balance of energy production, the greatest increase in the 2007–2021 period was achieved by the UK (+565.29%) and Poland (+412.43%), while in France the share decreased by −80.6%.

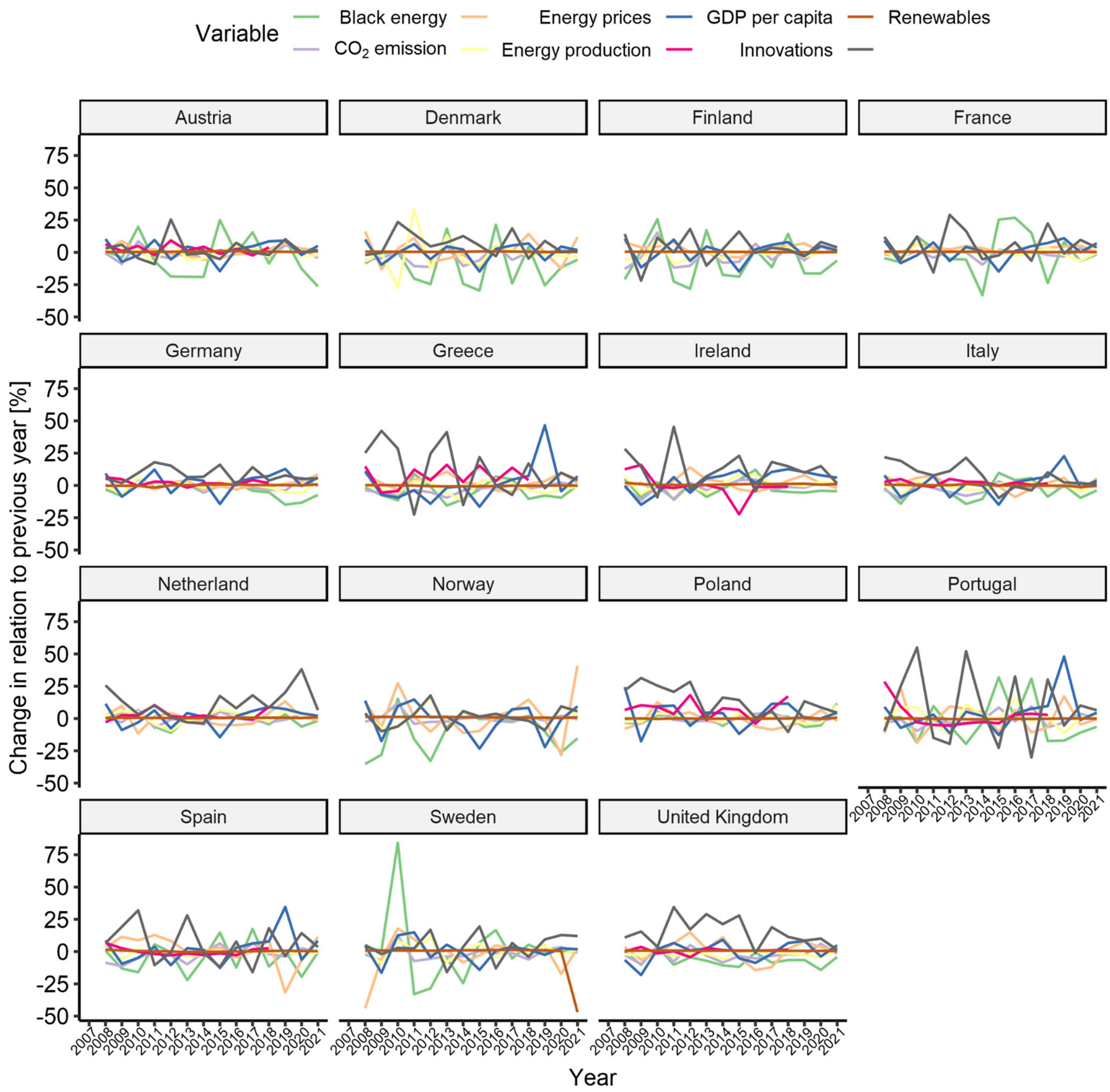

Figure 3. Relative changes in all variables used in the study.

4.2. Assess the Energetic Sustainability of the Chosen European Countries-Multiobjective Decision Analysis (MODA)

In order to propose a synthetic index to assess the degree of the sustainable energy development (SISED), the multiobjective decision analysis (MODA) was used. According to the standard MODA analysis process protocol, first the problem was defined. The overriding factor was established: it is the level of sustainable energy development in SISED. Then the two dimensions of energetic sustainability were created. These are:

(1) economic indices, and
(2) energy and climate.

Next, appropriate variables were assigned to each dimension. Economic indices included: energy price, innovations, and GDP per capita, while the energy and climate included: energy production, black energy, CO_2 emissions and the use of Renewable energy sources (Figure 4). The stimulating or de-stimulating character of the variables was also taken into account. The first group includes the following factors (the higher their value, the better):

- energy price,
- GDP per capita,

- renewables,
- innovation, R&D,

	Dimension	Variable	Direction of impact
Energy sustability	economic indices	energy price	stimulating
		innovations	stimulating
		GDP per capita	stimulating
	energy and climate indices	energy production	destimulating
		black energy	destimulating
		renewables	stimulating
		CO_2 emission	destimulating

Figure 4. Dimensions of energy sustainability and corresponding variables (green = stimulating, orange = de-stimulating).

The de-stimulating impact has been observed with respect to the following factors (the lower their value, the better):

- energy production,
- black Energy,
- CO_2 emissions.

The following step involved the determination of the single attribute value function (SAVF). To evaluate the single attribute of stimulants and destimulants, an increasing and decreasing exponential value function in this study was used

For the calculation of variable weights, the entropy weighting method was used according to these formulas:

$$w_j = \frac{1 - E_j}{\sum_{j=1}^{n}(1 - E_j)} \tag{1}$$

where:

$$E_j = -k\sum_{t=1}^{m} r_{ij} ln(r_{ij}) \tag{2}$$

where:

$$k = -\frac{1}{ln(n)} \tag{3}$$

It should be noted that the values of the single attribute value function and variable weights were calculated separately for each year from 2007 to 2021, and for each country. The cumulative value of the weights is presented in Figure 5. It shows the significance of individual variables and correlations between them in the 2007–2021 period.

The diagram shows the importance of individual variables (black energy, energy production, renewables, innovations, GDP per capita, energy price, CO_2 emission) in individual MANOVA models. The analysis of the weights shows that over the course of 15 years (from 2007 to 2021), e.g., the Black energy variable was, in 2007–2011, insignificant in terms of sustainable development. It was only after 2011 that it started to gradually increase in value. This means that it was only recently that the share of black energy (as raw material) started to become important in the area of sustainable development. On the other hand, the importance of the GDP per capita variable decreased after 2016.

The indicators of innovation, renewables, energy production and CO_2 emissions are the most significant for energy sustainability in the period from 2019 until the end of the third wave of the COVID-19 pandemic. In the period between 2019 and the end of the third wave of the COVID-19 pandemic, the greatest change in terms of the importance of indicators was observed for GDP per capita and black energy, which declined in importance.

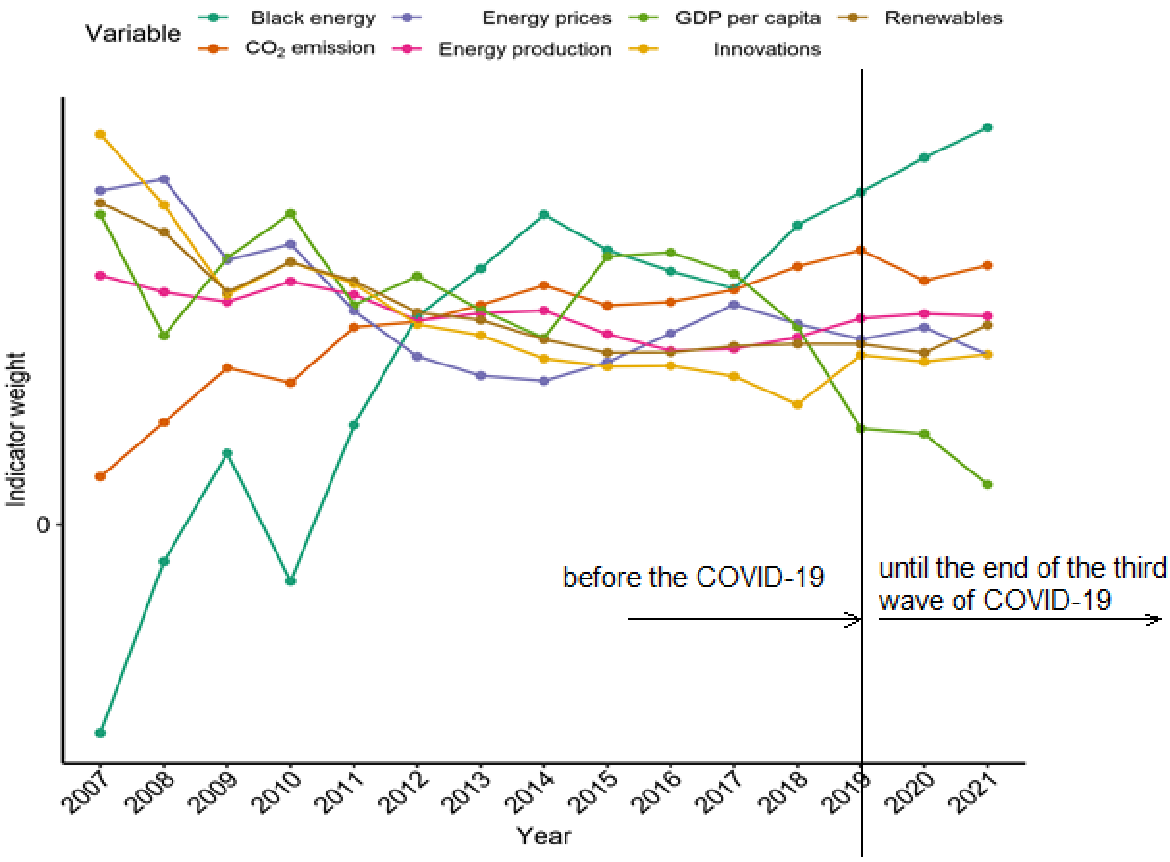

Figure 5. The variables' weights for multi attribute value functions.

Both the values obtained from exponential single attribute value functions and variables' weights were necessary to calculate the energetic sustainability index (ESi) with the use of multiple value attribution function (MAVF). This function allows taking cognisance of variables' importance for each year separately.

After calculating MAVF values, they were ranked from highest to lowest. The higher the value of the energetic sustainability index, the higher the development of the country in terms of energetic sustainability. The energetic sustainability indices and ranks are presented in Table 1.

It was found that the clear leader of the energy sustainability ranking for the entire study period (2007–2021) was Sweden (mean value: 2.73), while Ireland (mean value: 12.80) and Poland (mean value: 12.40) ranked last. Unfortunately, Poland has continued to score lowest (Rank = 15) in terms of energy sustainability since 2013. The average value of the tank index for the period 2007–2021 is presented in Table 2.

During the 2007–2021 period, the highest increase (by 8 positions) in the ranking was achieved by Denmark (from 11th in 2007 to 3rd in 2021), Finland (from 14th in 2007 to 7th in 2021), and Ireland (from 15th in 2007 to the 8th in 2021), which means an increase by 7 positions in the ranking.

Poland, on the other hand, has seen the greatest descent, from 9th in 2007 to 15th in 2021, which is a drop of 10 places in the ranking. In the remaining countries, changes remained within the range of 2 to 3 positions.

Overall, each of the EU countries analysed recorded a change in the value of energy sustainability indicators over the entire 2009–2021 period. Between 2018 and 2021 (until the end of the third wave of COVID-19), the largest increase in the energy sustainability ranking was observed in Finland (+7) and Spain (+5), while the largest decrease was observed in Germany and the UK (−6).

Table 1. Energy Sustainability Development (SISED) indices and ranks.

Country	2007		2008		2009		2010		2011		2012		2013		2014		2015		2016		2017		2018		2019		2020		2021	
	Es	R	Es	R	Es	R	Es	R	Es	R	Es	R	Es	R	Es	R	Es	R	Es	R	Es	R	Es	R	Es	R	Es	R	Es	R
Austria	0.63	3	0.61	5	0.60	3	0.58	4	0.59	2	0.62	1	0.64	1	0.66	1	0.64	1	0.64	1	0.62	2	0.64	1	0.43	5	0.42	6	0.46	5
Denmark	0.38	11	0.36	10	0.43	10	0.51	9	0.48	6	0.57	4	0.54	5	0.57	4	0.62	2	0.60	2	0.62	1	0.58	2	0.54	2	0.59	3	0.56	3
Finland	0.29	14	0.35	12	0.33	13	0.27	15	0.34	15	0.4	11	0.38	13	0.41	11	0.42	11	0.40	12	0.40	11	0.37	12	0.39	9	0.40	8	0.42	7
France	0.67	2	0.67	3	0.62	2	0.65	2	0.59	4	0.56	5	0.54	6	0.51	5	0.49	7	0.50	7	0.49	6	0.49	6	0.46	4	0.46	4	0.48	4
Germany	0.39	10	0.35	11	0.43	11	0.42	12	0.43	11	0.41	10	0.42	10	0.45	8	0.45	9	0.45	9	0.46	9	0.48	7	0.32	13	0.31	13	0.31	13
Greece	0.46	9	0.39	9	0.42	12	0.55	5	0.44	9	0.40	12	0.39	12	0.36	14	0.39	14	0.39	13	0.40	12	0.37	13	0.34	12	0.32	12	0.31	12
Ireland	0.20	15	0.15	15	0.32	14	0.32	13	0.36	13	0.36	15	0.38	14	0.38	13	0.40	12	0.38	14	0.38	14	0.38	11	0.37	11	0.39	10	0.40	8
Italy	0.50	8	0.46	8	0.51	6	0.52	8	0.46	7	0.48	7	0.49	7	0.47	7	0.48	8	0.50	6	0.49	7	0.46	9	0.38	10	0.38	11	0.37	11
Netherland	0.29	13	0.24	14	0.28	15	0.30	14	0.35	14	0.38	14	0.40	11	0.41	10	0.42	10	0.41	11	0.40	10	0.43	10	0.26	14	0.27	14	0.27	14
Norway	0.57	6	0.61	4	0.56	5	0.46	10	0.52	5	0.56	6	0.58	2	0.60	2	0.56	4	0.54	4	0.52	5	0.52	5	0.52	3	0.60	2	0.59	1
Poland	0.58	5	0.51	6	0.51	8	0.55	7	0.43	12	0.40	13	0.36	15	0.34	15	0.36	15	0.35	15	0.35	15	0.33	15	0.26	15	0.26	15	0.23	15
Portugal	0.71	1	0.68	2	0.59	4	0.75	1	0.67	1	0.59	2	0.56	4	0.50	6	0.50	5	0.50	8	0.48	8	0.48	8	0.42	6	0.43	5	0.43	6
Spain	0.52	7	0.50	7	0.51	7	0.55	6	0.45	8	0.43	8	0.44	8	0.40	12	0.40	13	0.43	10	0.40	13	0.36	14	0.39	8	0.41	7	0.40	9
Sweden	0.62	4	0.73	1	0.65	1	0.61	3	0.59	3	0.57	3	0.57	3	0.58	3	0.56	3	0.55	3	0.55	4	0.55	3	0.56	1	0.61	1	0.56	2
UK	0.35	12	0.34	13	0.44	9	0.44	11	0.44	10	0.42	9	0.43	9	0.43	9	0.50	6	0.52	5	0.55	3	0.54	4	0.40	7	0.39	9	0.40	10
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
	0.48	0.16	0.46	0.17	0.48	0.12	0.5	0.13	0.48	0.10	0.48	0.09	0.47	0.09	0.47	0.09	0.48	0.09	0.48	0.08	0.47	0.09	0.46	0.09	0.40	0.09	0.42	0.11	0.41	0.11

Table 2. The average value of the Rank index for the 2007–2021 period.

Countries	Average Rank Index Value in the Period 2007–2021	Change in the Ranking Position between 2007 and 2021	Change in the Ranking Position between 2018 (Prior to COVID-19) and 2021 (Until the End of the Third Wave of COVID-19)
Austria	2.73	−2	−4
Denmark	4.93	8	−1
Finland	11.60	5	7
France	4.47	−2	2
Germany	10.40	−3	−6
Greece	11.33	−3	1
Ireland	12.80	7	3
Italy	8.0	−3	−2
Netherland	12.53	−1	−4
Norway	4.27	5	4
Poland	12.40	−10	0
Portugal	4.47	−5	2
Spain	9.13	−2	5
Sweden	2.53	2	1
UK	8.40	2	−6

After that, the countries were divided into four groups considering the mean and standard deviation of SISED for each year separately. These are the following levels of sustainable energy development: group 1-safe level, group 2-medium level, group 3-warning level, group 4-dangerous level. Based on the analysis of the entire 2007–2021 period, it was found that Sweden and Denmark achieved the safe level (group 1) of sustainable energy development. At the other end of the spectrum, only Poland classified as having the dangerous level (group 4). The remaining countries fell into groups 2 and 3. Year-to-year changes in energy sustainability per country can be traced in Figures 6–9.

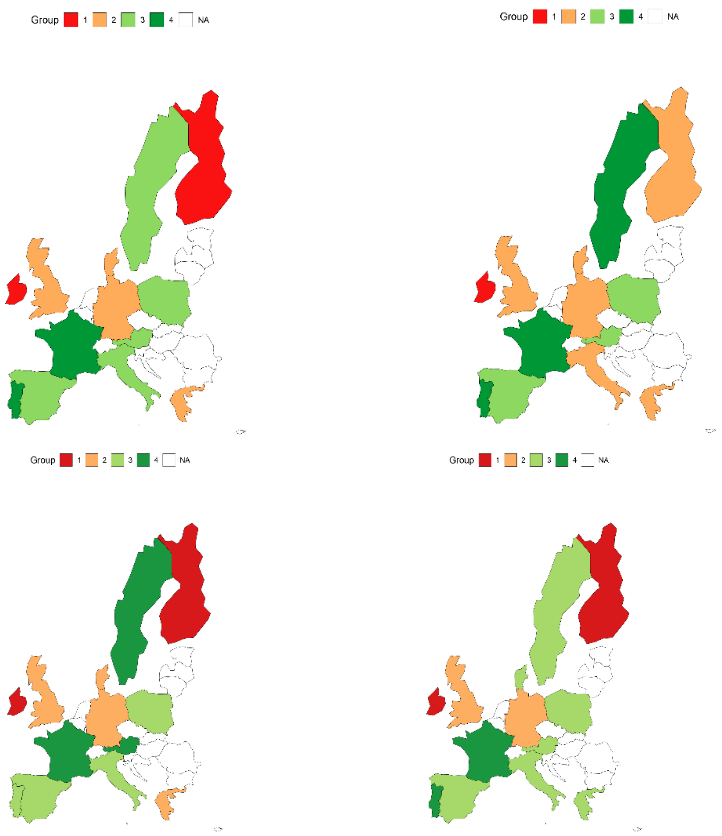

Figure 6. SISED for individual EU countries in 2007–2010.

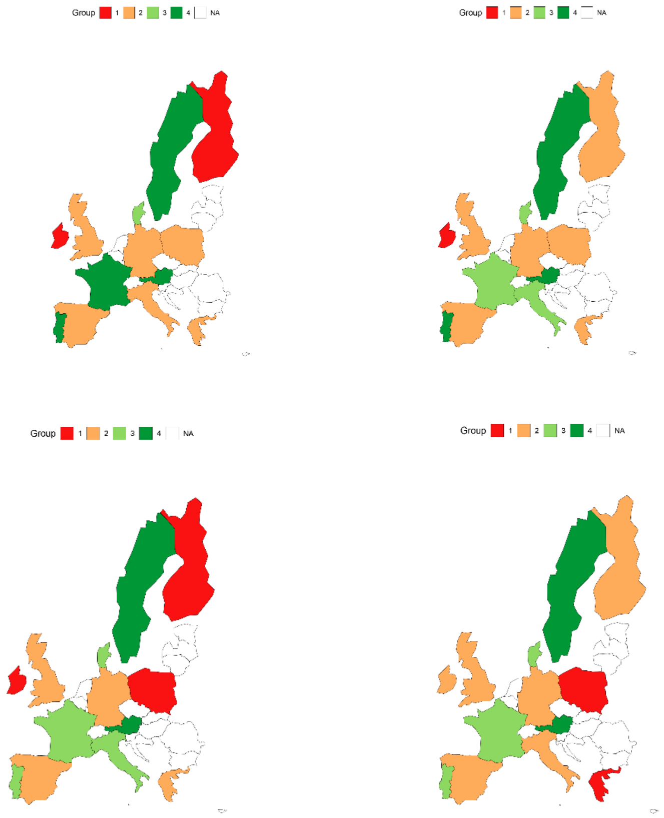

Figure 7. SISED for individual EU countries in 2011–2014.

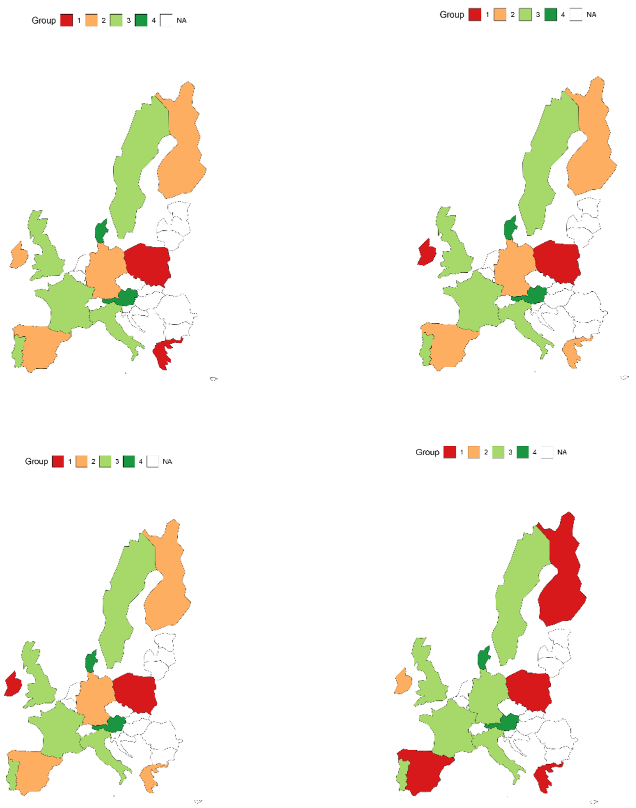

Figure 8. SISED for individual EU countries in 2015–2018.

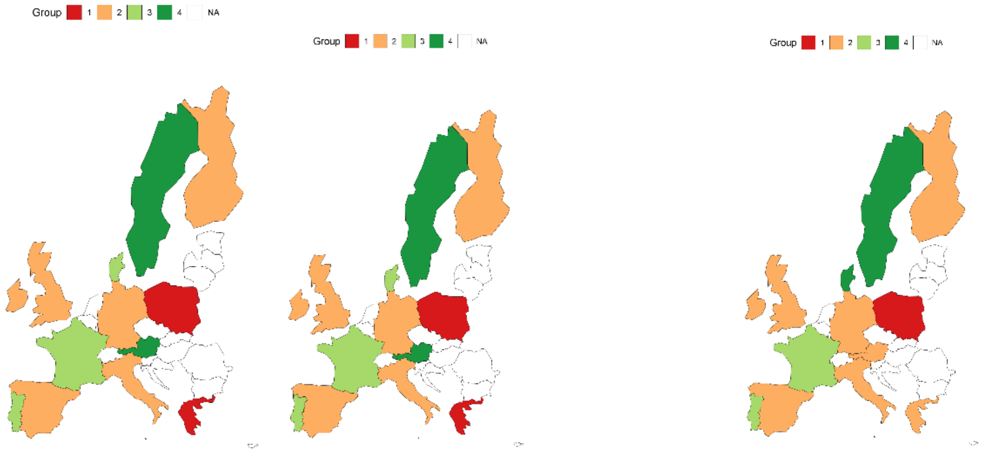

Figure 9. SISED for individual EU countries in 2019–2021.

Finally, in order to understand the influence of used variables on the overall Energy Sustainability score, the MAVF breakout plot was used. It divides the overall Energetic Sustainability score for each country (15 countries) into parts because of the partial variables score. The results of the analysis are presented in Figures 10–13.

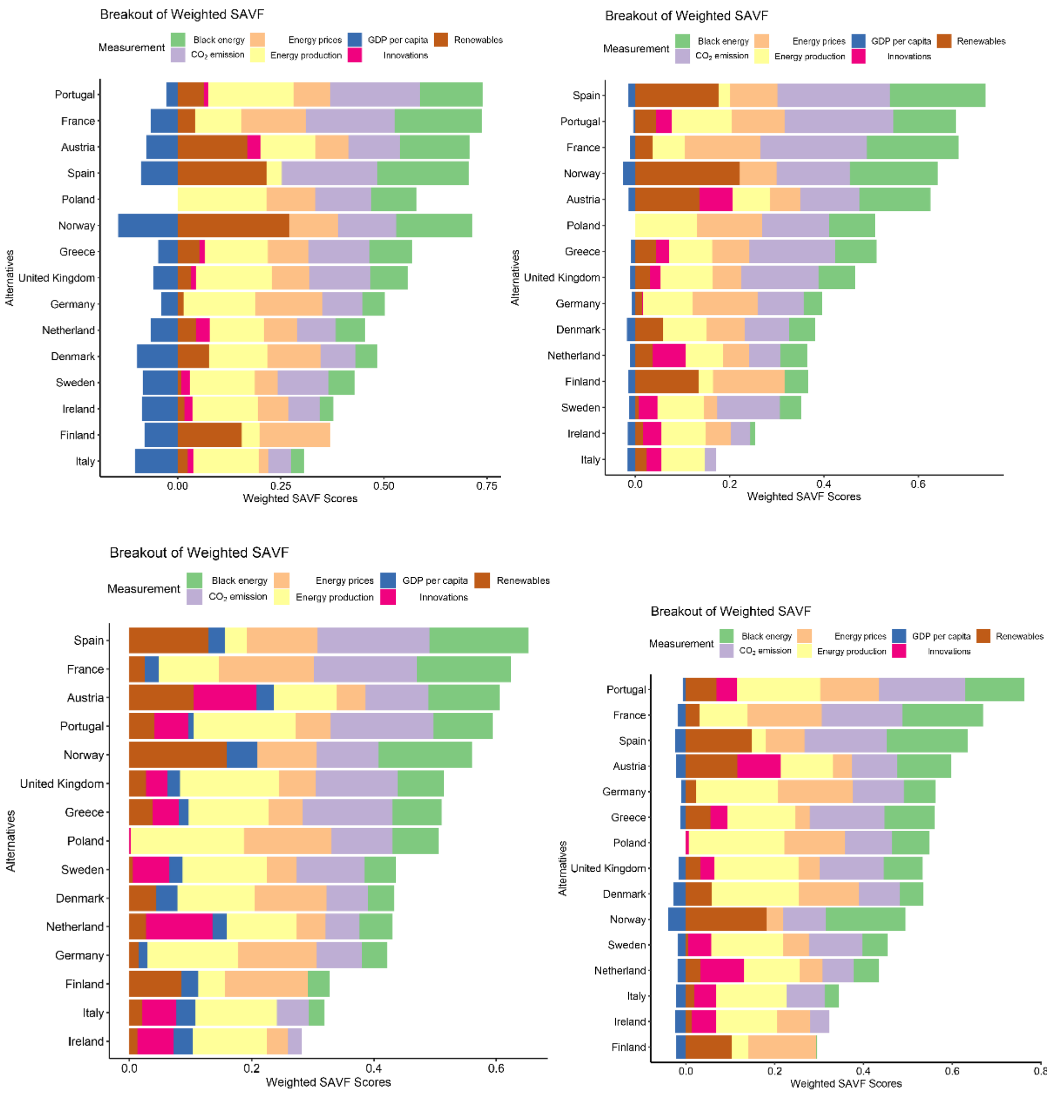

Figure 10. Influence of used variables on the overall SISED for all EU countries in 2007–2010.

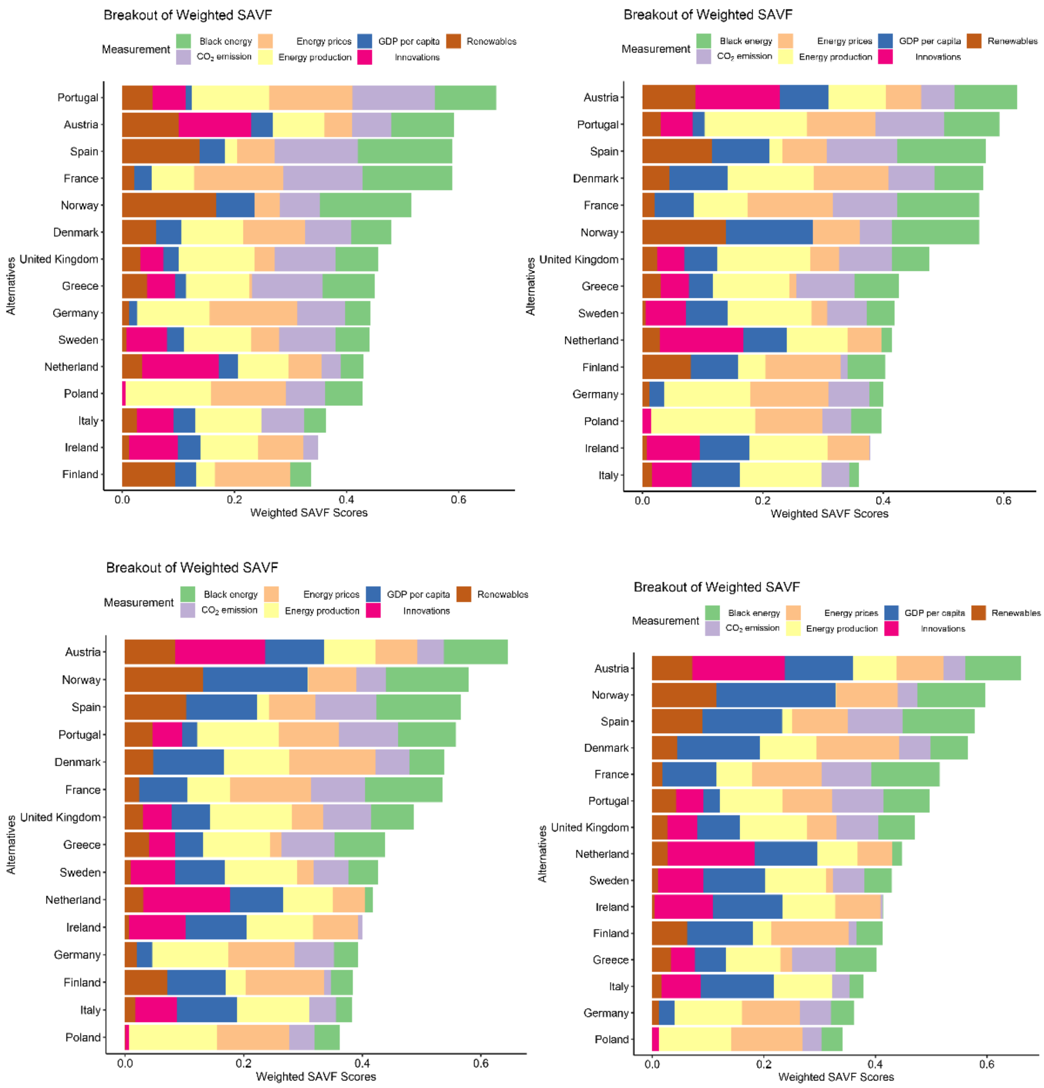

Figure 11. Influence of used variables on the overall SISED for all EU countries in 2011–2014.

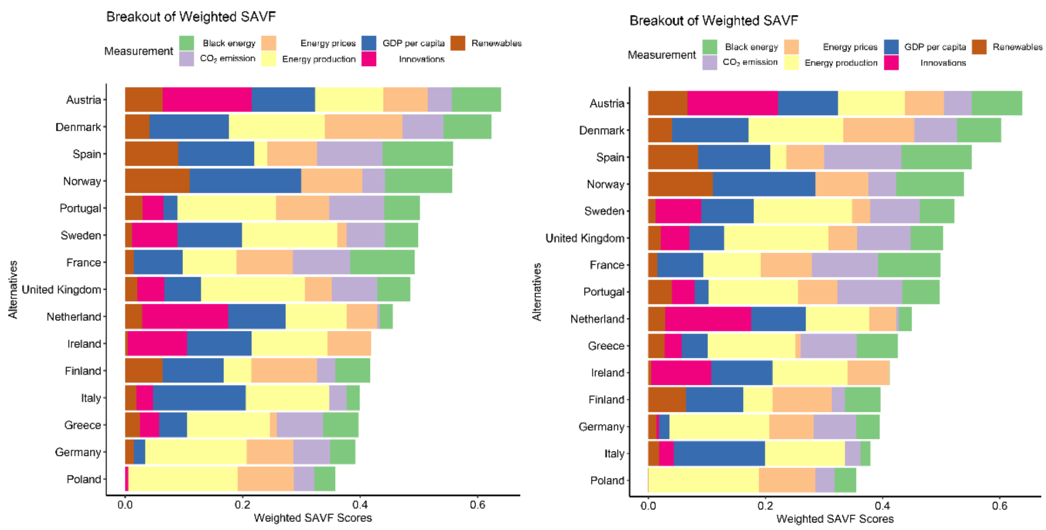

Figure 12. *Cont*.

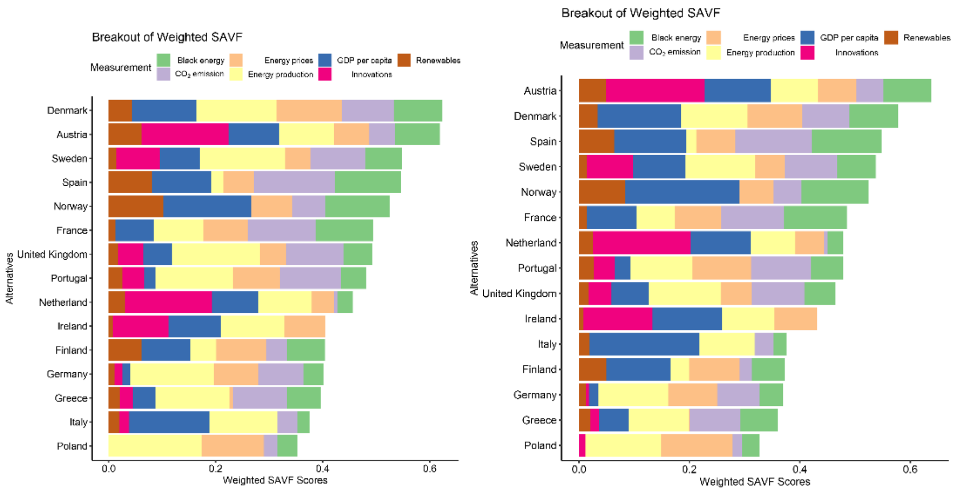

Figure 12. Influence of used variables on the overall SISED for all EU countries in 2015–2018.

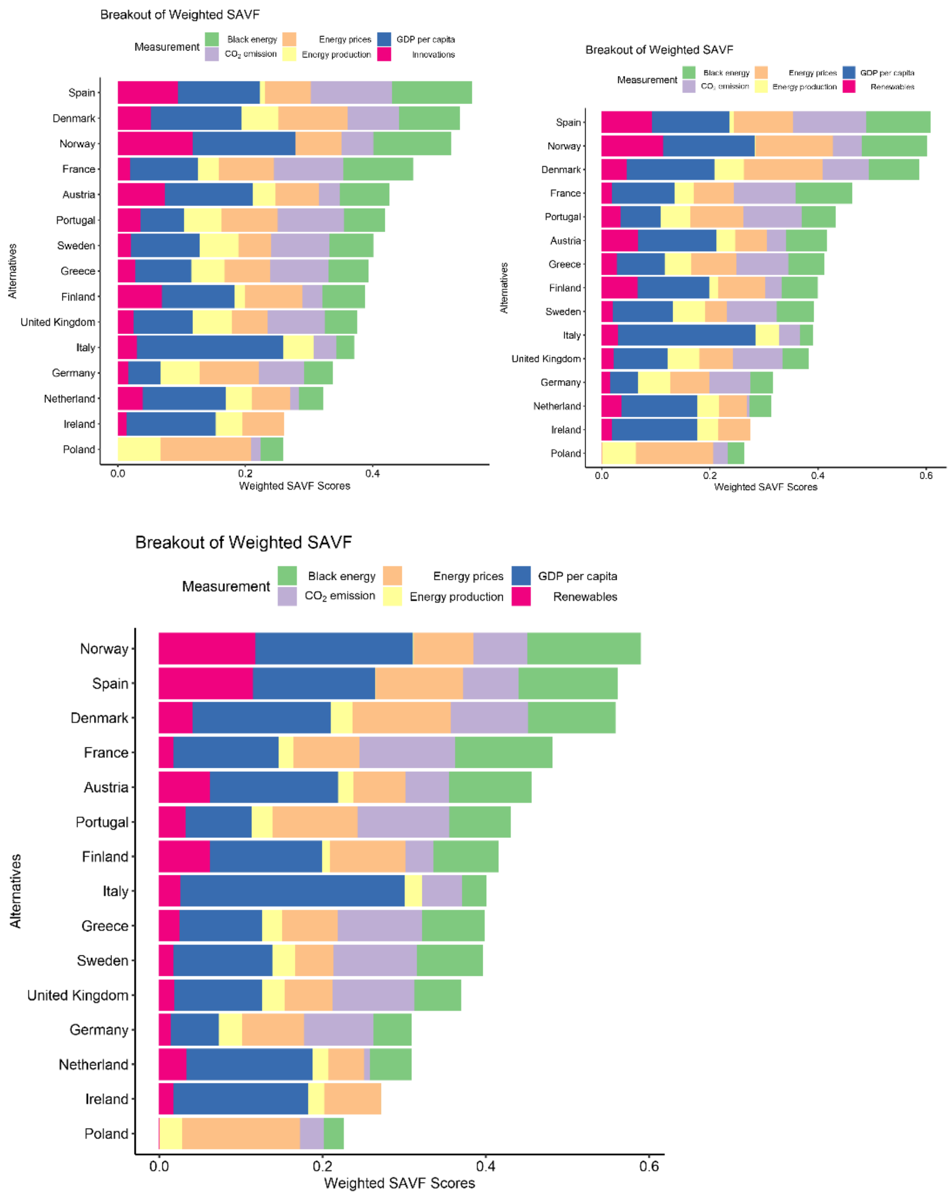

Figure 13. Influence of used variables on the overall SISED for all EU countries in 2019–2021.

The value breakout graph allows for a quick and easy comparison of how each attribute affected the alternatives.

5. Discussion

By 2030, coal consumption is projected to fall by 70% compared to 2015, and renewable sources will account for 60% of all energy generation. Some Member States have committed to phasing out coal by setting specific dates in their national energy and climate plans: Sweden and Austria in 2020, Portugal in 2021, France in 2022, Italy in 2025, Ireland in 2025, Greece in 2028, the Netherlands, Finland, Denmark, Spain in 2030, Germany in 2038. Germany assumes that, in 2030, the share of RES in its gross consumption forecast at 580 TWh will stand at 65%. In order to achieve this target, RES capacity of approximately 200 GW will need to be installed. France has set a target of 40% share of energy from RES in total electricity consumption by 2030. This target will be attained by generating 101–113 GW of installed RES power in 2028. Spain plans to generate 74% of electricity from renewable sources by 2030 (by 2050, RES is to represent 100%). Between 2021 and 2030, 59 GW of RES units are expected to be installed, bringing the total installed capacity of these sources to 122.7 GW.

The conducted research allowed the hypotheses to be verified. Hypothesis H1 was confirmed: There is a relationship between household electricity price, economic growth and innovation expenditure and CO_2 greenhouse gas emissions in the 2007–2021 period: the higher the household electricity price, economic growth and innovation expenditures, the lower the CO_2 greenhouse gas emissions.

On the other hand, hypothesis H2 was only partially confirmed: There is a relationship between GDP per capita, innovation expenditure, CO_2 emissions and electricity consumption (both renewable and black). The correlation depends on the analyzed time interval. From 2007 to 2012 it was minor, later-until 2019-it was moderate, while after the third wave of pandemic (2021) the correlation was strong. In contrast, the dependence of GDP per capita on other factors has decreased significantly since 2018 and in the period following the third wave of the pandemic in 2021 it became minor. This is probably due to the ongoing efforts to promote renewable energy sources, along with considerable EU and national subsidies for their construction.

Hypothesis H3 was also confirmed: A relationship can be found between energy price, GDP per capita and renewable energy consumption both before the COVID-19 pandemic (i.e., until 2019) and after the 3rd wave in 2021. The analysis shows that the amount of black energy generated by a country is inversely proportional to its level of sustainability. It is noticeable that the relationship between black energy and GDP is quite strong before the COVID-19 outbreak. However, it changed after the third wave of the pandemic: the relationship is considerably weaker and a decreasing trend is revealed. Although, since 2015, the CO_2 production trend was upward, it reversed during the pandemic and the relationship between black energy and CO_2 emissions started to become weaker.

A strong correlation between economic growth and CO_2 emissions across the examined countries and during this period was observed. No evidence was found of the impact of changes in the structure of electricity consumption of households on the level of CO_2 emissions and the impact of economic growth on electricity consumption of households after the third wave of the COVID-19 pandemic. This is important because CO_2 emissions data reveals a decline and re-emergence of emissions during the COVID-19 pandemic.

The conducted analysis of sustainable energy development showed a growing importance of the black energy variable in the achievement of sustainable development. This relationship has been observed since 2012. From 2017 to 2021, an almost linear increase is observed. This means that in the period until the end of the third wave of the COVID-19 pandemic (i.e., until April 2021), is no change in this relationship.

As a result of the presented MODA analysis, it was possible to assign countries to four groups according to their level of energy development (SISED), where group 1 means the highest SISED index, and 4-the lowest SISED index.

Each of the 15 European countries analyzed recorded a change in the value of energy sustainability indicators over the entire 2009–2021 study period. Between 2018 and 2021 (until the end of the third wave of the COVID-19 pandemic), the largest rise in the energy sustainability ranking was observed in Finland, while the largest decrease was observed in Germany and the UK (−6). This large decrease could be attributed to building insulation, reduced investment in innovation and the lockdown.

There is no doubt that the achievement of sustainable energy development goals requires the coordination of all policies influencing the development and use of energy.

The EU should continue to support its Member States, including those included in the 1st category. Following the third wave of the COVID-19 pandemic (2021), the least developed countries in terms of SISED are: Poland (15th position), Ireland (14th), the Netherlands (13th), and Germany (12th). It can be accounted by the fact that the Polish electricity sector is dependent on traditional fuel. An interesting result in Poland is the observed change in the structure of the impact of the energy price factor, which increased in relation to the energy production factor.

The most developed countries are the following: Norway (1st), Spain (2nd), Denmark (3rd) and France (4th). These values were the same in the period prior to the COVID-19 pandemic (in 2019). However, in the period before the COVID-19 pandemic (in 2019), there was a slight shift among the most developed countries: Spain (1st position), Denmark (2nd), Norway (3rd) and France (4th). An interesting result is the rise of Italy in terms of SISED, from the 11th to the 8th position after the third wave of the COVID-19 pandemic (2021), which is due to the greater per capita impact of the GPB factor than the energy production factor.

Despite the observed change in the structure of electricity consumption and the increased electricity consumption of households during the the COVID-19 pandemic, it did not significantly affect CO_2 emissions.

Regarding the indicators analyzed, a similar study by García-Álvarez et al was conducted [25]. They also focused on the energy sustainability index for selected EU-15 countries. However, they used different methods. Taking into account the above limitations, I attempted to compare the rankings for the EU-15 countries. The study analyzed here presents results covering the period 2002–2012, while my study includes data from 2007–2021. García-Álvarez et al. [25] grouped the EU-15 countries into three subgroups of five countries each, with high, medium and low rankings. Denmark, the Netherlands, France, Portugal, and the United Kingdom performed best in 2012. In my study, the group of countries with highest results in 2012 includes Austria, Portugal, Sweden, and Denmark.

However, in terms of indicators used and the research methodology, a similar study was conducted by M. Tutak, J. Brodny and P. Bindzar [31]. They presented their sustainable energy index for the EU-27 measured from 2009 to 2018. Research tools they used are similar to those applied in my study. According to the results of their study, [31] in which they grouped the EU-27 Member States into four subgroups (group 1-safe level, group 2-medium level, group 3-warning level, group 4-dangerous level), Sweden, Denmark, France performed best in 2018. According to my study, this group included Sweden, Denmark, and Austria, which proves that the results are consistent and confirms the usefulness of the proposed synthetic indicator of energy sustainability (SISED).

6. Conclusions

The article shows how the synthetic index of sustainable energy development (SISED) can be used for the analysis of trends in the development of the energy sector of EU countries in terms of sustainable development. This can be helpful in defining sustainable energy development goals in line with those contained in national and EU policies. Its application will also contribute to the assessment of the progress towards sustainable energy development and to defining new political measures necessary to achieve these goals.

The SISED index, among others, is used to compare data between countries in the areas of energy, environment and climate or economy. The SISED index allows data to be compared across countries in the areas of energy, environment, climate and economy, to show how they are interrelated, to assess and analyze trends, and to review policies [21,24,27,30]. These indicators allow stakeholders to assess their own progress toward energy sustainability and chart their own social and political course toward greater achievements in the area of energy.

The COVID-19 pandemic has brought certain changes in electricity consumption. It has also demonstrated the importance of a flexibility electricity system and its ability to balance supply and demand. It is crucial for the development of future low-emission power systems, which are based on increasingly variable supplies of electricity from RES. In this context, it is paramount to increase R&D expenditure in order to implement new solutions, including the possibility of increasing the energy storage capacity.

The research confirms that policy makers must act without delay and provide financial and legal means to accelerate the ongoing energy transition, which must be strengthened. In addition, developing a low-carbon economy requires ensuring that the energy system has the flexibility to move away from fossil fuel-based energy.

It is also proposed to introduce measures at the level of creating national and regional policies [81,83]. In managing change aimed at creating low-emission economies, the following actions are proposed:

(1) adjusting existing policies for the transition to a low-carbon economy,
(2) involving governmental and non-governmental institutions in the implementation of initiatives related to the use of renewable energy sources,
(3) creating appropriate tools and financial incentives for households to replace fossil fuel devices with low carbon devices.
(4) creating policies with incentives and preferential conditions, the use of renewable energy sources instead of black energy.

To this end, it is essential to involve various stakeholders in the transition to this economic model and to ensure that the UN Sustainable Development Goals are met. Future research should, therefore, support decision makers in the rapid implementation of appropriate measures, and this requires expanded collaboration among researchers representing different scientific disciplines. There is no doubt that the COVID-19 pandemic has also accelerated the implementation of changes in European energy systems to combat climate change.

The presented synthetic SISED indicators could be further refined in the context in which they are to be used in order to ensure their relevance and usefulness for policies. This would involve introducing more parameters to be investigated to take into account the specific context of the examined country and to ensure a balance in the representation of sustainable energy performance results.

There were some limitations in the studies related to the lack of some data, which were supplemented by approximation. In future research, attempts should be made to evaluate the proposed index in comparison with other European Union countries.

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Article

The Impact of the COVID-19 Pandemic on the Decision to Use Solar Energy and Install Photovoltaic Panels in Households in the Years 2019–2021 within the Area of a Selected Polish Municipality

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Abstract: The aim of this article is to show the impact of the COVID-19 pandemic on electricity consumption and, consequently, on decisions regarding the installation of photovoltaic panels using the example of a selected local authority in Poland—the Szemud Municipality. The analysis was conducted in 2022 and covered the years 2019–2021. An attempt was made to explore the factors that may have triggered an increase in the use of solar energy in households and identify the determinants of installing photovoltaic panels in the period under analysis. Previous analyses of the PV market (and the impact of the pandemic on it) have so far focused on the market as a whole, either in macro or global terms, while studies on smaller municipalities have been limited to examining changes in electricity consumption levels during the COVID-19 pandemic and during lockdown. Therefore, a research gap was identified in that there are no studies analyzing the reasons for the shift from conventional to PV-assisted energy in households, with the COVID-19 pandemic as the background of these changes. The literature research showed that there are currently no studies attempting to establish a link between the increased interest in this type of energy by local authorities and the COVID-19 pandemic. The research confirmed the hypothesis of increased interest in household PV during the pandemic. The main conclusions of the study boil down to the need for further support as well as promotion of the use of solar energy. In addition, the results derived from the empirical research indicate the need to take action at a policy level to counter adverse trends regarding undesirable social behavior.

Keywords: photovoltaics; pandemics; changes in energetic balance due to COVID-19; renewable sources of energy during pandemics

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1. Introduction

Production and energy use are responsible for over 75% of greenhouse gas emissions in the European Union [1]. In the "Steering Electricity Markets Towards Rapid Decarbonization" report by the International Energy Agency (IEA), it is forecasted that, by 2050, as the sectors currently based on fossil fuels become increasingly electrified, the demand for electrical energy will increase from 23,230 TWh in 2020 to 60,000 TWh [2]. In light of the declared global targets for climate change, decarbonization of the electrical sector is of key importance to accomplishing net-zero emissions by 2050. This determines the demand for energy from more environment-friendly sources, in which renewable energy sources (RESs) play a pivotal role.

As a member state of the European Union, Poland is taking steps to increase the share of RESs. In 2021, the Polish Council of Ministers approved a document entitled "Poland's Energy Policy until 2040" (PEP 2040), which assumes an increase in the share of renewable energy sources (RESs) in the national energy mix to at least 32% by 2030. This target is expected to be met through the development of photovoltaics and offshore wind farms [3]. Meanwhile, a series of programs called "My Electricity" has been implemented in Poland since 2019 and has just entered its fourth edition. Its goal is to encourage residents to install photovoltaic systems in exchange for subsidies [4]. Such programs are also being implemented at the local government level. This article focuses on the aspect of solar energy utilization in the form of prosumers' investments in the construction of photovoltaic installations in the area of a selected municipality in Poland. In recent years, a large increase in the number of photovoltaic panels installed by private investors in households has occurred, which prompted the following research question.

Question 1: *What factors are driving the embrace of prosumer PV installations in the selected municipality in Poland?*

Having reviewed statistical data and scientific findings, we saw that a large increase in new PV installations in Poland occurred over the period 2019–2021, which coincides with the COVID-19 pandemic. This led us to raise another research question.

Question 2: *Was it because of the pandemic that prosumers decided to install photovoltaic panels?*

The above questions were verified on the basis of a questionnaire addressed to the inhabitants of the Szemud Municipality in northern Poland and were accompanied by an extensive desk study. The topic of pandemic-driven energy use growth and the installation of photovoltaic panels is indeed popular worldwide, as confirmed by the literature research detailed in the following sections of this article.

2. Current Status of PV System Development in Poland

Economic, technological, and population growth have led to an increase in the demand for electrical energy worldwide [5]. Simultaneously, through the challenges associated with climate change and global warming one can observe a transformation of the energy sector into a more environmentally friendly one. We are witnessing a transition from systems based on fossil fuels to clean technologies based on sustainability [6]. The global RSE market is constantly expanding. The literature research suggests that the coronavirus pandemic did not slow this process down [7–11]. However, both households and industrial and service companies in Poland are facing higher energy bills [12,13] in addition to rampant inflation, the war between Ukraine and Russia, the restrictions and sanctions, and finally the fear of another coronavirus wave. This has fueled the concern about energy price hikes [14]. However, the problem of rising energy prices is not new. The higher energy bills are associated with the pro-environmental policy of the European Union (EU), which translates into rising charges for CO_2 emissions. This is shown in Figure 1 and has a significant impact on countries strongly reliant on energy generation based on fossil fuels, such as Poland [15]. In 2020, the amount of energy generated was 146.56 TWh, including 110.12 TWh of power from bituminous coal and lignite, which accounts for over 75% of the total [16,17].

Figure 1. CO_2 emissions allowance prices between 2015 and 2022 (EUR/tCO2) [18].

Figure 1 shows an increase from almost 10 EUR/tCO2 in 2015 to almost 90 EUR/tCO2 in 2021. This has directly affected the cost of purchasing electricity by end consumers. According to a Rachuneo.pl study, the annual cost of the consumption and distribution of electricity with a monthly consumption rate of 200 kWh in 2022 will be higher by about PLN 500 compared with 2019 [19]. This systematic and unavoidable increase in energy charges, but also the increase in electricity consumption, which is a natural result of economic and social development, has raised prosumer attitudes in Poland.

There is an increased interest in new solutions to both better manage electricity and reduce its price. These solutions are mainly based on investing in alternative renewable energy sources (RESs). There are, among other things, systems of renewable energy sources for power storage [20,21] and purpose-made subsidies for mounting RES systems [22]. Moreover, technological advancements based on alternative energy sources cost less than the conventional method [23–25]. M. Andrychowicz points to a method of optimization of local initiatives in the energy sector, such as energy cooperatives and energy clusters [20]. Lee Ch. Y. and Ahn J propose a method for photovoltaics cost optimization [26]. The subject is highly popular, so the return on investment from these solutions can be much more rapidly and easily achieved than in the past.

Thanks to technological advancements, the greatest ever decrease in photovoltaics (PV) installation costs occurred. According to the IRENA report, between 2010 and 2019 the cost of photovoltaics installations decreased by 82% [27]. Therefore, the main focus is on solar technologies, which are preferable to other technologies that use renewable energy sources, especially in households, according to statistics. As per the latest Polish Energy Market report, in April 2020 the power of photovoltaics installations was 9998.2 MW, more than a twofold increase compared with April 2021, when that value was 4739.6 MW. It is clear that photovoltaics systems are predominant in the Polish RES market, with a 52% share. Let us note that 64,249 new PV systems were installed, and their total power was 564.17 MW, which constitutes 92% of all new RES systems. However, the average power of a new photovoltaic system installed in April 2022 was 8.78 kW [28]. This demonstrates the great interest among individual households, where system of such power is sufficient to satisfy the demand for electrical power [29,30]. Figure 2 shows the increase in the number of PV installations in Poland, in which a sixfold increase in the use of this type of energy over just 4 years can be observed.

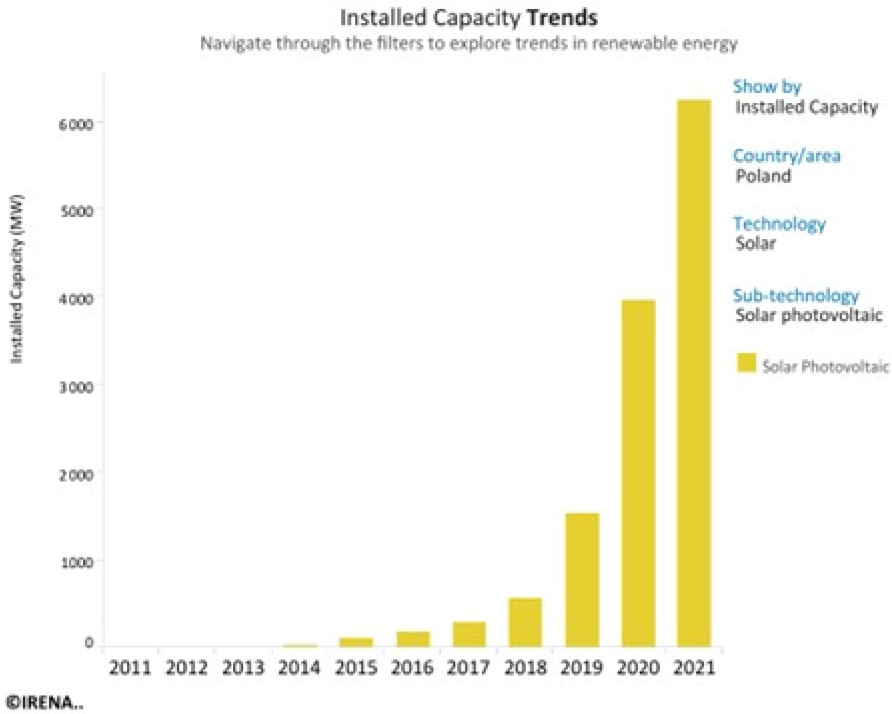

Figure 2. Installed capacity trends in Poland [10].

From the point of view of the research questions, the years 2019–2021 are particularly noteworthy, as this is when a significant increase in the number of PV installations occurred. What is puzzling, however, is that these are also the years of the COVID-19 pandemic crisis that triggered the closure of many industrial centers, mass layoffs, the need to work and study remotely, and the fear of shortages of basic goods, rising prices, less access to healthcare, and rising inflation that has not been tamed since. Those were uncertain years for most Polish consumers, and yet they chose to invest in costly photovoltaics installations. By browsing the offers of companies selling photovoltaic panels in the area of the selected municipality, we determined that the average cost of such an investment for a family of four was 23,000 PLN [31] or just over 5000 EUR. In 2021, the national minimum net salary was PLN 2061. Thus, the installation of a photovoltaics system for an average family would cost almost a year's salary for one person employed full-time and earning the minimum national salary. The return on investment is estimated at 10 years on average.

3. Literature Research and Hypothesis Development

Numerous findings regarding prosumer PV installations can be found in the literature. This demonstrates the great interest in this topic. The first research question posed in this article sets out to identify the factors that have led to the increased interest in PV among households. To do this, literature research was conducted. Different studies indicate that attitudes towards prosumer PV technology are an important factor determining the intention to invest in this technology [32,33]. Such attitudes are primarily influenced by affordability. Alam and Rashid [34] argue that consumers are more likely to opt for RESs when these are easy to install and simple to use, and all the more so if there is no need to hire technicians. Further research indicates that the belief in solar energy being a clean and emission-free energy source also positively impacts the willingness to install PVs [35]. The literature also addresses the issue related to the age of prosumers. It has been noted that the willingness of households to invest in PV is correlated with the age of prosumers and their awareness of such sources [36]. Many authors mention environmental, financial, and social considerations in general when analyzing the drivers of public acceptance of solar technologies [37–39]. Thus, it is difficult to unequivocally state the one factor that influences the decision to invest in PV solutions the most. However, it can be seen that this decision has many components and certainly depends on the current individual situation of the future prosumer. Nevertheless, an attempt was made in this study to identify these factors, and the results are discussed in the following sections of this article.

The willingness to invest in prosumer infrastructure can be motivated by many different factors, one of which is the volume of electricity consumption. An analysis of the literature was therefore carried out specifically for energy consumption. Due to the second question posed in the Introduction section, the focus was on literature research concerning energy consumption during the COVID-19 pandemic. A hypothesis was also formulated, which was then verified by means of a literature review followed by survey research.

Hypothesis 1: *The COVID-19 pandemic led to an increase in household energy consumption.*

The influence of pandemics on energy consumption has been the subject of research of several research teams. As early as 2020, Czosnyka M., Wnukowska B., and Karbowa K. investigated the situation in Poland between 1 March 2020 and 15 May 2020. According to their research, power consumption during that period was 6.9% lower than in the same period in 2019, and 8.1% lower in comparison with the same period in 2018 [40]. A similar trend was observed in Italy, where the pandemic led to a 37% decrease in comparison with the same period in the previous year [41]. The same trend was investigated in Kuwait by HM Alhajerii et al., who demonstrated that the pandemic curbed the demand for electrical power in the first half of 2020 [42]. The aforementioned studies concern power usage overall and do not distinguish between particular sectors of the economy. However, further studies identified an increase in demand for electrical power in households across different countries. A research team from India found a 15% increase in electrical power usage in households during a lockdown between April and June 2020 [43]. Another research team, led by Novianto, D., Koerniawan, M.D., Munawir, M., and Sekartaji, D., focused on the case of Indonesia and proved that, during the pandemic, regions home to the greatest urban centers experienced the highest median consumption along with an increase in the standard of living [44]. Similar conclusions were drawn by a team from Kazakhstan, who focused on Kazakh urban dwellers [45]. It can therefore be assumed that the demand for power in households increased while simultaneously decreasing as far as businesses and industries are concerned. Subsequent studies, e.g., that of M. Malec, G. Kinelski, and M. Czarnecka, who performed a demand analysis of business clients for electrical power in Poland, seem to uphold that theory. From their research, it is clear that the demand for power during the first lockdown decreased by as much as 23%, and the demand for power during the second lockdown decreased by 11% [46]. The impact of the COVID-19 pandemic on electrical power usage in households in Poland was presented by S. Bielecki et al., whose analysis proved that the demand for electrical power during the day increased due to the transition to remote work [47]. A study by P. Mastropietro, P. Rodilla, and C. Batlle concerned the impact of COVID-19 pandemic restrictions on the ability of households to pay electricity bills. They concluded that the poorest households needed financial aid to be able to use electrical power [48]. No such financial support for the poorest households is currently available in Poland. However, there is a program that subsidizes photovoltaics installations for households. Therefore, bearing in mind the strong influence of subsidies on PV installation decisions, we posited a second hypothesis.

Hypothesis 2: *Economic factors influence attitudes toward prosumer photovoltaics technology.*

As mentioned in the Introduction section, the fourth edition of the "My Electricity" program has been in operation in Poland since 2019. The first two recruitments for "My Electricity" contributed to the reduction of CO_2 by as much as 1,000,000,000 kg/year [49]. The main goal of the program is to increase the number of prosumers of PV micro-installations with a power of 2–10 kW among households in Poland. The programme's budget for the three first editions was over 1.8 billion PLN. Moreover, as part of these editions there were 444,000 applications from individuals who wanted to become prosumers [4]. The current edition of the program envisages a subsidy of 20,000 PLN, of which up to 4000 PLN is for autonomous photovoltaic installations, up to 5000 PLN is for photovoltaic installations with an additional product, up to 7500 PLN is for energy storage, up to 5000 PLN is for heat and cold storage, and up to 3000 PLN is for a Home Energy Management System (HEMS) [50,51]. Given that the average cost of installing photovoltaic panels is 23,000 PLN (roughly 5000 EUR) and the government subsidy runs up to 4000 PLN (850 EUR), in real terms we are reducing the cost by more than 17%. The authors of the research also viewed this as an impetus for prosumer investment.

However, apart from government domestic programs for prosumer support, there are also additional programs that have been paid for by local governments in an effort to decrease the carbon footprint within the area of their municipality. We focused in particular on a Polish municipality in order to analyze PV usage in the area. A public opinion survey was also performed, the findings of which are presented within the following sections of this article.

This hypothesis was confirmed not only by the reports and results published after the completion of the three phases of the "My Electricity" (Mój prąd) program, but also based on the survey. Indeed, the financial support—even if not substantial in real terms—served as a huge incentive for prosumers. Furthermore, we found studies in the literature pointing not only to the above considerations, but also to environmental ones. Two research teams performed a similar analysis of the correlations of the "My Electricity" program's beneficiaries to their location in Poland [52,53]. A research team composed of P. Olczak, A. Żelazna, D. Matuszewska, and M. Olek performed an analysis of the program's impact on the reduction in CO_2 emissions [22].

Undoubtedly, environmental considerations can today have an invaluable impact on consumer decisions. For this reason, and based on a review of the literature analyzing consumer preferences, we formulated a third hypothesis.

Hypothesis 3: *Environmental factors have a significant impact on attitudes toward prosumer PV technology.*

In 2011, researchers in Japan [54] showed that environmental considerations and an increase in public awareness have a positive impact on the diffusion of photovoltaic systems. The increased public awareness is a result of the perceived climate change and visible environmental degradation. In this regard, the number one topic is the emission of greenhouse gases, which contributes to an increase in global temperatures. In order to reduce these emissions, a switch to alternative energy sources and, in particular, renewable energy sources is being promoted [55–57]. In the literature, one can find studies confirming the fact that people with a high level of environmental awareness are more likely to switch to PV energy [58,59]. However, some studies indicate quite the opposite. Namely, they show that environmental aspects do not exert an influence on PV installation decisions [60,61]. We are, therefore, dealing with two different theories. It is therefore impossible to verify the hypothesis based on the literature alone. In order to verify the status quo, we decided to include questions related to environmental issues in the survey questionnaire. The verification of the hypotheses is presented later in this article.

4. Methodology

This study was conducted using different research methods (desk research, explorative, critical, and comparative analyses, and a broad review of the scientific and statistical literature). A statistical analysis tool, the r-Pearson's correlation coefficient, was also used. The primary method used in the research was the diagnostic survey method.

A diagnostic survey consists of collecting the opinions and views of the chosen community. Due to the relatively large size of the general population and the relatively high level of credibility of the obtained answers, in order to collect a representative research sample the method of choice was a survey. In this study, the tool used to record the answers of respondents was an online questionnaire survey accessible through an internet link. The link was posted on thematic forums and in social media groups. The answers to the ordered question sets were given anonymously and voluntarily. In order to obtain the maximum amount of information within the area of the research topic, the questionnaire was composed of open, half-open, and closed questions.

The conducted research concerned the analysis of factors that had an influence on decisions of the residents of a selected municipality in Poland, namely Szemud Municipality, to install photovoltaic panels. This included the identification of factors taken into account at the investment stage, an assessment of the impact of the pandemic on the work mode (on-site vs. remote), an assessment of electrical energy usage levels between 2019 and 2021, and an assessment of the impact of the pandemics on the energy bills paid by households. The research enabled us to draw a number of conclusions that helped to verify the hypotheses and achieve the research objectives.

5. Survey Study in the Area of the Selected Municipality

Szemud Municipality is located in northern Poland, in the central part of Pomerania, in the Wejcherowo district, and it covers an area of 175.76 km^2 (Figure 3). On 30 April 2022, the municipality had 18,840 residents, of whom 49.2% were women and 50.8% were men. Between 2002 and 2021, the number of residents increased by 65.2%. The mean age of the residents is 34.8 years.

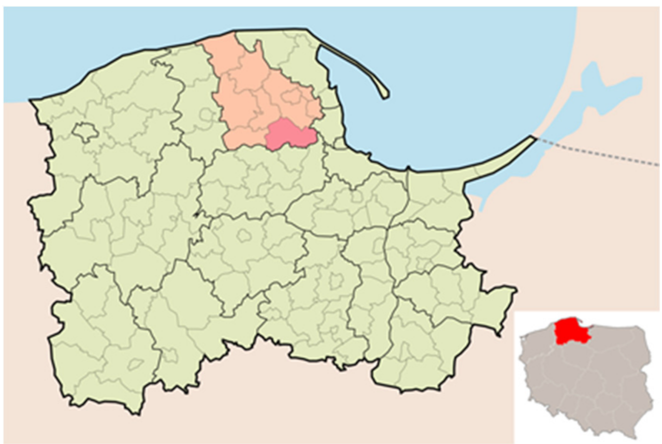

Figure 3. Location of Szemud Municipality [62].

In the survey, there were 189 participants. The responses were obtained within the period between 11 May 2022 and 30 May 2022. Details of the survey sample are included in Figure 4.

The questionnaire was directed to the residents of Szemud Municipality. The questionnaire was more often filled out by men (almost 63%). In terms of the age structure, there were five groups. The group that showed the greatest interest in the survey was the one with the age range of 36–45 years, and their share in the total was 29.5%. Another age range that was represented by the greatest number of people was 26–35 years with a share of 22%. The group with the lowest number of people was represented by young people aged 18–25 (11.5%) and people over 56 years of age (18%). The data confirm that young people who usually do not have their own house are not interested in the topic of photovoltaic panels. A similar situation occurred with elderly people, although their lack of interest may result from poor finances. The majority of respondents live in detached houses (84%), which constitute the most popular form of family house in Szemud Municipality. Multi-family houses are not allowed in the area of the analyzed municipality. Furthermore, analyzing the number of people within a household, the results show that the prevailing model is "two plus two", i.e., parents with two children (31%). This is followed by three-people households (22%) and two-people households (19%), while the group with the lowest number of people is constituted by households with only one person (11.5%). Additionally, the respondents declared that in 46% of the households there are persons who are enrolled in compulsory education.

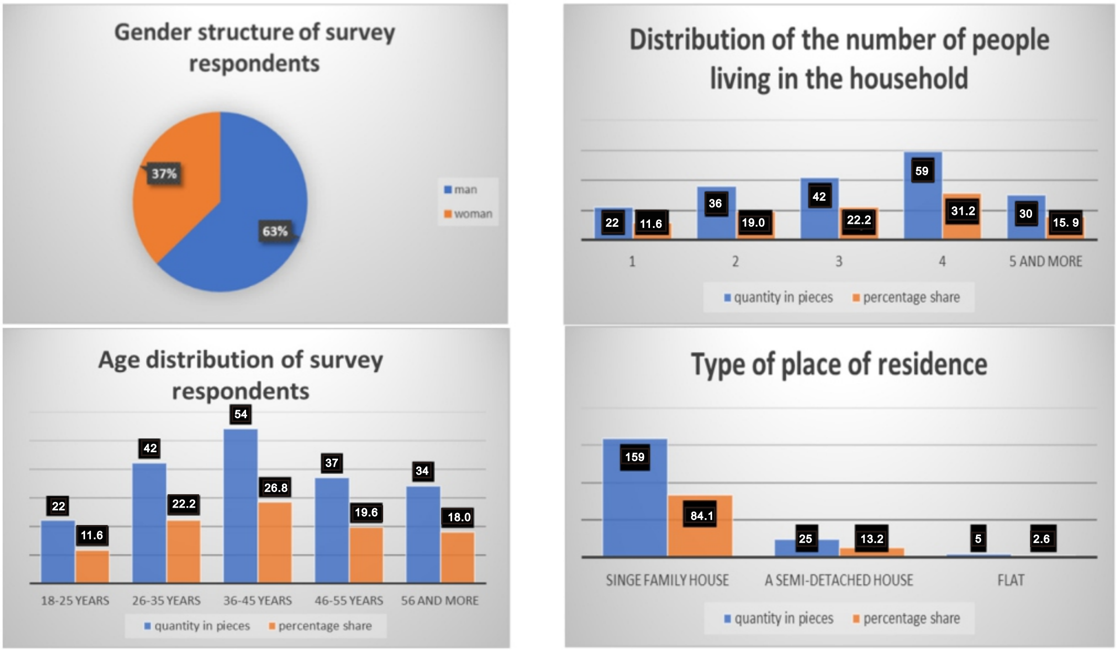

Figure 4. Research sample characteristics.

Table 1 shows the questions included in the questionnaire.

Table 1. List of questions used in the questionnaire.

No.	Scope/Content of the Question
1	Share of economically active people who switched to remote work in 2020 due to COVID-19
2	How many computers/laptops/tablets do you have in your household that are used on an ongoing basis?
3	What electrical household appliances do you use in your household?
4	In the last 2 years, have you noticed an increase in electricity consumption in your household?
5	Monthly consumption in individual quarters and the years 2019–2021
6	Are there any photovoltaic panels installed in the household?
7	Year of installation of photovoltaic panels
8	Determinants of the decision to install photovoltaic panels
9	Determinants of the installation of photovoltaic panels in the area of Szemud Municipality between 2019 and 2020 from a hierarchical perspective

Analyzing the responses to the question of switching to a remote work mode due to pandemic restrictions, it is clear that among economically active people in 2020, 29% switched to remote work from home. The remaining persons indicated the lack of a possibility to work remotely due to the specifics of their job and the fact that they would rather perform the work at their workplace.

Regarding the question on the number of computers, laptops, or tablets used on an ongoing basis in a household, the respondents indicated that the answer encompassing all four items (32%) was the most common. However, the least frequent answer was the one that led to the conclusion that the respondents were not in possession of such items at all (4%). Almost 18% of the respondents indicated that they used at least five items of this type on an ongoing basis.

In turn, as far as feedback on the use of home appliance electrical equipment in households is concerned, the respondents confirmed almost unanimously that they owned a TV set, a washing machine, a refrigerator, and a vacuum cleaner. Approximately 70% had a microwave oven, a cooktop, and an electrical kettle, while about 20% of the respondents used a toaster. Only a small percentage of respondents mentioned air conditioning.

Another group of questions concerned the usage of electrical power in the respondents' households. Almost all of the respondents (approximately 92%) agreed that, during the last three years, they had observed an increase in electrical power usage in their households. As for as the detailed questions on the level of year-to-year electrical power usage in a particular quarter, it can be assumed that, along with the outbreak of the pandemic, the respondents saw their monthly use of electrical power grow systematically. In 2019, the most prevalent range of consumption was 301–400 kWh, while the least prevalent rates of consumption were 200 kWh per month and over 501 kWh per month. However, in 2021, while the less than 200 kWh range remained the least frequent answer, the percentage of people declaring monthly consumption at this level significantly decreased to a small percentage. In turn, the most frequently declared monthly use of power was in the range between 401 and 500 kWh. Notable in this period is the significant percentage of respondents declaring that their power usage was in the range below 501 kWh (15–24% in 2021). The data confirm that, along with the COVID-19 pandemic in 2020, power usage tended to increase.

Regarding the use of photovoltaic panels, 21% of the respondents replied positively to the question of whether they have such installations on their property. This prevalence of renewable energy sources may be due to the fact that, for a dozen or so years, the area of the municipality became attractive to young people wishing to live close to a large agglomeration, i.e., Tricity, while embracing environmental protection solutions and recognizing the potential financial advantages for themselves. In terms of the year in which such panels were installed, the years 2020 and 2022 account for 67% of the responses. The record year was 2021, when approximately 32% of all panels were installed.

The respondents were also asked about the determinants of decisions on installing photovoltaic panels, which are shown in Figure 5.

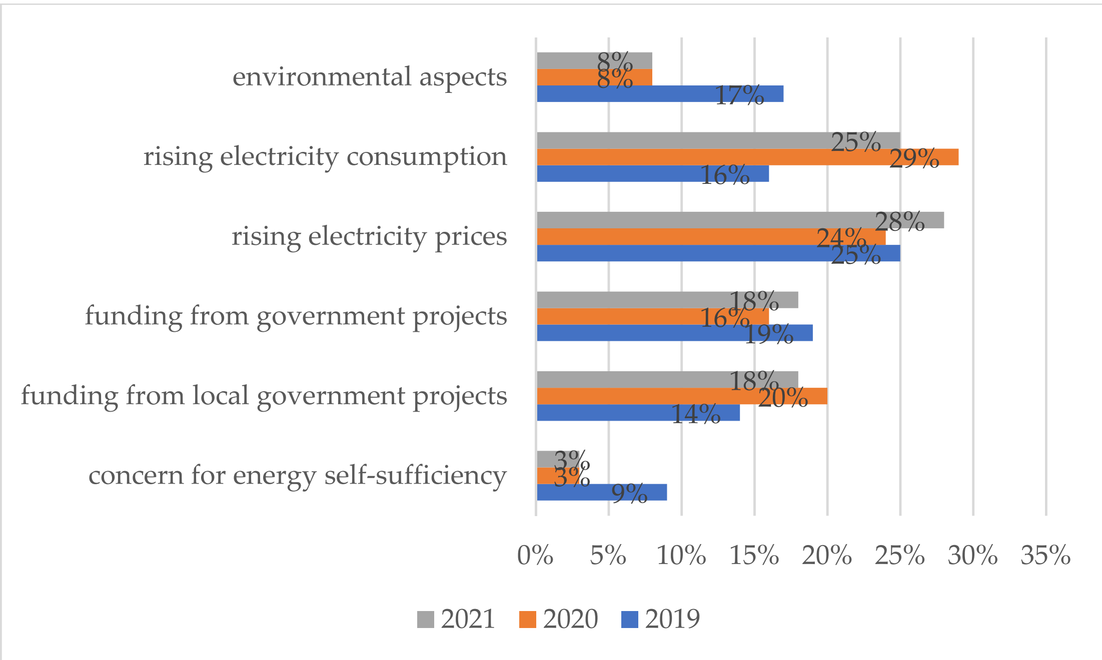

Figure 5. Determinants of photovoltaic panel installation in the area of Szemud Municipality between 2019 and 2020.

To assess possible changes in the share of the aforementioned determinants in the period 2019–2021, the respondents were asked to indicate the factors that had an influence on their decisions within the studied period. On the basis of the collected feedback, it can said that the most significant determinants were "the growing price of electrical power" and "the growing use of electrical power". However, the percentage of the former remained relatively stable in the following years. In turn, the "growing use of electric power" determinant showed a dynamic increase in 2020 at 29%, which was the highest increase reported for the determinants throughout 2019–2022. In the research, subsidies showed relatively stable results (approximately 20%). Regarding the impact of the environmental aspect on decision-making, it stood at 17% in 2019 but went down to 8% in the years that followed.

The research confirmed a high and increasing level of interest from the selected community in installing photovoltaics panels in their households and also showed that the COVID-19 pandemic boosted interest in renewable energy sources. However, within the given period, there was a change in the share of determinants that make people consider installing photovoltaic panels in their homes.

6. Results and Discussion

In order to verify Hypothesis 1, the strength and direction of the correlation between two variables were also measured. The first variable was the level of household electricity consumption as declared by survey respondents. The second variable was the number of photovoltaic installations in households of the surveyed community. A study of the Pearson's correlation coefficient for these two variables was conducted for the years 2019–2021. Table 2 shows the results of the correlation study.

Table 2. Results on the correlation of electricity consumption data and the number of photovoltaic installations in selected households in the Szemud Municipality in 2019–2021.

Declared Range of Monthly Electricity Consumption	The Value of the Correlation Index "r"
0–200 kWh	−0.51
201–300 kWh	−0.62
301–400 kWh	−0.72
401–500 kWh	0.64
501 and higher	0.54

The calculations indicate that the three ranges with the lowest declared electricity consumption show a moderately strong, albeit negative, correlation with the number of photovoltaic installations in the survey respondents' homes. On the other hand, a moderately strong positive correlation appeared with the two highest ranges of declared monthly electricity consumption. These results of the correlation study allow for a partial confirmation of Hypothesis 2, which relates to the increase in electricity consumption during the pandemic. The confirmation is partial because the survey respondents showed greater interest in installing photovoltaic panels only when their monthly electricity consumption was at least 401 kWh per month. Below this value, the correlation is negative.

6.1. Practical Implications

Regarding the application of our findings, this study indicates the need to focus on programs supporting RES development on a national, but also on a micro-regional, basis. Although Poland has a national project supporting the installation of photovoltaic panels, projects developed directly by local authorities may prove to be more effective, allowing for better allocation of earmarked funds. An important issue in the allocation of funds is an adequate analysis of the environment. In Poland, industry, the number of homes per square kilometer, and the wealth of the population are highly variable. These elements translate into the financial capacity of society, which in turn is reflected in the decision to invest in PV energy. Authorities at the regional level who are responsible for coordinating these types of projects have greater knowledge of the needs, requirements, opportunities, and constraints that exist in the areas under their administrative responsibility. This study confirms these aspects, while also indicating that managers of environmental projects at the regional level have greater flexibility. Of course, nationwide projects should not be abandoned, but, in view of the results of this study, consideration should be given to extending the implementation of environmental projects coordinated at the regional level.

6.2. Theoretical Implications

A further applied aspect is the need to pay attention to the environmental dimension of the conducted survey. As indicated earlier, the respondents to the survey, during the outbreak of the COVID-19 pandemic, significantly shifted away from pro-environmental arguments in favor of determinants of a typically economic nature, identifying the reasons for the investment undertaken in photovoltaic panels. In a sense, this attitude can be justified by the high degree of uncertainty, which has further increased with the development of the COVID-19 pandemic. Nevertheless, such an argument, when confronted with the growing environmental challenges facing societies, is hardly convincing. It would therefore be appropriate to consider taking action to remind citizens that, irrespective of the economic, political, or social situation, we cannot ignore ecological aspects when making decisions. The ecological challenges are so important that they must be the starting point and therefore be prioritized.

7. Conclusions

Among the challenges concerning sustainability, in both social and economic aspects, the issue of natural environment protection is a significant part of the discussed problem. In recent years, this has been reflected by the installation of photovoltaic panels in households. Through the results of the survey, Hypothesis 1 was confirmed: the COVID-19 pandemic led to an increase in household energy consumption. Respondents' answers clearly indicate that, along with the outbreak of the pandemic, some of the trends prior to 2020 had been markedly altered. Remote work, as well as online education, resulted in people spending more time at home. This in turn led to an increase in electrical power usage within the study period and to higher electricity bills as a consequence. However, the increasing power usage was not the only contributor to the decision to install photovoltaic panels. A significant determinant turned out to be the possibility of obtaining a subsidy from the government and local authorities. Respondents paid attention to the fact that a one-time investment in photovoltaic panels is a more attractive option than a systematic increase in electricity bills. Another interesting issue is the problem of assessing the impact of environmental protection on such decisions. The obtained feedback did not support Hypothesis 3, which relates to a pro-environmental rationale. The respondents, in the face of the outbreak of the COVID-19 pandemic, significantly de-emphasized pro-environmental argumentation in favor of concerns of an essentially financial nature. It can be assumed that, along with the normalization of the pandemic situation, the influence of ecological aspects will grow. However, the escalating war between Russia and Ukraine will have a lasting impact on possible decisions to install renewable energy systems as access to the conventional raw materials needed for electricity generation is under threat. This, in turn, may contribute to an increased interest in PV energy. Thus, the installation of PV panels in households may increase, albeit to a limited extent, the level of energy security of families, bearing in mind the growing economic problems associated with the energy transition. Moreover, Poland must reduce its carbon footprint, and the most effective method for doing this is restricting the use of fossil fuels to produce energy and replacing them with RESs. Apart from wind turbines, which are rarely installed in private households, solar energy is the second most popular choice as it gives a sense of security and has a direct impact upon the financial and energetic situation. This may be the key to meeting international energetic and environmental commitments.

It is important to realize that Poland, but also the European Union as a whole, faces a number of significant energy policy challenges. Dynamic changes in the market for raw materials for energy generation (as well as the scope of these changes and the intensifying rivalry for priority access to strategic raw materials), along with the simultaneous pressure to stimulate economic growth after the COVID-19 pandemic, affect the foundations of the assumptions of the EU energy strategy. On top of all this, let us also note the decrease in energy production in the European Union. This further reinforces the requirement that the security of the energy supply, increased competitiveness, and the sustainable development of the energy sector be listed among the main goals of this policy. Another important element of this policy is the growing diversification of the sources and directions of the supply of raw materials for energy generation within the territory of individual EU countries. This last demand in particular highlights the emerging conflict between the individual interests of member states and the Community and is often the cause of tensions within the European Union. Of course, installing photovoltaic panels will not solve these problems entirely, but it can at least reduce the negative effects resulting from the lack of access to energy at the micro level, which, in light of the uncertain geopolitical situation, may become a reality. Finally, knowledge of the factors that support the installation of individual photovoltaic systems is extremely important from the point of view of decision-making centers at the government level, but also at the local government level, which then have the authority to stimulate energy transition processes within the scope of their powers.

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Article

Non-Renewable and Renewable Energies, and COVID-19 Pandemic: Do They Matter for China's Environmental Sustainability?

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Abstract: Since the emergence of the COVID-19 pandemic, people all around the globe have seen its effects, including city closures, travel restrictions, and stringent security measures. However, the effects of the COVID-19 pandemic extend beyond people's everyday lives. It impacts the air, water, soil, and carbon emissions as well. This article examines the effect of energy and the COVID-19 pandemic on China's carbon dioxide emissions in light of the aforementioned context, using the daily data from 20 January 2020 and ending on 20 April 2022. Using the nonlinear autoregressive distributed lag model for empirical analysis, the findings indicate that COVID-19 pandemic confirmed cases and renewable energy advance environmental sustainability due to their negative effects on carbon dioxide emissions, whereas fossil fuel energy hinders environmental sustainability due to its positive effect on carbon dioxide emissions. Moreover, these results are also supported by the results of the frequency domain causality test and the Markow switching regression. In light of these results, there are several policy implications, such as vaccination, renewable energy utilization, and non-renewable energy alternative policies, which have been proposed in this paper.

Keywords: COVID-19 pandemic; renewable energy; fossil fuel energy; carbon dioxide emissions; nonlinear autoregressive distributed lag model; frequency domain causality test; Markow switching regression

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1. Introduction

The fast rise in global carbon dioxide emissions may be traced directly back to the over-reliance on the use of fossil fuels to fuel economic expansion. According to Our World in Data, worldwide carbon dioxide emissions reached 34.05 billion tons in 2018, up 617 million tons from 2017 and 1.85% from the previous year. Due to the constant increase in carbon dioxide emissions, the climate has become more variable, resulting in an increase in natural disasters. In recent years, countries throughout the globe have given increasing attention to the issue of carbon dioxide emissions. Since 2019, worldwide carbon dioxide emissions have begun to fall. Due to the effect of the COVID-19 outbreak in 2020, the majority of countries enacted preventative and control measures by halting work and production and isolating citizens at home. Some governments or areas also adopted efforts to "close off the country" and "shut off the city" to avoid and contain the outbreak, resulting in a significant decrease in global carbon dioxide emissions. Another piece of data from Our World in The data revealed that global carbon dioxide emissions totaled 31.98 billion tons in 2020, a decrease of 2.056 billion tons from 2019 and a decrease of 6.04 percent from the previous year.

The World Resources Institute stated that China, the world's biggest developing country, had the highest level of carbon dioxide emissions in the world in the year 2020, with 9893.5 million tons. The emissions of carbon dioxide that are produced in China account for 30.93% of the total world emissions of carbon dioxide. One of the most important considerations is the fact that China has, for a very long time, been driving fast economic expansion by increasing its use of fossil fuels. As a result, figuring out how to lower emissions of carbon dioxide is a challenging problem that China is now experiencing. In addition to this, this has been quite effective in attracting many academics to investigate this subject. Using novel dynamic autoregressive distributed lag and frequency domain causality methods, Abbasi et al. [1] discovered that, from 1980 to 2018, fossil fuel energy significantly increased carbon dioxide emissions over the long and short term. In addition, He [2] pointed out that by using data from 1971 to 2017 and the auto-regressive distributed lag method to undertake an empirical study, fossil fuel usage was placing rising pressure on environmental sustainability because of its beneficial effects on carbon dioxide emissions. Meanwhile, similar results were reported by Li and Haneklaus [3], He and Huang [4], Wang et al. [5], and He et al. [6]. Moreover, China's carbon dioxide emissions have also surfaced in a new scenario as a result of the emergence of COVID-19 and the conflict between Russia and Ukraine. This presents a new possibility for this study, which also offers an opportunity for further research.

Considering the aforementioned examination of the current circumstances, three kinds of hypotheses were proposed. Hypothesis 1 (H1) is that the COVID-19 pandemic negatively affects carbon dioxide emissions. Hypothesis 2 (H2) is that renewable energy negatively affects carbon dioxide emissions. Hypothesis 3 (H3) is that non-renewable energy positively affects carbon dioxide emissions. Based on this background, this article investigates the impacts of energy and the COVID-19 pandemic on China's carbon dioxide emissions (a proxy for environmental sustainability) from 20 January 2020 to 20 April 2022. The results of this empirical study that used a nonlinear autoregressive distributed lag model highlight that COVID-19 pandemic confirmed cases and renewable energy advance environmental sustainability with negative effects on carbon dioxide emissions, whereas fossil fuel energy precludes environmental sustainability, which has positive impacts on carbon dioxide emissions. Furthermore, these findings have confirmed the results of the frequency domain causality test and the Markow switching regression.

Moreover, the results of this research make three significant advances to the existing body of knowledge. Firstly, it has been brought to our notice that there is not a single piece of published research that focuses specifically on China and investigates the relationship between the COVID-19 pandemic, energy, and environmental sustainability. Secondly, there has been a significant amount of scientific input on the subject of energy and environmental sustainability. The COVID-19 pandemic was not included in the vast majority of the studies that were conducted on environmental sustainability and energy. Alternatively, the emphasis is placed on the rise of the economy, as can be observed from the great majority of the articles that were looked at in this context. This study, therefore, addressed the COVID-19 pandemic, environmental sustainability, and energy within the same framework in order to achieve a comprehensive understanding of the subject matter. Thirdly, a quantifiable contribution has been observed in the research that is now being conducted. Even though published works have used methods such as autoregressive distributed lag, the generalized method of moments, and Granger causality to measure the variables of interest, nonlinear models are still not very common. In order to accurately estimate the constraints and features of the COVID-19 pandemic, which is asymmetrical and characterized by unanticipated changes that linear models are unable to capture, nonlinear models, are required. In addition, linear models are incapable of handling the complex and asymmetric high-frequency data dynamics associated with COVID-19 data. As a result, enhanced nonlinear models such as the Fourier autoregressive distributed lag cointegration test, Breitung and Candelon causality test, and Markov switching regression were used to reexamine this subject.

To this end, the remainder of this work is organized as follows: Section 2 summarizes previous studies on this topic. Section 3 discusses the variables and econometric approaches. Section 4 presents the findings and discussions. Section 5 has the conclusion.

2. Literature Review

This section will be subdivided into three subsections, each discussing the paper's highlighted issues. The objective of the first subsection is to investigate the impact of the COVID-19 pandemic on environmental sustainability. The objective of the second subsection is to explore the impact of renewable energy on environmental sustainability. The objective of the third subsection is to examine the impact of non-renewable energy on environmental sustainability. They are presented with the following layout:

2.1. Effect of the COVID-19 Pandemic on Environmental Sustainability

The pandemic caused by COVID-19 is having an effect on human activities, which in turn will have an effect on carbon dioxide emissions. Based on data that was collected in almost real-time, Liu et al. [7] provided daily estimates of carbon dioxide emissions at the national level for a variety of different industries. They discovered that the pandemic's impacts on worldwide emissions decreased as lockdown prohibitions were loosened and several economic activities resumed, particularly in China and a some European countries. However, considerable differences in progress were observed between countries, with emissions tending to decline in the United States, where COVID-19 confirmed cases were still rising significantly. Meanwhile, Nguyen et al. [8] discovered that, as a consequence of the COVID-19 pandemic, the brief lockdown periods led to significant reductions in daily worldwide carbon dioxide emissions. In addition, the favorable effects on the local environment were obvious in the decreased output and global migration between cities and regions. Moreover, Aktar et al. [9] observed that the lockdown had precipitated a worldwide economic shock at an alarming rate, leading to severe recessions in several nations. At the same time, the lockdowns triggered by the COVID-19 pandemic radically altered global patterns of energy use and decreased carbon dioxide emissions. Tan et al. [10] found that carbon dioxide emissions for the globe and Malaysia were reduced substantially by 4.02% (1365.83 Mt carbon dioxide emissions) and 9.7% (225.97 Mt carbon dioxide emissions) in 2020, respectively, compared to 2019. In addition, Le Quéré et al. [11], Peng and Jimenez [12], Andreoni [13], and Bertram et al. [14] all corroborated this conclusion.

2.2. Effect of the Effect of Renewable Energy on Environmental Sustainability

Environmental contamination is one of the most important concerns affecting the contemporary world. Because it impacts billions of people, environmental degradation has attracted a considerable amount of attention from scientists and academics. The use of renewable energy as a viable alternative has garnered the support of a significant number of academics as a potential solution to this issue. Anwar et al. [15] investigated the influence that the usage of renewable energy had on carbon dioxide emissions in fifteen Asian economies from 1990 to 2014. After conducting an empirical investigation using methodologies such as impulse response function and variance decomposition, they came to the conclusion that consuming renewable energy sources resulted in lower levels of carbon dioxide emissions. Lei et al. [16] examined the dynamic effects of energy efficiency and renewable energy consumption on China's carbon dioxide emissions between 1991 and 2019. Using the non-linear autoregressive distributed lag technique, they revealed that renewable energy consumption with a positive shock had a large negative influence on carbon dioxide emissions, but renewable energy consumption with a negative shock resulted in an increase in pollutant emissions in the long term. Furthermore, positive shocks to renewable energy usage had a short-term negative impact on carbon dioxide emissions. Mirziyoyeva and Salahodjaev [17] used panel data methodologies to investigate the link between renewable energy and carbon dioxide emissions intensity in the most carbon-intensive countries from 2000 to 2015. Their findings, which were based on the two-step generalized moment method and fixed effects regression for empirical analysis, demonstrated that the use of renewable energy had a substantial and detrimental impact on carbon dioxide emissions. To be more specific, a reduction in carbon dioxide emissions of 0.98% was achieved for every percentage increase in the use of renewable sources of energy.

Furthermore, this result was supported by the research conducted by Rahman et al. [18], Fan and Tahir [19], Qudrat-Ullah [20], and Adebayo et al. [21].

2.3. Effect of Non-renewable Energy on Environmental Sustainability

For a very long time, fast economic expansion has been contingent on a large consumption of non-renewable energy. Despite the fact that this has led to an improvement in our quality of life, it has also resulted in significant harm to the environment. As a result of this, a significant number of academics have begun to investigate the effect that non-renewable energy has on the emission of carbon dioxide. Mohsin et al. [22] adopted nonlinear techniques such as causality-in-quantiles, wavelet coherence, and quantile-on-quantile regression to investigate the influence of fossil fuel energy consumption on carbon dioxide emissions in European and Central Asian countries from 1989 to 2021. They identified that the use of energy derived from fossil fuels had a beneficial effect on carbon dioxide emissions in the short, medium, and long term; however, the impact varied depending on the periods and frequencies at which it occurred. Tan et al. [23] investigated, via the use of the dynamic autoregressive distributed lag method, how changes in China's non-renewable energy consumption influenced carbon dioxide emissions from 1990 to 2019. They determined that greater usage of fossil fuels led to higher carbon dioxide emissions. Specifically, carbon dioxide emissions per capita increased by 0.311% for every 1% rise in per capita fossil fuel usage. Similarly, Uzair Ali et al. [24] used yearly data from 1971 to 2014 to evaluate the influence of fossil fuel usage on carbon dioxide emissions in India, Pakistan, and Bangladesh. They unearthed that, in the long run, fossil fuel usage had a positive influence on carbon dioxide emissions using a panel autoregressive distributed lag. Moreover, Rezaei Sadr et al. [25] assessed this issue based on panel data from 1995 to 2019 using fully modified ordinary least squares and dynamic ordinary least squares regression techniques in three Western European countries. They found that crude oil consumption had the greatest influence on both models in terms of carbon dioxide emissions. Additionally, this finding was corroborated by the studies carried out by Vo and Vo [26], Mujtaba et al. [27], Omri and Saidi [28], and Saleem et al. [29].

3. Variable Description and Econometric Approach

3.1. Variable Description

The goal of this study is to identify the effect of energy and the COVID-19 pandemic on environmental sustainability (carbon dioxide emissions are a proxy for environmental sustainability) using a sample from China. The daily dataset covers the time span beginning on 20 January 2020 and ending on 20 April 2022. There are four variables being investigated in this paper. They are the COVID-19 confirmed cases, renewable energy, fossil fuel energy, and carbon dioxide emissions. Because the daily data on renewable energy and fossil fuel energy cannot be available, the stock prices of the two most representative renewable energy companies and fossil energy companies in China are considered proxy variables for renewable energy and non-renewable energy, respectively. The basic idea behind this concept is that changes in the price of energy may almost instantaneously be reflected in both supply and demand for energy. To put it another way, the ebb and flow of energy prices may, to a certain degree, mirror the state of affairs regarding energy consumption. These highlighted variables are sourced from Johns Hopkins University, the Chinese Center for Disease Control and Prevention, Carbon Monitor, and Invest.com. The forms and definitions of these four investigated variables are provided in Table 1, which is required for gaining an in-depth understanding of them for the whole work.

Table 1. Results of variable description.

Variable	Form	Definition	Source
Carbon dioxide emissions	corb	Carbon dioxide emissions per day million tons in log	Carbon Monitor
COVID-19 pandemic	covid	Number of COVID-19 confirmed cases in log	Johns Hopkins University; Chinese Center for Disease Control and Prevention
Renewable energy	rene	Stock price of Fujian Funeng Company (600483) in log	Invest.com
Fossil fuel energy	foss	Stock price of China Shenhua Energy Company (601088) in log	Invest.com

3.2. Econometric Approach

3.2.1. Unit Root Test

In this study, we investigate the stationary characteristics of these four highlighted variables by using the Augmented Dicky–Fuller test and the Fourier-Augmented Dicky–Fuller test. The expression of the Augmented Dicky–Fuller test is shown as follows:

$$\Delta y_t = \rho y_{t-1} + \rho_1 \Delta y_{t-1} + \rho_2 \Delta y_{t-2} + \ldots + \rho_n \Delta y_{t-n} + \delta \chi_t + \mu_t \quad (1)$$

where Δ denotes the difference operator; μ_t denote the white noise. The introduction of the lagged term was undertaken so as to solve the problem of autocorrelation. It is well known that the Augmented Dicky–Fuller test does not have the capacity to identify the structural breakpoints of these investigated variables. It is possible that these investigated variables went through certain structural modifications, which might lead to a variety of different kinds of nonlinearity. Omay [30], Tsong et al. [31], and Narayan and Popp [32] improved the Augmented Dicky–Fuller test for a nonlinear framework by using a Fourier function that was made up of a variety of frequency components. The following equation provides a definition of a Fourier function:

$$y_t = \rho_0 + \rho_1 t + \sum_{i=1}^{p} \gamma_i \sin\left(\frac{2\pi i t}{n}\right) + \sum_{j}^{p} \beta_i \cos\left(\frac{2\pi j t}{n}\right) \quad (2)$$

where ρ_0 denotes the coefficient of intercept; ρ_1 denotes the coefficient of trend; γ_i denotes the dynamics displacement; β_i denotes the amplitude; p is less than half of n; t belongs to one and two; i and j denote the nonlinear parameters. Nonlinearity occurs when either i or j is significant in statistic. However, the highlighted variable will be linear when i and j are zero.

3.2.2. Fourier Autoregressive Distributed Lag Cointegration Test

The cointegration test was carried out so that we could identify these highlighted variables that were responsible for the study's long-term connection. In order to achieve cointegration, all these four highlighted variables must be integrated using the same sequence. The Fourier autoregressive distributed lag cointegration developed by Güriş [33], Yilanci and Tunali [34], and Westerlund and Edgerton [35] is used in this paper. When compared with conventional cointegration tests developed by Kremers et al. [36], Doornik [37], and MacKinnon [38], the Fourier autoregressive distributed lag cointegration test is superior because of its ability to identify a series of nonlinear long-run associations. This test removes the need to determine the duration of the breaks and prevents power loss that may occur when using dummies for an excessive amount of time. For this test, the formula is shown as follows:

$$\Delta y_{1t} = d_t + \Delta y_{1,t-1} + \tau \Delta y_{2,t-1} + \mu_t \quad (3)$$

where the null hypothesis is that there is no cointegration while the alternative hypothesis is that there is a cointegration.

3.2.3. Markov Switching Approach

The Markov switching approach, which was developed by Hamilton [39] and is a superior alternative in comparison to other statistical procedures, was used on the variables of research because of the nonlinearity characteristic of the variables as well as a quick shift in the variation in the variables of the study. This technique is an option that does not follow a linear progression. The fundamental ideas behind this approach are very malleable and may be modified in response to changes in regime transitions. In fact, this method is applicable in situations in which the variables are not stationary. Nonlinearity happens when a process passes through discrete changes in regimes, which are occurrences in which the dynamic behavior of a certain series behaves differently, as described by Hamilton [40]. This is when nonlinearity arises. The following is an expression that may be used to describe the Markov switching regression with two different regimes:

$$y_t = a_1 + \sum_{i=1}^{p} b_{1,i} y_{t-1} + a_{1,t} \text{ with } s_t = 1 \quad (4)$$

$$y_t = a_2 + \sum_{i=1}^{p} b_{2,i} y_{t-1} + a_{2,t} \text{ with } s_t = 2 \quad (5)$$

where $a_{1,t} \sim N(0,\ \sigma_i^2)$; s_t denotes the state variable constrained by the first-order Markov chain. In order to represent the different probabilities of transition, the following matrix structure may be utilized:

$$P = \begin{bmatrix} \rho_{11} & \rho_{12} \\ \rho_{21} & \rho_{22} \end{bmatrix} \quad (6)$$

if the ρ_{ij} value is quite small, the structure will continue to be in state i for a considerable amount of time. The expected state duration is $\frac{1}{\rho_{ij}}$, and the number of regime (r) is greater than two.

3.2.4. Non-Linear Autoregressive Distributed Lag Approach

In order to investigate the connection between the highlighted variables, the non-linear autoregressive distributed lag approach is employed in this article. The asymmetric autoregressive distributed lag approach can be applied in situations in which the highlighted variables are either I(0) or I(1), or both I(0) and I(1). The non-linear autoregressive distributed lag approach requires efficient lag selection, and endogeneity problems may be alleviated by choosing an appropriate lag length. Following Shin et al. [41] and Katrakilidis and Trachanas [42], having an appropriate lag can also be helpful in tackling the challenges posed by probable multicollinearity in the non-linear autoregressive distributed lag approach. The non-linear autoregressive distributed lag approach is used to segregate variables based on the positive and negative shifts that each variable exhibits. In the model, fossil fuel energy, renewable energy, and the number of COVID-19 confirmed cases are reduced to positive and negative movements. The variables are transformed into shocks as $rene^+$, $rene^-$, $foss^+$, $foss^-$, $covid^+$, and $covid^-$. Furthermore, the partial sum of the movements for rene, foss, and covid is presented as follows:

$$rene^+ = \sum_{i=1}^{t} \Delta rene^+ + \sum_{i=1}^{t} \max(rene_i,\ o) \quad (7)$$

$$rene^- = \sum_{i=1}^{t} \Delta rene^- + \sum_{i=1}^{t} \min(rene_i,\ o) \quad (8)$$

$$foss^+ = \sum_{i=1}^{t} \Delta foss^+ + \sum_{i=1}^{t} \max(foss_i,\ o) \quad (9)$$

$$foss^- = \sum_{i=1}^{t} \Delta foss^- + \sum_{i=1}^{t} \min(foss_i,\ o) \quad (10)$$

$$covid^+ = \sum_{i=1}^{t} \Delta covid^+ + \sum_{i=1}^{t} \max(covid_i,\ o) \quad (11)$$

$$covid^- = \sum_{i=1}^{t} \Delta covid^- + \sum_{i=1}^{t} \min(covid_i,\ o) \quad (12)$$

the basic model used in this paper is shown as follows:

$$\text{corb}_t = a_0 + a_1\text{rene}_t + a_2\text{foss}_t + a_3\text{covid}_t + \mu_t \tag{13}$$

where a_0 denotes the constant; $[a_1,\ a_3]$ denote the estimated coefficients; μ_t denotes the white noise. Moreover, the following equation can be used to combine both long-run and short-run dynamics in the non-linear autoregressive distributed lag model.

$$\begin{gathered}\Delta\text{corb}_t = b_0 + \sum_{i=1}^{t} b_1\Delta\text{corb}_{t-i} + \sum_{i=1}^{t} b_2\Delta\text{rene}_{t-i}^{+} + \sum_{i=1}^{t} b_3\Delta\text{rene}_{t-i}^{-} + \\ \sum_{i=1}^{t} b_4\Delta\text{foss}_{t-i}^{+} + \sum_{i=1}^{t} b_5\Delta\text{foss}_{t-i}^{-} + \sum_{i=1}^{t} b_6\Delta\text{covid}_{t-i}^{+} + \sum_{i=1}^{t} b_7\Delta\text{covid}_{t-i}^{-} + \mu_t\end{gathered} \tag{14}$$

where b_0 denotes the constant; $[b_1,\ b_7]$ denote the estimated coefficients; μ_t denotes the white noise. By simply adding an error correction term to Equation (14), it is possible to convert Equation (14) into an error correction model.

$$\begin{gathered}\Delta\text{corb}_t = c_0 + \sum_{i=1}^{t} c_1\Delta\text{corb}_{t-i} + \sum_{i=1}^{t} c_2\Delta\text{rene}_{t-i}^{+} + \sum_{i=1}^{t} c_3\Delta\text{rene}_{t-i}^{-} + \\ \sum_{i=1}^{t} c_4\Delta\text{foss}_{t-i}^{+} + \sum_{i=1}^{t} c_5\Delta\text{foss}_{t-i}^{-} + \sum_{i=1}^{t} c_6\Delta\text{covid}_{t-i}^{+} + \sum_{i=1}^{t} c_7\Delta\text{covid}_{t-i}^{-} + \\ \lambda\text{ect}_{t-1} + \mu_t\end{gathered} \tag{15}$$

where c_0 denotes the constant; $[c_1,\ \lambda]$ denote the estimated coefficients; ect denotes the error correction term; μ_t denotes the white noise.

3.2.5. Frequency Domain Causality Test

This approach is inspired by the work that was undertaken by Geweke [43], and Hosoya [44], who developed measurements of causality in the frequency domain. First, assume that $z_t = [x_t,\ y_t]'$ is an observing time series's two-dimensional vector at $t \in [1,\ T]$. Let z_t be a vector autoregressive representation with a finite order:

$$\Theta(L)z_t = \mu_t \tag{16}$$

where $\Theta(L) = I - \Theta_1 L - \ldots - \Theta_p L^p$ is a 2×2 lag polynomial with $L^k z_t = z_{t-k}$. Let the error vector (μ_t) be the white noise that has $E(\mu_t) = 0$ and $E(\mu_t\mu_t') = \sum$, where $\sum$ denotes the positive definite. For the sake of clarity, we disregard any deterministic components in Equation (1), despite the fact that empirical applications frequently contain constants, trends, or dummy variables. Assume that G denotes the lower triangular matrix of the Cholesky decomposition $G_t' G_t = \sum^{-1}$ such that $E(\eta_t\eta_t') = I$ and $\eta_t = G\mu_t$. Under the assumption that the system is stationary, the MA representation of the system appears as follows:

$$z_t = \Phi(L)\mu_t = \begin{bmatrix}\Phi_{11}(L) & \Phi_{12}(L)\\ \Phi_{21}(L) & \Phi_{22}(L)\end{bmatrix}\begin{bmatrix}\mu_{1t}\\ \mu_{2t}\end{bmatrix} = \psi(L)\eta_t = \begin{bmatrix}\psi_{11}(L) & \psi_{12}(L)\\ \psi_{21}(L) & \psi_{22}(L)\end{bmatrix}\begin{bmatrix}\varepsilon_{1t}\\ \varepsilon_{2t}\end{bmatrix} \tag{17}$$

where $\Phi(L) = \Theta(L)^{-1}$ and $\psi(L) = \psi(L)G^{-1}$. The spectral density x_t can be described employing this representation as follows:

$$f_x(\omega) = \frac{\left\{\left|\psi_{11}\left(e^{-i\omega}\right)\right|^2 + \left|\psi_{12}\left(e^{-i\omega}\right)\right|^2\right\}}{2\pi} \tag{18}$$

Following Hosoya [44] and Geweke [43], the measure of causality is defined as follows:

$$M_{y\to x}(\omega) = \log\left[\frac{2\pi f_x(\omega)}{\left|\psi_{11}\left(e^{-i\omega}\right)\right|^2}\right] = \log\left[1 + \frac{\left|\psi_{12}\left(e^{-i\omega}\right)\right|^2}{\left|\psi_{11}\left(e^{-i\omega}\right)\right|^2}\right] \tag{19}$$

When $\psi_{12}(e^{-i\omega})$ is zero, the measure is zero, in which situation we claim that y does not cause x at frequency ω. When the elements of z_t is cointegrated at $I(1)$, $\Theta(L)$ has a unit root. The remaining roots are not included inside the unit circle. Taking z_{t-1} away from both sides, Equation (15) yields:

$$\Delta z_t = (\Theta_1 - I)z_{t-1} + \Theta_2 z_{t-2} + \ldots + \Theta_p z_{t-p} + \mu_t = \widetilde{\Theta}(L)z_{t-1} + \mu_t \quad (20)$$

where $\widetilde{\Theta}(L) = \Theta_1 - I + \Theta_2 L + \ldots + \Theta_p L^p$. when y is not a cause of x in the usual Granger sense, following Toda and Phillips (1994), the [1, 2]-element of $\Theta(L)$ or $\widetilde{\Theta}(L)$ is zero. The orthogonalized MA representation can be used to determine the measure of causality in the frequency domain:

$$\Delta z_t = \widetilde{\Phi}(L)\mu_t = \widetilde{\Psi}(L)\eta_t \quad (21)$$

where $\widetilde{\Psi}(L)$ is equal to $\widetilde{\Phi}(L)G^{-1}$; η_t is equal to $G\mu_t$; G denotes a lower triangular matrix such that $E(\eta_t\eta_t^{'})$ is equal to I. Following Engle and Granger [45], $\beta^{'}\widetilde{\Psi}(1)$ is equal to zero in a bivariate cointegrated system. When β is a cointegration vector, $\beta^{'}z_t$ will be stationary. Similar to the situation of stationarity, the resultant causality measure is shown as follows:

$$M_{y\to x}(\omega) = \log\left[1 + \frac{\left|\widetilde{\psi}_{12}(e^{-i\omega})\right|^2}{\left|\widetilde{\psi}_{11}(e^{-i\omega})\right|^2}\right] \quad (22)$$

There is potential for the causality measure to be used in systems with a higher dimension. The approach proposed by Hosoya [46] is predicated on the bivariate causality measure that is obtained by "conditioning out" the third variable. Assume that the causal effect of y_{1t} on y_{2t} in a three-dimensional system with $y_t = [y_{1t}, y_{2t}, y_{3t}]^{'}$ is measured. Meanwhile, assume that w_t denotes the projection residual from a projection of y_{3t} onto the Hilbert space $H \in [y_{1t}, y_{t-n}]$. In addition, $\epsilon_t(\nu_t)$ denotes the projection residual from a projection of $y_{1t}(y_{2t})$ on $H \in [w_t, w_{t-n}]$. The form is shown as follows:

$$\begin{bmatrix} \Delta y_{1t} \\ \Delta y_{2t} \\ \Delta y_{3t} \end{bmatrix} = \begin{bmatrix} \psi_{11}(L) & \psi_{12}(L) & \psi_{13}(L) \\ \psi_{21}(L) & \psi_{22}(L) & \psi_{23}(L) \\ \psi_{31}(L) & \psi_{32}(L) & \psi_{33}(L) \end{bmatrix} \begin{bmatrix} \eta_{1t} \\ \eta_{2t} \\ \eta_{3t} \end{bmatrix} \quad (23)$$

where $\epsilon_t = \psi_{11}(L)\eta_{1t} + \psi_{12}(L)\eta_{2t}$; $\nu_t = \psi_{21}(L)\eta_{1t} + \psi_{22}(L)\eta_{2t}$. The causality measure developed by Hosoya [46] is equal to the bivariate causality measure between ϵ_t and ν_t:

$$M_{y_1\to y_2|y_3}(w) = M_{\epsilon\to\nu}(w) \quad (24)$$

consequently, the causality measure in higher-dimensional systems may be stated as a bivariate causality measure as long as the variables are correctly converted.

4. Results and Discussions

4.1. Unit Root Test

In this article, two distinct types of unit root tests are used in order to validate the stationarity of the four variables that were under investigation. They are the Augmented Dicky–Fuller test and the Fourier-Augmented Dicky–Fuller test. The results are shown in Table 2.

The results of the Augmented Dicky–Fuller test are shown in Panel A of Table 2. It is found that carbon emissions and renewable energy are not stationary, while COVID-19 confirmed cases and fossil energy are stationary at levels. However, after taking the first difference, these four investigated variables become stationary. Moreover, the Fourier-Augmented Dicky–Fuller test is used to confirm these four investigated variables. The reason is that the Fourier-Augmented Dicky–Fuller test has the benefit of identifying the stationarity features of a nonlinear series. The results of the Fourier-Augmented Dicky–Fuller test are shown in Panel B of Table 2. Carbon emissions are seen to be nonstationary, whereas the other three variables are stationary at their levels. However, these four variables under consideration are stationary in their first differences.

Table 2. Results of unit root test.

Panel A: Augmented Dicky–Fuller Test		
Variable	Level	First difference
corb	−2.352	−2.746 ***
covid	−5.419 ***	−9.028 ***
rene	−1.945	−14.425 ***
foss	−3.802 **	−23.817 ***
	Panel B: Fourier-Augmented Dicky–Fuller test	
Variable	Level	First difference
	−2.089	−2.228 ***
corb	(1.000)	(3.000)
	[−3.48]	[−3.79]
	−6.189 ***	−8.589 ***
covid	(1.000)	(5.000)
	[−4.47]	[−3.56]
	−4.557**	−22.774 ***
rene	(4.000)	(4.000)
	[−2.95]	[−3.67]
	−4.291 *	−24.481 ***
foss	(5.000)	(5.000)
	[−2.66]	[−3.56]

Note: frequency shown in the parentheses; critical value of F-statistic shown in the bracket; *** 1% significant level; ** 5% significant level; * 10% significant level.

4.2. Fourier Autoregressive Distributed Lag Cointegration Test

The objective of this subsection is to investigate the link between these four examined variables in the long run. In contrast to previous research such as Aruga et al. [47] and Iqbal et al. [48], the Fourier autoregressive distributed lag cointegration test is utilized to determine the long-term relationship between carbon emissions, renewable energy, fossil energy, and COVID-19 confirmed cases. The Fourier autoregressive distributed lag cointegration test has the advantage of capturing long-run associations between series, even if the series is nonlinear and has unknown structural breakpoints. The results of the Fourier autoregressive distributed lag cointegration test are shown in Table 3.

Table 3. Results of Fourier autoregressive distributed lag cointegration test.

Model	**F-Statistics**	**Frequency**	**Akaike Information Criterion**
corb = f(covid, rene, foss)	−9.892 *** Critical value 10% −3.20	1 Critical value 5% −3.67	28.156 Critical value 1% −4.66

Note: Akaike information criterion selects the minimum value; *** 1% significant level.

The findings in Table 3 suggest that the absolute value of the F-statistics (9.892) is greater than the absolute value of the 1% critical value (4.66). As a result, it is concluded that the null hypothesis of no cointegration is rejected at a 1% significant level. In other words, the long-term association between carbon emissions and the three other variables under study can be validated.

4.3. Effects of Energy and COVID-19 Pandemic on Environmental Sustainability

This subsection takes the nonlinear auto-regressive distributed lag technique to look at how energy and the COVID-19 pandemic affect carbon dioxide emissions, which are a proxy for environmental sustainability. The results are shown in Table 4.

Table 4. Results of effects of energy and COVID-19 pandemic on environmental sustainability.

Variable	Corb: Environmental Sustainability
$covid^{+}$	−0.006 *** (−8.339)
$covid^{-}$	0.001 *** (7.352)
$rene^{+}$	−0.016 *** (−7.013)
$rene^{-}$	0.024 *** (5.925)
$foss^{+}$	0.080 ** (2.035)
$foss^{-}$	0.065 *** (2.579)
ect_{-1}	−0.036 *** (−5.337)
c	0.038 ** (1.969)

Note: c constant; the value of t-statistics shown in the parentheses; ** 5% significant level; *** 1% significant level; ect error correction term.

According to Table 4, a negative variation in COVID-19 confirmed cases is associated with a reduction in carbon dioxide emissions, while a positive variation in COVID-19 confirmed cases is associated with an increase in carbon dioxide emissions. One probable explanation for this discovery is that, in order to slow the spread of COVID-19, the Chinese government has implemented related rules requiring the reduction or closure of some factories' production. At the same time, travel and transit constraints are one of the factors that may contribute to this result. Of course, this finding was also supported by Li et al. [49] and Habib et al. [50]. Meanwhile, this finding corroborates the validity of Hypothesis 1 (H1). Equally, in China, a positive movement in renewable energy consumption reduces carbon dioxide emissions, while a negative movement in renewable energy usage raises carbon dioxide emissions. These findings were consistent with Radmehr et al. [51], who studied this topic in European Union countries. Similarly, with a sample of India, Qayyum et al. [52] also verified these findings. However, these results contradict those of Kirikkaleli and Adebayo [53] and Sinha and Shahbaz [54], who discovered a positive correlation between the two variables. This is probably because of the fact that renewable technologies focus on clean energy. It is devoted to satisfying present and future demands and is a source of pollution reduction. These findings in China are achievable, as the country has undertaken a number of policies to increase the use of renewable energy and decrease the use of polluting fossil fuels. This conclusion also demonstrates that the rationale behind Hypothesis 2 (H2) is correct. Moreover, the shocks from fossil fuels have a favorable impact on carbon dioxide emissions. Farhani and Shahbaz [55] validated similar results using data from ten countries in the Middle East and North Africa from 1980 to 2009. One probable explanation is that China's economic progress over the last 30 years has been fueled by the substantial use of fossil fuels. This finding further substantiates support for Hypothesis 3 (H3).

4.4. Robustness Test

The Markow switching regression model is used to reevaluate the impact of energy and the COVID-19 pandemic on carbon dioxide emissions. This is implemented to maintain the accuracy and reliability of the results in Table 4. The results are shown in Table 5.

The results in Table 5 show that in the first and second regimes, the COVID-19 pandemic confirmed cases and renewable energy have a negative impact on carbon dioxide emissions, whereas fossil fuel energy has a favorable impact. These findings are basically congruent with those provided in Table 4. In other words, the findings in Table 4 are reliable and accurate.

Table 5. Results of robustness test.

Variable	Regime 1	Regime 2
covid	−0.016 *** (−3.750)	−0.007 *** (−7.863)
rene	−0.006 *** (−10.197)	−0.082 *** (−7.108)
foss	0.027 *** (15.958)	0.034 *** (16.755)
c	1.526 *** (7.056)	1.533 *** (13.033)

Note: c constant; the value of z-statistics shown in the parentheses; *** 1% significant level.

4.5. Frequency Domain Causality Test

In this subsection, the frequency domain casualty test is used to explore the causal relationship between the COVID-19 pandemic confirmed cases, renewable energy, fossil fuel energy, and carbon dioxide emissions. An advantage of this method is that the causal link between carbon dioxide emissions and the investigated variables can be captured at different frequencies. The results are shown in Table 6.

Table 6. Results of frequency domain causality test.

Hypothesis	Short-Run		Medium-Run		Long-Run	
	$w_i = 2.50$	$w_i = 2.00$	$w_i = 1.50$	$w_i = 1.00$	$w_i = 0.05$	$w_i = 0.01$
covid ↛ corb	9.023 *** (0.000)	5.359 * (0.092)	7.689 ** (0.042)	7.134 ** (0.047)	10.278 *** (0.000)	11.284 *** (0.000)
rene ↛ corb	1.231 (0.517)	1.355 (0.503)	1.014 (0.604)	5.447 * (0.086)	16.631 *** (0.000)	17.463 *** (0.000)
foss ↛ corb	10.577 *** (0.000)	15.962 *** (0.000)	13.307 *** (0.000)	17.968 *** (0.000)	18.018 *** (0.000)	20.259 *** (0.000)

Note: *p*-value shown in the parentheses; * 10% significant level; ** 5% significant level; *** 1% significant level.

The results of Table 6 demonstrate that at all frequencies, COVID-19 pandemic confirmed cases cause carbon dioxide emissions. This suggests that COVID-19 pandemic confirmed cases are a reliable assessment of China's carbon dioxide emissions. Meanwhile, fossil fuel energy causes carbon dioxide emissions at all frequencies. This indicates that it is capable of accurately predicting carbon dioxide emissions. Renewable energy, however, cannot cause carbon dioxide emissions in the short run, but it can cause carbon dioxide emissions in the long run. In addition, it is possible to consider these findings to be supplementary to the results presented in Table 4.

5. Conclusions

Every facet of society has been impacted as a result of the combined effects of the COVID-19 pandemic and the conflict that is now going on between Russia and Ukraine. Therefore, this paper examines the effects of energy and the COVID-19 pandemic on China's carbon dioxide emissions (a proxy for environmental sustainability) from 20 January 2020 to 20 April 2022. By using a nonlinear autoregressive distributed lag model for empirical study, the results demonstrate that the COVID-19 pandemic confirmed cases and renewable energy promote environmental sustainability with negative consequences on carbon dioxide emissions, while fossil fuel energy inhibits environmental sustainability, resulting in positive consequences on carbon dioxide emissions. In addition, the outcomes of the frequency domain causality test and the Markow switching regression confirm these findings.

In light of the empirical results discussed in this paper, several policy implications have been presented. First, it is advantageous to environmental sustainability for the government to adopt relevant actions, such as boosting the vaccination rate and enhancing the early warning level of COVID-19, to reduce the rising trend of the number of confirmed cases of COVID-19. Second, the government needs to put more effort into the production of renewable energy and its usage. The rationale for this is that these actions could help the environment remain healthy in the long run. Third, as is well known, the consumption of fossil fuels has been the primary driver of China's economic expansion and the leading cause of environmental degradation for a very long time. In order to achieve both environmental and economic sustainability, the government should expedite the development of alternatives to fossil fuels.

This paper's findings provide three noteworthy contributions to the current body of knowledge. First, it has come to our attention that no piece of literature that investigated the connection between the COVID-19 pandemic, energy, and environmental sustainability was targeted at China. Second, there is an extensive research contribution in the field of environmental sustainability and energy. The majority of investigations into environmental sustainability and energy did not include the COVID-19 pandemic. Instead, the focus is on economic progress, as seen by the vast majority of papers examined in this context. This research thus examined the COVID-19 pandemic, environmental sustainability, and energy in the same framework in order to gain an in-depth understanding of the topic. Third, in the current studies, a quantitative contribution has been found. Nonlinear models are unusual, despite the fact that a number of techniques, including autoregressive distributed lag, generalized method of moments, and Granger causality, have been used in publications to evaluate the variables of interest. Nonlinear models are essential for estimating the limitations and characteristics of the COVID-19 pandemic, which are asymmetrical and marked by unexpected changes that linear models can not represent. Furthermore, linear models cannot deal with the complicated and asymmetric high-frequency data dynamics linked with COVID-19 data. Consequently, improved nonlinear models such as the Fourier autoregressive distributed lag cointegration test, nonlinear autoregressive distributed lag, Breitung and Candelon causality test, and Markov switching regression were used to re-investigate this topic.

Lastly, both the limitations of this study as well as possible future directions that this line of inquiry may go are noted in this paper. First, due to China's vast area, the extent of the COVID-19 outbreak in various regions varies substantially. Future scholars may split China into three regions, namely the eastern region, the central region, and the western region, and conduct a separate examination of this topic, which may result in more intriguing discoveries. Second, this article only uses China as a sample, so the findings may be biased. Future researchers may thus add the United States, the United Kingdom, India, and other countries to the sample and re-analyze this issue using the panel technique, which may result in more trustworthy and robust conclusions. Third, using the prices of renewable energy and nonrenewable energy to replace the usage of renewable energy and nonrenewable energy may be contentious. Future researchers may re-conduct empirical studies on this issue using other proxy variables or daily data on energy usage, which may lead to more credible and intriguing findings.

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Article

In Search of Non-Obvious Relationships between Greenhouse Gas or Particulate Matter Emissions, Renewable Energy and Corruption

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Abstract: The article concerns the issue of the existence of non-obvious relationships and of potential correlations between the emission of greenhouse gases and particulate matter (PM), renewable energy and corruption perceptions. Additionally, it analyses the possible impact of these above-mentioned connections on the economic, environmental and social situation in the context of further economic development, including during the COVID-19 pandemic and in relation to European countries. The issue of reducing dirty energy sources and corrupt activities is not only a problem considered at the state level, but it is very closely related to the operation of many private enterprises. The conducted research applied methods of desk research as well as comparative quantitative analyses and used extensive statistical data of most European Union member states as well as the United Kingdom and Norway. The ambiguity of the results obtained in the research does not allow for an explicit verification of the existence of relationships between corruption and the pro-ecological initiatives influencing the lower intensity of greenhouse gases and particulate matter (PM) to the atmosphere or increasing share of renewable energy in the whole energy consumption. However, in many analysed cases it is possible to observe the occurrence of the indicated relationships, which, although not considered to be a rule, may give direction to further detailed research in this area, in particular in order to show the resulting beneficial or unfavourable implications for the performance and development of companies and the economy as a whole with rules of sustainability.

Keywords: environmental protection; environmental problems; greenhouse gas; particulate matter (PM); renewable energy; corruption

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1. Introduction

Environmental greenhouse gas pollution, in particular CO2 emissions resulting from energy generation as well as dust emissions into the atmosphere, have been a key problem in the international fora for many years. As a result, many pro-ecological initiatives are being undertaken in the context of further development of the global economy in order to reduce the scale of this phenomenon. An example to be cited may be 17 Sustainable Development Goals set under the 2030 Agenda and a strong emphasis laid there on activities in favour of green energy solutions and clean air [1–5]. Similarly to the actions of the European Commission, which on 14 July 2021, adopted a package of legislative proposals "Fit for 55" [6]. This was done under the European Green Deal, whose priority is to strengthen the EU's position as a global climate leader. This will be a challenge for many Member States and is already the subject of harsh domestic criticism and purely political disputes, especially when the exceptionally strong lobby of industry organizations and trade unions in the "dirty" energy sectors in some countries is taken into account. The question is, how can progress in this area be operationalized and possible obstacles and limitations identified, bearing in mind numerous comments and even questioning the measures of achieving the sustainable development goals [7–9]?

The problem of reducing the greenhouse gas emissions intensity of energy consumption has been studied for many years, but there are no clear deadlines for its solution yet [10–14]. The same applies to the intensity of emissions of air pollutants, in particular as a consequence of industrial activity. Here, too, despite enormous efforts at the level of international settlements and agreements as well as national activities, often forced by pressure from environmentalists, no success, even a relative one, can be seen and further pro-ecological initiatives in this area are still needed [15–17]. On the other hand, changes in the share of renewable energy in gross final energy consumption on a national scale are much more positive. It should determine not only further actions in the area of reduction in conventional energy sources, but also contribute to the reduction in environmental pollution [18–21].

Having decided to conduct in-depth desk research in these areas, the authors of this article made an attempt to go beyond the existing analytical schemes and to indicate the factor which may positively affect the incomplete implementation of energy goals in the aspect of lower energy consumption and air pollution, and at the same time convergent with the aforementioned Agenda 2030. Importantly, according to the authors, the issue of reducing dirty energy sources is not only a problem considered at the state level, but it is very closely related to the operation of many private enterprises. It is obvious that large energy companies are often transnational corporations whose power of impact often exceeds the capabilities of many countries in the world and which, like most companies, give priority to the shareholder profit maximisation [22,23]. Can one risk a hypothesis then that if, in the countries where corruption phenomena, which are really a sign of weakness of certain public administrative bodies, occur more often, they become a factor inhibiting many processes including, for example, decarbonisation of air, reduction in the emissions of particulate matter and other air pollutants and implementation of renewable energy sources? It is an important issue because corruption, most often measured by the indicator of its perception, does not only destroy citizens' trust in the state [24], but also blocks investor activities, including those in the area of environmental protection. Generally, its occurrence makes these processes run more slowly and does not attract anybody's interest due to the high costs of their implementation and the lack of financial aid from the state. In this situation, in the countries suffering from a high level of corruption, investors do not want to carry out investment activities so as not to expose themselves to the risk of their failure and consequently to financial losses [25,26].

Hence, this article is primarily aimed at the verification of the existence of relationships between the corruption perceptions and the greenhouse gas emissions intensity from energy consumption, the air emissions (particulate matter) intensity from industry and the share of renewable energy in gross final energy consumption by sector. That means, we set ourselves the task of verifying whether it is possible to combine and draw conclusions from two seemingly different research areas: the first one concerning air emissions, greenhouse gases or energy production, and the second, typically socio-economic, which is the corruption measure. Facing the research gap thus defined highlights the originality of our studies; in particular, the literature review shows no previous studies in this scope. The authors noticed the need, apart from cyclical measurement of standard indicators of pollutant emissions, greenhouse gases or energy production, to also identify variables that may significantly affect them. The potential value of the approach we propose will allow for the extension of the field of previous research to include socio-economic aspects and to include non-obvious variables in future analyses.

The conducted research applied the methods of desk research as well as comparative and quantitative analyses, as presented in the section on data and research methodology. For the purpose of this goal, the authors used extensive statistical data on the implementation of some sustainable development goals, the greatest advantage of which is a clear methodology and the possibility of international comparisons.

The authors of the article began this research with a thorough and detailed study of the scientific literature on the subject in the selected area, which allowed highlighting the research gap indicated above. Then, the selection of diagnostic indicators and the selection of countries for the research sample was made, mainly taking into account the complementarity of the variables. The next stage was the presentation of the research results, highlighting their most important elements, which formed the background of the in-depth discussion carried out later. At the end, the final conclusions were presented, including our theoretical contribution, research limitations and quite clear practical implications. All research stages undertaken by the authors were reflected in the structure of the article.

2. Theoretical Framework

A prerequisite for the development of civilisation is a high rate of economic growth, which often results in serious ecological problems, usually overlooked in the corporate accounts due to the classical paradigm of economic rationality generally followed by business companies. As a result, a growing development of civilisation intensifies ecological crises which include a climate crisis, the effects of which are currently so clearly seen by people [27]. Nevertheless, the ecological crisis is manifested not only in the deteriorating state of climate or standard of living of a large part of population, but also in the changes of the entire natural system as well as rising unemployment or financial and economic crises [28–30]. At this point, it is worth emphasising that, to a large extent, this crisis is related to the crisis of human behaviour in the modern world dominated by consumerism, relativism and widespread ignorance [31], all of which degrade all possible manifestations of ethical attitudes, and, consequently, man's responsibility towards other people and the environment often becomes superficial. However, some initiatives are being launched to take into account the Sustainable Development Goals, which can be seen in the financial sector, where financing projects which harm the environment is often abandoned [32]. There is a question, however, to be asked as to why the largest financial institutions did not revise their policy in this area until recently. After all, the significance of the problem of human responsibility for the natural environment was already indicated in the 1980s, with emphasis laid on the relevance of this phenomenon as well as its increasing importance caused by the development of civilisation and growing globalisation [33]. In addition, a strong disruption of the system of values is being observed in science, which is supposed to be based on the truth, freedom, honesty and other axiological foundations [34].

The issues related to the exploitation of the natural environment are the subject to be considered not only by scientists and pro-ecological organisations, but also by every country or business company [35]. The ongoing ecological crisis may soon lead to an ecological catastrophe with unpredictable consequences for the entire world economy as well as human existence and our planet as a whole [36,37]. Therefore, in face of the aforementioned crisis, we need a collective determination to protect our planet [38], bold and fundamental changes in the economic and population policies of states [30], which will also result in the strengthening of the conducted environmental policy. The problem of environmental protection is one of the greatest challenges of humanity in the history of the world, because without maintaining the ecological balance, not only can conducting economic activity turn out to be seriously threatened or even impossible in the near future, but there is also a direct threat to human life [38]. Nowadays, the most important environmental problems include those related to the abuse of natural resources and a negative impact of the global economic system on air, water and soil [39]. It is thought that one of the most urgent solutions is to reduce the concentration of greenhouse gases produced by the power generation sector and industry; they include: carbon dioxide, nitrogen oxide, sulfur oxides or methane [40], and to reduce excessive air pollution with particulate matter, which includes different types of dust: combustible, cement-lime, refractory material, silicon, artificial fertilisers, carbon-graphite, soot and other dusts [41]. Greenhouse gases result in a greenhouse effect, and the emission of particle pollutants PM2.5 and PM10, discharged into the atmosphere as a result of production processes and combustion of solid fuels by industrial plants and households affects human health; and in the long run, it may have consequences for the smooth functioning of the global economy [42,43]. Naturally, there are also other problems, namely: excessive consumerism resulting in a predatory economy of natural resources and overproduction of waste, climate changes resulting from environmental erosion [28], and the phenomenon of the world demographic explosion lasting since the beginning of the last century [44] or broadly perceived urbanisation [45].

It is not difficult to notice that undertaking pro-ecological activities, conducive to the sustainable development of the modern economy, and more broadly to ecological security, has been a leitmotif in the activities of many countries and non-governmental global organisations for a long time [46]. Initiatives in favour of energy production from renewable sources, i.e., those that do not wear out during their operation, play a special role here. This energy is commonly referred to as renewable or green energy and comes from the sun, wind, river water and sea waves, biomass, biogas, biofuels, nuclear energy as well as heat obtained from land, air and water [47]. Its ecological, economic and social benefits are currently undeniable, which is seen by more and more societies, companies as well as countries which are willing to grant subsidies for the development of renewable energy sources [48]. It is worth emphasising that despite the negative effects of the COVID-19 pandemic, "renewable energy set a record in new power capacity in 2020 and was the only source of electricity generation to register a net increase in total capacity", China strengthened its commitment to overcome the climate crisis, and the United States re-acceded to the Paris Agreement at the beginning of 2021 [49].

Bearing this in mind, it is worth popularising activities aimed at the environmental protection and reduction in the use of non-renewable fossil fuels. Unfortunately, on a global scale, most economic entities do not have adequate financial resources and need incentives or aid from the state in the form of appropriate financial and/or legal mechanisms to implement green economic initiatives in favour of energy saving, waste reduction, clean production or technological eco-innovations. Such a situation does not have to, although it may, be conducive to the emergence of corruption, which is often defined as abuse of power to achieve private goals, while it must be remembered that corruption occurs not only in the public but also in the private sector [50], and its effect is a higher cost and longer duration of project implementation, lower quality and reduced benefits for most stakeholders [51].

Generally, corruption is born as a result of socio-economic inequalities, but it exists everywhere, knows no borders and is considered a real threat to economic development on both a micro and macroeconomic scale [52]. For example, the level of corruption in the European Union has not improved in the last 12 months, as almost 1/3 of its citizens confirm that the scale of corruption in their country has increased, and 44% of them say that its level has remained unchanged [53]. Such a situation may cause concern, especially since, as a rule, corruption distorts the functioning of market mechanisms, limits the investment potential of entities and inhibits economic growth [54]. In addition, it distorts the transparency and structure of public spending, reduces the profitability of public investments, disrupts the implementation of social goals, bureaucratises state administration, creates ineffective administrative structures and reduces the level of public trust in state authorities [55] and entrepreneurs participating in corruption processes. As a result, the search for relationships which do not always prove explicit between corruption, its perception and undertaking these pro-ecological initiatives seems to be an interesting subject of theoretical deliberation as well as a justified research topic.

3. Data and Research Methodology

The quantitative data obtained for the research presented in the article come from official statistics published by Eurostat on the implementation of the Sustainable Development Goals by 2030. The authors analyzed over several dozen different indicators in this area and chose the ones related to the energy sector. The member states of the European Union, Norway and the United Kingdom were selected for the analysis. The adopted period of time of the analysed data was determined by their availability, it covers the period of 2012–2019. It is also worth emphasizing that the data selected by the authors had a very high degree of completeness, i.e., for most countries they were up-to-date and usable for all the years covered by the study. As new data flow in, the authors will continue their research in the future.

The study examined primarily the correlations between four indicators at the level of each country in the analysed group. The indicators analysed in the study were: corruption perceptions index, greenhouse gas emissions intensity of energy consumption, the air emissions intensity from industry and the share of renewable energy in gross final energy consumption by sector. The detailed definitions of each indicator are as follows:

- Corruption Perceptions Index (CPI) is a composite index based on a combination of surveys and assessments of corruption from up to thirteen different sources and scores and ranks countries based on how corrupt a country's public sector is perceived to be. Importantly, the CPI includes only sources that provide a score for a set of countries or territories and that measure perceptions of corruption in the public sector. For a country or territory to be included in the ranking, what should be emphasized is that it must be included in a minimum of three of the CPI's data sources. The CPI is published on a regular basis, usually annually by the widely recognized and trusted international organization, which is Transparency International [56].
- Greenhouse Gas Emissions Intensity of Energy Consumption (GHGEI) is an indicator calculated as the ratio between energy-related GHG emissions and gross inland consumption of energy [57]. It expresses how many tones CO2 equivalents of energy-related GHGs are emitted in a certain economy per unit of energy that is consumed. Such data on energy emissions are sourced from the GHG emissions reported to the United Nations Framework Convention on Climate Change (UNFCCC) [58].
- Air Emissions Intensity from Industry (AEI) measures the emissions intensity of fine particulate matter (PM2.5) from the manufacturing sector (NACE Rev. 2 sector 'C') [59]. Fine and coarse particles (PM10) are less than 10 micrometres in diameter and can be drawn deep into the lungs, where they can cause inflammation and exacerbate the condition of people suffering from heart and lung diseases. More specifically, fine particles (PM2.5) are less than 2.5 micrometres in diameter and are therefore a subset of the PM10 particles. Note that their negative health impacts are more serious than those of PM10 because they can be drawn further into the lungs and may be more toxic. Whereas emissions intensity is calculated by dividing the sector's PM emissions by its gross value added (GVA), which is defined as output (at basic prices) minus intermediate consumption (at purchase prices).
- Share of Renewable Energy in Gross Final Energy Consumption by Sector (SRE) is an indicator that measures the share of renewable energy consumption in gross final energy consumption according to the Renewable Energy Directive. In this case, the important thing is that the gross final energy consumption is the energy used by end-consumers (final energy consumption) plus grid losses and self-consumption of power plants [60].

We have fully assumed the credibility of the data obtained from the sources and institutions collecting the data we use. Individual deficiencies in the data were shown and they did not affect the analyses performed. The authors carried out a comparative analysis of all indicators in the selected countries, using basic descriptive statistics. In general, they focused on calculating the dynamics of changes of each indicator and measuring the correlations between them, using standard characteristics and strength ranges of correlation: 0.90–1.00 (−0.90 to −1.00)—very high correlation; 0.70 to 0.89 (−0.70 to −0.89)—high correlation; 0.50–0.69 (−0.50 to −0.69)—moderate correlation; 0.30–0.49 (−0.30 to −0.49)—low correlation; 0.00–0.29 (0.00 to −0.29.)—negligible correlation. Due to the limited volume of the article, the authors cannot present all the results, but only the selected ones, which, in their opinion, may constitute valuable research material and a starting point for further research in the future. Including the potential expansion of research with new indicators, such as macro-economic aggregates or financial results of energy companies.

4. Results of the Authors' Own Research

Within the statistical analysis, the authors examined the aforementioned four indicators in nearly thirty countries. Unfortunately, we had to limit the number of countries surveyed due to the problem with the availability of complete statistical data.

Table 1 shows the observed correlations between the indicators examined in each country. Additionally, in order to expose all very strong and strong correlations (both positive and negative), they were highlighted in gray color in the table. In many cases, there were relationships between the emissions of gases or pollutants and the share of renewable energy as well as strong relationships between these indicators and corruption (for example, Austria, Lithuania, Greece, Hungary or Italy). Although there are not enough cases to consider them a rule, this situation points to another area, i.e., corruption, that may have an impact on the lack of more intensive activities in the field of pro-ecological initiatives in each country. It should be noted, however, that in the countries of the so-called Old Union, these relationships are weaker than in the case of the new member states, in which modernisation processes in industry, aimed at switching to cleaner energy sources, began much later and are still in progress (the effect of belonging to an economic system based on central planning and state ownership).

Table 1. Correlation matrices between the analyzed indicators in individual countries.

Country	Indicator	CPI	GGE	AEI	SRE
Austria	CPI	1.0000	−0.4909	−0.8593	0.8331
	GGEI	−0.4909	1.0000	0.4340	−0.6982
	AEI	−0.8593	0.4340	1.0000	−0.9366
	SRE	0.8331	−0.6982	−0.9366	1.0000
Belgium	CPI	1.0000	0.0520	0.1814	−0.1526
	GGEI	0.0520	1.0000	0.6113	−0.6814
	AEI	0.1814	0.6113	1.0000	−0.9133
	SRE	−0.1526	−0.6814	−0.9133	1.0000
Bulgaria	CPI	1.0000	−0.4594	0.2987	0.4542
	GGEI	−0.4594	1.0000	−0.5984	−0.9580
	AEI	0.2987	−0.5984	1.0000	0.6554
	SRE	0.4542	−0.9580	0.6554	1.0000
Croatia	CPI	1.0000	−0.2224	−0.4458	0.6369
	GGEI	−0.2224	1.0000	0.8680	−0.5759
	AEI	−0.4458	0.8680	1.0000	−0.3324
	SRE	0.6369	−0.5759	−0.3324	1.0000
Cyprus	CPI	1.0000	0.4981	−0.6426	−0.6090
	GGEI	0.4981	1.0000	−0.4487	−0.9310
	AEI	−0.6426	−0.4487	1.0000	0.7408
	SRE	−0.6090	−0.9310	0.7408	1.0000
Czechia	CPI	1.0000	−0.4841	−0.9652	0.6922
	GGEI	−0.4841	1.0000	0.4398	−0.8019
	AEI	−0.9652	0.4398	1.0000	−0.6127
	SRE	0.6922	−0.8019	−0.6127	1.0000
Denmark	CPI	1.0000	0.8451	0.5774	−0.7962
	GGEI	0.8451	1.0000	0.5069	−0.9454
	AEI	0.5774	0.5069	1.0000	−0.4743
	SRE	−0.7962	−0.9454	−0.4743	1.0000

Table 1. *Cont.*

Country	Indicator	CPI	GGE	AEI	SRE
Estonia	CPI	1.0000	−0.6694	0.0122	0.8938
	GGEI	−0.6694	1.0000	0.1457	−0.7849
	AEI	0.0122	0.1457	1.0000	0.0907
	SRE	0.8938	−0.7849	0.0907	1.0000
Finland	CPI	1.0000	0.7067	0.8968	−0.7605
	GGEI	0.7067	1.0000	0.7563	−0.9348
	AEI	0.8968	0.7563	1.0000	−0.9222
	SRE	−0.7605	−0.9348	−0.9222	1.0000
France	CPI	1.0000	0.2996	nd	−0.2164
	GGEI	0.2996	1.0000	nd	−0.7086
	AEI	nd	nd	1.0000	nd
	SRE	−0.2164	−0.7086	nd	1.0000
Germany	CPI	1.0000	−0.2701	nd	0.4695
	GGEI	−0.2701	1.0000	nd	−0.9521
	AEI	nd	nd	1.0000	nd
	SRE	0.4695	−0.9521	nd	1.0000
Greece	CPI	1.0000	−0.8453	0.3693	0.8037
	GGEI	−0.8453	1.0000	−0.2513	−0.8536
	AEI	0.3693	−0.2513	1.0000	−0.0784
	SRE	0.8037	−0.8536	−0.0784	1.0000
Hungary	CPI	1.0000	0.6808	−0.5028	0.8895
	GGEI	0.6808	1.0000	−0.2197	0.7475
	AEI	−0.5028	−0.2197	1.0000	−0.7378
	SRE	0.8895	0.7475	−0.7378	1.0000
Iceland	CPI	1.0000	0.4814	0.8476	−0.3920
	GGEI	0.4814	1.0000	−0.2092	−0.5929
	AEI	0.8476	−0.2092	1.0000	−0.1706
	SRE	−0.3920	−0.5929	−0.1706	1.0000
Ireland	CPI	1.0000	−0.4326	−0.5705	0.6176
	GGEI	−0.4326	1.0000	0.8261	−0.9548
	AEI	−0.5705	0.8261	1.0000	−0.8243
	SRE	0.6176	−0.9548	−0.8243	1.0000
Italy	CPI	1.0000	−0.9181	−0.8778	0.7966
	GGEI	−0.9181	1.0000	0.9974	−0.9361
	AEI	−0.8778	0.9974	1.0000	−0.9138
	SRE	0.7966	−0.9361	−0.9138	1.0000
Latvia	CPI	1.0000	−0.0638	0.0544	0.6870
	GGEI	−0.0638	1.0000	0.0010	−0.5143
	AEI	0.0544	0.0010	1.0000	0.0818
	SRE	0.6870	−0.5143	0.0818	1.0000
Lithuania	CPI	1.0000	−0.8027	−0.9219	0.9148
	GGEI	−0.8027	1.0000	0.9416	−0.8552
	AEI	−0.9219	0.9416	1.0000	−0.9219
	SRE	0.9148	−0.8552	−0.9219	1.0000
Luxembourg	CPI	1.0000	−0.2037	−0.1051	0.0258
	GGEI	−0.2037	1.0000	0.8741	−0.8753
	AEI	−0.1051	0.8741	1.0000	−0.8000
	SRE	0.0258	−0.8753	−0.8000	1.0000
Malta	CPI	1.0000	0.3630	−0.2282	−0.5324
	GGEI	0.3630	1.0000	−0.3176	−0.9384
	AEI	−0.2282	−0.3176	1.0000	0.3084
	SRE	−0.5324	−0.9384	0.3084	1.0000

Table 1. *Cont*.

Country	Indicator	CPI	GGE	AEI	SRE
Netherlands	CPI	1.0000	0.6125	0.8367	−0.7540
	GGEI	0.6125	1.0000	0.6027	−0.5575
	AEI	0.8367	0.6027	1.0000	−0.8450
	SRE	−0.7540	−0.5575	−0.8450	1.0000
Norway	CPI	1.0000	0.3138	0.4084	−0.5079
	GGEI	0.3138	1.0000	−0.3550	0.0723
	AEI	0.4084	−0.3550	1.0000	−0.9138
	SRE	−0.5079	0.0723	−0.9138	1.0000
Poland	CPI	1.0000	0.2743	−0.4510	0.1662
	GGEI	0.2743	1.0000	0.7444	−0.5886
	AEI	−0.4510	0.7444	1.0000	−0.1702
	SRE	0.1662	−0.5886	−0.1702	1.0000
Portugal	CPI	1.0000	0.4762	−0.3076	0.1801
	GGEI	0.4762	1.0000	−0.1426	−0.2473
	AEI	−0.3076	−0.1426	1.0000	−0.8055
	SRE	0.1801	−0.2473	−0.8055	1.0000
Romania	CPI	1.0000	−0.3982	−0.6349	0.3426
	GGEI	−0.3982	1.0000	0.8014	−0.1665
	AEI	−0.6349	0.8014	1.0000	−0.5609
	SRE	0.3426	−0.1665	−0.5609	1.0000
Slovakia	CPI	1.0000	−0.6940	−0.8675	0.5028
	GGEI	−0.6940	1.0000	0.9095	−0.8554
	AEI	−0.8675	0.9095	1.0000	−0.8128
	SRE	0.5028	−0.8554	−0.8128	1.0000
Slovenia	CPI	1.0000	0.0007	−0.8051	−0.7389
	GGEI	0.0007	1.0000	−0.3230	0.0168
	AEI	−0.8051	−0.3230	1.0000	0.8200
	SRE	−0.7389	0.0168	0.8200	1.0000
Spain	CPI	1.0000	0.0590	0.8761	−0.4871
	GGEI	0.0590	1.0000	0.4668	−0.7642
	AEI	0.8761	0.4668	1.0000	−0.7874
	SRE	−0.4871	−0.7642	−0.7874	1.0000
Sweden	CPI	1.0000	0.8712	0.6010	−0.7199
	GGEI	0.8712	1.0000	0.7346	−0.8732
	AEI	0.6010	0.7346	1.0000	−0.9649
	SRE	−0.7199	−0.8732	−0.9649	1.0000
United Kingdom	CPI	1.0000	−0.6728	−0.1733	0.5667
	GGEI	−0.6728	1.0000	0.4690	−0.9784
	AEI	−0.1733	0.4690	1.0000	−0.3634
	SRE	0.5667	−0.9784	−0.3634	1.0000

Source: Authors' own material.

The process of switching to green energy sources is noticeable, which should be an encouragement for those countries where such transformations are just in their infancy. Of course, the power of corruption on such processes remains an open question, but the potential impact is perceptible. The results highlighting the inverse relationship between the greenhouse gas emissions intensity of energy consumption indicator and the share of renewable energy in gross final energy consumption by sector indicator (as in Belgium, Finland, Ireland or even Lithuania) are definitely optimistic. This should direct further intensive actions in this area, by other countries too.

Table 2 presents the dynamics of changes of these indicators in each country in the years 2012–2019. In most cases, the results are disappointing, especially in the area of reduction in greenhouse gas or particulate matter emissions, as quite small year-on-year decreases were observed here, and sometimes there were also increases. Such a situation definitely proves an ineffective national environmental policy and the need to intensify activities in this area. If we add to this the lack of systematic declines in the corruption perceptions indexes in the analysed countries, then we can presume an obvious lack of consistency and firm decisions in environmental aspects on the part of the government or legislators. For example, repeated announcements of a complete withdrawal from energy production based on fossil fuels, e.g., when using coal (lignite or hard coal), in many countries are not implemented. In addition, what is worrying is the share of green energy sources in total energy production, which is not high enough in many analysed countries all the time.

Table 2. Comparison of the dynamics of the analysed indicators in 5 selected countries in the years 2012–2019.

Country	Indicator	2013/2012	2014/2013	2015/2014	2016/2015	2017/2016	2018/2017	2019/2018
Austria	CPI	100.00	104.35	105.56	98.68	100.00	101.33	101.32
	GGEI	99.19	96.61	100.85	100.84	101.31	99.76	98.82
	AEI	100.00	75.00	100.00	100.00	100.00	66.67	-
	SRE	99.79	102.72	99.85	99.62	99.30	102.01	99.47
Belgium	CPI	100.00	101.33	101.32	100.00	97.40	100.00	100.00
	GGEI	95.92	98.73	105.01	92.90	99.76	103.95	97.47
	AEI	88.89	100.00	100.00	100.00	87.50	100.00	-
	SRE	107.91	105.14	99.79	109.05	104.12	104.01	104.71
Bulgaria	CPI	100.00	104.88	95.35	100.00	104.88	97.67	102.38
	GGEI	94.43	101.10	101.64	95.25	101.79	91.40	98.18
	AEI	111.76	115.79	118.18	107.69	100.00	96.43	-
	SRE	119.33	95.51	101.17	102.73	99.69	110.11	104.72
Croatia	CPI	104.35	100.00	106.25	96.08	100.00	97.96	97.92
	GGEI	97.81	99.25	97.20	101.44	98.80	96.80	98.75
	AEI	100.00	88.89	95.83	86.96	105.00	90.48	-
	SRE	104.80	99.20	104.14	97.58	96.51	102.81	101.49
Cyprus	CPI	95.45	100.00	96.83	90.16	103.64	103.51	98.31
	GGEI	99.51	100.69	99.61	99.31	97.41	96.11	100.96
	AEI	150.00	142.42	97.87	91.30	111.90	102.13	-
	SRE	118.48	108.48	108.24	99.29	106.53	132.32	99.29
Czechia	CPI	97.96	106.25	109.80	98.21	103.64	103.51	94.92
	GGEI	94.34	100.26	101.02	102.27	96.55	97.32	96.46
	AEI	100.00	100.00	71.43	100.00	80.00	100.00	-
	SRE	108.69	108.23	99.96	99.05	99.14	102.31	107.31
Denmark	CPI	101.11	101.10	98.91	98.90	97.78	100.00	98.86
	GGEI	104.46	94.38	93.66	101.93	92.95	99.85	92.12
	AEI	100.00	100.00	100.00	100.00	50.00	200.00	-
	SRE	106.71	107.91	105.26	103.84	108.19	102.12	105.06
Estoni	CPI	106.25	101.47	101.45	100.00	101.43	102.82	101.37
	GGEI	99.09	102.55	90.67	100.55	110.57	89.16	88.07
	AEI	121.31	79.73	164.41	69.07	137.31	47.83	-
	SRE	99.22	103.24	109.13	100.66	101.58	102.83	106.32
Finland	CPI	98.89	100.00	101.12	98.89	95.51	100.00	101.18
	GGEI	102.83	90.15	96.44	103.03	93.35	100.82	94.57
	AEI	90.91	100.00	100.00	100.00	90.00	100.00	-
	SRE	106.95	105.59	101.40	99.22	104.88	100.59	104.67
France	CPI	100.00	97.18	101.45	98.57	101.45	102.86	95.83
	GGEI	99.53	93.93	100.25	103.10	100.36	95.80	99.50
	AEI	100.00	100.00	100.00	100.00	100.00	100.00	-
	SRE	104.78	103.70	103.04	104.31	102.60	103.40	104.69

Table 2. *Cont.*

Country	Indicator	2013/2012	2014/2013	2015/2014	2016/2015	2017/2016	2018/2017	2019/2018
Germany	CPI	98.73	101.28	102.53	100.00	100.00	98.77	100.00
	GGEI	100.00	99.27	100.21	99.79	96.94	98.04	96.89
	AEI	100.00	100.00	100.00	100.00	100.00	100.00	-
	SRE	101.60	104.54	103.62	99.89	103.94	107.73	104.08
Greece	CPI	111.11	107.50	106.98	95.65	109.09	93.75	106.67
	GGEI	99.89	95.93	95.20	95.77	101.72	98.07	92.01
	AEI	96.00	112.50	103.70	92.86	96.15	100.00	-
	SRE	111.53	102.33	100.04	98.09	112.40	104.34	109.01
Hungary	CPI	98.18	100.00	94.44	94.12	93.75	102.22	95.65
	GGEI	97.77	98.99	100.38	100.64	99.24	99.23	99.36
	AEI	87.50	114.29	87.50	114.29	100.00	112.50	-
	SRE	104.35	90.21	99.16	99.19	94.20	92.56	100.63
Iceland	CPI	95.12	101.28	100.00	98.73	98.72	98.70	102.63
	GGEI	93.66	100.66	105.42	102.47	96.39	92.92	100.45
	AEI	85.11	90.00	102.78	75.68	92.86	-	-
	SRE	100.08	98.90	97.86	104.62	98.21	104.36	101.96
Ireland	CPI	104.35	102.78	101.35	97.33	101.37	98.65	101.37
	GGEI	101.23	97.57	99.32	98.40	98.73	98.36	94.99
	AEI	100.00	100.00	50.00	100.00	100.00	100.00	-
	SRE	108.22	113.00	105.56	101.34	114.18	104.04	110.07
Italy	CPI	102.38	100.00	102.33	106.82	106.38	104.00	101.92
	GGEI	95.55	99.89	99.54	100.00	95.31	100.36	98.21
	AEI	87.50	100.00	100.00	100.00	85.71	100.00	-
	SRE	108.42	102.04	102.60	99.37	104.89	97.42	102.16
Latvia	CPI	108.16	103.77	101.82	101.79	101.75	100.00	96.55
	GGEI	100.47	97.87	103.26	100.70	96.29	100.96	100.00
	AEI	104.65	116.67	95.24	90.00	93.33	104.76	-
	SRE	103.72	104.30	97.18	98.93	105.06	102.59	102.36
Lithuania	CPI	105.56	101.75	101.72	100.00	100.00	100.00	101.69
	GGEI	100.45	96.07	97.95	100.66	95.00	101.39	100.49
	AEI	90.00	66.67	83.33	100.00	80.00	100.00	-
	SRE	105.84	103.98	109.14	99.47	101.66	94.84	103.10
Luxembourg	CPI	100.00	102.50	103.66	95.29	101.23	98.78	98.77
	GGEI	97.63	97.58	95.83	96.58	98.82	99.35	101.09
	AEI	80.95	129.41	72.73	87.50	85.71	91.67	-
	SRE	112.36	127.72	111.59	107.50	115.61	144.77	78.54
Malta	CPI	98.25	98.21	109.09	91.67	101.82	96.43	100.00
	GGEI	98.32	98.97	83.66	85.28	96.61	96.16	101.91
	AEI	66.67	100.00	100.00	100.00	150.00	100.00	-
	SRE	131.38	126.17	107.90	121.27	116.29	110.38	106.53
Netherlands	CPI	98.81	100.00	101.20	98.81	98.80	100.00	100.00
	GGEI	101.70	100.84	102.38	98.48	97.13	99.47	98.41
	AEI	100.00	100.00	100.00	100.00	83.33	100.00	-
	SRE	100.69	115.43	104.67	102.36	111.27	113.69	119.46
Norway	CPI	101.18	100.00	102.33	96.59	100.00	98.82	100.00
	GGEI	93.75	113.33	98.40	101.41	93.78	97.94	103.38
	AEI	105.26	85.00	105.88	94.44	94.12	100.00	-
	SRE	101.97	103.78	100.00	101.25	102.22	101.71	103.93
Poland	CPI	103.45	101.67	103.28	98.41	96.77	100.00	96.67
	GGEI	98.20	99.57	100.11	98.59	99.23	98.01	97.06
	AEI	105.41	92.31	94.44	94.12	106.25	94.12	-
	SRE	104.49	101.32	102.36	95.90	97.52	103.24	105.99
Portugal	CPI	98.41	101.61	101.59	96.88	101.61	101.59	96.88
	GGEI	95.14	97.39	105.98	97.81	104.71	96.07	91.93
	AEI	95.33	99.02	96.04	95.88	95.70	97.75	-
	SRE	104.58	114.82	103.41	101.15	99.18	98.67	101.37

Table 2. *Cont*.

Country	Indicator	2013/2012	2014/2013	2015/2014	2016/2015	2017/2016	2018/2017	2019/2018
Romania	CPI	97.73	100.00	106.98	104.35	100.00	97.92	93.62
	GGEI	99.57	100.11	100.11	96.46	98.44	100.23	96.51
	AEI	87.88	89.66	103.85	96.30	88.46	95.65	-
	SRE	104.65	104.01	99.76	101.00	97.69	97.63	101.74
Slovakia	CPI	102.17	106.38	102.00	100.00	98.04	100.00	100.00
	GGEI	97.93	97.77	99.28	100.12	97.94	100.62	95.34
	AEI	100.00	75.00	88.89	100.00	100.00	75.00	-
	SRE	96.94	115.59	109.99	93.37	95.31	103.76	142.01
Slovenia	CPI	93.44	101.75	103.45	101.67	100.00	98.36	100.00
	GGEI	97.89	91.79	101.90	102.96	97.76	99.78	98.03
	AEI	114.29	106.25	94.12	87.50	100.00	100.00	-
	SRE	107.48	96.98	101.87	96.05	98.55	98.71	102.79
Spain	CPI	90.77	101.69	96.67	100.00	98.28	101.75	106.90
	GGEI	96.69	102.00	102.43	94.70	100.72	98.22	96.02
	AEI	76.92	90.00	111.11	90.00	100.00	111.11	-
	SRE	107.22	105.27	100.64	107.16	100.80	99.38	105.20
Sweden	CPI	101.14	97.75	102.30	98.88	95.45	101.19	100.00
	GGEI	97.72	96.90	105.61	93.68	96.63	97.63	97.71
	AEI	100.00	88.89	87.50	85.71	100.00	100.00	-
	SRE	101.53	102.02	102.18	100.72	101.55	100.91	103.18
United Kingdom	CPI	102.70	102.63	103.85	100.00	101.23	97.56	96.25
	GGEI	98.99	96.93	94.61	96.09	97.79	98.93	98.32
	AEI	108.33	107.69	92.86	92.31	100.00	100.00	-
	SRE	123.83	121.96	124.46	107.72	109.15	112.98	110.76

Source: Authors' own material.

A very positive aspect is the increase in the share of renewable energy in gross final energy consumption in former post-communist countries and new members of the European Union, such as the Czech Republic, Poland, Slovakia and Estonia. On the other hand, the high value of air emissions intensity from industry is still worrying in many of the surveyed countries (such as France, Greece, Spain), where much more emphasis should be placed on gradual reduction in this indicator. Finally, the minimization of gas emissions intensity of energy consumption at the level of most countries is also not visible. Despite many declarations, even among the leaders of "clean climate" (in Sweden, Finland or Norway), it is difficult to emphasize here significant progress in this area.

5. Discussion

The ambiguity of the results obtained in the research does not allow for an explicit verification of the existence of relationships between corruption and the analysed pro-ecological initiatives in terms of the greenhouse gas emissions intensity of energy consumption, the air emissions intensity from industry (particulate matter) or the share of renewable energy in gross final energy consumption by sector. Certainly, some interdependencies between the analysed indicators are conspicuous, but their direction and strength are different in each analysed country. Thus, despite some similarities in the results obtained, it is not possible to make generalisations and create a thesis about the existence of correlations between the analysed indicators.

However, on the subject of the relationships between the indicators under consideration, it is worth trying to have a broader discussion in order to show the resulting beneficial or unfavourable implications for the performance and development of companies and the economy as a whole, in particular the green economy. It should be noted that in the case of the sought relationships, it would be desirable to have a negative correlation, which means that the increase in the value of the corruption index is accompanied by a decrease in the average values of indicators describing pro-ecological initiatives. Such a situation would be beneficial both for stimulating initiatives to protect the natural environment and eliminating or significantly reducing corruption.

Corruption is a serious threat in many countries around the world, and the results of research into the causes and consequences of corruption are so diverse that it is worth examining this issue in relation to other variables, especially those representing environmental issues. Corruption has a significant impact on economic and social development as it affects investment, capital flows, economic growth, trade and services, social inequalities, government spending, the shadow economy and crime and is subject to many institutional, jurisdictional, social and economic determinants [55]. The estimation of the World Bank shows that the annual amount of bribes paid is about one trillion USD and total costs of corruption are approximately equal to up to four percent of the global GDP [61].

According to other empirical studies, corruption affects the economy and hinders both public and private investment, and high levels of corruption correspond to a higher share of the informal economy in percentage of GDP and vice versa [62]. Research shows that a high level of corruption may significantly limit the generation of financial resources and affect the size and scope of government spending, and a high share of government spending usually results in lower corruption rates [63,64]. The analysis of the impact of corruption on total investment also indicates a possible impact of corruption on GDP, which is confirmed by a strong correlation between GDP per capita and corruption, where countries with a higher GDP per capita score better in the Corruption Perceptions Index [62]. In the group of several European countries, there is also a correlation between the predictability of corruption and investment in relation to GDP and the existence of a negative correlation between the distribution of income and the level of corruption, the latter of which is not particularly high, which makes it difficult to explain it in a simple way [62]. Hessami [65] also writes about the fact that corruption can affect public spending. Interestingly, he observes that higher levels of corruption lead to distortions and higher public spending in sectors based on public procurement, such as health and environmental protection together with waste management, and lower spending on recreation, culture and religion. However, there is some doubt as to whether this increase in spending goes together with an improved quality of projects carried out in these sectors. On the other hand, the quality of public institutions, expressed in the rule of law and effectiveness of action, has a positive impact on reducing the level of corruption [66].

It is worth noting that corruption has a negative impact not only on the economy, but also on the integrity of people, which is expressed in the strong correlation between the intrinsic, individual honesty of people and the prevalence of rule violations by them [67].

The cited research results justify the need to determine the impact of corruption on environmental issues, for instance to make the government aware that its existence may have a negative impact on the speed and effectiveness of initiatives and implementation of indispensable pro-ecological solutions.

Nowadays, however, initiatives to protect and improve the state of the natural environment should be undertaken not only on a macro or meso scale, but primarily on a microeconomic scale. Besides, they should be correlated with the activities of state institutions and supported by the state ecological policy, creating all standards, regulations and other mechanisms concerning environmental issues [68]. Furthermore, these initiatives should be a consequence of extensive environmental education of the society, including teaching people the respect for the natural environment [69,70], as well as the result of disseminating ecological knowledge at the level of business enterprises, especially in the aspect of educating specialists in the field of environmental protection, providing environmental knowledge to engineers or using new technologies to generate renewable energy [71]. The development of the Internet may be useful here, as it has a significant impact on improving Industrial Green Total Factor Productivity (IGTFP) in some regions of China, and its long-term effect may encourage the use of Chinese experiences in other countries [72].

Of course, extensive cooperation between people, governments, industry and the energy sector is also needed to deal effectively with the various aspects of environmental pollution, especially air pollution, which has become a major environmental cause of premature death and numerous human health problems, which sooner or later will affect world economic development [73]. Thus, the most important thing is that the policymakers promote the transformation of high-carbon industries, encourage investments in pro-ecological technologies and improve energy efficiency as part of the synergistic reduction in pollutant emissions [74].

From the economic, political and human point of view, alternative (renewable) energy sources seem to be the best solution, the main advantage of which is neutral impact on the environment. Their use is generally not associated with the formation of harmful substances, which has a significant impact on improving the condition of the environment and counteracting the climate crisis. In many countries, however, the development of the renewable energy sector is still not properly supported by decision-makers and largely depends on their political sympathies or beliefs about the importance of alternative energy sources for socio-economic development and environmental sustainability in the future [75] (e.g., EU members are obligated to increase the share of renewable energy sources, the situation is not very optimistic). Other studies show that in the years 2020-2021, companies from the alternative energy sector turned out to be the largest stock exchange beneficiaries, which may suggest a growing social awareness for environmental protection, even with the raging COVID-19 pandemic, which has even become a driving force behind pro-ecological thinking [75].

The existing situation confirms the legitimacy of changes in the energy sector and the need for a definite resignation from the use of conventional energy sources. Therefore, companies from the energy sector should increase their efforts to increase the use of renewable energy sources and implement all kinds of technological innovations or eco-innovations, contributing to the creation of a green economy. The use of ecological innovations (eco-innovations), whose primary goal focuses on the environmental issues [76], will also be extremely useful here, but their implementation also has a positive effect on the cost reduction, greater production efficiency or improved product quality [77]. Ecological innovations, which are assumed to bring economic benefits and lead to an increase in the company's value, combine innovations with ecology in such a way as to create sustainable and environmentally friendly solutions, the implementation of which results in both better environmental protection and increased competitiveness of the companies implementing them [78]. As a result, ecological innovations fulfill the ecological and economic goals of the company, creating a coherent whole in this respect, which in turn is consistent with the principles of the concept of sustainable development [79] and should be an effective way of mitigating the current ecological crisis and preventing it in the future.

A good solution may be the promotion of electromobility, which essentially contributes to an increase in energy efficiency and reduction in pollution to the environment, especially lower air pollution, while being an important element of actions for sustainable transport [80,81]. Thanks to appropriate measures to govern changes in the transport system, they can effectively reduce the amount of particulate matter and positively counteract climate change [82]

An important, but rather temporary and quite expensive market tool that stimulates economic growth while reducing carbon dioxide emissions can be trading in carbon dioxide emissions, which not only contributes to cost reduction and further development of low-emission technologies by reinvesting income, but also promotes low-carbon technological innovation [83]. In addition, this carbon trading may, in part, contribute to the faster structural adjustment of a highly polluted industry and eliminate obsolete manufacturing solutions [84].

The creation of a green economy as a result of the implementation of pro-ecological initiatives is the right direction for the development of the global economy, because it forces greater economic efficiency, creates new jobs, attracts investors, protects nature, meets social expectations, and at the same time generates profits. A green economy, as a UN initiative designed to motivate policymakers to support environmental investments, builds social equity while reducing environmental risks and scarcities [85]. Thanks to this "an inclusive green economy is an alternative to today's dominant economic model, which exacerbates inequalities, encourages waste, triggers resource scarcities, and generates widespread threats to the environment and human health" [85]. Unfortunately, as already mentioned, changes in the approach to the environment involve additional capital, because pro-ecological solutions are very expensive and require significant financial outlays [86], especially in the implementation of innovative ecological technologies which should simultaneously ensure environmental protection and corporate development [78,87]. Where there is a lot of money, there is always a temptation towards financial abuse and corruption phenomena, even at the expense of polluting the environment or even a complete lack of its protection. Even more so, because many enterprises and entrepreneurs cannot afford (for economic reasons) to introduce the postulated environmental changes without the aid from the state or international organisations.

Therefore, it should be assumed that corruption or its perception may also have a negative impact on the implementation of pro-ecological initiatives aimed at reducing and/or eliminating greenhouse gas or particulate matter emissions or investments in the development of renewable energy, which is an alternative to energy generated from fossil fuels. On the example of non-democratic countries rich in natural resources, where there are weak public institutions, it can be seen that high profits from the exploitation of natural resources definitely favor the growth of corruption [88]. The lack of transparency in the distribution of environmental funds, payment delays or embezzlement may further discourage entities from taking these actions, for example for the fear of threat to corporate development, higher costs of doing business or promotion of ineffective companies that do not meet the project requirements, but pay bribes or are well connected [63]. Furthermore, there are also unjust rules for the assessment of submitted investment projects or the need to pay additional fees to win favour or protectionism of officials, which is particularly conspicuous in the context of acquisition of public funds and in relations with the public sector [62].

To confirm that the described situation is true and extremely important not only in the practical aspect of socio-economic life, but also in the scientific approach to this problem, one can cite the global initiative of the member states of the United Nations, such as The Sustainable Development. This initiative is a common plan for peace and prosperity for people and the planet now and in the future, in which economic growth depends on fighting climate change and working to protect our oceans and forests [89]. As mentioned, this initiative has 17 goals that humanity should strive to achieve. Among them, we can find two goals: 7 and 16, which relate directly to the issues addressed in this article. Therefore, Goal 7 relates to "Ensure access to affordable, reliable, sustainable and modern energy" and Goal 16 is to significantly reduce corruption in all its forms following the recommendations: "Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels" [89]. Goal 16 is especially important, because corruption causes ineffectiveness in many areas of socio-economic life, undermines the credibility and competitiveness of the country, lowers its GDP, increases inequalities in society, causes a decline in the quality of public services and limits government spending [52,53], and certainly does not encourage the implementation of Goal 7. The consequence of accepting corruption will be lower tax revenues, distrust of public institutions, difficulties with implementing regulations and maintaining law and order, or a lack of funds for the implementation of important public investments, not to mention environmental protection activities.

6. Conclusions

To recapitulate, the authors attempted to investigate and verify the existence of relationships between the corruption perceptions and the greenhouse gas emissions intensity of energy consumption, the air emissions intensity from industry and the share of renewable energy in gross final energy consumption. It seems that the very fact of recognising a possibility of correlation between the indicators discussed in the article should lead to such reasoning, especially since pro-ecological initiatives are inextricably related to the Sustainable Development Goals. Environmental pollution through dust emissions or climate changes as a consequence of greenhouse gas emissions are a sufficient reason to firmly reduce any incentives aimed at blocking activities in this area, especially bearing in mind corruption. Although it was not possible to unequivocally confirm the existence of the above-mentioned relationships, several interesting conclusions can be drawn on the basis of the results.

Firstly, especially during the COVID-19 pandemic, which has radically changed the business landscape around the world, economic activity and interpersonal relationships should be dominated by honesty, trust and responsibility, because it is these characteristics of people that seem to be the panacea for the current global ecological crisis. This trust and responsibility facilitate cooperation between entities of economy, improving the government's and the economy's quality and in turn reducing the level of corruption [90]. Of course, the high level of democracy plays an important role here, as it guarantees economic freedom that reduces the level of corruption, and, at the same time, points out an interesting relation between democracy and corruption [64,91]. However, it should be remembered that democracy reduces corruption, but only when public institutions operate quickly and effectively and are fully functional and have strong democratic roots, and are not devoid of them [63]. For example, only 4 in 10 people in the EU believe their governments fought the epidemic in a transparent manner, and more than half of the population in the EU believe their governments are driven by private interests rather than public interests [92]. This allows us to assume that governments are not fully committed to environmental protection issues, including the reduction in the emission of greenhouse gases and particulate matter (PM) or the greater use of renewable energy and therefore it is worth talking and writing about.

Secondly, if we want to prevent the emergence of corruption, which may inhibit the implementation of pro-ecological initiatives aimed at reducing and/or eliminating greenhouse gas and particulate matter emissions and investments in the development of renewable energy, it is necessary not only to fight it, but first of all to ensure a large-scale promotion of the principles of business and clerical ethics. Besides, what is also needed is a stable and well-managed economy and strong and efficient state institutions which do not tolerate corrupt behaviours, reduce the corruption level and make it remain low [93]. Research on corruption in European Union countries shows that the governments of the Member States and EU institutions still have a lot to do to ensure their citizens a life free from corruption [92]. Therefore, it is already necessary to take and/or continue activities aimed at, among others: constantly building people's trust in rulers and institutions, transparent decision-making and law-making processes, counteracting protection, increasing transparency and access to public services, and increasing accountability for abuses of power.

Thirdly, it is necessary to radically change the approach to the problem of pollution caused by the conventional energy sector, primarily by promoting the development of renewable energy and encouraging energy companies to systematically increase the share of clean energy production, i.e., from renewable sources.

It is worth emphasizing that renewables energy may eliminate the use of fossil fuels for electricity by 2035 and replace fossil fuel usage altogether by year of 2050 [94], but consistency in action and concrete decisions of all decision-makers on a global scale are needed. Except that, the concept of the green economy should emerge as a strategic priority for all governments [85] and be developed with the active participation of various stakeholder groups, as well as appropriately communicated to the public. This is so important that, according to many scientists, without fully appreciating and broadcasting the scale of the environmental problems as well as the proposed solutions, society will fail to achieve even small sustainability goals (including the energy sector) and will not contribute to overcoming the ecological crisis [95].

Our research, to some extent, supplemented the previous theoretical considerations on the relationship between indicators concerning gas emissions, pollutants or energy production and other potential variables. In our case, the choice fell on an indicator of corruption perception, that allows to take into account the meaning of the socio-economic background in the aspect of the influence of energy production and consumption on the condition of the natural environment. We argue that the diagnostics of the corruption perception indicator we have chosen covers the entire spectrum of the functioning of the political or administrative sphere in individual countries. This, in turn, makes our research attempt more comprehensive and repeatable by other researchers (whether for other countries or periods). Additionally, based on research precaution, we anticipate more than we postulate that the academic consequences of this research for the future of scientific literature will be further analysed in the field of identifying other variables and factors that, indirectly, but nevertheless affect the results and harmfulness of the energy sector, and in particular the so-call dirty part of energy sector (based on fossil fuels), that is most dangerous for the environment and climate change. Besides, research shows that researching the relationships between greenhouse gas or particulate matter emissions or the volume of renewable energy production and the level of corruption may contribute to the popularization of pro-ecological activities aimed at building and developing a green economy, which is desirable in the face of contemporary environmental threats.

Regarding the limitations and possible future research directions, it should be noted that a barrier in the research was the inability to analyze the strength and direction of the impact of corruption on the presented indicators. Therefore, in the future it would be worth using the case study method, which could solve the mentioned problem. As a continuation of this initiative, the authors intend to focus further research on the analysis of cases of specific countries where green energy sources are still marginal and the "dirty energy" lobby exerts strong pressure on the government to constantly extend the deadline for ceasing the use of hard coal or lignite for energy production.

7. Implications

We consciously resign from dividing the implications into managerial, practical or social ones, taking into account the importance and scale of the problem we are discussing. It is difficult to question many years of and various international initiatives, such as those undertaken at the level of the United Nations, the European Union, and indirectly at various climate summits, which concern the protection of the natural environment, clean air and climate. Hence, the global focus on more and more detailed initiatives and activities aimed at reducing the production of dirty energy and pollutant emissions should encourage joint ownership and cooperation in this area by governments, large energy companies, but also non-governmental organizations. The crowned example of this is the corruption problem we diagnose, which may, after all, be a significant obstacle in the implementation of the goals resulting from the principles of sustainable development and the 2030 agenda or the Fit for 55 package. Here, therefore, we see a huge role of experts, specialists from non-governmental organizations, but also control bodies in individual countries, in order not only to monitor the results of the energy industry and its harmfulness to the environment and climate, but also to point out potential obstacles hindering the achievement of the assumed goals. Social context, and even acceptance of corrupt behavior, is still an unimaginably great problem in some of the surveyed countries. That is why the continuous education of the society in the area of producing clean energy and minimizing the emission of harmful pollutants and gases must also be maintained. Only with work on the ground and, of course, with appropriate legal regulations and effective enforcement of regulations, it will be possible to influence global energy companies (but also some governments) in terms of reducing the harmfulness of the energy sector and its transformation towards the production of clean (renewable) energy.

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Article

Combating Energy Poverty in the Face of the COVID-19 Pandemic and the Global Economic Uncertainty

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Abstract: The effects of the global COVID-19 pandemic on the energy sector and the economy as a whole are being followed by the global energy crisis, which has been exacerbated by the war in Ukraine. The situation is particularly difficult for European countries, which are heavily dependent on imported energy from Russia. In the face of such economic uncertainty, it is necessary to analyze and assess the energy poverty situation in the region. The article overviews the extent of energy poverty among European Union (EU) countries and determines regional differences by comparing the situation, trends and policy measures applied, followed by the challenges and opportunities to combat energy poverty among households during the global COVID-19 crisis and economic uncertainty. A scientific literature review was performed and the effect of the COVID-19 pandemic on the energy poverty of households was identified. Moreover, a set of indicators reflecting the extent of energy poverty in different EU countries has been developed and an analysis of indicators was performed by comparing the situation, trends and policy measures applied.

Keywords: energy poverty; COVID-19; economic uncertainty; energy policy; policy measures

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1. Introduction

In the beginning of 2019, the world faced the COVID-19 pandemic [1], which was followed by the global energy crisis in the end of 2021. The energy prices increased significantly and the share of people unable to pay their bills for energy increased in many regions [2,3]. The European Union (EU) is dependent on imported energy, especially natural gas, where the biggest portion has come from Russia for many years [4]. Russia's aggression against Ukraine, which began on 24 February 2022, and Europe's response to the illegal invasion, have exacerbated the energy crisis in Europe. Energy prices have risen significantly; the government of Germany froze the certification of the Nord Stream 2. The burden of rising energy prices is falling on households through the rising prices of different products and services and a higher share of income for energy bills. According to the statistics, the population unable to adequately heat their homes rose almost 20% during the first year of the COVID-19 pandemic (from 6.9% to 8.2%) [5]. The results of the study by Che and Jiang [6] confirmed that economic uncertainty effects expenditure and energy poverty among people. Such conclusions have been reached in the analysis of both developing and developed countries, including nine European countries. It can be assumed that with significant increases in energy prices, energy poverty and the risk to face it will increase in the near future [7]. Therefore, it is very important to pay significant attention to this problem, both at regional and at a national level.

For many years, the EU energy policy has had a clear direction toward the transition to green energy and the increase in energy efficiency. A big effort has been done and huge amounts of documents have been written to encourage this energy transition. However, the challenges that face the European energy sector today requires fundamental actions to accelerate the energy transition and decrease energy dependence from Russia. A total of 90% of the EU gas consumption is imported, of which around 45% comes from Russia.

Moreover, 25% of the oil and 45% of the coal comes from Russia. It should be noted that the level of imported energy varies across countries. The ability of countries to adapt to the changed situation also varies. Some countries have been able to react quickly and abandon energy from Russia, e.g., the Baltic states. Such a rapid abandonment was due to actions to increase the level of energy security in the region. However, other countries need a long transition process. Therefore, the EU has tried to find alternative energy sources and to start to free themselves from Russian fossil fuels by 2030. All these changes will have an impact on the energy price and will be felt by final energy consumers, at least in the short term.

However, there is no single EU-wide measure to reduce the effects of the pandemic and the energy crisis on the energy poverty of households. Countries are looking for ways to tackle rising inflation and rising energy prices. For example, the government of Poland temporarily abolished the value added tax on food and gas, as well as reduced the tax on fuel. In other countries, the interest in support measures for renewable technologies development in the household sector has increased significantly. For example, in Lithuania, the support measures for solar energy have had a huge popularity in the last year.

The fight against energy poverty in Europe is taking place through the increase in energy efficiency and the development of renewable energy in households. Despite the active initiation of actions at the EU level to combat energy poverty, the focus and policies across member states vary. Significant differences can be observed both in the national documents of the countries and in their strategies and energy development plans. In the face of the challenges caused by the COVID-19 pandemic to the energy sector [3,8,9], it is necessary to analyze and monitor how the current pandemic situation may affect energy poverty among households. The research analyzing energy poverty issues has risen significantly in recent years [10–12]; moreover, there is a huge amount of studies analyzing and evaluating the impact of the pandemic to the energy sector. Despite that, there are very few studies examining the linkages between the impact of the pandemic on energy poverty in the context of the COVID-19 pandemic, despite the fact that the impact of energy on households is obvious. The current paper seeks to overview the extent of energy poverty among EU countries and to determine the regional differences by comparing the situation, trends and policy measures applied, followed by the challenges and opportunities to combat energy poverty among households during the global COVID-19 crisis and in the context of economic uncertainty. The identification of disparities and insights provided are important for the improvement of the current energy policy of the EU in the context of the global energy crisis and energy dependency from Russian oil and natural gas. The paper could serve as a basis for future research. Moreover, the situation analysis and the identified regional disparities among member states will allow to develop and implement new and more effective measures.

The rest of the paper divided into several subsections. The second section of the paper provides a literature review and identifies the effect of the COVID-19 pandemic on the energy poverty of households. The third section presents the methods and data of the research. The fourth section provides an overview of energy poverty in the EU member states, where the EU policy measures to fight against energy poverty are discussed, the diversity of energy poverty in Europe in terms of different indicators is analyzed and the national policy measures to fight energy poverty in the context of the COVID-19 pandemic are provided.

2. Literature Review

The COVID-19 pandemic caused multiple effects on the energy sector and its sustainability. There are several review articles in the scientific literature analyzing the impact of the pandemic on the energy sector as a whole or on its specific aspects. The study by Siksnelyte-Butkiene [3] reviewed publications analyzing the changes caused by the pandemic in the energy sector. It identified the five main impact areas, such as: the impact on consumption and energy demand; the impact on air pollution and air quality; the impact on investments in new renewable energy projects; the impact on the energy poverty of households; and the impact on energy system flexibility. Kumar et al. [13] highlighted the relationship between the pandemic and greenhouse gas (GHG) emissions and reviewed scientific literature in the field. Moreover, the authors compared the GHG emissions in different time horizons and made projections for the post-COVID-19 era. Based on the projections and data analysis of different indicators, the recovery plan in the context of sustainable energy development was presented and insights towards the sustainable development goals were provided. Krarti and Aldubyan [14] provided a systematic review analysis for the identification of energy consumption trends in the residential sector. The results showed a significant increase in consumption due to higher occupancy during working hours, where energy for heating, lighting and air conditioning purposes were used much more intensively as before the pandemic. The analysis allowed to create recommendations for the efficient usage of energy. Moreover, the investments in renewable energy technologies were stressed in the article as one of the solutions to fight against increase in energy consumption and energy bills. In order to find out effects of the COVID-19 pandemic to the energy system and electricity grids, Navon et al. [15] reviewed scientific literature and analyzed and measured data. The authors presented patterns of electricity demand and generation, deviations and performed load forecasting. Zhong et al. [16] performed a comprehensive review of the pandemic effects to the electricity sector. The changes in electricity demand, daily load profile and load composition were determined, especially in the period of lockdowns. Moreover, the changes in renewable penetration were detected, the high pressure on system operators was identified and the challenges for the whole energy system maintenance and management were stressed. Lu et al. [17] overviewed the consequences of the pandemic on the energy price, demand, energy policy issues, countermeasures and scientific research directions. Moreover, the necessity to promote the transition to renewable energy was highlighted in the study.

The restrictions imposed during the lockdowns caused many challenges for many sectors of the economy. The growing number of cases slowed down production and caused supply difficulties for many economical activities, the economic uncertainty affected investments, restrictions affected the incomes of employees, changed energy consumption patterns and increased the energy bills of households. Several studies analyzing the impact of the pandemic on energy poverty can be found in the literature. However, there are relatively few studies of this issue, although the scale of the problem is undoubtedly large.

Some studies focused on the assessment of the level of energy poverty in the context of the pandemic. Nagaj and Korpysa [18] measured the increase of the level of energy poverty during the first years of the pandemic in Poland. The research results revealed that the lockdowns affected the disposable income of people and increased the share of expenditures for energy needs. It was determined that the most vulnerable households have been affected the most by the pandemic. While the results of the study by Biernat-Jarka et al. [19] showed that the level of energy poverty in Poland has been steadily declining since before the pandemic. The same results are demonstrated in studies by other authors in different countries of the world. Clark et al. [20] analyzed energy poverty among students in New Zealand. It was found that the pandemic affected energy consumption and increased energy bills among students. As a result, students already experiencing energy poverty experienced significant stress. Mamica et al. [21] analyzed the factors which affect the extent of energy poverty among Polish students. The study also considered the changes of energy consumption during the first lockdown. It was determined that the share of income to meet energy needs increased. As a result, the level of inappropriate temperature in the dwellings of students was identified.

The increase of the level of energy poverty can cause multiple effects on other social issues. The research by Memmott et al. [22] revealed that the increase of the level of energy poverty can affect the extent of racial disparities among energy-poor people. The authors analyzed the energy poverty issue during the first months of the pandemic in the United States. It was found that Black and Hispanic people, people with young children and people living in inefficient dwellings were more likely to experience energy deprivation.

Although the same conditions existed before the pandemic, the scale of the problem increased significantly during the pandemic. Ambrose et al. [23] overviewed the extent of energy poverty and policy measures in the United Kingdom. A significant increase in the number of fuel-poor households during the first year of the COVID-19 pandemic was found. The authors paid attention to the psycho-social aspects of energy-poor people during the lockdowns, where poor quality and energy inefficient dwellings negatively affected daily life. Accordingly, the study revealed the additional consequences of the pandemic for energy-poor households and determined the key aspects for policy on energy poverty in the context of the pandemic. First of all, the necessity to improve the energy efficiency of buildings was stressed. Secondly, the need to address the financial difficulties of households was identified. Thirdly, the need to provide access to high-quality public spaces, at least during the closures, was emphasized.

Other studies focused on the analysis between the energy poverty issues and air pollution in the context of the pandemic. The results of the study by Shupler et al. [24] showed that the restrictions imposed not only decreased the disposable income of people, but also forced households to change cleaner cooking fuels to more polluting ones. Martinez-Soto et al. [25] analyzed how the increase of energy poverty affected the air pollution in Chile. The commercial and low- and middle-income residential areas were analyzed, and the results compared before the pandemic and in the first year of the pandemic. It was found that the pollution significantly increased in areas where live people with higher income. Low-income households could not afford to warm up enough. Accordingly, it indicated that the pandemic also exacerbated the problem and scale of the energy deprivation that low-income households had already experienced before the pandemic. The results of the study also proved the necessity to develop clean energy technologies in the country, where wood is the main source for heating. The relationship between the CO_2 emissions and the social groups of households was revealed in the study by Huang and Tian [26]). The input–output model was applied for the analysis of eight developing countries. The significant CO_2 emissions inequality was noticed among countries under analysis, especially in Russia and China. Moreover, the considerable inequality of CO_2 emissions among the different social groups was found in many of the countries analyzed. The hypothetical extraction method was applied for the examination of the COVID-19 impact on CO_2 emissions inequality among different income groups. Overall, the decrease in emissions inequality was found. However, the simulations showed that inequality in emissions among countries and different income groups of households will persist. Therefore, the implementation of energy efficiency measures and the development of new renewable energy projects are essential, not only for the reduction of global emissions, but also for alleviating the issues of energy poverty. Gebreslassie [27] revealed the challenges posed by the pandemic in tackling energy poverty due to technology supply disruptions. The author presented a case study of Ethiopia, where the decrease of income of solar technologies end-users and the lack of technologies in the market were found. This situation is forcing the closure of local businesses operating in the solar energy market and is affecting the electrification of remote areas.

The linkages between the COVID-19 pandemic effects and the energy poverty of households are shown in Figure 1. Based on these links, this study hypothesizes that the pandemic increased energy poverty among European households. The research methodology and data are presented and justified in the next section.

The other part of the articles analyzed measured the elevating energy poverty or risk to face it. For example, Mastropietro et al. [28] reviewed and classified the measures for the energy consumers' protection around the world. The authors identified the advantages and disadvantages of the measures. Moreover, the necessity for proper financing was stressed. The other study by Mastropietro [29] assessed emergency measures in Spain by applying the regulatory theory and analysis of international practice. It was concluded that measures should be based on clear strategy, and the author highlighted the importance of communication strategies to reach more households and achieve the effectiveness of the measures implemented. Bienvenido-Huertas [30] analyzed the unemployment benefits, as well as social measures and their effectiveness, in Spain during the first lockdown. According to the results, these measures can mitigate energy poverty among people who lost their jobs. However, the measures taken are insufficient and need to be reconsidered and improved in the context of the pandemic situation. The author proposed, as an effective instrument, to consider a percentage discount on energy bills.

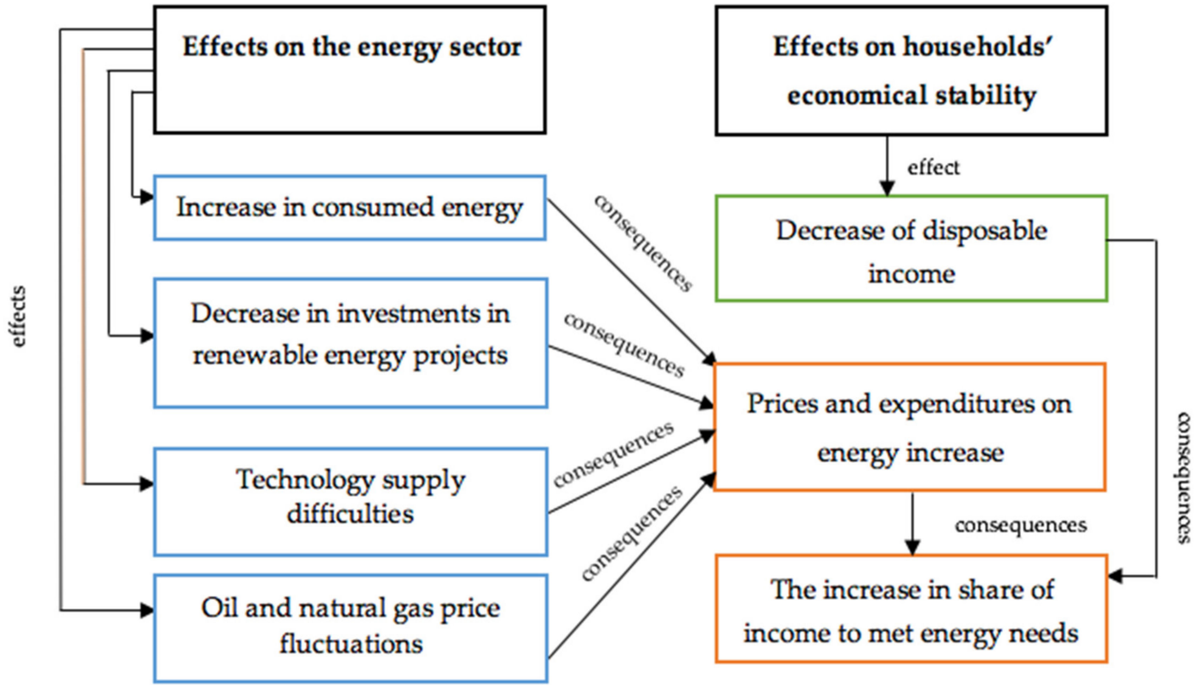

Figure 1. The links between the COVID-19 pandemic effects and energy poverty of households.

Interesting research was performed by Bouzarovski et al. [31], where the national energy and climate plans were evaluated in terms of the alleviation of energy poverty. The national documents of the countries were analyzed according to energy justice principles, which were grouped into two categories, "access to justice" and "provision of resources". According to the results, such countries as Belgium, Cyprus, France, Italy, Lithuania, Malta, Romania and Spain have a well-developed energy poverty policy in different decision-making areas. Moreover, it was found that southern and eastern countries pay more attention to the reasons and consequences of the issues of energy poverty. These countries can be identified as having a specific direction to improve the energy efficiency of buildings and household income, while countries with well-developed energy policies and social mechanisms focus on governance capacity to combat the problem.

Carfora et al. [7] made a forecast of energy poverty across the EU countries until 2025. According to the results, the increase of energy-poor households due to economic, energy, social and environmental conditions will be addressed slowly and at different rates among countries. Forecasts to 2022 showed that the biggest increase in energy poverty will be in Bulgaria, Latvia, Italy and Greece. The decrease of the problem is expected in Ireland, The Netherlands, Slovakia and Sweden within the short term. The study also shows that the pandemic has extended the gap between leaders and the most backward countries.

3. Methods and Data

The methodology of the research consists of four main steps. Firstly, a review of the scientific literature in the Web of Science database on the combination of topics "COVID" and "energy poverty" was performed. The effects of the pandemic on the energy sector were identified and studies on the impact on energy poverty were analyzed. This allowed to determine the links between the COVID-19 pandemic effects and the energy poverty of households. Secondly, a set of indicators reflecting the extent of energy poverty in different EU countries has been developed on the basis of established links. Thirdly, an analysis of indicators was performed and the regional differences among countries were determined by comparing the situation, trends and policy measures applied. Fourth, the national policy measures to combat the growth of energy poverty are reviewed.

Three groups of indicators are used to evaluate the impact of the pandemic to the energy poverty among households in the EU countries. In order to encourage the repeatability of the research and the application of the proposed indicator set for the monitoring of the progress in the future, the aim was to make all indicators easy to find and publicly available. It sought to create a set that was suitable for all countries. All selected indicators are standardized and comparable. The level of energy poverty is expressed through three self-reported subjective indicators. The indicators related to energy poverty issues from the EU Statistics on Income and Living Conditions (EU-SILC) are an important measure to track the progress across the EU member states. These indicators are quite widely used in different studies, both to compare them over different periods and to construct indices for energy poverty assessments [12]. As objective indicators are used energy prices and net income. The changes in electricity and gas prices for households, including all taxes and levies, are measured. Moreover, the mean net income among households reveals energy poverty inequality among people in each country. Indicators set for the evaluation of the impact of the COVID-19 pandemic on the extent of energy poverty in European countries is presented in Table 1.

Table 1. Indicators set.

Indicators Group	Indicators	Justification	Data
Energy poverty level	Share of people unable to keep home adequately warm	Changes in population unable to heat home adequately reveals consumption changes, changes in disposable income of people and energy prices.	[5]
	Share of people having arrears on utility bills	Changes in people having arrears on utility reveals consumption changes, changes in disposable income of people and energy prices.	[5]
	Share of people living in buildings with leakages	Changes in share of population living in buildings with leakages show the implementation of EU energy policy priorities at national level.	[5]
Energy price	Electricity prices for household consumers (including all taxes and levies)	Electricity price changes are directly related to the issue of energy poverty through the share of income to meet energy needs.	[4]
	Gas prices for household consumers (including all taxes and levies)	Gas price changes are directly related to the issue of energy poverty through the share of income to meet energy needs.	[4]
Energy poverty inequality	Mean net income	The changes of mean net income among households reveals the effect of the pandemic to households' income.	[4]

To assess the impact of the COVID-19 pandemic on energy poverty among different EU countries, the selected indicators before and during the first year of the pandemic are analyzed. In order to analyze as up-to-date information as possible, gas and electricity prices are compared over a two-year period. Although the EU is a single region with common energy policy goals, such as renewable energy development, the decrease of GHG emissions, improvements in energy efficiency and the strengthening of energy security, the economic and energy situations of the countries differ. Moreover, the geographical situation of each country has a significant impact on the energy expenditures of households. In order to highlight the regional differences among the EU member states, the countries were divided into five regions according to the country's geographical and economic situation. These regions are: Nordic Europe (Denmark, Finland and Sweden), Nord-East Europe (Czech Republic, Estonia, Latvia, Lithuania, Poland and Slovenia), southeast Europe (Bulgaria, Hungary, Romania and Slovakia), southern Europe (Croatia, Cyprus, Greece, Italy, Malta, Portugal and Spain) and western Europe (Austria, Belgium, France, Germany, Ireland, Luxembourg and The Netherlands).

4. An Overview of Energy Poverty in Europe

Despite that the EU is a single region with the common goals for economic, social, environmental and energy policies, the national achievements of each EU member state differ. The differences between countries are related to geographical, historical, resource, social and other aspects. Therefore, the different policy objectives of the EU are determined for each member state according to its current situation and ability to achieve them. Accordingly, it is reasonable to analyze the energy poverty situation in Europe by dividing the countries according to their level of the economic development and geographical location in the region. This section provides the EU policy measures to combat against the energy poverty of households, with the analysis of selected indicators reflecting the change of energy poverty after the first year of the pandemic, and a review of national policy measures to fight against energy poverty in the context of energy crisis.

4.1. The EU Policy Measures to Fight against Energy Poverty

The alleviation of energy poverty among European households is one of the main EU energy policy priorities. Although, it should be emphasized that the proper attention to this problem rose only in the last decade. The statistics show that buildings are the biggest energy consumer in European countries, as they are responsible for 36% of the energy-related GHG emissions and consume 40% of the energy in the EU. Nevertheless, approximately 75% of the buildings are inefficient and old (over 50 years) in the EU and the renovation rate is only 1% per year [32]. In order to the improve energy efficiency of buildings, the EU released the Energy Performance of Buildings Directive (2010/31/EU) [33] and the Energy Efficiency Directive (2012/27/EU) [34]. The application of principles of energy performance in national building codes allowed for twice the reduction of the energy consumption of buildings. Following the introduction of energy performance rules in national building codes, today buildings consume half the energy compared to buildings in the 1980s.

The fight against energy poverty is reflected in the Clean Energy for all Europeans Package [35], where the need to improve energy efficiency is stressed. The European Commission highlighted the necessity to reduce energy poverty or the risk to face it as a key pillar towards the implementation of the Green Deal ambitions [36]. After the European Green Deal followed the amendment of the Energy Performance of Buildings Directive (2010/31/EU) and the Energy Efficiency Directive (2012/27/EU). The new Energy Performance of Buildings Directive (2018/844/EU) [37] stressed the importance of technological improvements for the construction sector and the necessity to increase the building renovation rate. The new Energy Efficiency Directive (2018/2002) [38] upgraded the policy framework to 2030 and set up the target of energy efficiency for at least 32.5%. The establishment of the Renovation Wave strategy [39] was introduced as a key document to drive energy efficiency and increase energy affordability among households in member states. The document proposes measures, regulatory and financing schemes to boost building renovation. The strategy seeks to double annual renovation rates in the next decade. The renovation of old and inefficient buildings will allow to reduce GHG emissions, increase the quality of life of households, reduce energy bills and also create jobs in the construction sector. In addition, other effects related to the decrease of energy consumption can be identified, such as a possible reduction in energy dependence on imported energy, the increase in energy security, etc.

In the second half of 2021, the world was hit by an energy crisis. Energy prices have started to rise sharply. In October 2021, the European Commission presented a toolbox of measures for the EU member states to support addressing the negative impact of the pandemic on energy prices and to shield households and businesses from rising energy prices and energy poverty [40]. The measures are categorized in two terms: the immediate response and the medium response. According to the European Commission [40], the priority should be given to those measures which quickly and effectively mitigate the price spikes for the most vulnerable groups of people. Moreover, it was emphasized that the measures applied should be easily adjusted, and the interference into market dynamics should be avoided. Moreover, the transition to the low-carbon economy cannot be slowed down by applied measures. The immediate response includes such measures as: direct support to the low-income households through tax reduction, vouchers, the covering of a part of energy bills, a disconnection ban for the energy grid, temporary payments deferral and the introduction of new renewable energy support schemes. In the medium period, the measures are focused on an increase in energy efficiency and the decrease of dependency on fossil fuels. These medium term measures have been pillars of the EU energy policy for many years.

Moreover, energy prices in Europe rose very sharply immediately after the Russian invasion of Ukraine on 24 February 2022. In response, the European Commission on 8 March 2022 published a communication on how to achieve Europe's energy independence from Russian fossil fuels before 2030 [41]. The document outlines measures for how to address the higher energy prices and analyzed the issues related to energy security. The resilience of the EU energy system will be based on two pillars. First of all, the diversification of natural gas suppliers (liquefied natural gas terminals, import from non-Russian gas suppliers, development of biomethane and renewable hydrogen production) should be implemented. Secondly, faster renewable energy development, the reduction of the use of fossil fuels and the increase in energy efficiency should be implemented in each member state.

4.2. Diversity of Energy Poverty in Europe in Terms of Different Indicators

Data before and after the first years of the pandemic are analyzed to assess the impact of the pandemic on the energy poverty of households (except for energy prices, which are analyzed before and after the second year of the pandemic). Despite the challenges faced by the energy sector, the ability to heat homes adequately continued to show an improvement in many countries (Figure 2). However, a very clear exception is Germany, where the inability to heat homes rose by 260% (from 2.5% to 9%). The significant percentage increases were also found in Luxembourg, Spain, Sweden and Slovenia. A small increase was also found in France, Belgium, Romania, Denmark and Estonia. Meanwhile, many other countries did not have such significant price volatility, and the indicator continued to decline steadily as in previous periods. Nevertheless, the EU-27 average has increased for the first time since 2012, and this increase is significant (from 6.9% to 8.2%), representing almost 19% growth. Such a sharp rise in the indicator signals the necessity to find measures to reduce energy prices.

A clear decline of people living in houses with leakages was observed in northeastern countries (Figure 3). Contrary to northeastern countries, the indicator rose in all Nordic countries. Moreover, a significant increase was found in France, Ireland, Spain and Cyprus. The EU-27 average increased for the first time from 2013 (more than 10% and counts 14% of the EU population).

There has also been an increase in arrears to utility bills for the first time in EU-27 since 2013 (from 6.2% to 6.3%). Arrears growth was mainly in the west, southeast and Nordic countries (Figure 4). Exceptionally high percentage changes were observed in Spain, Germany, Austria, Luxembourg and Denmark. Meanwhile, a significant decline was observed in the northwestern group (except for the Czech Republic).

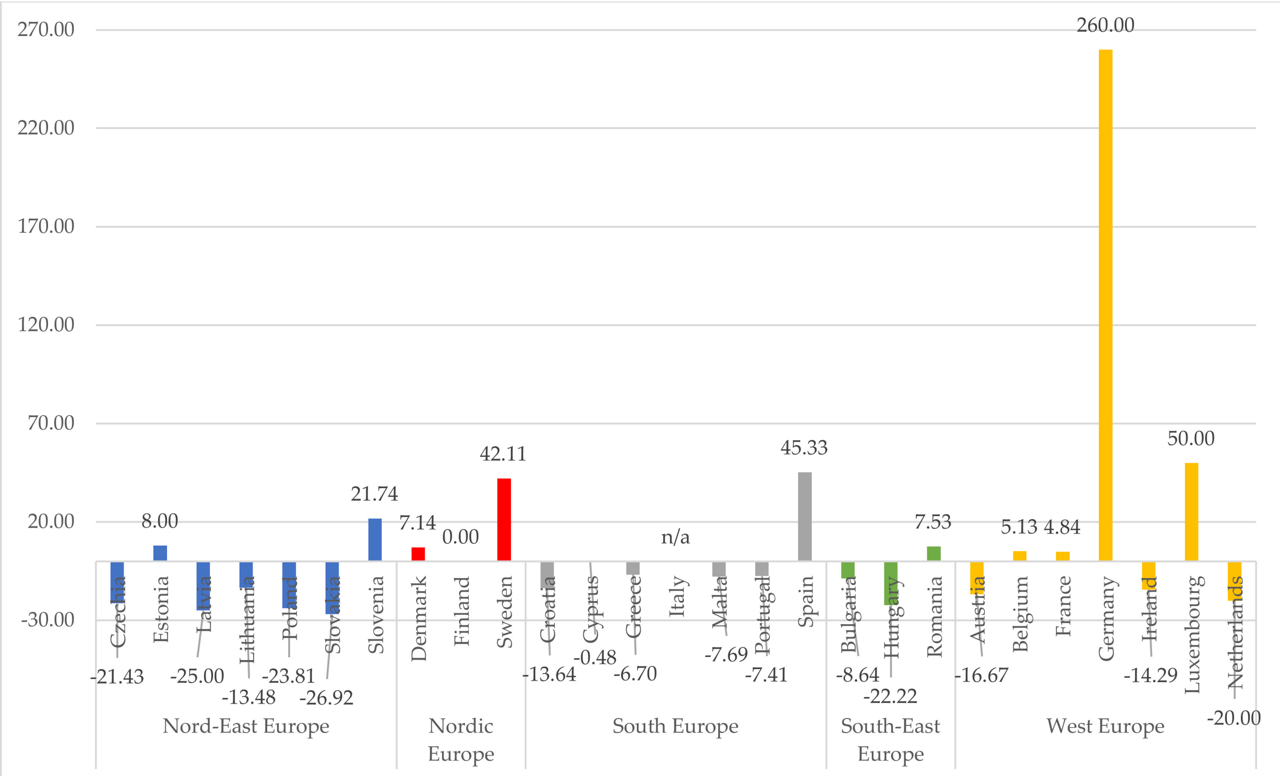

Figure 2. Inability to keep home adequately warm—EU-SILC survey, changes in the period of 2019–2020, %. Note: the data of Italy is not available.

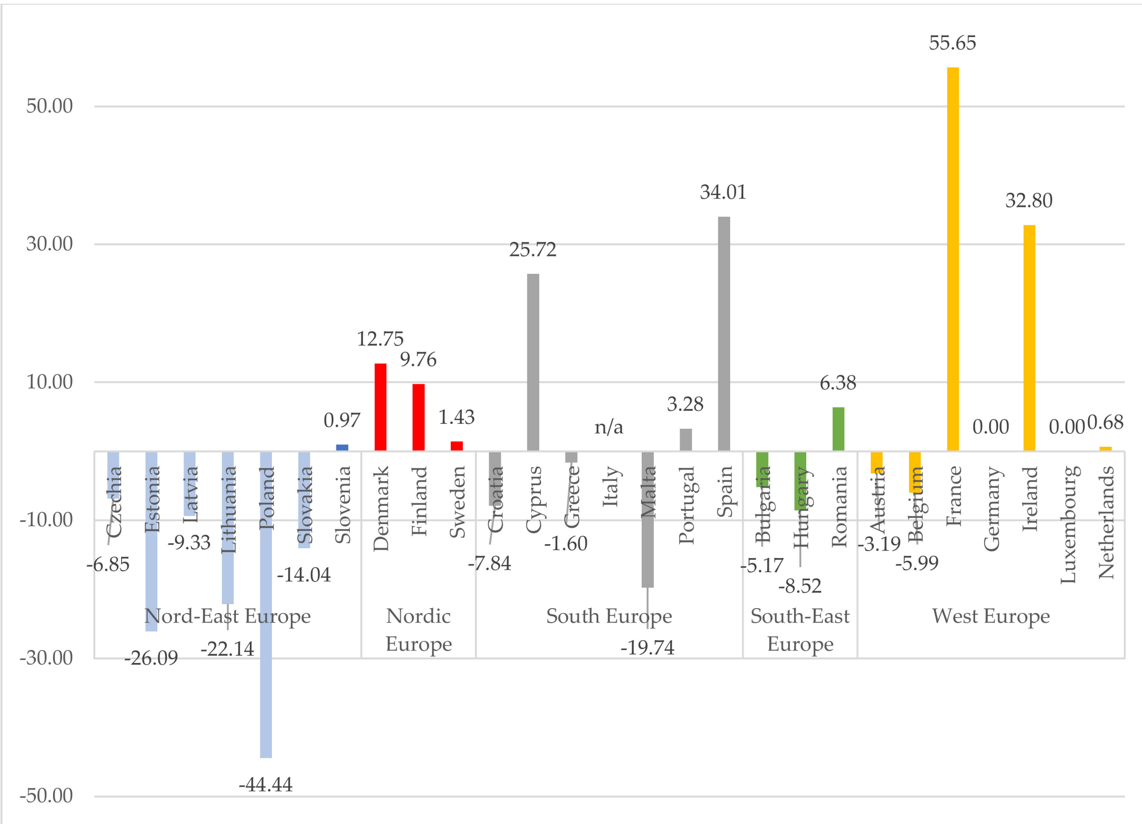

Figure 3. People living in houses with leakages, EU-SILC survey, changes in the period of 2019–2020, %.

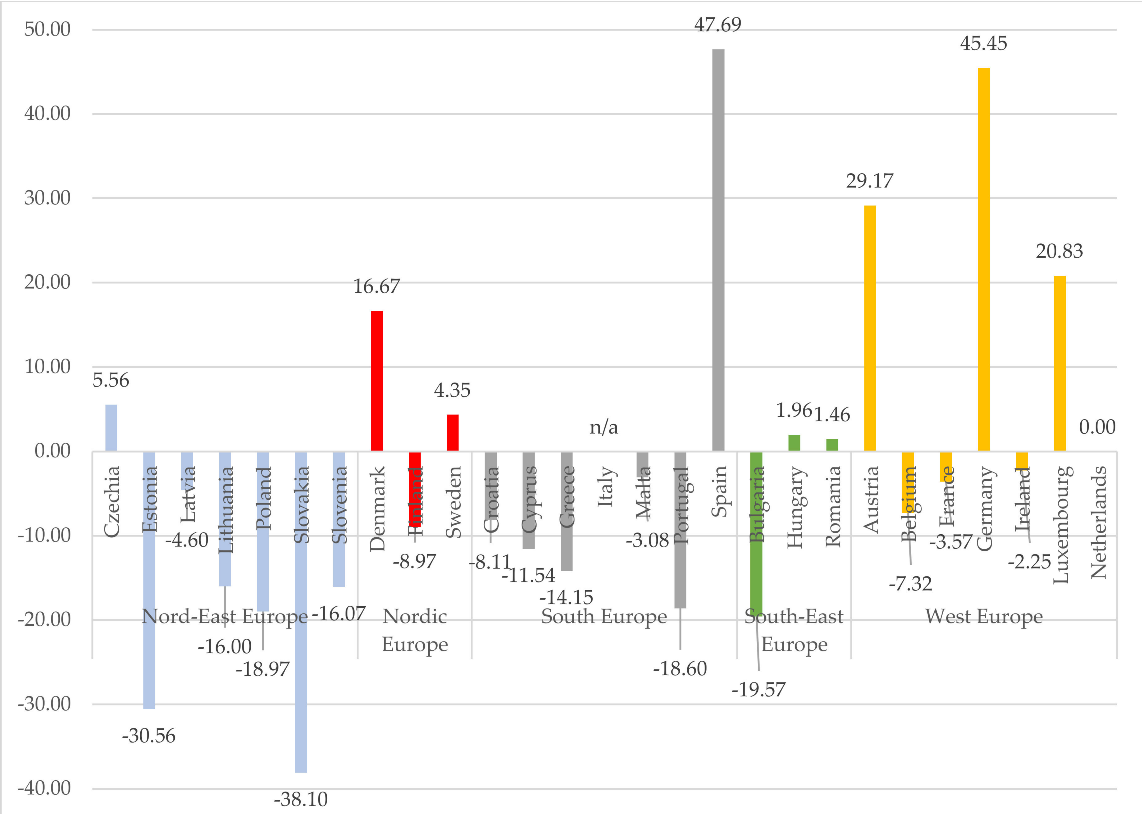

Figure 4. Arrears on utility bills—EU-SILC survey, changes in the period of 2019–2020, %. Note: the data of Italy is not available.

Figures below show the changes of mean net income in the period of 2019–2020 in euros (Figure 5) and in the purchasing power standard (Figure 6). Household incomes in euros have risen in all countries except France. The highest net income growth was in the northeastern, southeastern and southern countries. The biggest increase was found in Lithuania, reaching 13.34%. The analysis of income according to the purchasing power standard showed a decrease in income in all Nord group countries and even four countries of the western countries. The small increases in household income in euros and the decrease in revenue according to the purchasing power standard are the main reasons for the changes of the EU-SILC indicators presented earlier. The analysis of the first years of the pandemic already shows the impact on household income and confirms the statements raised after the analysis of the scientific literature (Figure 1). It can be assumed that the consequences of the pandemic will become even more pronounced in the following periods.

Figure 7 presents distribution of countries by the inability to keep homes adequately warm and the income. The point of intersection of the axes is the EU-27 average. Western countries have the highest income rate and a lower rate of inability to heat homes than the EU average. Northeastern countries can be characterized as lower than the EU average income, but also lower than average level of the inability to heat houses (except Lithuania).

Changes in energy prices were measured over a two-year period. Rising electricity prices rose in many countries (Figure 8). More than ten percent points of electricity price increase were found in Poland, Romania and Luxembourg. Moreover, a significant decrease in electricity prices was observed in The Netherlands, Latvia, Sweden, Cyprus and Hungary. At the same time, gas prices had fallen in almost all countries (Figure 9). The most favorable changes for consumers were in the northeastern countries. Significant natural gas price declines were also seen in the southeast group countries. The analysis of statistical data confirms that the decline in household disposable income, rising energy prices and energy supply difficulties have increased the share of income of energy consumers to pay energy bills. Thus, the research confirms the hypothesis raised after the scientific literature review, that the pandemic increased the energy poverty among European households.

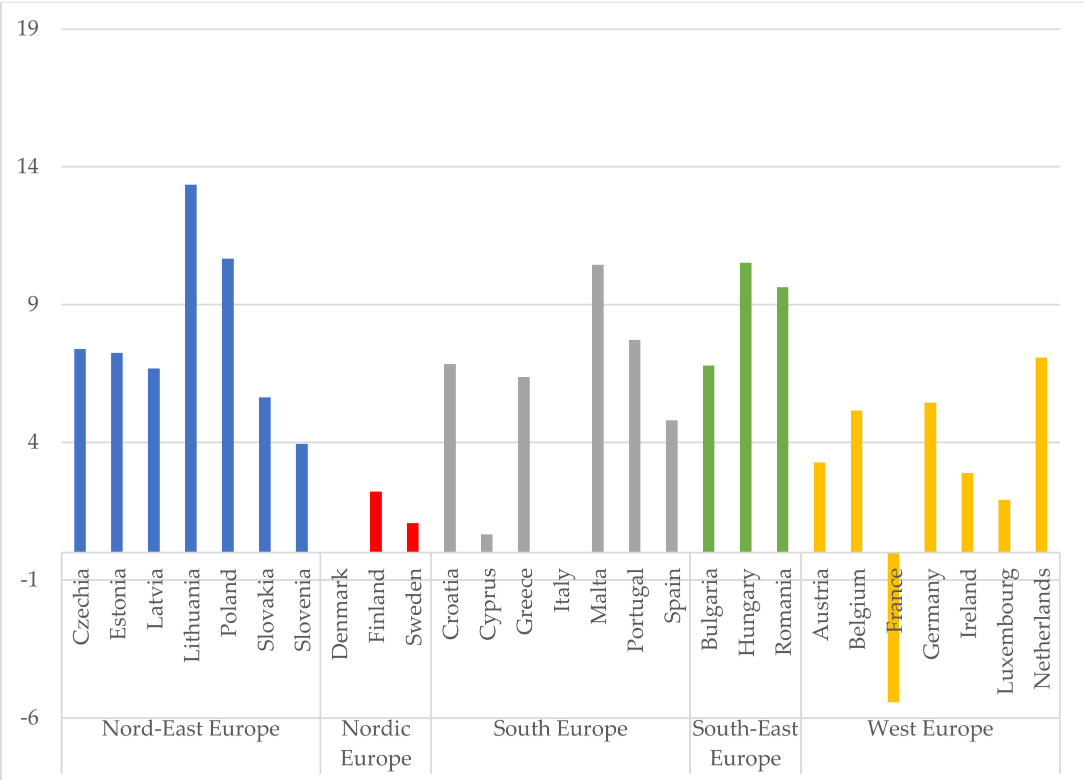

Figure 5. Mean net income, EUR, changes in the period of 2019–2020, %. Note: the data of Italy is not available.

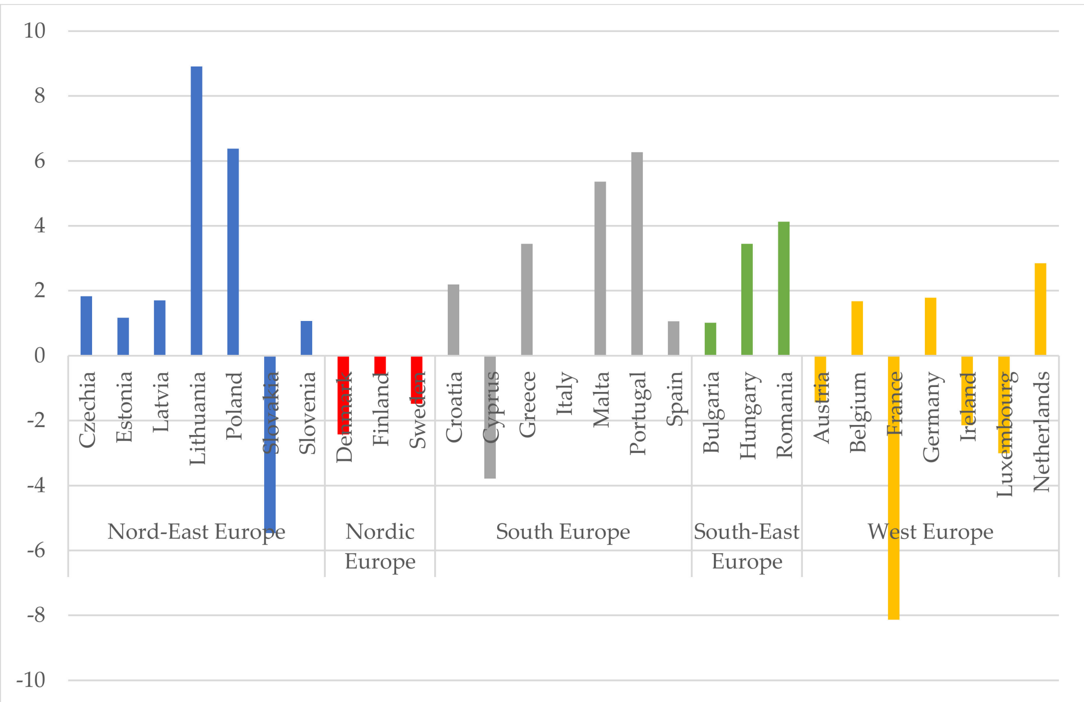

Figure 6. Mean net income, Purchasing power standard, changes in the period of 2019–2020, %. Note: the data of Italy is not available.

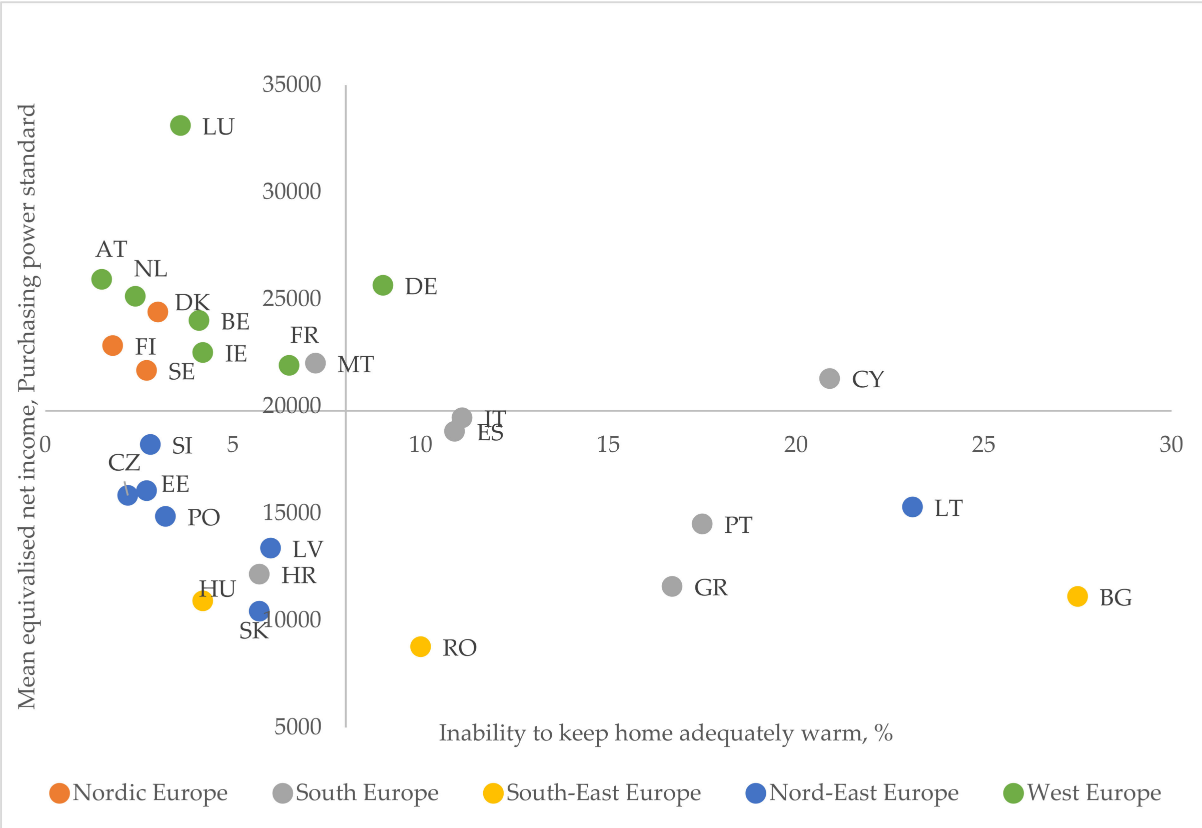

Figure 7. Distribution of countries by inability to keep home adequately warm and income.

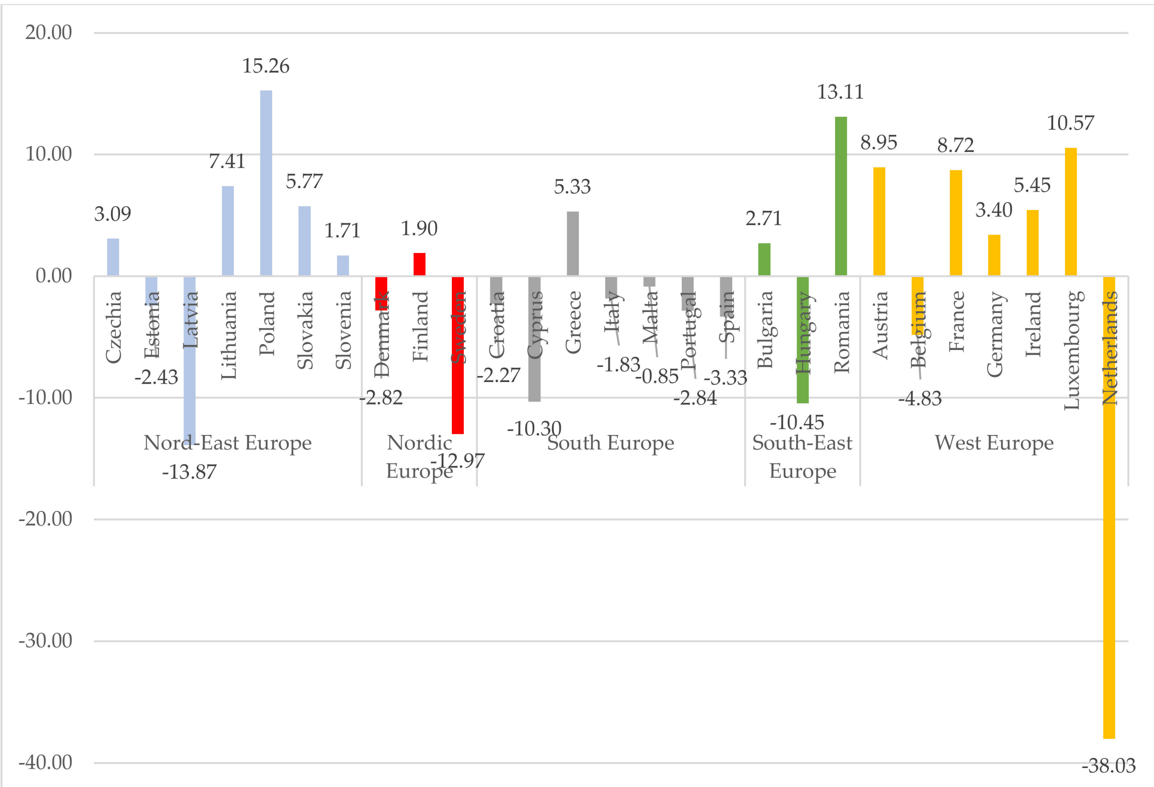

Figure 8. Electricity prices for household consumers, 2500 kWh < consumption < 5000 kWh, changes in the period of 2019–2021, %.

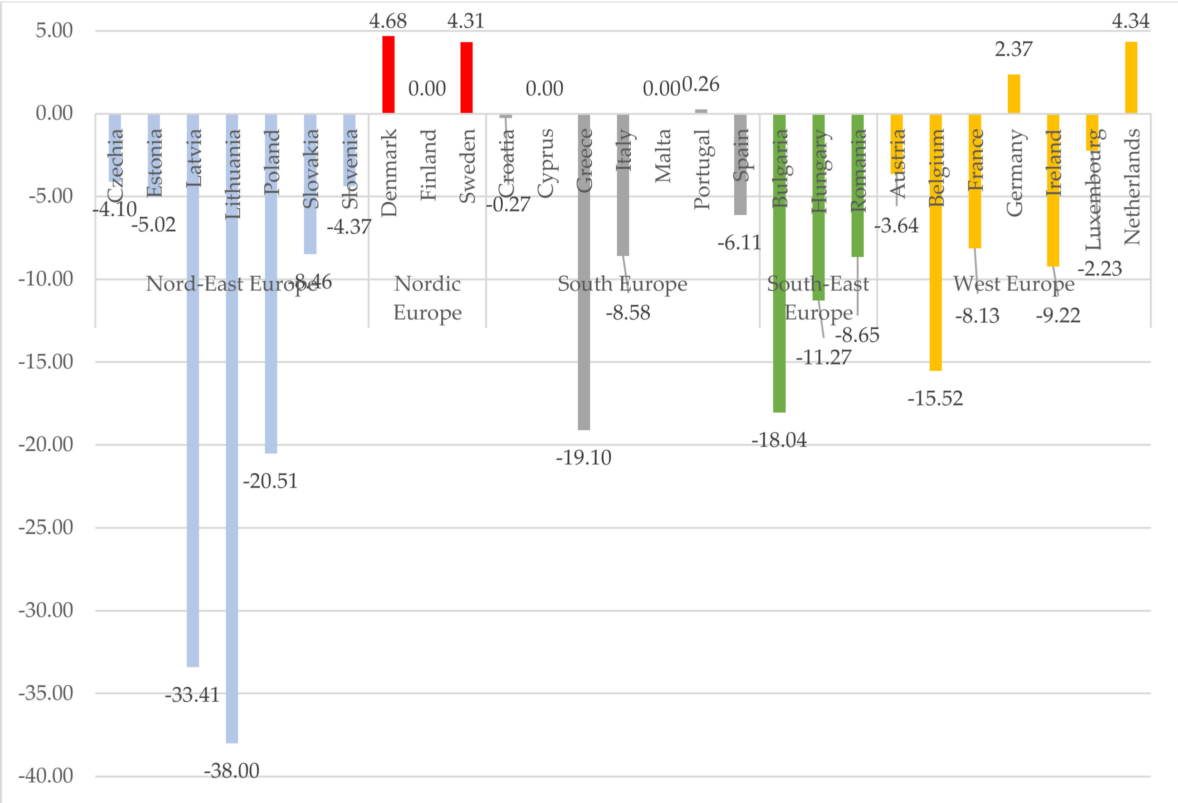

Figure 9. Gas prices for household consumers, consumption < 200 GJ, changes in the period of 2019–2021, %.

However, it must be emphasized that in the second half of 2021, electricity and gas prices began to rise sharply in Europe. The situation was caused by the global energy crisis. The rise in prices was also affected by rising tensions between Russia and Ukraine. In the end of 2021, the search for measures to reduce energy prices and support energy consumers was actively initiated at both the European and national level. The Russian invasion of Ukraine has exacerbated the energy crisis in Europe. Energy prices rose sharply in very few days. This economic uncertainty has led Europe to take active actions to diversify energy resources in Europe and reduce import dependency.

4.3. National Policy Measures to Fight Energy Poverty in the Context of the COVID-19 Pandemic

The consequences of the COVID-19 pandemic to the energy sector and the disposable income of people have prompted national governments to create and apply various measures to shield energy consumers from rising prices and energy deprivation. The legal framework of the EU allows its member countries to take actions to address the negative effects of the pandemic and energy price fluctuations. This subsection overviews the national policy measures by countries to combat the wholesale energy price spikes and energy poverty in the context of the COVID-19 pandemic and the global economic uncertainty. The most applied measures among the EU countries are the temporary and targeted reduction of energy taxes and duties, state aid through vouchers or subsidies for energy consumers (especially the most vulnerable) and protection to avoid disconnection from the energy grid. Table 2 presents the summary of policy measures to support households to deal with rising energy prices and to combat energy poverty.

Table 2. National policy measures for households by countries *.

Group	Countries	Temporary Payments Deferral	Vouchers, Subsidies or Discount on Bills	Disconnection Ban for Energy Grid	Tariff Adjustments, Retail or Wholesale Price Regulation	Tax (VAT) Reduction	Profit Regulation	Other
South Europe	Croatia		+		+	+		
	Cyprus				+	+		+
	Greece		+		+	+		+
	Italy	+	+	+	+	+	+	+
	Malta				+			
	Portugal		+	+	+	+		+
	Spain		+	+	+	+	+	+
West Europe	Austria		+	+	+			+
	Belgium		+	+	+	+		+
	France	+	+	+	+		+	+
	Germany	+	+	+	+	+	+	
	Ireland	+	+	+		+		+
	Luxembourg				+			+
	The Netherlands		+	+	+	+		
Nord-East Europe	Czech Republic	+		+		+		+
	Estonia					+		+
	Latvia		+		+			
	Lithuania	+	+		+	+		+
	Poland	+	+	+	+	+		
	Slovakia	+						
	Slovenia		+		+			+
South-East Europe	Bulgaria	+			+		+	
	Hungary			+	+			
	Romania		+		+	+	+	
Nordic Europe	Denmark		+					
	Finland						+	
	Sweden		+					

* "+" means, that the measure is applied. Note: Due to the rapidly changing situation and the immediate decisions to reflect the situation under economic uncertainty, some measures may not be included due to unavailability of English documents. Source: prepared according to [42–44] and different national media sources and documents.

In order to affect the end price for energy consumers, such measures as tariff adjustments, retail or wholesale price regulations were applied in many countries. For example, in Belgium, a social tariff was introduced, and green certificates were replaced by excise duties. In the end of 2021, the government of Bulgaria announced a price freeze for electricity and heating until the end of March 2022. A temporary electricity price cap was introduced in the end of 2021 and 2022 in France. A levy on the wholesale electricity price was reduced in Germany from the beginning of 2022. Heating price caps are to be applied from 2022 in Greece. Energy prices for households are regulated in Hungary. A tax rebate of 30% for heat and electricity was introduced for Irish households. A lot of different tariff adjustments were established in Italy for households and industry consumers. The costs for electricity distribution network services, the difference between natural gas tariffs for consumption above 221 kWh per month and the difference between tariffs in municipalities with extreme high heating tariffs were covered by the Latvian government for the first four months of 2022. The fees in electricity prices were reduced in Luxemburg. The Spanish government cut VAT, excise duties and generation taxes on electricity. Moreover, a gas price cap and a guarantee of a minimum electricity supply for low disposable income households were introduced. A temporary reduction of excise duties for fuel, gas and heating and waived electricity network fees were implemented in Slovenia.

Another of the mostly applied measures is vouchers to energy users, especially the most vulnerable. For example, in the end of January 2022, the government of Austria announced a one-off energy cost compensation for households. The households will receive 150 EUR, while the most vulnerable households will receive compensation of 300 EUR. Belgium introduced 80 EUR energy voucher for the most vulnerable people and 100 EUR voucher for all electricity consumers, with the money deduced from their energy bills. Denmark established a tax-free voucher of about 504 EUR for the vulnerable households living in an area with gas-based district heating or having individual gas-based heating systems. The 100 EUR energy voucher for around 38 million people (earning less than 2000 EUR/month net) was established in France. Differentiated subsidies depending on the extent of electricity consumed and group of households were established in Greece. Moreover, subsidies of 20 EUR/MhW for households using natural gas were established in 2022. The 100 EUR voucher for all electricity consumers and a one-off check of 125 EUR on fuels were established in Ireland. The voucher from 15 EUR to 20 EUR each month for the most vulnerable households to pay electricity bills was established in Latvia to the end 2022. The voucher of 195 EUR for three winter months was established in Sweden to support the households who consume more than 2000 kWh electricity per month. A one-off voucher for 150 EUR or 200 EUR for vulnerable groups of energy consumers was established in Slovenia. The vulnerable energy consumers in Croatia get a 27 EUR voucher to pay their electricity bills. Moreover, a 54 EUR voucher was introduced for gas expenditures.

Moreover, VAT subsidies for energy were established in many countries (e.g., Greece, Lithuania, Cyprus, Romania, Germany, Ireland, Croatia, Italy, Poland, etc.). Poland stands out among the countries that have applied VAT corrections, reducing VAT on gas, food and fertilizers to 0%, on heating to 5% and on diesel and petrol to 8%. These corrections were established for the first six months of 2022. Moreover, in 2021, Poland reduced the VAT on electricity from 23% to 5% and waived the excise duty.

Some countries applied subsidies or a discount on energy bills. Cyprus established a 10% discount on energy bills for all energy consumers and has significantly reduced the VAT on energy bills for the most vulnerable people. The discount on electricity prices for low-income consumers and the discount on network fees for all consumers were applied in Estonia. A 10 cent subsidy for fuel was established in Portugal.

Many countries have already established and successfully applied several measures to support energy consumers coping with electricity and gas price spikes. A good example can be seen in Belgium. The social energy tariff was applied in Belgium during the pandemic for low-income households, targeting nearly half a million citizens. Belgium also supported people which were not eligible to receive the social tariffs and established a fund for gas and electricity. Certain taxes were corrected to compensate the price increase and a VAT reduction from March 2022 to July 2022 was established. Moreover, other measures were implemented, such as a disconnection ban, price freeze and energy voucher for the most vulnerable people. Moreover, another one-off voucher of 100 EUR on electricity bills to all households to the end of 2022 was established. This set of measures protects the most vulnerable energy consumers, does not distort the market and allows to inhibit increasing energy poverty among low-income households.

Some of the measures taken by the countries also can help to achieve long-term strategic energy policy goals. Such measures are related to the development of renewable energy and the improvement of the energy efficiency of buildings and technologies. Austria froze the mandatory renewable electricity contributions for 2022. The surcharge for renewable energy was reduced by more than 40% in Germany. Czech Republic presented a temporary measure for two months at the end of 2021 related to the benefits of renewable energy, where people using renewable energy were dismissed from energy fees. Subsidies for the improvement of the energy performance of buildings were established in Romania. The investments in renewable energy were increased in many countries (e.g., Greece, Lithuania, Denmark, etc.), e.g., support of the replacement of individual gas heating systems was applied in Lithuania and Denmark.

Other measures have also been applied, such as: temporary payment deferrals and disconnection bans were applied in many countries; the government of Lithuania delayed the electricity market liberalization process for six months; a temporary reduction of 20% in public transport fees was applied in Ireland; to protect the most vulnerable households from rising prices, the cost-of-living allowance was increased by 200 EUR in Luxemburg; the social bonus to the most vulnerable households was increased significantly in Spain.

It should be noted that although the countries apply many different measures, mostly they are temporary and can only be used for a limited time. It is therefore necessary to focus on the search and selection of measures that will not only mitigate the effects of increased prices, but also have long-term results. Such long-term measures must be aimed at increasing energy independence at the national and household level through the renewable energy development and high-energy performance in buildings and consumption.

5. Conclusions

The analysis of the recent research analyzing the impact of the COVID-19 pandemic to the energy sector allowed to identify the consequences of the COVID-19 pandemic to the energy poverty of households. In summary, it can be stated that the pandemic affected the energy demand of households, energy prices, investments in new renewable energy projects and caused energy supply difficulties that affects the energy price for final energy consumers and the increased expenditures on energy. In addition to all this, it also affected households' economic stability and the disposable income of people. As a consequence, the share of income to pay energy bills increased.

A set of three groups of indicators reflecting the extent of energy poverty in different EU countries has been developed. To highlight regional differences among the EU member state countries, they were divided into five regions according to the country's geographical and economic situation.

Although the increased energy bills affect all energy consumers, the most affected are low-income households, who have to spend a large share of their income to meet their energy needs. After the first year of the pandemic, the share of population unable to heat their homes adequately increased by almost 19% (from 6.9% to 8.2%). It should be noted that from 2012, this indicator tended to decrease every year. Moreover, the extent of this indicator varied among countries during the first year analyzed, and the possible real effect can be measured in the future studies by not forgetting to take into account the current global energy crisis following the Russian invasion of Ukraine.

The increase in electricity and gas prices are observed in all EU countries in 2022. The degree and linkages between wholesale and retail prices in countries depends on the structure and regulation of retail prices and energy mix of each country. In order to help people deal with rising energy bills, various measures were applied among the member states. Mostly, EU countries applied temporary and targeted reductions of energy taxes and duties, provided state aid trough vouchers or subsidies for energy consumers (especially the most vulnerable) and offered a disconnection ban. Although the European Commission provides recommendations and guidelines on how to tackle rising energy prices, the measures to be taken are adopted at the level of each member state. As a result, both the measures taken and the extent to which they are applied vary widely among countries. Measures taken by some countries are even distorting the market, for example the VAT reduction in Poland. Therefore, the recommendations should be more specific and some of them should be implemented at the level of all EU member countries.

Dependence on Russian gas and oil has shown its price to EU countries. Many member states are not prepared to stop the import of energy resources from Russia. Uncompleted homework, such as the purchase of liquefied natural gas terminals, the diversification of energy sources and the sufficient development of renewable energy has pushed many countries "into the corner". Therefore, the immediate reaction of the countries and active actions are needed at the moment to solve the problem of energy shortages and the dependence on energy resources from Russia in the context of Russian invasion of Ukraine on 24 February 2022.

It is essential that each EU member state pursue the goals of diversifying energy sources, increasing energy security and energy efficiency. The development of renewable energy and energy storage technologies, the improvement in energy efficiency with new technologies and energy efficiency measures (renovation wave) can reduce energy poverty among households significantly. It also will have many other effects on the energy security of the whole region and in each country. The investments in low-carbon energy solutions will help to reduce the volatility of energy prices and the imbalances in energy demand and supply by fluctuations in global fossil fuel prices, and other factors such as sanctions for Russia or other possible external factors.

However, further efforts at the EU level and at the national level are needed to reduce the energy burden on consumers, especially households. In order to achieve the main goals of the energy policy for the whole region, part of the measures should be adopted on a regional basis, e.g., measures to support renewable energy technologies.

The current study has limitations, as the research period due to data availability is short and cannot fully reflect the nature of the problem. A future longer-term analysis is necessary to provide more in-depth analysis. Europe's transition from imported fuels and its possible impact on energy poverty also requires detailed research.

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