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# Transformation of Energy Markets

## Description, Modeling of Functioning Mechanisms and Determining Development Trends

Edited by

Michał Bernard Pietrzak and Marta Kuc-Czarnecka

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*Editors*
Michał Bernard Pietrzak
Gdańsk University of Technology
Poland

Marta Kuc-Czarnecka
Gdańsk University of Technology
Poland

*Editorial Office*
MDPI
St. Alban-Anlage 66
4052 Basel, Switzerland

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# About the Editors

**Michał Bernard Pietrzak**

Michał Bernard Pietrzak, PhD, D. Sc is an associate professor at the Gdansk University of Technology, Faculty of Management and Economics. He is an experienced econometrician specializing in the application of quantitative methods, with particular emphasis on the methods of multivariate comparative analysis, financial econometrics and spatial econometrics. His research results are confirmed by more than 70 articles published in the Web of Science Core Collection, where the Web of Science h-index is 16. The research problems he has undertaken have been related to the fields of Economics, Management, and Finance.

**Marta Kuc-Czarnecka**

Marta Kuc-Czarnecka, PhD, works as an associate professor at the Faculty of Management and Economics, Gdansk University of Technology. She is an experienced researcher specializing in the application of quantitative methods to selected economic problems. It has 16 publications on the Web of Science Core Collection, where the Web of Science h-index is 5. Marta Kuc-Czarnecka specializes in methods of multivariate comparative analysis. The main area of her research is the creation and validation of composite indicators that allow for multidimensional assessment of economic phenomena, for example: competitiveness and innovation.

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*Editorial*

# Transformation of Energy Markets: Description, Modeling of Functioning Mechanisms and Determining Development Trends

**Michał Bernard Pietrzak * and Marta Kuc-Czarnecka**

Faculty of Management and Economics, Gdańsk University of Technology, Narutowicza 11/12, 80-233 Gdańsk, Poland; mkuc@zie.pg.gda.pl
* Correspondence: michal.pietrzak@zie.pg.gda.pl

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## 1. Introduction

One of the key contemporary economic and social issues today is the global energy transition [1–3]. Energy transition processes are having a significant impact on the development of world economies, increasing their TFP and leading to an increase in their level of innovation through the transfer of myriad new technologies [4,5]. These processes also contribute to an increase in foreign direct investment and, consequently, an increase in the level of business investment, the competitiveness of economies and changes in the labor market [6,7]. Additionally, contributing to the systematic and dynamic development of the energy transition are the significant increase in the wealth of the population, the change in the degree of social and income inequality, the change in consumption patterns and the significantly increased consumption of energy by households, which until recently relied exclusively on the use of energy from conventional sources [8–12].

It should be noted that the ongoing energy transition processes most strongly affect the development of energy markets, the largest of which are the electricity primary fuel markets. Currently, energy markets represent an increasingly significant aspect of modern economies in terms of business investment, the share of the sector's output in GDP, as well as research and development. In recent years, the renewable energy sector has also been gaining importance as a natural complement to the two aforementioned markets [13–15]. Undoubtedly, the development of the renewable energy sector is linked to the goals of sustainable development [16–19], where the greatest emphasis is placed on caring for the environment and transitioning from classical energy sources to renewable and non-carbon sources. In addition, it is assumed that entrepreneurship is to take on a new meaning and is to be implemented as part of the emergence of sustainable start-ups and the transition of businesses to meet sustainable goals and increase the use of renewable energy [20–22].

All the above-mentioned aspects of the development of modern economies point to the need to take a fresh look at the development and functioning of energy markets. Of particular importance seems to be the analysis of changes in the prices of electricity and primary fuels and the relationship between these markets and the renewable energy market. Equally important are analyses to identify development trends already occurring in the energy markets and to make predictions about the formation of these trends in the future. Such identified studies should provide valuable guidance for the purposes of conducting current energy policy and creating institutional and legal conditions for the development of energy markets. Conclusions from research on energy markets also provide substantive arguments for the assumptions of global energy strategies, as well as the energy strategy of individual countries.

## 2. A Short Review of the Contributions in This Special Issue

Dynamically developing energy transition processes and their increasingly stronger links with the electricity market, the primary fuels market and the RES sector are an important argument for the creation of a Special Issue under the title of "Transformation of energy markets: Description, modeling of functioning mechanisms and determining development trends", in which 12 research papers were published.

The paper [23] presents a new approach to the evaluation of the energy transformation process in the Member States of the European Union. In their study, the authors used the variables describing SDGs 7, 8, 10, 11 and 12 to assess the economic potential and current energy consumption patterns. Using an innovative set of diagnostic features and applying taxonomic methods, the authors grouped the EU countries according to the emissivity of their economies and the potential to fulfil the assumptions of the energy transition process. The authors note that there is a systemic problem with the implementation of energy transition and that not all countries will be able to meet the goals set by the EU. For many countries, this process can be demanding and backbreaking. The countries included in this group contain Bulgaria, Croatia, Greece, Latvia, Lithuania, Portugal, and Romania, as they are high-emission economies with relatively poor populations. At the other extreme, i.e., characterized by the tremendous potential for a smooth transition in the energy transformation process, there are countries with a high share of renewable energy sources, namely, the Nordic countries and Estonia. The authors emphasize the importance of a harmonized energy transition process, noting that the suspension of energy transformation processes may move from one region to the entire member state, or that it is possible for the economy of one of the countries, or a group of countries, to undergo a serious economic crisis. Thus, such eventualities would bring some countries back to the starting point and jeopardize the future of the entire EU energy project [24].

The authors of [25] investigated whether the COVID-19 pandemic had a noticeable effect on energy consumption and affected the business cycle. It turns out that socio-economic development and energy transformation processes may be hampered or even stopped by unforeseen events, an example of which undoubtedly being the outbreak of the coronavirus pandemic [26]. Two hypotheses were proposed: that energy consumption is the leading factor shaping the business cycle, and that there is a translation of the clock of energy consumption into business cycles. Using spectral analysis and the business cycle clock, the authors determined the phase spectrum between energy consumption (in GWh) and GDP. They confirmed that energy consumption can be used as a leading indicator of the business cycle, indicating that the largest decrease in energy consumption occurred during the first lockdown. Smaller declines during successive waves of the COVID-19 virus are mainly due to smaller restrictions and their weaker impact on economic activity. As for business clocks, the authors' research showed that only Sweden and Norway remained around their long-term trend, and in other cases, the business cycle phase shifted from deep recession to the middle level or to recovery.

The authors of [27] focus on the challenges and opportunities for the development of photovoltaics in Poland, taking into account the aspect of information asymmetry between energy source producers and consumers. The qualitative research conducted on Polish small- and medium-sized enterprises showed that the main source of information asymmetry is the operation of the regulator, the technological conditions related to the early stage of technology development and the lack of appropriate knowledge held by the end customer about the investment. The authors also pointed out that this highly dynamically developing sector in Poland suffers from a high rotation of employees, especially those with special technological competencies, and volatile political decisions.

In [28], the authors focus on energy consumption in health care facilities, trying to set the determinants of electricity and thermal energy costs in relation to the size and intensity of work in Polish clinics. Multivariate backward stepwise regression analysis was used to analyze financial and resource data of all Polish hospitals from 2010 to 2019. An interesting element was also the division of the country into four climatic zones. The obtained results showed that energy consumption not only depends on the operational activities of Polish hospitals but is also related to the geographical location. This was especially true for surgical hospitals; the warmer the climatic zones, the higher the EEC.

In the case of non-surgical hospitals, no influence of the climatic zone on the EEC was observed.

The authors of [29] deal with factors determining the demand for energy consumption from renewable sources in European countries. The study presents institutional, social, historical and economic factors shaping the demand for energy from renewable sources. Despite the general awareness of Europeans and a positive attitude towards green energy, these factors are not universal in all countries. Based on the BACE model methodology, the authors showed that there is a divergence concerning REC in Europe. Additionally, the lags are visible in the case of Croatia, Cyprus, Latvia, Lithuania, Poland, Romania, Slovakia, and Slovenia, where GDP and FDI growth could help in a faster transition to less climate-damaging energy. The study also confirmed that global awareness of climate change increased after the Paris Agreement, creating room for changes in energy policy in both developed and developing countries in Europe.

As in the case of article [3,30] also refers to the process of energy transformation, with the difference being, however, that it focuses on this process only in Poland, taking into account international obligations and the current national policy. The author emphasizes that regardless of the scenario realized, the transition to green energy and the reduction in CO2 emissions will inevitably entail an increase in energy prices, thus possibly leading to energy poverty for some Poles. The author also emphasizes that Poland's lack of climate neutrality in 2050 will mean that it will not fully participate in the global technological revolution. As a remedy, he recommends a diversified scenario with natural gas, stressing that due to political and historical reasons, nuclear power has no real chance of being accepted in the country. The solution to the problems raised in the article [30] is undoubtedly the further development of the RES sector, which, as shown in articles [31,32], is able to meet in full, for the most part, the energy needs of the regions.

The author of the article [33] undertook the research topic of the relationships between crude oil prices and exchange rates. While this is a fairly popular issue, there is no one consistent answer regarding the shape and direction of this relationship. The author, basing his analysis on the nonlinear Granger causality tests and SVR models, showed the existence of stronger bidirectional causal relations between crude oil prices and exchange rates EUR/USD and GBP/USD, and weaker relations between crude oil prices and JPY/USD. The revealed existence of bidirectional causal relations between crude oil and exchange rates' returns implies the potential possibility of using lagged values of one of these variables as the regressor for the second one.

In [34], the author was devoted to the issue of energy poverty in households run by individuals aged 60 and older. The article uses the energy poverty index, which has not been used in Poland so far; the energy poverty index is a composite indicator containing both objective and subjective assessments of the housing situation of the elderly. Its values were then the basis for multidimensional statistical analyses of households, including cluster analysis. The results obtained by the author suggest that households consisting of elderly people are strongly diversified and that the energy deprivation of Polish households, of people aged 60 and older, seems to occur mainly among specific socio-professional clusters (living in the countryside, having low education and low income). The author points out that these are people whose apartments are, in most cases, heated with coal, and its rejection at the national level may deepen the energy exclusion of older people. To prevent this, it is suggested to expand gas pipelines to also connect households located in rural areas.

The authors of [35] refer to the spatial relationship of air pollution, economic growth, and renewable energy consumption. The authors of the study looked at the classical environmental Kuznets curve (EKC) and enriched it with spatial dependencies. A non-obvious solution was to create a neighborhood matrix not based on geographic location, but based on the values of the ecological footprint measure. The results of the spatio-temporal Durbin model determined the indirect effects, showing that the Kuznets curve has an inverse U-shaped relationship between the per capita GDP and $CO_2$ emission. It is worth noting that relatively highly developed countries were among those in which the change in energy from renewable sources consumption had the greatest impact on the $CO_2$ emissions in other countries. The results of the research show the importance of pro-ecological activities not only within a given country. The spatial spillovers in this regard are also significant.

In [36], the author took a closer look at the impact of structural changes in the global market of crude oil and energy products after the outbreak of the COVID-19 pandemic on the competitiveness of the wholesale fuel market in Poland. The estimated NARDL model indicated a significant change in the short-run pass trough of inputs to wholesale prices in the first year of the COVID-19 pandemic.

Another article linking the impact of COVID-19 to the energy market is [37]. The authors set themselves the goal of assessing the similarity between the time series of energy commodity prices and the time series of daily COVID-19 cases using the DTW method (Dynamic Time Warping) and hierarchical clustering. The results of the conducted analyses showed that not all energy sources responded in the same way to the shock caused by the COVID-19 virus pandemic. It turned out that most similar to COVID-19 are the time-series for coal and palm oil. The smallest similarity was noted in the case of gasoline, ethanol, and ULSD. The taxonomic grouping made it possible to distinguish a group of raw materials depending on their degree of response to a pandemic in its three different sub-periods. Generally speaking, ULSD, heating oil, crude oil, and gasoline form a group weakly related to COVID-19, while coal, natural gas, palm oil, $CO_2$ allowances, and ethanol are strongly connected.

A recent paper [38] addressed the problem of analyzing oil consumption in Poland, which is one of the country's main sources of primary energy. Unfortunately, Poland covers only 3% of its oil consumption domestically, with the remaining demand met by foreign suppliers. Therefore, the article analyzes current oil consumption, taking into account political and economic conditions and the RES sector. The article proposes a model of oil consumption for the domestic market based on artificial neural networks, which was used to produce consumption forecasts of this primary fuel.

## 3. Conclusions

Having presented the content of all the articles that make up the Special Issue "Transformation of energy markets: Description, modeling of functioning mechanisms and determining development trends", it should be stated that the problem of development of energy markets is crucial within the framework of the ongoing energy transition. Certainly, the processes of energy transition will continue to develop dynamically, which will undoubtedly affect changes in energy markets, including the further systematic development of the RES sector. In this case, the institutional and legal regulation of the production and sale of renewable energy seems important. This is not an easy task, because in the case of the RES sector, the focus should not be on post-independent, renewable energy sources, but on the energy mix. Formal regulation of the sale of combined energy from different renewable sources seems to be the biggest challenge. However, the development of energy markets in this direction should raise the level of energy security both in selected countries and around the world.

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

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Article

# The Connections between COVID-19 and the Energy Commodities Prices: Evidence through the Dynamic Time Warping Method

**Krzysztof Dmytrów [1,*], Joanna Landmesser [2] and Beata Bieszk-Stolorz [1]**

[1] Institute of Economics and Finance, University of Szczecin, 71-101 Szczecin, Poland; beata.bieszk-stolorz@usz.edu.pl
[2] Institute of Economics and Finance, Warsaw University of Life Sciences, 02-787 Warsaw, Poland; joanna_landmesser@sggw.edu.pl
* Correspondence: krzysztof.dmytrow@usz.edu.pl; Tel.: +48-691981555

**Abstract:** The main objective of the study is to assess the similarity between the time series of energy commodity prices and the time series of daily COVID-19 cases. The COVID-19 pandemic affects all aspects of the global economy. Although this impact is multifaceted, we assess the connections between the number of COVID-19 cases and the energy commodities sector. We analyse these connections by using the Dynamic Time Warping (DTW) method. On this basis, we calculate the similarity measure—the DTW distance between the time series—and use it to group the energy commodities according to their price change. Our analysis also includes finding the time shifts between daily COVID-19 cases and commodity prices in subperiods according to the chronology of the COVID-19 pandemic. Our findings are that commodities such as ULSD, heating oil, crude oil, and gasoline are weakly associated with COVID-19. On the other hand, natural gas, palm oil, $CO_2$ allowances, and ethanol are strongly associated with the development of the pandemic.

**Keywords:** energy commodity prices; COVID-19 pandemic; Dynamic Time Warping (DTW); hierarchical clustering

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## 1. Introduction

The impact of COVID-19 cannot be compared to any previous global crisis because the challenges of the current pandemic are much greater than during previous events. This is mainly due to the fact that we live in a much more globalised world. The current pandemic has considerable potential to devastate the economy. The result is a slowdown in economic development or even recession. The introduction of various types of lockdowns and the fear of the effects of the disease encompassing the whole of society lead to an amplification of its negative effects [1]. This should therefore be managed effectively [2,3].

Energy risk has always been one of the main risk factors for most companies involved in key industrial sectors, both in developed and developing countries. Energy commodity risk management is a key issue for most industrial companies, as it can seriously affect their competitiveness and future profitability. Global economic developments, emerging technological advances, and economic, geopolitical, and environmental events have caused a significant increase in the volatility of energy commodity prices over the past 20 years [4]. One such event is the COVID-19 pandemic. The negative effects of the pandemic, which were first felt in China and, from 2020 onwards, have spread worldwide. China accounts for a significant share of global commodity imports, which has had a knock-on effect on the entire international commodity market, and this may in turn affect economic growth [5–7]. Negative effects include disruptions in global supply and demand chains and thus disruptions in the supply of goods. While the economic impact of the epidemic is multifaceted, this article assesses the connections between the increasing incidence and the energy sector. Commodity prices around the world have fallen significantly since the coronavirus outbreak. This may be attributed to the fall in demand in China, where manufacturing, air travel, and transport fuels have been severely affected [8]. The global supply chain and financial system have been disrupted. In particular, lockdowns and the halting of international travel have reduced fuel consumption and consequently caused a lack of demand for oil [9]. Commodity prices reacted strongly to the COVID-19 crisis, showing significant daily and weekly declines since February 2020. Price volatility across all types of commodities has also increased. In particular, the ups and downs of oil prices in March and April 2020 exceeded the fluctuations experienced during the global financial crisis of 2008–2009. In addition, the volatility of metal and agricultural commodity prices clearly exceeded the levels of recent years [10]. Unconventional policy decisions by national governments can be more dangerous than the pandemic itself.

According to the World Bank [11], the primary spill-over effects affecting commodity prices depend on the type of commodity. At the outbreak of the COVID-19 pandemic [12]:

(i) the monthly price of crude oil plunged by almost 50% to a historic low, and some benchmarks recorded negative levels,
(ii) metal prices fell, with the most significant declines in zinc and copper, directly related to the slowdown in global economic activity,
(iii) agricultural commodity prices, which are less related to economic growth, have not declined significantly, with the exception of rubber, which is directly related to transport activities.

Already in the early stages of the pandemic, the energy sector was affected by COVID-19. This was mainly due to demand shocks. The decline in oil prices was due to the fall in demand. This also contributed to a decline in production. This was particularly evident in countries with price competition between the Organisation of the Petroleum Exporting Countries (OPEC) and Russia. The outbreak of the pandemic also had a negative impact on the nonenergy commodities sector. Many authors highlight the linkages between commodities, which may change during crises [13–16]. The link between energy and nonenergy commodities is most often analysed. Hence, the idea was born to investigate the linkage between energy commodities. The applied DTW method makes it possible to examine the similarities between the energy commodity price series and the series describing the number of cases.

It is still unclear when and how the COVID-19 outbreak will be brought under control. Therefore, it remains one of the important questions to be addressed to determine to what extent the outbreak has affected commodity prices so far. As the data and literature on the impact of the COVID-19 pandemic are still developing, definitive conclusions probably need to wait until the end of the pandemic.

It is expected that the COVID-19 pandemic will have a lasting impact on the consumption of energy resources, especially oil. During the epidemic, projections for oil demand have been revised as being down by major forecasters. They claim that the pandemic could have an impact on oil consumption by changing consumer behaviour. Air travel may be permanently reduced as business travel is restricted in favour of remote meetings, which reduces the demand for jet fuel. Working from home could reduce gasoline demand, but this may be offset by increased use of private vehicles if people refuse to use public transport.

Certainly, the pandemic has so far had a big impact on energy prices. The collapse in oil consumption in March and April 2020 resulted in a sharp decline in oil prices. In response, many oil producers cut production, in particular the Organization of the Petroleum Exporting Countries (OPEC) and its partners. As a result, the prices rebounded at a record pace from lows reached during the first phase of the pandemic. In the meantime, demand is also gradually increasing and is expected to stabilise in 2021 as vaccines become widely available and travel restrictions are eliminated.

The main purpose of our paper is the assessment of the similarity between the time series of energy commodity prices and the time series of daily COVID-19 cases using the dynamic time warping (DTW) method. We use the DTW measure to group energy commodities according to their price evolution and analyse the time shifts between daily COVID-19 cases and commodities prices. We conduct the analysis by subperiods in accordance with the timeline of the COVID-19 pandemic.

We find this motivation important, because direct relationships between the COVID-19 cases (or the phenomena that directly result from them) have already been widely analysed. In our research, we do not look for the direct impact of the COVID-19 cases on the energy commodity prices but rather the similarity in their courses. We also try to answer the question, if we can expect the changes in energy commodity prices on the basis of the evolution of the new COVID-19 cases (and find the time lag, after which we can expect the reaction of the prices to the changes of COVID-19 cases).

We put forward the following research hypotheses:

**Hypothesis 1 (H1).** *The evolution of energy commodity prices is the result of the evolution of daily COVID-19 cases.*

**Hypothesis 2 (H2).** *The reaction of the energy commodity prices to daily COVID-19 cases is diverse with respect to their type.*

We organise the manuscript as follows: in Section 2 (Literature Review), we present the current research in the field of relationships between the spread of the COVID-19 pandemic on various aspects of the global economy, including the prices of energy commodities. In Section 3 (Materials and Methods), we describe the data used in the research and applied research methodology: the Dynamic Time Warping (DTW) method and hierarchical clustering. In Section 4 (Results and Discussion), we present the obtained results and discuss them in light of previous studies in this field. In the last section (Conclusions), we give the findings and present directions for future research.

## 2. Literature Review

Since the beginning of the pandemic, studies have been initiated worldwide on its impact on the economies of individual countries and on the global economy. As the pandemic continues to evolve, so do the results of early studies. In the early stages of the pandemic, studies of its negative impact on global GDP began to emerge [17–21]. The decline in countries' GDP was very much reflected in financial performance on the global stock exchange [22]. Due to the estimated losses and decline in stock markets, there was a need for major policy interventions, both fiscal and monetary, and economic assistance to protect human health, prevent economic losses, and safeguard the financial health of the stock market [23]. According to the existing literature [24,25], COVID-19 is similar to other crisis periods and thus can trigger financial panics and drive governments' economic policy adjustments [26]. Zhang, Hu, and Ji [27] find that possible unconventional policy interventions could be more dangerous than the pandemic itself. However, the impact on policy need not be negative. Apergis and Apergis [28] investigate the effect of the COVID-19 and oil prices on the US partisan conflict. Their findings imply that political leaders aim low for partisan gains during stressful times. Along with the numerous socioeconomic problems, there have also been technical problems faced by energy companies. One of the important challenges during the pandemic period has been the effective management of the energy sector. Demand for energy decreased due to a partial shutdown of industrial activity and stagnation in the transport sector (aviation, public transport, and individual transport). Satellite images from the European Space Agency show a decrease in nitrogen dioxide ($NO_2$) levels in the lower atmosphere during the blockade period. This is particularly evident in the world's major cities [29].

A body of research has emerged in the literature related to the impact of COVID-19 on commodity prices, including energy commodities. Amongst them, there is a number of research on the impact of the pandemic on oil prices. Albulescu [21,30] shows that the initial daily number of reported cases of new COVID-19 infections had a marginal negative impact on oil prices in the long run. COVID-19 primarily affected financial market volatility and economic policy uncertainty, which in turn affected oil price dynamics and volatility. Devpura and Narayan [31] show that COVID-19 incidence and deaths contributed to oil price volatility ranging from 8% to 22%. Ertuğrul, Güngör, and Soytaş [32] analyse the impact of the COVID-19 outbreak on the volatility dynamics of the Turkish diesel market. The abnormally high volatility started after 11 March 2020, the day the first case of COVID-19 was announced in Turkey. Volatility peaked in mid-April 2020 due to restrictions imposed by the Turkish government. Initial diesel purchases were dictated by uncertainty, followed by a steady decline in consumption. In response to Turkey's normalisation policy, volatility approached zero over time. Gil-Alana and Monge [33] analyse the time series of WTI crude oil prices. They show that oil price shocks during the first pandemic period were transitory, although they will have long-lasting effects. Narayan [34] in his study finds that the oil price is more influenced by negative news about oil prices than the number of COVID-19 cases. This dominant influence of news is particularly evident once a certain threshold of price volatility is exceeded.

Changes in energy commodity prices affect changes in other commodity prices. Ezeaku, Asongu, and Nnanna [12] analyse the impact of oil supply and global demand shocks on commodity prices in metals and agricultural commodity markets in the context of the COVID-19 pandemic. This pandemic has already had a significant impact on the economies of most countries and on international financial and commodity markets. The real-time reactions of metal prices to the oil shock differed between precious metals (gold and silver) and other base metals (copper and aluminium). Gold and silver prices reacted negatively to the oil shock throughout the pandemic period studied. Copper reacted positively to the oil shock from day 0 to day 130 (end of May 2020), after which its reaction to the oil shock became negative during the remaining period. The aluminium price, on the other hand, reacted positively to the oil shock over the entire period. The estimated impact of oil shocks on the prices of selected agricultural commodities varied for each commodity. Maize and wheat prices reacted positively and significantly to oil shocks, while the reaction of soybean and paddy rice prices to oil shocks turned negative. Baffes, Kabundi, and Nagle [35] argue that unlike the demand for agricultural commodities, a slowdown in economic activity strongly affects the demand for energy and metals due to its higher income elasticity. Research by Vu et al. [36] indicates that different agricultural shocks can also affect the oil price differently. This is the case for maize used for ethanol production.

In the contemporary literature on the economic impact of the pandemic, there have been studies on the mining industry. Laing [37] analyses the declines in commodity prices. The mining industry saw a dramatic drop in demand due to the suspension of most industrial and construction production. This reduction in demand resulted in drastic price falls for a number of metals and minerals in March and April 2020. These falls were most drastic in the case of aluminium and copper. This led, in effect, to a fall in the share prices of many large international mining companies. The situation showed great similarities with the crisis of 2008–2009. Whether the pandemic's drops in the value of large mining companies will continue and whether they will lead to drops on the scale of the previous crisis depends on the duration of the lockdown and on economic and social conditions. However, a clear difference between COVID-19 and the 2008–2009 crisis is the case of the gold industry. Today, investors and entrepreneurs have even moved away from the supposed safe haven of gold, choosing instead to hoard currencies, such as the US dollar, needed to finance companies that have experienced unprecedented revenue declines.

In their paper, Lin and Su [14] analyse the linkages between commodities. They point out that due to COVID-19, energy commodity prices, as well as the financial market as a whole, exhibit many strange phenomena, such as extremely high price volatility, negative oil prices, and rapidly increasing systemic risk [38]. On 2 March 2020, the number of COVID-19 pneumonia infections in the United States crossed the double-digit mark and started to rise continuously. This time span exactly coincides with a sharp jump in the linkage index, indicating a strong impact of COVID-19 on the change in the prices of energy commodities and products. Prior to this moment, the total linkage index had always remained stable and showed only a few spikes and long-term trends. When a major economic event takes place, financial market analysts and investors pay attention to whether and how the strength and structure of the linkages between these commodities change. In March 2020, the total linkages between energy commodity markets experienced a sharp exponential increase. Such a change is similar to the situation in the 2008 financial crisis. However, the impact of COVID-19 appears to have lasted for only two months, and total linkages returned to average levels as early as May 2020. The authors find that the pandemic has a limited impact on pairwise linkages between energy commodities. From a structure perspective, only WTI and gasoline changed the direction of net linkages, while other commodities show only a change in intensity. This implies that the correlation structure of energy commodities is more or less stable even during the pandemic period. With the gradual containment of the spread of COVID-19, the energy market is slowly recovering. Although the price of energy commodities is still low, spill-over relationships between different markets are returning to prepandemic conditions.

As Tröster and Küblböck [10] note, the global spread of COVID-19 poses a huge challenge for developing countries. In addition to the health and economic crisis, many of them faced additional problems related to their dependence on commodities. Commodity price movements reflect changes in supply and demand in commodity markets but are also largely driven by policy measures to contain the pandemic. The crisis has once again exposed the structural weaknesses of commodity-dependent developing countries.

Foglia and Angelini [39] study the volatility linkages between oil price and clean energy sector firms (wind, solar, and technology) over the period 2011–2020 with the COVID-19 outbreak. The results indicated a significant change in both static and dynamic volatility linkages around the COVID-19 outbreak. WTI oil went from being a transmitter of volatility (before the pandemic outbreak) to a receiver of risk after the onset of the global COVID-19 pandemic. The recent pandemic intensified the spread of volatility, supporting financial contagion effects. The results of the study supported the hypothesis that dynamic linkages between oil and the clean energy sector peak during turbulent periods. The study shows that the cleantech sector has become important in optimal diversification strategies. The results obtained can be used in portfolio decisions and regulatory policymaking, especially in the current context of high uncertainty.

Nyga-Lukaszewska and Aruga [40] study how the pandemic affects oil and gas prices. For this purpose, they use energy market reactions in the United States and Japan. In the study, they analyse data covering the so-called 'first wave of the pandemic'. They show that there are differences in the energy market response between the two countries. A possible explanation for these results could be the differences in the development of the pandemic in the US and Japan, as well as the different role of the two countries in the energy markets. The number of COVID-19 cases in the USA during the initial phase of the pandemic was more than a hundred times higher than in Japan. Most US states enacted stricter regulations on staying indoors. These included fines and other penalties for violating lockdown laws. In Japan, the government did not enact such strict lockdown laws, and as a result, many people continued to commute to work by public transportation, even after the state of emergency was declared.

Chaudhary, Bakhshi, and Gupta [41] analyse the impact of COVID-19 on returns and volatility of stock indices of 10 major countries based on the GDP. The study period covers the first six months of the pandemic. They note the inherent uncertainty in the market, in that it is difficult to predict the long-term economic impact of COVID-19. This difficulty is due to the lack of existence of a comparable historical benchmark on which such predictions should be based.

Czech and Wielechowski [42] in their study evaluate the impact of COVID-19 on stock indices related to the alternative and conventional energy sector. The analysed indices decline as the government anti-COVID-19 policy becomes more stringent, but the relationship is statistically significant only in the high-volatility regime. The alternative energy sector, represented by the MSCI Global Alternative Energy Index, seems to be more resistant to COVID-19 than the conventional energy sector. This might imply that the novel coronavirus pandemic has not depreciated but emphasised the growing concern about climate change and environmental pollution. Research by Norouzi et al. [43] has shown that conventional electricity sources are not flexible enough to cope with a crisis during the pandemic. Electricity from renewable sources is more reliable than fossil fuels due to its availability in most regions.

Habib et al. [44] analyse asymmetric links between the COVID-19 outbreak, oil prices, and atmospheric $CO_2$ emissions. They use the unique Morlet's wavelet method in the analysis. The results of their study show strong but diverse relationships between the variables studied. The results also show that COVID-19 influenced oil prices and contributed most to the reduction of $CO_2$ emissions. The authors also show a negative relationship between COVID-19 and $CO_2$ emissions.

Hassan and Riveros Gavilanes [45] use daily data to model the dynamic impact of the COVID-19 pandemic on the stock indices of the first affected countries and on global commodity markets. The panel least squares Vector Auto-Regressive (VAR) estimation results confirm the negative short-term impact of the virus spread rate on the returns of the stock market indices. The virus spread rate is significant in explaining changes associated with platinum, silver, West Texas Intermediate (WTI), and Brent crude oil prices. The largest decline is observed in the case of the price of a barrel of oil, where an increase in the virus spread rate caused Brent and WTI crude oil prices to decline by 4.08% and 3.26%, respectively.

Shehzad et al. [46] use the Exponential Generalized Autoregressive Conditional Heteroskedasticity (EGARCH) model to assess the impact of the COVID-19 crisis on Dow Jones and West Texas Intermediate (WTI) oil returns in relation to other crises. Their results indicate that COVID-19 and the accompanying lockdown negatively affect both rates of return and that the impact on oil prices is more significant than on the Dow Jones index. They show that COVID-19 negatively affects investors' ability to determine optimal portfolios and thus the stability of financial and energy markets more than the global financial crisis of 2007–2009.

Ahmed et al. [47] study the impact of COVID-19 on the Indian stock and commodity markets during the different phases of lockdown. They also compare the impact of COVID-19 on the Indian stock and commodity markets during the first and second waves of the COVID-19 spread. They apply the conventional Welch test, heteroskedastic independent *t*-test, and the GMM multivariate analysis on the stock return, gold prices, and oil prices. They show that during different phases of the lockdown in India, COVID-19 has a negative and significant impact on oil prices and stock market performance. In contrast, with respect to gold prices, the impact is positive and significant. COVID-19 has a significant impact on the stock market performance of other South Asian countries. However, this impact is only for a short period and diminishes in the second wave of the COVID-19 spread.

Chien et al. [48] investigate the time-frequency relationship (the time-frequency relationship) between the COVID-19 pandemic and oil and stock market volatility, geopolitical risk, and economic policy uncertainty in the US, Europe, and China. They use the coherence wavelet method and the wavelet-based Granger causality tests to analyse the data. The results indicate a dramatic fall in oil and equity prices as COVID-19 intensified, proving to be much stronger after 5 April 2020. The oil market shows low co-movement with the stock exchange, exchange rate, and gold markets.

Other global and local factors also influence the demand for and supply of energy commodities. Not all changes occurring in the energy market should be explained solely by the impact of COVID-19. There are many factors that exist independently of the emergence of the pandemic. The "oil price war" between Saudi Arabia and Russia also contribute to the decline and destabilisation of oil prices in the first half of 2020 [49]. The crisis caused by COVID-19 reveals the structural weaknesses of commodity-dependent developing countries [10,50]. The negative relationship between commodity dependence and economic and social development is primarily related to deteriorating terms of trade and volatility in global commodity prices. Differences in the health of the energy sector in different regions of the world and countries should not only be viewed in terms of the spread of the virus. These differences are influenced by the fact whether a given country is only a consumer or a consumer and producer (exporter) of fuel and energy resources [40].

From a consumer perspective, many factors influence the prices of energy carriers. The most important of these are: costs of production, political situation, economic factors, freak weather conditions, ecological factors, social factors, and currency markets [51].

Our research goes in a different direction, hence, the proposal to detect similarities between commodity price developments and the number of COVID-19 cases, as well as similarities between the prices of individual commodities.

## 3. Materials and Methods

### 3.1. Overview of the Research Area

We base our research on the data coming from two sources. Data regarding daily COVID-19 cases come from https://ourworldindata.org/covid-cases service (accessed on 19 April 2021). Prices of commodities come from the https://stooq.com/ service (accessed on 19 April 2021). Data covered the period from 2 January 2020 until 15 March 2021. We analyse the prices of the following energy commodities:

- Brent crude oil (USD/barrel),
- $CO_2$ allowances (Euro/tonne),
- Heating oil (USD/gallon),
- Palm oil (INR/10 kg),
- ULSD (Ultra Low-Sulphur Diesel) (USD/gallon),
- Coal (USD/tonne),
- Natural gas (USD/mmbtu (mmbtu stands for millions of British thermal units (1 mmbtu $\approx$ 293 kWh))),
- Gasoline (USD/gallon),
- Ethanol (USD/gallon),
- Uranium (USD/lb).

The analysed period included days when there were no quotations (weekends and holidays). Therefore, for such days we interpolate the quotations on the level of average calculated from the values from the last day before and the first day after the period without quotations. Moreover, in order to mitigate the impact of possible errors arising from such a procedure, we calculate a 7 day moving average. We also calculate the 7 day moving average for the COVID-19 daily cases, in order to mitigate the effects of under-reporting them during weekends or holidays and over-reporting in subsequent days. Therefore, we set the period under analysis to 5 January 2020–12 March 2021.

We present the courses of the process of analysed commodities in Figures 1 and 2.

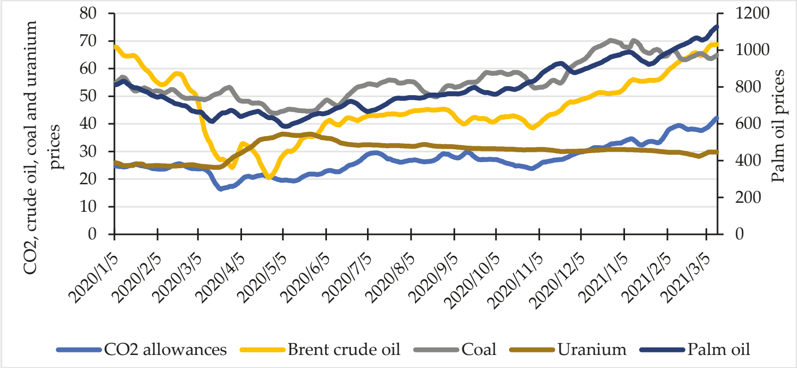


**Figure 1.** $CO_2$ allowances, crude oil, coal, uranium, and palm oil prices. Source: own elaboration on the basis of data from www.stooq.com (accessed on 19 April 2021).

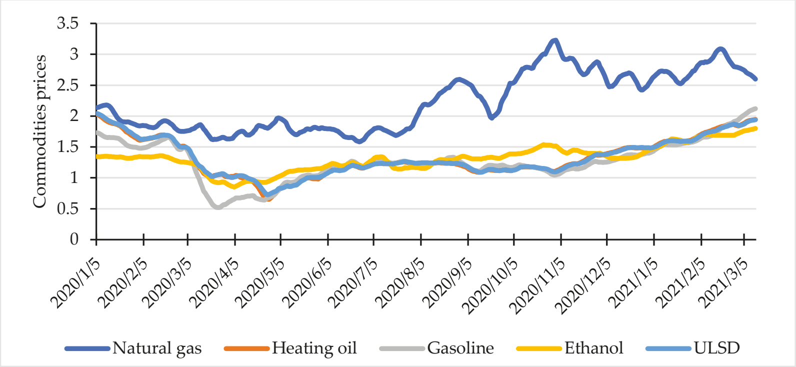


**Figure 2.** Natural gas, heating oil, gasoline, ethanol, and ULSD prices. Source: own elaboration on the basis of data from www.stooq.com (accessed on 19 April 2021).

When analysing the course of prices of energy commodities, we can make several interesting observations. First, the uranium prices seem unrelated to the COVID-19 pandemic. The uranium price is generally more or less constant; only during the first wave of the pandemic (March 2020–beginning of May 2020) did it note an increase by about 40%. Since then, it was constantly, slowly decreasing until the end of the observation period.

We can make another interesting remark on the prices of heating oil, ULSD, and gasoline. Their courses are very similar to each other during the whole observation period. This was especially visible in the case of the pair ULSD—heating oil. It is perfectly understandable because these two fuels are essentially the same ones. A visible decrease in prices of these three commodities can be seen since the beginning of the pandemic, and it accelerated after the declaration of the pandemic by the World Health Organization (WHO)—11 March 2020. The decline of the gasoline decrease was deeper but ended earlier than for ULSD and heating oil, at the end of March 2020. Prices of heating oil and ULSD stopped falling at the end of April 2020. Since then, they gradually began to increase and continued this trend until the end of the observation period.

Ethanol prices noted a small decrease after the declaration of the state of pandemic, and since the beginning of April 2020, they were generally increasing with small fluctuations. Prices of natural gas showed no response to the first wave of the pandemic. After being at more or less the same level with fluctuations, it noted a big increase during August 2020 and remained on more or less the same level with big fluctuations afterward.

We observe a quite similar general course for the pair of coal–palm oil. Their prices were decreasing until the end of the first wave of the pandemic and started to grow afterward. The $CO_2$ allowances prices noted a small decrease after the declaration of the pandemic state and were gradually increasing with fluctuations until the end of the observation period.

However, we observe the most interesting dynamics in the case of the crude oil price. It was decreasing since the beginning of the observation period, and the decline has been very sharp after the declaration of the pandemic state. After a significant increase after the first price depression (by 24%), it noted the second large drop until 25 April 2020 (by over 35%). It started to regain its value afterward and continued with fluctuations until the end of the observation period, when the price of crude oil reached virtually the same level as at the beginning.

Since the beginning of the COVID-19 outbreak, the three waves have swept over the world. The first one took place during Spring 2020, the second one—in Autumn 2020—Winter 2020/2021, and the third one started at the end of February 2021 and is on an upward curve (as of mid-March 2021—Figure 3). The first COVID-19 wave, as compared to the second one, was very shallow, but when we look at the prices of selected commodities (crude oil, gasoline, heating oil, ULDS, or ethanol), they reacted on this first wave much stronger than on the second one.

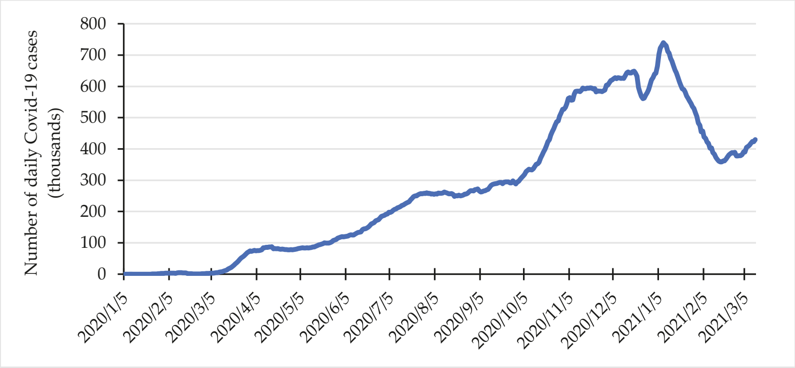


**Figure 3.** Daily COVID-19 cases. Source: own elaboration on the basis of data from https://ourworldindata.org/covid-cases (accessed on 19 April 2021).

### *3.2. Research Methodology*

To compare the time series for COVID-19 cases and for energy commodities prices, we use the Dynamic Time Warping (DTW) distance method. It calculates an optimal match between two given time series, performing nonlinearly in the series by stretching or compressing them locally in order to make one resemble the other as much as possible. This distortion (called warping) allows an adjustment of the time axis to find similar but phase-shifted sequences [52].

The DTW method, invented by Bellman and Kalaba [53], was originally developed for dealing with speech recognition problems [54–57]. It has been further used in a wide spectrum of different applications, e.g., in the field of music information retrieval [58], for gesture recognition [59], in bioinformatics [60], in finance [61], and for labour market analyses [62].

The DTW is an algorithm for measuring similarity between two temporal sequences that utilises dynamic programming to find an optimal alignment between them with respect to a given scoring function.

Let $X = (x_1, x_2, \ldots, x_N)$ and $Y = (y, y_2, \ldots, y_M)$ be two time series. In the first step, in order to make meaningful comparisons between two time series, both must be normalised. In the case of time series, a standard method of processing raw data is $z$-normalisation. The need for time series normalisation is often emphasised in classification methods with the dynamic time warping and other distance measures [63,64].

In the next step, we define the local cost measure for two elements of $X$ and $Y$ as:

$$c\left(x_i, y_j\right) = \left|x_i - y_j\right|, i = 1, 2, \ldots, N, j = 1, 2, \ldots, M \quad (1)$$

Evaluating this measure for each pair of elements of $X$ and $Y$, we obtain the local cost matrix ($LCM \in \mathbb{R}^{N \times M}$). Then, our goal is to find the optimal alignment between series $X$ and $Y$ having minimal overall cost.

Such a point-to-point alignment between $X$ and $Y$ can be represented by a time warping path, which is a sequence $p = (p_1, \ldots, p_L)$, with $p_l = (n_l, m_l) \in \{1, \ldots, N\} \times \{1, \ldots, M\}$ for $l \in \{1, \ldots, L\}(L \in \{\max(N, M), \ldots, N + M - 1\})$, satisfying the boundary, monotonicity, and step size conditions [65]. The boundary condition ensures that the first and the last element of $p$ are $p_1 = (1, 1)$ and $p_L = (N, M)$ (the first (last) index from the first sequence must be matched with the first (last) index from the other sequence). The other two conditions ensure that the path always moves up, right, or up and right of the current position, i.e., $p_{l+1} - p_l \in \{(1, 0), (0, 1), (1, 1)\}$ for $i = 1, \ldots, L - 1$. Every index from the time series $X$ must be matched with one or more indices from the time series $Y$ (and vice versa).

The optimal match is denoted by the match that satisfies all the abovementioned restrictions and that has the minimal total cost, where the total cost $c_p(X,Y)$ of a warping path $p$ is defined as:

$$c_p(X,Y) = \sum_{l=1}^{L} c\left(x_{n_l}, y_{m_l}\right) = \sum_{l=1}^{L} \left|x_{n_l} - y_{m_l}\right| \tag{2}$$

The optimal match between $X$ and $Y$ is then:

$$DTW(X,Y) = c_{p*}(X,Y) = \min\left\{c_p(X,Y)\middle|p \in P\right\} \tag{3}$$

where $P$ is the set of all possible warping paths.

The DTW algorithm finds the path that minimises the alignment between $X$ and $Y$ by iteratively stepping through the local cost matrix and aggregating the cost. The optimal path $p$ could be found using a dynamic programming algorithm, building the accumulated cost matrix $D$ in the following way:

$$\begin{gathered} D(1,m) = \sum_{k=1}^{m} c(x_1, y_k) \text{for } m = 1, \ldots, M \\ D(n,1) = \sum_{k=1}^{n} c(x_k, y_1) \text{for } n = 1, \ldots, N \\ D(n,m) = c(x_n, y_m) + \min\{D(n-1,m), D(n,m-1), D(n-1,m-1),\} \\ \text{for } 1 < n \leq N, 1 < m \leq M \end{gathered} \tag{4}$$

The DTW distance, i.e., the stretch-insensitive measure of the difference between the two time series, which is also the minimal distance between series $X$ and $Y$, is then defined as $DTW(X,Y) = D(N,M)$.

Once the accumulated cost matrix $D$ is constructed, the optimal warping path $p$ could be found by the simple backtracking from the top-right corner of this matrix (from the point $D(N,M)$) and traversing to the bottom-left. The traversal path is identified based on the neighbour with minimum value.

The shapes of the warping curves provide information about the pairwise correspondences of time points. Graphically, the optimal warping path $p$ runs along a "valley" of low cost and avoids "mountains" of high cost [66]. If $p$ is above diagonal, then the time series $X$ leads $Y$. It is also possible to determine by how many lags time series $X$ leads time series $Y$. For this purpose, we calculate the median value for the differences between the indices of $p$ [52]. Negative values indicate that the time series $X$ leads time series $Y$, positive that $Y$ leads $X$.

In our paper, the values of the DTW distance between the time series analysed are computed using the `dtw` package (version 1.22-3) for R [67].

The calculated distances have a straightforward application in hierarchical clustering and classification [68]. Clustering is a technique in which similar data are divided into homogeneous groups. There are many clustering methods. They can be divided into homogeneous groups, optimising the initial division of objects. They are widely used in general and spatial economics research [69–76].

After measuring the similarities between the time series using DTW, we perform the agglomerative hierarchical clustering, mainly due to its great visualisation power. In this contribution, to carry out the hierarchical cluster tree, the average linkage with the squared Euclidean distance is used.

## 4. Results and Discussion

With accordance to the timeline of the COVID-19 pandemic, we perform the research in four periods:

- the whole period (5 January 2020–12 March 2021),
- first subperiod, covering data from the beginning until the peak of the first wave of the pandemic (27 April 2020).
- second subperiod, covering data from the peak of the first wave until the peak of the second one (28 April 2020–7 January 2021).
- third subperiod, covering data from the peak of the second wave (8 January 2021) onwards.

In the whole period and in every subperiod, we perform the analysis in the following steps:

1. We standardise all time series.
2. We calculate the DTW distance between the standardised COVID-19 time series and time series of all commodities.
3. We calculate the DTW distance matrix between all commodities.
4. On the basis of distance matrix calculated in point 3, we conduct the hierarchical clustering of commodities. We check the robustness of clustering by comparing obtained results with the results obtained by the *k*-medoids and divisive hierarchical clustering.
5. We analyse pairs of the best- and the worst-fitted time series.
6. We group the commodities with respect to their distance from the COVID-19 time series. We create the two groups—with distance smaller than median (denoted by A) and larger than median (denoted by B).
7. We identify the lags between the COVID-19 and commodities time series by determining the median differences between the optimal path indices.

After standardisation of all time series, the preliminary analysis showed that the course of the uranium prices was different than both COVID-19 cases and prices of commodities to such extent that it formed a separate cluster, with all other commodities being in the second one, both over the full period and in subperiods. Therefore, we decided to remove the uranium from further analysis.

### 4.1. Full Period

We present the dendrogram for the prices of analysed commodities in Figure 4.

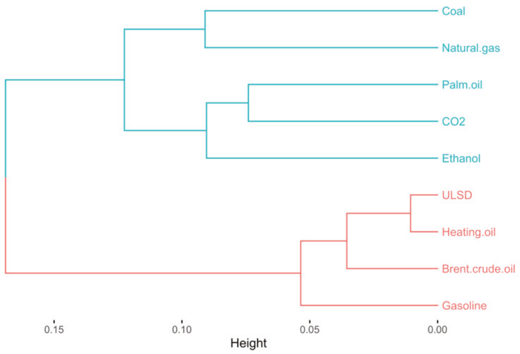
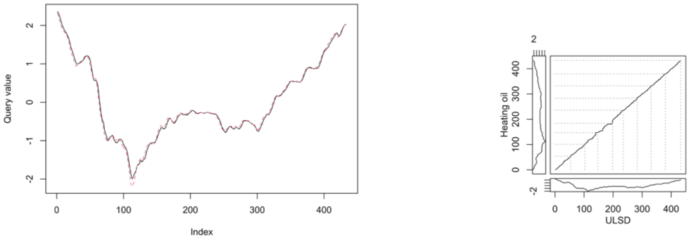


**Figure 4.** Dendrogram for hierarchical clustering of prices of commodities for the full period. Source: own elaboration on the basis of data from www.stooq.com (accessed on 19 April 2021).

On the basis of the dendrogram, we distinguish two clusters of commodities, with ULSD, heating oil, crude oil, and gasoline forming the first one, which was much more homogenous than the second one (which is quite obvious, as the dynamics of prices of ULSD, heating oil, gasoline and Brent oil are very similar—Figures 1 and 2. We obtain the same results for the *k*-medoids and divisive hierarchical clustering methods.

The two most similar commodities with respect to time-series courses are ULSD and heating oil. The DTW distance for them is the smallest and equals 0.011. We present here two-way and three-way alignment plots in Figure 5.

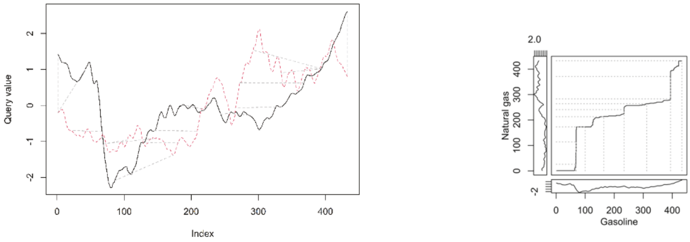


(**a**) (**b**)

**Figure 5.** Alignment plots for ULSD and heating oil for the full period. (**a**) Two-way, (**b**) Three-way. On the two-way plot the black solid line for ULSD, the red dashed line for heating oil. Source: own elaboration on the basis of data from www.stooq.com (accessed on 19 April 2021).

Both charts indicate that the courses of ULSD and heating oil are virtually identical—two-way plots are practically overlapping, and the three-way plot goes through the minor diagonal. In addition, from the two-way alignment plot, we can judge about the differences between indices—there is virtually no difference (the price of heating oil is just one day ahead of ULSD price).

The pair of most different commodities with respect to time-series course in the whole period is gasoline and natural gas. This pair has the largest DTW distance, equal to 0.246. We present their two-way and three-way alignment plots in Figure 6.



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

**Figure 6.** Alignment plots for gasoline and natural gas for the full period. (**a**) Two-way, (**b**) Three-way. On the two-way plot the black solid line for gasoline, the red dashed line for natural gas. Source: own elaboration on the basis of data from www.stooq.com (accessed on 19 April 2021).

The courses of gasoline and natural gas prices are different to a large extent. Moreover, they have visible phase differences. In the first period, the price of natural gas is ahead of the price of gasoline. Next, at the time of declaration of the state of pandemic, there was a deep decline in the price of gasoline, which was followed about just above three months later by the price of natural gas. After less than three months, the price of natural gas noted a steep increase, which was followed by the price of gasoline after about two months. On the whole period, the median time difference between phases of both charts is equal to 5 days (phases of prices of the natural gas occur earlier).

### *4.2. First Subperiod (5 January 2020–27 April 2020)*

We present the dendrogram for the prices of analysed commodities in the first subperiod in Figure 7.

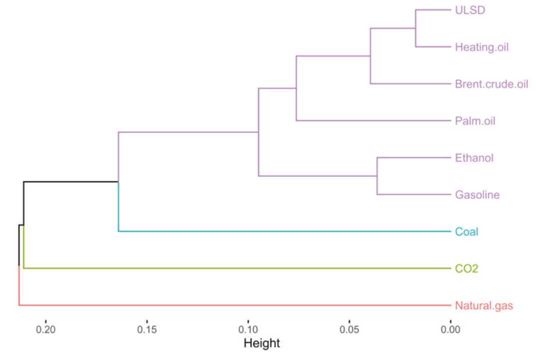
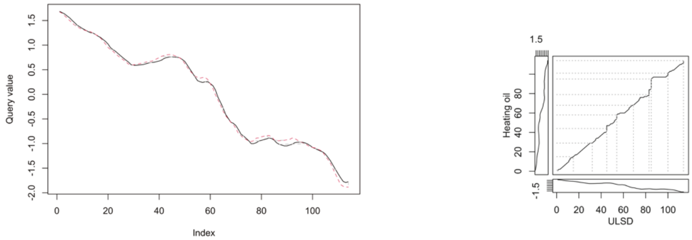


**Figure 7.** Dendrogram for hierarchical clustering of prices of commodities for the first subperiod. Source: own elaboration on the basis of data from www.stooq.com (accessed on 19 April 2021).

In the first subperiod, we distinguish four clusters of commodities. However, three clusters are the ones with only one member—natural gas, $CO_2$ allowances, and coal. All the remaining commodities create the fourth, large cluster. We obtain the same results for the *k*-medoids and divisive hierarchical clustering methods.

As in the case of the full period, ULSD and heating oil are the two most similar commodities in terms of their price developments in the first subperiod. The DTW distance between them is 0.017. We present their two-way and three-way alignment plots in Figure 8.



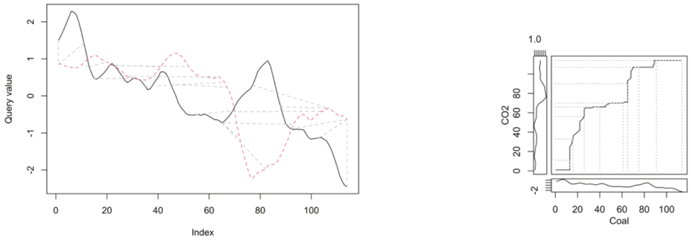
(**a**) (**b**)

**Figure 8.** Alignment plots for ULSD and heating oil for the first subperiod. (**a**) Two-way, (**b**) Three-way. On the two-way plot the black solid line for ULSD, the red dashed line for heating oil. Source: own elaboration on the basis of data from www.stooq.com (accessed on 19 April 2021).

The prices of both commodities have practically the same course. They are declining in the whole analysed subperiod. Only a very small discrepancy in their courses is visible after 90 days. The median phase difference is 0 days.

The most different pair of commodities consist of coal and $CO_2$ allowances prices. The DTW distance between them in the first subperiod is equal to 0.324. We present their two-way and three-way alignment plots in Figure 9.

We can hardly see any similarities in courses of prices of coal and $CO_2$ allowances. What is quite interesting is that the most visible fluctuations of prices of both commodities occurred in two directions. The biggest fluctuation for both of them takes place at more or less the same time, i.e., on the 80th day. The price of $CO_2$ allowances decreases, while the price of coal at the same time increases. A similar (but to a much smaller degree) relation could be observed at the very beginning of the subperiod. The median phase difference between prices of coal and $CO_2$ allowances is 20 days (phases of the prices of coal occur earlier). If we consider this shift, then the direction would be similar.



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

**Figure 9.** Alignment plots for coal and $CO_2$ allowances for the first subperiod. (**a**) Two-way, (**b**) Three-way. On the two-way plot the black solid line for coal, the red dashed line for $CO_2$ allowances. Source: own elaboration on the basis of data from www.stooq.com (accessed on 19 April 2021).

### *4.3. Second Subperiod (from 28 April 2020 to 7 January 2021)*

In the period between the peaks of the first and second waves of the pandemic, a dendrogram for the prices of analysed commodities is presented in Figure 10.

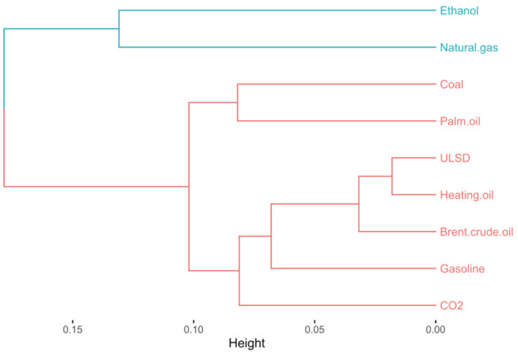


**Figure 10.** Dendrogram for hierarchical clustering of prices of commodities for the second subperiod. Source: own elaboration on the basis of data from www.stooq.com (accessed on 19 April 2021).

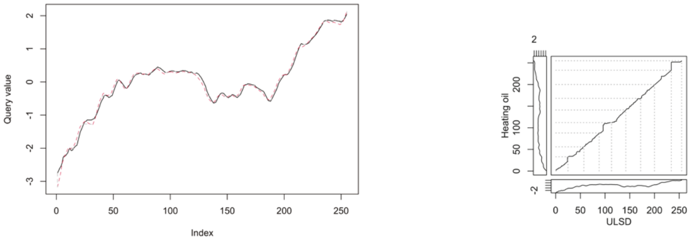
For the second subperiod, we distinguish the two clusters of commodities with respect to similarity of the courses of their prices. One cluster consists of only two commodities—ethanol and natural gas. All remaining commodities create the second cluster. We obtain the same results for the *k*-medoids and divisive hierarchical clustering methods.

The same, as in the full period and the first subperiod, commodities have the most similar courses of their prices in the second subperiod—ULSD and heating oil. The DTW distance between them was 0.018. We present their two-way and three-way alignment plots in Figure 11.

As in the previous subperiod and the whole period, the dynamics of prices of ULSD and heating oil are virtually the same. In addition, there is no phase difference between them (median phase difference is equal to 0).

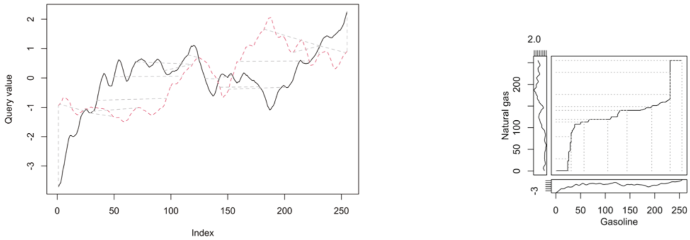
The two most different commodities in the second subperiod with respect to changes of their prices are gasoline and natural gas. The DTW distance between the time series of their prices is equal to 0.229. We present their two-way and three-way alignment plots in Figure 12.

In the same periods, the directions of gasoline and natural gas prices are generally reversed (the period from the 30th to the 100th day and from the 150th day onwards). When we consider the median difference between the indices of both series (the gasoline indices are 3.5 days ahead), the picture does not change much. Between days 30 and 100, changes of the gasoline prices are ahead of changes of the natural gas prices, while between days 150 and 200, the opposite is true.



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

**Figure 11.** Alignment plots for ULSD and heating oil for the second subperiod. (**a**) Two-way, (**b**) Three-way. On the two-way plot the black solid line for ULSD, the red dashed line for heating oil. Source: own elaboration on the basis of data from www.stooq.com (accessed on 19 April 2021).



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

**Figure 12.** Alignment plots for gasoline and natural gas for the second subperiod. (**a**) Two-way, (**b**) Three-way. On the two-way plot the black solid line for gasoline, the red dashed line for natural gas. Source: own elaboration on the basis of data from www.stooq.com (accessed on 19 April 2021).

### 4.4. *Third Subperiod (8 January 2021, Onwards)*

The third subperiod covers the data from the peak of the second wave of the pandemic, until the end of the observation period. We present the dendrogram for the prices of analysed commodities in this subperiod in Figure 13.

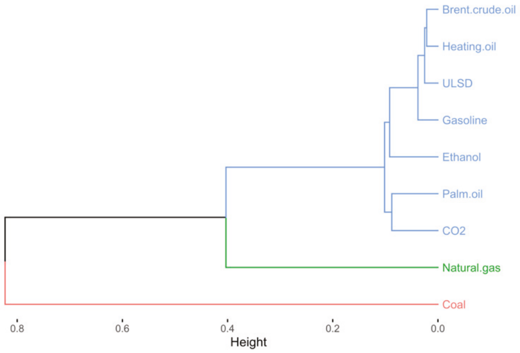
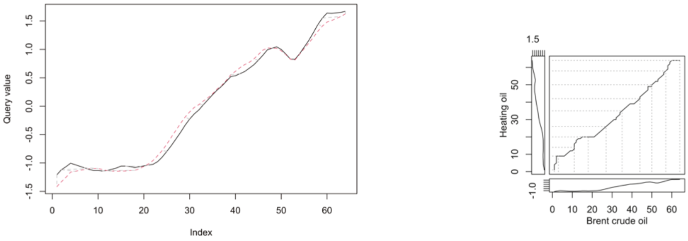


**Figure 13.** Dendrogram for hierarchical clustering of prices of commodities for the third subperiod. Source: own elaboration on the basis of data from www.stooq.com (accessed on 19 April 2021).

There are three visible clusters for the third subperiod. Two of them have just one member—coal and natural gas. All remaining commodities form the third, rather homogeneous cluster. The reason for this is that while the coal price is in this subperiod decreasing with high fluctuations, the natural gas price increases and then decreases, and the prices of all other commodities are generally increasing throughout the whole subperiod. We obtain the same results for the *k*-medoids and divisive hierarchical clustering methods.

It is quite surprising that in the third subperiod, the two most similar commodities with respect to time series of their prices are not ULSD and heating oil (as in all previous situations) but crude oil and heating oil. The DTW distance between them is 0.021. We present their two-way and three-way alignment plots in Figure 14.

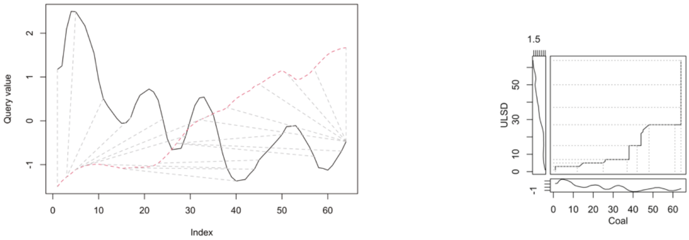


(**a**) (**b**)

**Figure 14.** Alignment plots for crude oil and heating oil for the third subperiod. (**a**) Two-way, (**b**) Three-way. On the two-way plot the black solid line for crude oil, the red dashed line for heating oil. Source: own elaboration on the basis of data from www.stooq.com (accessed on 19 April 2021).

The time series for Brent crude oil and heating oil in the third subperiod are very similar. However, their similarity is not as great as in the cases of previous subperiods and the whole period for the pair ULSD—heating oil. The higher DTW distance confirms this finding. The median phase difference for Brent crude oil and heating oil in the third subperiod is 0.

The two most different time series in the third subperiod are for the pair coal–ULSD. The DTW distance between them is 0.974. We present their two-way and three-way alignment plots in Figure 15.



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

**Figure 15.** Alignment plots for coal and ULSD for the third subperiod. (**a**) Two-way, (**b**) Three-way. On the two-way plot the black solid line for coal, the red dashed line for ULSD. Source: own elaboration on the basis of data from www.stooq.com (accessed on 19 April 2021).

The time series of coal prices and ULSD for the third subperiod are almost completely different. Prices of ULSD increase throughout the analysed subperiod (with two small declines). On the other hand, the coal prices are decreasing with very strong fluctuations. The indices of coal prices are ahead of indices of the ULSD prices, which means that the time series for ULSD lead the time series for coal (with a median time of 22 days). However, it is impossible to talk about any shift between these two series—they are completely uncorrelated.

In the next step of the research, we analyse the similarities of time series for commodities prices to the time series of daily COVID-19 cases in the full period and three subperiods. The group with a distance smaller than the median is denoted by "A" and not smaller than median by "B". We present the results in Table 1.

**Table 1.** Groups of commodities with respect to similarity of time series of their prices to the COVID-19 daily cases.

| Commodities | Whole Period | First Subperiod | Second Subperiod | Third Subperiod |
|---|---|---|---|---|
| $CO_2$ allowances | A | A | B | A |
| Natural gas | A | A | B | A |
| Heating oil | B | B | A | B |
| Brent crude oil | B | B | A | B |
| Gasoline | B | B | B | B |
| Ethanol | B | B | B | B |
| Palm oil | A | A | A | A |
| ULSD | B | B | B | B |
| Coal | A | A | A | A |

Source: own elaboration.

The most similar time series of commodity prices to the time series of COVID-19 daily cases are the time series for palm oil and coal. The most dissimilar ones were gasoline, ethanol, and ULSD. Quite surprisingly, the heating oil prices for the second subperiod are in the group of more similar ones. It is worth noting that crude oil, heating oil, gasoline, ethanol, and ULSD prices are dissimilar to the COVID-19 daily cases for the whole period. They are also dissimilar for the first subperiod (the pandemic outbreak) and in the third subperiod. Some of them (heating oil and Brent crude oil) are amongst the more similar ones in the second subperiod. We might explain it by the fact that the prices of these commodities react strongly to the declaration of the pandemic state—as the number of COVID-19 cases is increasing, the prices of these commodities fall sharply. In the second subperiod, when the global markets have somehow become accustomed to the situation, in some cases, these differences are not so visible. The situation in the third subperiod is similar to the first one—the changes in the prices of these commodities have different directions than the changes of the daily COVID-19 cases.

The remaining commodities—$CO_2$ allowances, natural gas, palm oil, and coal—have prices that react much weaker to the pandemic. Therefore, their time series are more similar to the daily COVID-19 series than the series that react to them in the opposite directions.

Eventually, we analysed the time shifts between the daily COVID-19 cases and commodities prices. We present the median differences between the indices of the compared time series in Table 2. Negative values mean that the COVID-19 time series is ahead of the commodities series (the COVID-19 time series leads the commodity series), and positive values mean the opposite.

**Table 2.** Median differences (in days) between the indices of the COVID-19 daily cases and prices of commodities.

| Commodities | Whole Period | First Subperiod | Second Subperiod | Third Subperiod |
|---|---|---|---|---|
| $CO_2$ allowances | −43 | −39 | 6 | 23 |
| Natural gas | −11.5 | −45 | 12 | 24 |
| Heating oil | −61 | −31 | 15 | 23.5 |
| Brent crude oil | −57 | −40 | 12 | 23 |
| Gasoline | −55 | −34 | 15.5 | 27 |
| Ethanol | −32 | −36 | 17 | 20 |
| Palm oil | −34 | −39 | 9 | 23 |
| ULSD | −66 | −27.5 | 15 | 22 |
| Coal | −24 | −11 | 10 | 1 |

Source: own elaboration.

For the whole period, the median differences between indices of the COVID-19 daily cases and the commodities indices are negative. The biggest difference (the largest time shift) concerns the prices of ULSD and heating oil—over two months. This means that the time series of the COVID-19 cases leads the prices of these two analysed commodities, and the prices of these commodities follow the similar direction as the COVID-19 daily cases after more than two months. The smallest difference (11.5 days) occurs in the case of natural gas.

In the first subperiod, the situation is similar as in the whole period—the COVID-19 time series is ahead of the time series for prices of all commodities. These differences are generally smaller than for the whole period, with three exceptions: natural gas (for which it is the biggest—1.5 months), ethanol, and palm oil. It is caused by the reaction of commodity prices (first falling, then rising) to the increase in daily COVID-19 daily cases.

The second subperiod is characterised by much smaller values of the time shift between the time series of the COVID-19 daily cases and prices of commodities. However, the biggest difference between this and the first subperiod is the opposite sign of this shift. When we combine this with the fact that the DTW distances between the time series of commodities prices and the COVID-19 daily cases are the smallest, it turns out that in this subperiod, the time series for commodities are much more similar to the COVID-19 time series than in the first subperiod. A smaller time shift also means that the directions of compared series are largely the same. We can also interpret it as the markets becoming accustomed with the pandemic situation.

The third subperiod is characterised by higher values of time shift between the prices of commodities and the COVID-19 daily cases (with the exception of coal). However, all median values are positive for this period, which means that the time series for commodities overtook the time series of daily Covid-19 cases. This can be the manifestation of the situation that the markets anticipate the pandemic evolution. Epidemiologists, doctors of infectious diseases, predict courses of the pandemic; therefore, the changes on the markets could happen earlier than changes of Covid-19 cases.

In the case of the energy commodity market, the analysis of oil and gas prices in particular has received considerable attention. Our research results show that gas and oil prices differ from COVID-19. Similar results have been obtained by other researchers. Nyga-Łukaszewska and Aruga [40] show that in the USA, the cumulative number of COVID-19 cases has a statistically negative effect on the oil price, while it has a positive effect on the gas price. In Japan, this negative impact is only seen in the oil market with a two-day lag. The number of cases has no effect on the Japanese oil and gas markets. The authors explain their findings by the fact that the spread of the virus is different in the two compared countries and the measures taken by the governments to prevent the epidemic are different.

When examining the similarities in the evolution of energy commodity prices, we can see that in each subperiod natural gas differs from the other commodities (generally, it forms a distinct cluster). This is confirmed by Lin and Su [14], who show that natural gas prices are the least correlated with the prices of other commodities. This is the case both before and during the pandemic. The study also confirms the very strong correlation between heating oil and diesel price.

Analysing the time series of selected energy commodities, an initial decline in prices is evident, followed by an increase. This is consistent with the predictions of Liu, Wang, and Lee [77], who indicate the existence of a negative relationship between oil and stock returns. However, they find that the COVID-19 pandemic outbreak can have a significantly positive impact on oil and stock market returns. They even suggest that there is no need for governments to take actions to avoid the possible negative impact of the pandemic on the oil and stock market in the short term.

The DTW method we use is widely applicable for determining the distance (similarity) matrix between time series. Classification or clustering based on the distance matrix between time series belongs to distance-based methods [78]. There are many possible distance measures and methods for clustering or classification. Bagnal et al. [79] compare 18 different time-series classification techniques. Classifications based on the DTW method are always among the best.

## 5. Conclusions

After falling in early 2020, energy prices rebounded. Later, the combination of production cuts and a pickup in consumption helped prices to recover. To this day, the energy commodities have recouped their losses from the COVID-19 pandemic. Almost all analysed commodity prices are now above prepandemic levels.

In our research, we examine the similarity between the time series of energy commodity prices and the time series of daily COVID-19 cases. The most similar to the COVID-19 are the time series for coal and palm oil, and the most dissimilar for gasoline, ethanol, and ULSD. The analysis carried out over three subperiods shows that the Brent crude oil and heating oil prices react strongly to the outbreak of the pandemic. This confirms hypothesis H2. As the global markets adjust to the situation, the changes in the prices of these commodities are more similar to the changes in the daily COVID-19 cases. However, the price evolution in the third analysed subperiod is in the opposite direction to the changes in the number of infected individuals.

In addition, the time shifts between the daily COVID-19 cases and commodities prices are analysed using the dynamic time warping method. In the first subperiod, the time series of the COVID-19 cases lead the prices of all energy commodities. The smallest time shift concerns the prices of coal; the largest is noted for natural gas. In the second and third subperiod, the markets become accustomed to the pandemic situation, and the shifts have the opposite sign, which means that the time series for energy commodities precede the time series of COVID-19 cases. It seems that at this stage of the pandemic, the markets anticipate its evolution. Thus, the hypothesis H1 is confirmed partially, only for the first subperiod of the analysis.

Our analysis also allows the grouping of energy commodities using a hierarchical clustering algorithm. We distinguish commodity clusters with respect to the three analysed subperiods. In general, it can be stated that commodities such as ULSD, heating oil, crude oil, and gasoline form a group weakly related to COVID-19, while coal, natural gas, palm oil, $CO_2$ allowances, and ethanol are strongly connected.

We are aware of the limitations of the research methodology we have adopted. Its biggest limitation is that, based on it, we are not able to investigate what variables/phenomena directly affect the prices of energy commodities we analyse. The increase in COVID-19 cases resulted in the introduction of restrictions by country authorities, which disrupted the movement of goods and people, resulting in reduced mobility. During the first wave of the pandemic, production in some industries was also suspended, resulting in a drop in demand for energy and fuel. Investor sentiment in capital markets also deteriorated. All these phenomena directly affected the prices of energy raw materials. In order to study this impact in detail and assess its significance, econometric models with control variables would need to be built, and causality can be inferred from them. The fact that the issue of the impact of pandemics on various socioeconomic phenomena is very important is demonstrated by the number of scientific publications appearing on the subject. The link between the development of the pandemic and these phenomena can be investigated using a number of methods. Many of these studies are presented in the literature review.

Our research does not aim to find the exact relationships between the prices of the energy commodities and COVID-19-related phenomena (we can find many such analyses in the literature). We aim to find connections and similarities between the development of the pandemic (measured by the number of new COVID-19 cases) and the prices of the energy commodities. By these means, we can find the commodities for which the dynamics of their prices is the most similar to the course of the pandemic. In our case, there are the prices of coal, palm oil, and, to a lesser degree, the prices of $CO_2$ allowances and natural gas. Knowing this, we may expect that the prices of these commodities would be affected by similar occurrence in the future. In addition, our framework can be used for other types of commodities (e.g., metals, agricultural products, or prices on real estate markets). This is a future direction of our research. Our further research plans also include building econometric models for energy commodity prices with control variables.

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# Competition in a Wholesale Fuel Market—The Impact of the Structural Changes Caused by COVID-19

**Sylwester Bejger**

Faculty of Economic Sciences and Management, Nicolaus Copernicus University in Toruń, 87-100 Toruń, Poland; sylw@umk.pl

**Abstract:** Liquid fuels obtained in refining crude oil are one of the most important energies in economic activity. The domestic wholesale market for liquid fuels is of decisive importance for price formation in the national economy. The noncompetitive behavior of the market players at this level of the distribution chain can significantly affect all downstream price levels and the producer–consumer surplus balance. Therefore, the competitiveness of this market should be screened and assessed regularly, especially when significant external factors change. This article attempts to evaluate the impact of structural changes on the global market of crude oil and energy products after the outbreak of the COVID-19 pandemic on the competitiveness of the wholesale fuel market in Poland. Using asymmetry of the reaction of product prices to changes in the prices of inputs as a marker of noncompetitive behavior and the NARDL model as a test specification, the price paths of market players before and after the occurrence of structural changes in the inputs' processes were examined. Significant changes in the competitive behavior of players were revealed after the occurrence of structural changes at the beginning of the pandemic period in the year 2020. These changes may indicate enhanced competition and mitigation of potential market power abuse.

**Keywords:** liquid fuel market; asymmetric pass-through; competition; structural breaks; NARDL model

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## 1. Introduction

Liquid fuels obtained in the process of refining crude oil are one of the most essential energies in economic activity. Especially critical are fuels used in transportation. Due to the mass character of the product and a large share in the operating costs of many sectors of the economy, the prices of liquid fuels have a significant impact on the level of welfare of both enterprises and households. Moreover, due to the oligopolistic or even monopolistic structure of many domestic markets on the refining/wholesale level on one hand and relative ease of observation of price movements on the other, the liquid fuel market is under constant scrutiny of the public opinion, which is very sensitive to any abuse of market power or uncompetitive behavior. The domestic wholesale market for liquid fuels is of decisive importance for price formation in the national economy. The uncompetitive behavior of the market players at this level of the distribution chain can significantly affect all downstream price levels and the producer–consumer surplus balance. Therefore, the competitiveness of this market should be screened and assessed frequently, especially when significant external factors change.

Empirical detection of competition distortion in any industry is not an easy task. General discussion of the quantitative methods and approaches to competition and antitrust analysis could be found in [1,2] and in a broad spectrum of guidelines and documents produced by domestic competition authorities, advisory organizations, and consulting companies. One of the most popular empirical approaches to competition analysis is the use of behavioral screens or markers [3,4]. Screens are generally designed to flag firms' behavior or market outcomes which may raise suspicions that firms have, in fact, abused market power or colluded. The screen takes as inputs observable economic data and information (such as information on various product and market characteristics, data on costs, prices, market shares, multiple aspects of firm behavior, etc.) and flags (marks) markets that may have been affected by competition's distortion. One of the markers most often used in liquid fuel markets is a marker of asymmetric reaction of product prices to changes in main cost factors, called an asymmetric pass-through or APT in short.

The relevant market for the research is a Polish wholesale market for liquid motor fuels. Two goals are pursued during the study: to check whether structural changes were, in fact, observed in the analyzed processes in the first year of the pandemic and examine the possible differences in the symmetry of prices' response in the period 2015–2020 and in the subsample of the year 2020. As the first year of the pandemic was characterized by structural changes in many economic processes, the research hypothesis, which is subject to verification, states that the APT analysis could provide evidence of changes in price competition in a wholesale market in that period as the reaction to that turbulence.

## 2. Literature Review

The studies of pass-through of the prices of the main inputs to the prices of the final or semi-final products or services constitute a well-established strain in economic literature. An especially significant result was detecting various kinds of temporal asymmetry in the transmission of input's (upstream) prices to prices of the outputs (downstream prices). An important study of Bacon [5] started a widespread discussion of the "rockets and feathers" phenomenon in observable price series and established terminology used in this particular domain. Peltzman [6] analyzed 165 producer goods and 77 consumer goods and concluded that the "rockets and feathers" pattern could be found in two-thirds of these markets. In many studies, asymmetries in the adjustment of downstream prices to upstream prices' change have extensively been investigated using different empirical models in a wide range of commodity markets ([7–9]).

The phenomenon of the asymmetric transmission of costs (inputs, upstream prices) to the price of product or service (downstream price) can be considered as:

- magnitude asymmetry, in which the amount of downward price change differs depending on the direction of upstream price change, observed in a long-run horizon (Figure 1).
- pattern asymmetry, in which the speed of downward price change differs depending on the direction of upstream price change, detected in the short-run horizon (Figure 2).

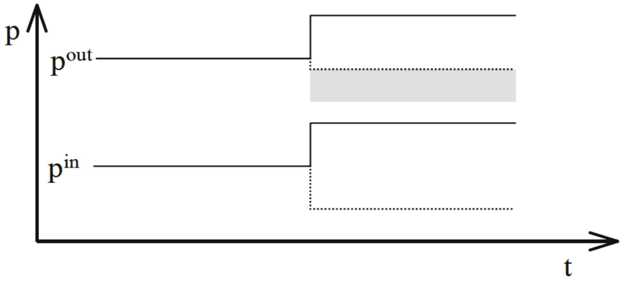


**Figure 1.** Magnitude asymmetry.

The asymmetric pass-through of different shocks at a macro or a microeconomic level has received particular attention in the markets of crude-derived fuels. The APT is not limited to the liquid fuel markets, but it was the study [5] focusing on crude gasoline asymmetric pass-through that impacted widespread studies on that topic. Moreover, that study focused on the specific direction of asymmetry, positive asymmetry, showing and underlining that kind of APT to the public. That kind of APT, called "downward sticky pricing" or "rocket and feather" behavior of prices, means that downstream prices react "faster" to upstream prices' increase than to decrease. One can consider a pass-through of crude oil prices to the prices of refined petroleum products and other commodities as the most extensively examined so far. The studies, especially connected with prices' paths of gasoline and motor diesel oil in the retail and wholesale level of a market, seem to be of special importance. A brief summary of the essential articles shows Table 1.

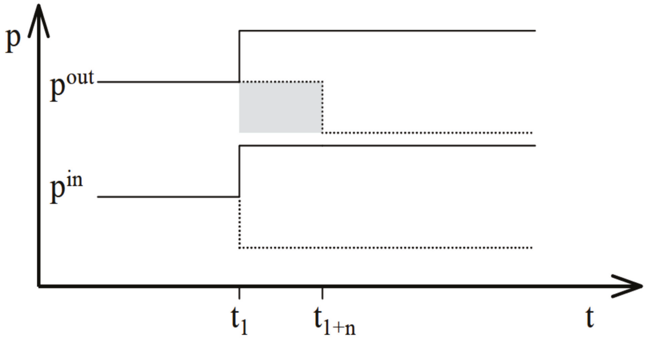


**Figure 2.** Pattern asymmetry.

**Table 1.** Selected APT studies on liquid fuel markets.

| Study | Subject | Positive APT | Frequency of Data |
|---|---|---|---|
| [5] Bacon (1991) | U.K. gasoline market, retail | yes | biweekly |
| [10] Karrenbrock (1991) | U.S. gasoline prices, retail | yes | monthly |
| [11] Kirchgässner and Kübler (1992) | Germany gasoline prices, retail | mixed results | monthly |
| [12] Shin (1994) | U.S. gasoline market, wholesale average products' prices | no | monthly |
| [13] Borenstein et al. (1997) | U.S. gasoline market, retail | yes | weekly |
| [14] Duffy-Deno (1996) | regional gasoline market, wholesale and retail prices | mixed results | weekly |
| [15] Reilly and Witt (1998) | U.K. gasoline market, retail | yes | monthly |
| [16] Asplund et al. (2000) | Swedish gasoline market, retail | yes | monthly |
| [17] Eckert (2002) | Canada (Ontario province gasoline market), retail | yes | weekly |
| [18] Bejger and Bruzda (2002) | Polish wholesale prices, a dominant player | yes | weekly |
| [19] Radchenko (2004) | U.S. gasoline market, retail | yes | weekly |
| [20] Oladunjoye (2008) | three U.S. wholesale markets | yes | weekly |
| [21] Meyler (2009) | 12 initial Euro-member countries | weak evidence of APT | weekly |
| [22] Clerides (2010) | 27 E.U. countries | mixed results | weekly |
| [23] Polemis (2012) | Greece | yes | weekly |
| [24] Greenwood-Nimmo and Shin (2013) | U.K. gasoline market, retail | yes | monthly |
| [25] Lamotte et al. (2013) | France diesel and gasoline market, retail | yes | weekly |
| [26] Atil et al. (2014) | U.S. market spot prices | no | monthly |
| [27] Chattopadhyay and Mitra (2015) | Indian gasoline market | yes | monthly |
| [28] Siok Kun Sek (2017) | Malaysia macroeconomic indices—crude oil | yes | annual |
| [29] Farkas and Yontcheva (2019) | Hungarian wholesale and retail prices | yes | weekly |
| [30] Bejger (2019) | Polish wholesale market, two major players | mixed results | daily |

Studies conducted so far point to a few primary sources of APT. One of them can be customer's imperfect information and search costs in retail markets [31]. The other is connected with asymmetric short-run costs of changes in inventories or asymmetric valuation of inventories enhanced by FIFO accounting ([32,33]).

However, the most important hypothesis of the source of positive APT is the significant market power of the players in a concentrated and imperfectly competitive industry ([13,19,34] support this claim). When exogenous events raise market prices generally, and the market price moves from one competitive price to another, the lack of competition in the transition period or short term affords sellers with market power the opportunity to raise prices quickly. When markets decline, the lack of competitive pressures permits sellers to delay the reduction in prices. Consequently, purchasers with market power will delay price increases as long as they can. When exogenous events occur that lower prices, they will choose among competitive sellers to force a price decline as quickly as possible.

Positive APT in the fuel supply chain means that "the prices of downstreams rise faster than fall." Such an observation motivated, apart of scientific research, competition authorities' sector inquiries and decisions on oil refineries and petroleum markets (for official competition inquires see [35–40]. Positive APT is not explicitly listed as an anticompetitive practice in the European or USA competition legislation but is commonly treated as one of the markers of anticompetitive behavior ([2,41]) often used in market's screening. As such, positive APT can be seen as a sign of potential anticompetitive horizontal practices, namely exploitation of market power and tacit collusion. Those practices are frequently connected with another circumstantial evidence of concerted practice, which is parallel pricing. One can conclude that if the structure and parameters of a relevant market under investigation foster potential abuse of competition, APT can be treated as the first proxy of a competition's status.

## 3. Materials and Methods

The detailed analysis of the Polish refining industry, the liquid fuels' wholesale market, and the price creation policy contains [42]. It is worth recapitulating briefly the most important factors supporting the APT examination. The refining industry in Poland is a pure duopoly with players: Orlen Group (PKN Orlen, or PKN for short) and LOTOS Group (LOTOS in short). The Polish liquid fuel market at the wholesale level is a nearly duopolistic market with two major players: PKN, with an approximate market share of 60%, LOTOS with a share of 30%, and a small fringe of independent suppliers. The refining industry and wholesale level of a market is highly concentrated with the HHI index for refining on a level of 0.52 in the year 2020 and for the wholesale fuel market on a level of about 0.5. (In general, the assessment of the value of an HHI index should be market-specific and depends on the purpose of its calculation. As a point of reference for its values in the sense of the degree of concentration, the USA Department of Justice's merger guidelines are often used, where the value of the HHI index greater than 0.180 indicates high market concentration.) There exist capacity constraints for domestic production and high barriers to entry (due to logistic infrastructure and regulations). The key refined products are homogenous motor fuels (according to E.U. regulations, there are: unbranded diesel oil for road transport 10 ppm Sulphur, unbranded unleaded 95 octane gasoline 10 ppm Sulphur). A second important factor that directly influenced APT research is an implied mechanism of price creation at the wholesale level. Based on the author's previous research [42,43], one can assume that the pricing mechanism of the players corresponds to the well-known import parity pricing (IPP in short) formula. The IPP is based on the assumption that fuel for road use is a tradable good, and the ex-refinery price depends indirectly on the price of crude and the costs of refining at domestic refineries but directly on the price that the purchaser has to pay for this product in a relevant hub plus transport costs and other relevant spreads for the site chosen for storage. Theoretically, the IPP is the maximum level that the domestic producers' wholesale price can reach if there are no obstacles to import. In the context of the APT study, the IPP schema allows inclusion as a price determinant (cost factor) a properly chosen benchmark price for each wholesale product. That reference price could be an equally important price determinant as crude price or exchange rate (especially in the short term, say a week), and hence, a pass-through of that reference price to the wholesale prices should be examined.

To summarize, it should be stated that the market under examination is a duopolistic one with high concentration and homogenous products. Demand for products is relatively inelastic. Prices of the downstream products are strategic variables for the players and are fully transparent. Both industry and market exhibit high barriers to entry (capital, logistical, and political). There are capacity constraints for domestic production.

All of the factors are considered as fostering collusion in an industry. That statement is based on noncooperative game theory models of the competition showed in [2], and listed factors belong to the so-called “plus factors” set, used in antitrust litigation ([44,45]). This supports the hypothesis of possible anticompetitive behavior of the players in a market and potential abuse of market power by them. It allows for direct connection to APT examinations with the assessment of the competitiveness of the Polish liquid fuel market, as possible APT is an effect of anticompetitive behavior of the players.

The presented study is performed for the sample covering the period 2015–2020. The downstream prices under examination for APT were: wholesale price of an unleaded standard 95 octane gasoline reported by PKN in PLN per $m^3$, the wholesale price of an unleaded standard 95 octane gasoline reported by LOTOS in PLN per $m^3$, the wholesale price of standard diesel oil for road transport (brand name of PKN: Ekodiesel) reported by PKN in PLN per $m^3$, the wholesale price of standard diesel oil for road transport (brand name of LOTOS: Eurodiesel) reported by LOTOS in PLN per $m^3$.

As important cost factors or IPP determinants of downstream prices, the following inputs are used: Brent crude oil spot price, published by EIA, in USD per $m^3$, New York Harbor Regular Gasoline spot price, published by EIA, in USD per $m^3$ (possible IPP benchmark price), New York Harbor Ultra-Low Sulfur No 2 Diesel spot price, in USD per $m^3$ (possible IPP benchmark price), USD/PLN average exchange rate, reported by Polish Central Bank.

All of the series are observed daily. They have undergone the necessary transformations. The series have been synchronized to a five-working-day regular daily series. The units of measure have been unified to 1 $m^3$. All of the series have been logarithmically transformed to allow interpretation of the multiplayer as a percent change. Transformed variables are named as: L_Diesel, L_Gas95, O_Diesel, O_Gas95, Brent, NYH_Gas, NYH_Diesel, USD_PLN, where prefix L stands for Lotos and O stands for Orlen. Domestic prices are not transformed to USD to allow examination of asymmetry in reaction to depreciation/appreciation of domestic currency (PLN). A similar approach was used in [46] and [47]. The phenomenon under examination is connected with inherently dynamic processes, though the author only focused on dynamic modeling. As a process-generating theoretical model, the nonlinear, autoregressive-distributed lag (NARDL) specification is used. The NARDL model was proposed in [46]. NARDL approach was used in a context of APT research previously (e.g., [24,26,27,30,47]). A NARDL unrestricted specification and bound testing of cointegration allow for asymmetries in both the short- and long-run parameters. The ability to simultaneously estimate both long and short-run asymmetries in a computationally simple and tractable manner is a very flexible approach and provides a straightforward means of testing both long- and short-run symmetry restrictions. In a visual layer, one can assess the asymmetry of dynamic adjustment using asymmetric, dynamic multipliers graph calculated on the basis of estimation of NARDL parameters.

The structure of NARDL ($p$, $q$) model derives from the ARDL ($p$, $q$) model ([48,49]):

$$y_t = \alpha_0 + \sum_{j=1}^{p} \phi_j y_{t-j} + \sum_{j=0}^{q} \boldsymbol{\theta}'_j \boldsymbol{x}_{t-j} + \varepsilon_t \tag{1}$$

The NARDL ($p$, $q$) model can be understood as an extension of the model (1). Its specification is based on an approach to modeling asymmetric cointegration based on partial sum decompositions, which has been applied in [50]. The starting point is the following asymmetric long-run regression equation:

$$y_t = \boldsymbol{\beta}^{+'} \boldsymbol{x}_t^{+} + \boldsymbol{\beta}^{-'} \boldsymbol{x}_t^{-} + u_t,\ \Delta \boldsymbol{x}_t = \boldsymbol{v}_t, \tag{2}$$

where $y_t$ is a scalar I(1) variable; $\boldsymbol{x}_t$ is a $k \times 1$ vector of regressors defined such that $\boldsymbol{x}_t = \boldsymbol{x}_0 + \boldsymbol{x}_t^{+} + \boldsymbol{x}_t^{-}$ and $\boldsymbol{x}_t^{+} = \sum_{j=1}^{t} \Delta \boldsymbol{x}_j^{+} = \sum_{j=1}^{t} max(\Delta \boldsymbol{x}_j, 0)$; and $\boldsymbol{x}_t^{-} = \sum_{j=1}^{t} \Delta \boldsymbol{x}_j^{-} = \sum_{j=1}^{t} min(\Delta \boldsymbol{x}_j, 0)$ are partial sum processes of positive and negative changes in $\boldsymbol{x}_t$ around known threshold zero.

In the NARDL ($p$, $q$) in-levels, model (2) is embedded into (1), and the final equation is written as follows:

$$y_t = \alpha_0 + \sum_{j=1}^{p} \Phi_j y_{t-j} + \sum_{j=0}^{q} (\boldsymbol{\theta}_j^{+\prime} \boldsymbol{x}^{+}{}_{t-j} + \boldsymbol{\theta}_j^{-\prime} \boldsymbol{x}^{-}{}_{t-j}) + \varepsilon_t, \tag{3}$$

where $y_\mathrm{t}$ is a scalar dependent variable; $\boldsymbol{x}_\mathrm{t}$ is a $k \times 1$ vector of regressors decomposed as $\boldsymbol{x}_t = \boldsymbol{x}_0 + \boldsymbol{x}_t^{+} + \boldsymbol{x}_t^{-}$; $\Phi_j$ 's are the autoregressive parameters; $\boldsymbol{\theta}_j^{+}$ and $\boldsymbol{\theta}_j^{-}$ are the asymmetrically distributed lag parameters; and $\varepsilon_t$ is an iid process with zero mean and constant variance $\sigma_\varepsilon^2$.

The key role in APT examination plays conditional error correction form (conditional ECM, sometimes called CECM; see [46,48]):

$$\begin{aligned}\Delta y_t = \rho\xi_{t-1} + \sum_{j=1}^{p-1} \gamma_j \Delta y_{t-j} + \sum_{j=0}^{q-1} (\boldsymbol{\pi}_j^{+\prime} \Delta \boldsymbol{x}^{+}{}_{t-j} + \boldsymbol{\pi}_j^{-\prime} \Delta \boldsymbol{x}^{-}{}_{t-j}) + \varepsilon_t = \rho \mathrm{y}_{t-1} + \boldsymbol{\theta}^{+\prime} \boldsymbol{x}^{+}{}_{t-1} + \boldsymbol{\theta}^{-\prime} \boldsymbol{x}^{-}{}_{t-1} + \\ + \sum_{j=1}^{p-1} \gamma_j \Delta y_{t-j} + \sum_{j=0}^{q-1} (\boldsymbol{\pi}_j^{+\prime} \Delta \boldsymbol{x}^{+}{}_{t-j} + \boldsymbol{\pi}_j^{-\prime} \Delta \boldsymbol{x}^{-}{}_{t-j}) + \varepsilon_t\end{aligned} \tag{4}$$

where $\xi_t = y_t - \boldsymbol{\beta}^{+\prime} \boldsymbol{x}_t^{+} + \boldsymbol{\beta}^{-\prime} \boldsymbol{x}_t^{-}$ is the nonlinear error correction term, with $\boldsymbol{\beta}^{+} = -\frac{\theta^{+}}{\rho}$ and $\boldsymbol{\beta}^{-} = -\frac{\theta^{-}}{\rho}$ being the asymmetric long-run parameters (long run multipliers); $\boldsymbol{\pi}_i^{+}$ and $\boldsymbol{\pi}_i^{-}$ parameters capture short-run asymmetries; and $\rho$ is an error correction coefficient.

The APT examination based on CECM (4) involves falsifying hypotheses of cointegration existence, detailed tests of symmetry restrictions, and visual exploration of adjustment's paths.

For cointegration testing, two tests for the existence of a stable long-run levels relationship may be used. The $\mathrm{t_{BDM}}$ statistic proposed by Banerjee et al. in [51] tests:

$\mathrm{H_0}$: $\rho = 0$ (no long-run level relationship)
$\mathrm{H_1}$: $\rho < 0$

and the $\mathrm{F_{PSS}}$ statistics by Pesaran, Shin and Smith, described in [48], tests:

$\mathrm{H_0}$: $\rho = \boldsymbol{\theta}^{+} = \boldsymbol{\theta}^{-} = 0$
$\mathrm{H_1}$: $\rho = \boldsymbol{\theta}^{+} = \boldsymbol{\theta}^{-} \neq 0.$

The asymptotic distributions of $\mathrm{t_{BDM}}$ and $\mathrm{F_{PSS}}$ test statistics are nonstandard under their respective null hypotheses, and their exact asymptotic distributions are generally complicated to derive. Therefore, Pesaran et al. in [48] proposed the "bound testing" approach for cointegration testing in ARDL/NARDL specification.

Tests for asymmetry of pass-through can be divided into long-run and short-run asymmetry tests. The NARDL model in the form (4) allows for three general forms of asymmetry:

- long-run amount or "reaction asymmetry", associated with $\boldsymbol{\beta}^{+} \neq \boldsymbol{\beta}^{-}$;
- short-run amount or "impact asymmetry", associated with the inequality of the coefficients on the contemporaneous first differences $\Delta x_t^{+}$ and $\Delta x_t^{-}$;
- speed asymmetry or "adjustment asymmetry", captured by the patterns of adjustment from initial equilibrium to the new equilibrium following an economic perturbation (i.e., the dynamic multipliers). Adjustment asymmetry derives from the interaction of impact and reaction asymmetries in conjunction with the error correction coefficient, $\rho$.

The null and alternative hypotheses for long-run asymmetry have a form:

$\mathrm{H_0}$: $\boldsymbol{\beta}^{+} = \boldsymbol{\beta}^{-}$ (restriction of long-run symmetric reaction)
$\mathrm{H_1}$: $\boldsymbol{\beta}^{+} \neq \boldsymbol{\beta}^{-}$

Short-run asymmetry is tested by testing a restriction:

$\mathrm{H_0}$: $\sum_{j=0}^{q-1} \boldsymbol{\pi}_j^{+} = \sum_{j=0}^{q-1} \boldsymbol{\pi}_j^{-}$ (additive symmetry)

against alternatives of inequality.

Another form of restriction to be tested in short-run cases is the so-called "impact multipliers symmetry restriction":

H$_0$: $\pi_0^{+} = \pi_0^{-}$

which can be tested to capture a one-period asymmetry reaction.

All symmetry restrictions (both long and short-run) can be tested by the Wald test.

Speed asymmetry could be inferred from NARDL on the basis of dynamic multipliers calculation.

As [46] showed, it is possible to derive asymmetric dynamic multipliers associated with unit changes in $\boldsymbol{x}_t^{+}$ and $\boldsymbol{x}_t^{-}$, respectively, on $y_t$. The cumulative dynamic multipliers can be calculated as follows from the NARDL-in-levels representation (3) or from CECM (4):

$$\boldsymbol{m}_h^{+} = \sum\nolimits_{j=1}^{h} \frac{\partial y_{t+j}}{\partial x_t^{+}},\ \boldsymbol{m}_h^{-} = \sum\nolimits_{j=1}^{h} \frac{\partial y_{t+j}}{\partial x_t^{-}} \ \text{for h} = 0, 1, 2, \ldots \tag{5}$$

In addition to the main research tool, which is the NARDL model and set of statistical tests connected, standard integration tests such as the ADF test ([52]), KPSS test ([53]), and Zivot–Andrews test [54] being used.

## 4. Results

The study begins with a visual and statistical analysis of time series. The graphs of the series and descriptive statistics are reported in Figure 3 and Table 2.

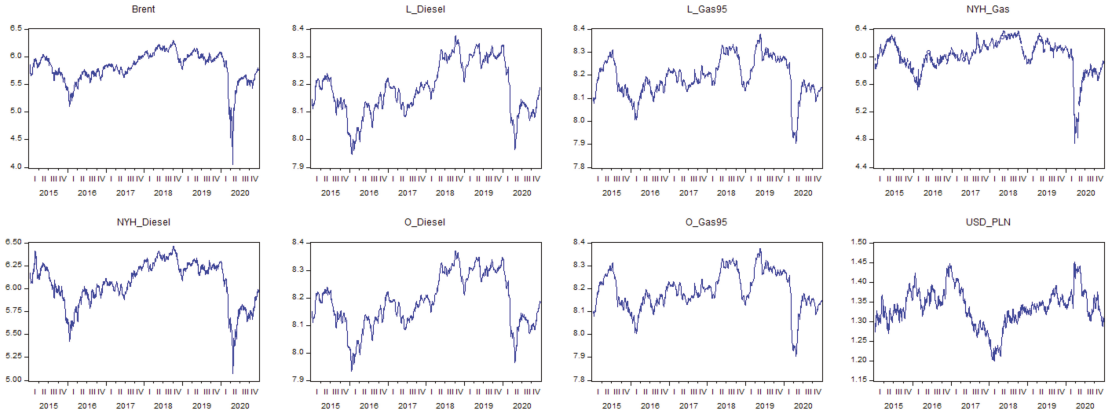


**Figure 3.** Time series under examination.

**Table 2.** Descriptive statistics.

| Statistics | Brent | L_Diesel | L_Gas95 | NYH_Gas | NYH_Diesel | O_Diesel | O_Gas95 | USD_PLN |
|---|---|---|---|---|---|---|---|---|
| mean | 5.806 | 8.185 | 8.192 | 6.011 | 6.057 | 8.185 | 8.192 | 1.336 |
| median | 5.838 | 8.182 | 8.182 | 6.047 | 6.084 | 8.181 | 8.182 | 1.335 |
| maximum | 6.294 | 8.375 | 8.377 | 6.374 | 6.465 | 8.371 | 8.376 | 1.451 |
| minimum | 4.049 | 7.946 | 7.903 | 4.742 | 5.069 | 7.933 | 7.903 | 1.199 |
| std. dev. | 0.271 | 0.094 | 0.083 | 0.237 | 0.236 | 0.094 | 0.083 | 0.047 |
| skewness | −1.368 | −0.050 | −0.459 | −1.693 | −0.781 | −0.057 | −0.459 | −0.233 |
| kurtosis | 6.873 | 2.252 | 3.574 | 7.967 | 3.244 | 2.259 | 3.575 | 3.502 |
| Jarque–Bera | 1393.352 | 35.307 | 72.549 | 2238.746 | 154.786 | 34.803 | 72.664 | 29.049 |
| observations | 1487 | 1487 | 1487 | 1487 | 1487 | 1487 | 1487 | 1487 |

Visual exploration of the time series leads to three conclusions: First, at the beginning of 2020, a structural disturbance resulted in a significant drop in prices. This disturbance hit Brent, NYH_Gas, and NYH_Diesel particularly hard. Secondly, the prices of wholesale products also collapsed during the period, but a similar collapse took place at the beginning of 2016, which is especially visible in the case of diesel oil. Thirdly, the price's response to the disruption of 2020 is different for a class of products (gasoline, diesel oil) but similar for both players by products.

Table 2 shows that empirical distributions are lightly or moderately negatively skewed, except for Brent and NYH_Gas series, which have substantial long left tails. It confirms the conclusion from visual examination to some extent. Both of the series are significantly more leptokurtic than others, as well. The normality of distributions is rejected in all of the cases.

For the bound testing for cointegration based on (4), the key step is an integration's order testing. This approach yields consistent estimates of the long-run coefficients that are asymptotically normal irrespective of whether the underlying regressors are I(1) or I(0), but the bound test could lead to spurious results in the presence of I(2) variables. Therefore, the unit root tests—Augmented Dickey–Fuller (ADF) and Kwiatkowski–Phillips–Schmidt–Shin (KPSS) are carried out to check the stationarity and number of integration order of the variables. As visual exploration shows a high possibility of structural breaks in a series, the Zivot–Andrews unit root test with automatically detected breaks is performed, as well. Results of ADF and KPSS tests show Tables 3 and 4.

**Table 3.** ADF test results—levels and first differences.

| Variable | Prob. * | Variable | Prob. * |
|---|---|---|---|
| Brent | 0.094 | $\Delta$(Brent) | 0.000 |
| L_Diesel | 0.243 | $\Delta$(L_Diesel) | 0.000 |
| L_Gas95 | 0.054 | $\Delta$(L_Gas95) | 0.000 |
| NYH_Gas | 0.092 | $\Delta$(NYH_Gas) | 0.000 |
| NYH_Diesel | 0.318 | $\Delta$(NYH_Diesel) | 0.000 |
| O_Diesel | 0.308 | $\Delta$(O_Diesel) | 0.000 |
| O_Gas95 | 0.077 | $\Delta$(O_Gas95) | 0.000 |
| USD_PLN | 0.037 | $\Delta$(USD_PLN) | 0.000 |

Note: * one-sided *p*-values from [55].

**Table 4.** KPSS test statistics.

| Variable | Value of Test Statistics |
|---|---|
| $\Delta$(Brent) | 0.0396 |
| $\Delta$(L_Diesel) | 0.0627 |
| $\Delta$(L_Gas95) | 0.0558 |
| $\Delta$(NYH_Gas) | 0.0319 |
| $\Delta$(NYH_Diesel) | 0.0633 |
| $\Delta$(O_Diesel) | 0.0621 |
| $\Delta$(O_Gas95) | 0.0583 |
| $\Delta$(USD_PLN) | 0.0648 |

Note: Asymptotic critical values *: 0.739 (1%) 0.463 (5%) 0.347 (10%), [53], Table 1.

Given the results in Table 3, we will reject the null at all significance levels, since the *p*-value is 0 for each of the differenced series under consideration and the null hypothesis is a unit root. In particular, since the test is conducted under first differences, it shows that there are no unit roots in first differences, and so each of the series must be either I(0) or I(1). The results of the KPSS test (Table 4) confirm the stationarity of differenced series. As there is a high possibility of structural breaks in the series, the next step deals with that problem. Figure 4 depicts Zivot–Andrews test statistics with estimated structural break date.

One can observe that the most significant break in almost all of the series (except USD_PLN series) is detected at the beginning of the 2020 year. The exact dates of estimated breakpoints and test for integration in the presence of those breaks are contained in Table 5.

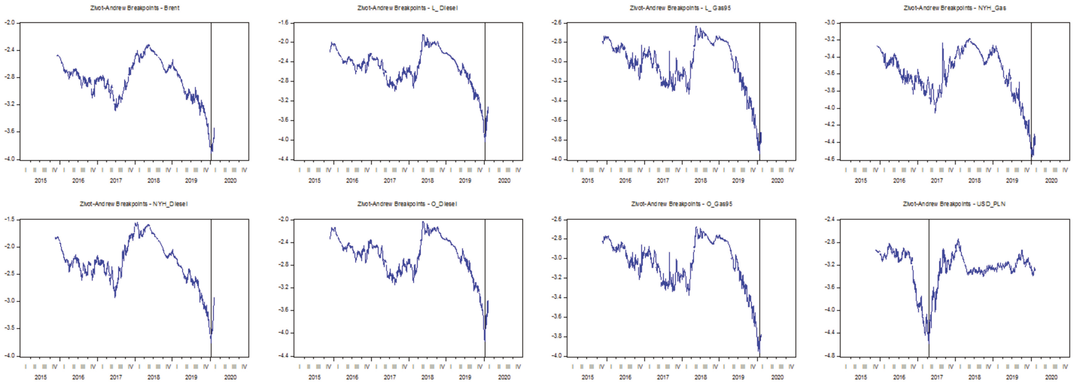


**Figure 4.** Zivot–Andrews breakpoints (marked by vertical, grey line).

**Table 5.** Zivot–Andrews unit root test.

| Variable | Estimated Break Date | Zivot–Andrews Test Statistics | Integration |
|---|---|---|---|
| Brent | 1/07/2020 | −3.7864 | yes |
| L_Diesel | 1/08/2020 | −4.0122 | yes |
| L_Gas95 | 1/22/2020 | −3.9042 | yes |
| NYH_Gas | 1/07/2020 | −3.5573 | yes |
| NYH_Diesel | 1/07/2020 | −3.7869 | yes |
| O_Diesel | 1/07/2020 | −4.0752 | yes |
| O_Gas95 | 1/22/2020 | −3.9317 | yes |
| USD_PLN | 4/24/2017 | −4.6356 | yes? |

Note: Test critical values: −5.34 (1%), −4.93 (5%), −4.58 (10%).

Values of the Zivot–Andrews test statistics are higher than the critical value for 10% significance level (except USD_PLN series), which implies integration of variables of order at least one. The same test repeated for the first differences showed no higher level integration. The test confirms that the beginning of a pandemic in 2020 caused the most important structural breaks in a whole sample period for all of the series besides exchange rate (where the break is located in the 2017 year).

The second and the main objective of the study is to find out how the COVID-19 outbreak affected the price behavior of market players. As structural changes in all of the series (except USD/PLN exchange rate) that took place at the beginning of 2020 were confirmed, it was therefore justified to move to the next stage of the study. This stage consisted of three steps: The first step was an APT examination of the 2015–2020 sample period; the second step was APT research in a subsample of the 2020 year, only; and the final step was a comparison of the results of two previous steps. General research assumption considers the empirical model of a form:

The wholesale price of a product of player i = f (exchange rate USD/PLN, upstream price)

As there are two players, two downstream products, and two possible upstream inputs (the price of crude or price of an appropriate benchmark), there are eight pass-through models to examine. Each model consists of an independent variable and two regressors. A testable model using NARDL specification, derived from (4) had a form:

$$\Delta y_t = const + \rho y_{t-1} + \theta_u^+ us^+{}_{t-1} + \theta_u^- us^-{}_{t-1} + \theta_x^+ x^+{}_{t-1} + \theta_x^- x^-{}_{t-1} + \sum_{j=1}^{p-1} \gamma_j \Delta y_{t-j} + \sum_{j=0}^{q-1} (\pi_{uj}^+ \Delta us^+{}_{t-j} + \pi_{uj}^- \Delta us^-{}_{t-j} + \pi_{xj}^+ \Delta x^+{}_{t-j} + \pi_{xj}^- \Delta x^-{}_{t-j}) + \varepsilon_t, \tag{6}$$

where $y_t$ = L_Diesel, L_Gas95, O_Diesel, O_Gas95 (downstream prices); $us_t$ = USD_PLN (important cost factor); and $x_t$ = Brent, NYH_Gas, NYH_Diesel (upstream prices). Following (6), $\beta_u^+ = -\frac{\theta_u^+}{\rho}$, $\beta_u^- = -\frac{\theta_u^-}{\rho}$, $\beta_x^+ = -\frac{\theta_x^+}{\rho}$, and $\beta_x^- = -\frac{\theta_x^-}{\rho}$ are the asymmetric long-run parameters; $\pi_{uj}^+$, $\pi_{uj}^-$, $\pi_{xj}^+$, $\pi_{xj}^-$ parameters capture short-run asymmetries, especially $\pi_{u0}^+$, $\pi_{u0}^-$, $\pi_{x0}^+$, $\pi_{x0}^-$, the impact parameters; and $\rho$ is an error correction coefficient.

To check for the existence of asymmetric pass-through, we estimate the unrestricted NARDL models (6) with a maximum order of lags chosen based on the AIC information criterion for all of the possible empirical specifications. Cointegration tests and symmetry tests were performed next, on the basis of estimation. The naming convention of symmetry restriction is as follows: W_LR_u denotes the test of restrictions imposed on long-run multipliers associated with a positive and negative change in the exchange rate; W_LR_x denotes the test of restrictions imposed on long-run multipliers associated with positive and negative changes in the regressor $x$; W_SRa_u and W_SRa_x denote short-run additive symmetry restrictions (exchange rate, regressor $x$); and W_SRi_u and W_SRi_x denote short-run impact symmetry restriction (exchange rate, regressor $x$). The values of test statistics for symmetry restrictions are Wald's test t-statistics. Table 6 reports the most important results of the estimation and testing phase.

Considering the results presented in Table 6, one can see that, in all cases, the estimated coefficients of the error correction term, the asymmetric long-run parameters, and the impact parameters (capturing the most direct short run asymmetric transmission) are significant at 1% level in all of the estimated models. The values of statistics FPSS and tBDM of the cointegrations tests allow us to reject the null hypothesis of non-cointegration in all of the cases. That implies that the USD/PLN exchange rate and the prices of Brent crude oil, NYH_Gasoline, and NYH_Diesel are important drivers for wholesale fuel prices in the Polish market in the long run. The models with IPP benchmark prices perform slightly better in terms of $R^2$ and Akaike criteria. The long-run coefficient values are all below 0.5 for both players, which indicates that wholesale consumers are fairly insulated from fluctuations in the prices of inputs in the long run. The estimated error correction term values are consistent with the theoretical structure of a model (all are negative). Speed of adjustment toward the long-run equilibrium is about 1.4 to 1.8 % in the case of crude oil and about 2.3 to 2.6 % in the case of benchmarks. This supports the possible IPP schema of pricing.

APT evaluation in a given sample period consisted of testing symmetry restriction and visual exploration of the graphs of asymmetric multipliers. Figures 5–8 contain multipliers' graphs for each of the players and wholesale price as a reaction to change in upstream price and USD/PLN exchange rate. The name of a regressor $x$ is given in parenthesis in the graphs of multipliers for an exchange rate.

**Table 6.** NARDL estimation results—whole sample.

| **Dependent Variable $y$** | **L_Gas95** | | | **O_Gas95** | | |
|---|---|---|---|---|---|---|
| **Regressor $x$** | **Brent** | | | **Brent** | | |
| **Model Estimated** | **NARDL (2, 3, 6, 1, 1)** | | | **NARDL (2, 3, 6, 2, 1)** | | |
| **Parameter** | **Value** | **t-Statistic** | **Prob.** | **Value** | **t-Statistic** | **Prob.** |
| $\rho$ | −0.0184 | 4.6142 | 0.0000 | −0.0183 | −4.6289 | 0.0000 |
| $\beta_x^+$ | 0.3447 | 5.9610 | 0.0000 | 0.3388 | 5.8663 | 0.0000 |
| $\beta_x^-$ | 0.3327 | 7.0445 | 0.0000 | 0.3302 | 7.0074 | 0.0000 |
| $\beta_u^+$ | 0.4424 | 2.5902 | 0.0097 | 0.4650 | 2.7388 | 0.0062 |
| $\beta_u^-$ | 0.4922 | 2.7103 | 0.0068 | 0.4992 | 2.7616 | 0.0058 |
| $\pi_{x0}^+$ | 0.1015 | 14.7830 | 0.0000 | 0.1057 | 15.5825 | 0.0000 |
| $\pi_{x0}^-$ | 0.0460 | 8.6850 | 0.0000 | 0.0414 | 7.8978 | 0.0000 |
| $\pi_{u0}^+$ | 0.1709 | 4.8705 | 0.0000 | 0.1573 | 4.5288 | 0.0000 |
| $\pi_{u0}^-$ | 0.1742 | 4.4618 | 0.0000 | 0.1225 | 3.1735 | 0.0015 |

**Table 6.** *Cont.*

| Cointegration tests | Stat. Value | | | Stat. Value | | |
|---|---|---|---|---|---|---|
| F_PSS | 4.4084 | | | 4.3978 | | |
| t_BDM | −4.6063 | | | −4.6288 | | |
| **Symmetry restrictions *** | **Stat. Value** | | **Prob.** | **Stat. Value** | | **Prob.** |
| W_LR_x | 0.8047 | | 0.4211 | 0.5774 | | 0.5637 |
| W_LR_u | −0.8020 | | 0.4227 | −0.5516 | | 0.5811 |
| W_SRa_x | 0.0891 | | 0.9290 | 0.0168 | | 0.9865 |
| W_SRa_u | - | | - | 1.2112 | | 0.2260 |
| W_SRi_x | 5.5583 | | 0.0000 | 6.5196 | | 0.0000 |
| W_SRi_u | −0.0532 | | 0.9575 | 0.5664 | | 0.5712 |
| **Diagnostics** | **Stat. Value** | | | **Stat. Value** | | |
| Adjusted R-squared | 0.4626 | | | 0.47465 | | |
| Akaike criterion | −7.8763 | | | −7.9000 | | |
| **Dependent variable y** | **L_Gas95** | | | **O_Gas95** | | |
| **Regressor *x*** | **NYH_Gas** | | | **NYH_Gas** | | |
| **Model Estimated** | **NARDL (5, 7, 7, 6, 1)** | | | **NARDL (2, 7, 7, 6, 1)** | | |
| **Parameter** | **Value** | **t-Statistic** | **Prob.** | **Value** | **t-Statistic** | **Prob.** |
| $\rho$ | −0.0235 | −4.7419 | 0.0000 | −0.0255 | −5.2034 | 0.0000 |
| $\beta_x^+$ | 0.4076 | 8.6752 | 0.0000 | 0.3973 | 9.2056 | 0.0000 |
| $\beta_x^-$ | 0.4088 | 10.5452 | 0.0000 | 0.4023 | 11.2861 | 0.0000 |
| $\beta_u^+$ | 0.5157 | 3.9843 | 0.0001 | 0.5199 | 4.3534 | 0.0000 |
| $\beta_u^-$ | 0.4852 | 3.4795 | 0.0005 | 0.4738 | 3.6835 | 0.0002 |
| $\pi_{x0}^+$ | 0.0860 | 11.9715 | 0.0000 | 0.0888 | 12.3307 | 0.0000 |
| $\pi_{x0}^-$ | 0.0839 | 14.0467 | 0.0000 | 0.0743 | 12.4278 | 0.0000 |
| $\pi_{u0}^+$ | 0.1975 | 5.8268 | 0.0000 | 0.1911 | 5.6277 | 0.0000 |
| $\pi_{u0}^-$ | 0.1839 | 4.9148 | 0.0000 | 0.1302 | 3.4724 | 0.0005 |
| **Cointegration tests** | **Stat. Value** | | | **Stat. Value** | | |
| F_PSS | 4.6027 | | | 5.5271 | | |
| t_BDM | −4.7419 | | | −5.2034 | | |
| **Symmetry restrictions *** | **Stat. Value** | | **Prob.** | **Stat. Value** | | **Prob.** |
| W_LR_x | −0.0951 | | 0.9242 | −0.4082 | | 0.6832 |
| W_LR_u | 0.5614 | | 0.5746 | 0.9220 | | 0.3567 |
| W_SRa_x | 0.5465 | | 0.5847 | 0.6168 | | 0.5375 |
| W_SRa_u | 4.2265 | | 0.0000 | 5.0797 | | 0.0000 |
| W_SRi_x | 0.1976 | | 0.8433 | 1.3517 | | 0.1767 |
| W_SRi_u | 0.2274 | | 0.8201 | 1.0173 | | 0.3092 |
| **Diagnostics** | **Stat. Value** | | **Prob.** | **Stat. Value** | | **Prob.** |
| Adjusted R-squared | 0.5179 | | | 0.5135 | | |
| Akaike criterion | −7.9667 | | | −7.9642 | | |
| **Dependent Variable *y*** | **L_Diesel** | | | **O_Diesel** | | |
| **Regressor *x*** | **Brent** | | | **Brent** | | |
| **Model Estimated** | **NARDL (6, 7, 6, 5, 4)** | | | **NARDL (6, 7, 4, 5, 1)** | | |
| **Parameter** | **Value** | **t-Statistic** | **Prob.** | **Value** | **t-Statistic** | **Prob.** |
| $\rho$ | −0.0145 | −3.2293 | 0.0013 | −0.0180 | −3.9953 | 0.0001 |
| $\beta_x^+$ | 0.2685 | 3.7197 | 0.0002 | 0.2962 | 5.3192 | 0.0000 |
| $\beta_x^-$ | 0.3045 | 5.1427 | 0.0000 | 0.3270 | 7.1528 | 0.0000 |
| $\beta_u^+$ | 0.4298 | 2.2871 | 0.0223 | 0.4646 | 3.0276 | 0.0025 |
| $\beta_u^-$ | 0.2485 | 1.1875 | 0.2352 | 0.3066 | 1.8294 | 0.0676 |
| $\pi_{x0}^+$ | 0.0842 | 14.7962 | 0.0000 | 0.0914 | 15.2815 | 0.0000 |
| $\pi_{x0}^-$ | 0.0473 | 10.8075 | 0.0000 | 0.0501 | 10.8846 | 0.0000 |
| $\pi_{u0}^+$ | 0.1896 | 6.6684 | 0.0000 | 0.1579 | 5.2730 | 0.0000 |
| $\pi_{u0}^-$ | 0.1119 | 3.5508 | 0.0004 | 0.0813 | 2.4530 | 0.0143 |

**Table 6.** *Cont.*

| **Cointegration tests** | **Stat. Value** | | | **Stat. Value** | | |
|---|---|---|---|---|---|---|
| F_PSS | 3.0988 | | | 3.9556 | | |
| t_BDM | −3.2293 | | | −3.9953 | | |
| **Symmetry restrictions *** | **Stat. Value** | | **Prob.** | **Stat. Value** | | **Prob.** |
| W_LR_x | −2.2093 | | 0.0273 | −2.2677 | | 0.0235 |
| W_LR_u | 2.5808 | | 0.0100 | 2.7004 | | 0.0070 |
| W_SRa_x | −0.6325 | | 0.5271 | −0.0655 | | 0.9477 |
| W_SRa_u | 3.5810 | | 0.0004 | 5.0124 | | 0.0000 |
| W_SRi_x | 4.4120 | | 0.0000 | 4.7040 | | 0.0000 |
| W_SRi_u | 1.5481 | | 0.1218 | 1.4506 | | 0.1471 |
| **Diagnostics** | **Stat. Value** | | **Prob.** | **Stat. Value** | | **Prob.** |
| Adjusted R-squared | 0.5393 | | | 0.5023 | | |
| Akaike criterion | −8.3062 | | | −8.2045 | | |
| **Dependent Variable** | **L_Diesel** | | | **O_Diesel** | | |
| **Regressor *x*** | **NYH_Diesel** | | | **NYH_Diesel** | | |
| **Model Estimated** | **NARDL (4, 5, 6, 3, 3)** | | | **NARDL (6, 5, 6, 5, 3)** | | |
| **Parameter** | **Value** | **t-Statistic** | **Prob.** | **Value** | **t-Statistic** | **Prob.** |
| ρ | −0.0237 | −4.1402 | 0.0000 | −0.0260 | −4.2966 | 0.0000 |
| $\beta_x^+$ | 0.3608 | 9.1020 | 0.0000 | 0.3477 | 9.0231 | 0.0000 |
| $\beta_x^-$ | 0.3900 | 14.1542 | 0.0000 | 0.3836 | 14.3144 | 0.0000 |
| $\beta_u^+$ | 0.5357 | 5.3596 | 0.0000 | 0.5354 | 5.5299 | 0.0000 |
| $\beta_u^-$ | 0.4072 | 3.5731 | 0.0004 | 0.3840 | 3.4447 | 0.0006 |
| $\pi_{x0}^+$ | 0.1035 | 13.9049 | 0.0000 | 0.1042 | 13.1859 | 0.0000 |
| $\pi_{x0}^-$ | 0.0988 | 14.3219 | 0.0000 | 0.1056 | 14.4689 | 0.0000 |
| $\pi_{u0}^+$ | 0.1571 | 6.0076 | 0.0000 | 0.1330 | 4.7955 | 0.0000 |
| $\pi_{u0}^-$ | 0.1499 | 5.1160 | 0.0000 | 0.1197 | 3.8509 | 0.0001 |
| **Cointegration tests** | **Stat. Value** | | | **Stat. Value** | | |
| F_PSS | 3.6012 | | | 3.8066 | | |
| t_BDM | −4.1402 | | | −4.2966 | | |
| **Symmetry restrictions *** | **Stat. Value** | | **Prob.** | **Stat. Value** | | **Prob.** |
| W_LR_x | −1.5487 | | 0.1217 | −1.9532 | | 0.0510 |
| W_LR_u | 1.9250 | | 0.0544 | 2.3293 | | 0.0200 |
| W_SRa_x | −0.1349 | | 0.8926 | −0.2044 | | 0.8380 |
| W_SRa_u | 0.0375 | | 0.9701 | 0.8145 | | 0.4154 |
| W_SRi_x | 0.3926 | | 0.6946 | 1.4799 | | 0.1391 |
| W_SRi_u | 0.1539 | | 0.8777 | 0.2683 | | 0.7885 |
| **Diagnostics** | **Stat. Value** | | **Prob.** | **Stat. Value** | | **Prob.** |
| Adjusted R-squared | 0.5973 | | | 0.5696 | | |
| Akaike criterion | −8.4677 | | | −8.3487 | | |

Notes: F_PSS, t_BDM: F-statistics of F_PSS and t-statistics of t_BDM bound testing approach; the critical values for Case 3 unrestricted intercept and no trend; k = 4 and usual significance levels: F-stat. I(0), I(1); t-stat. I(0), I(1), 1%: 3.74; 5.06; 1%: −3.43; −4.6; 5%: 2.86; 4.01; 5%: −2.86; −3.99; 10%: 2.45; 3.52; 10%: −2.57; −3.66. * For symmetry restrictions, hypothesis values of a Wald test t-statistics are reported.

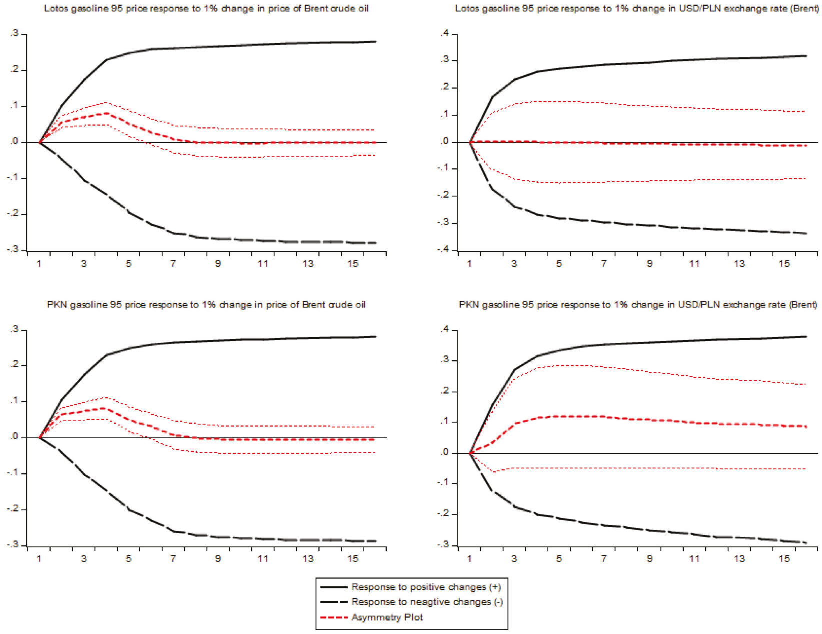


**Figure 5.** Dynamic multipliers—whole sample, wholesale Gasoline 95, and Brent crude.

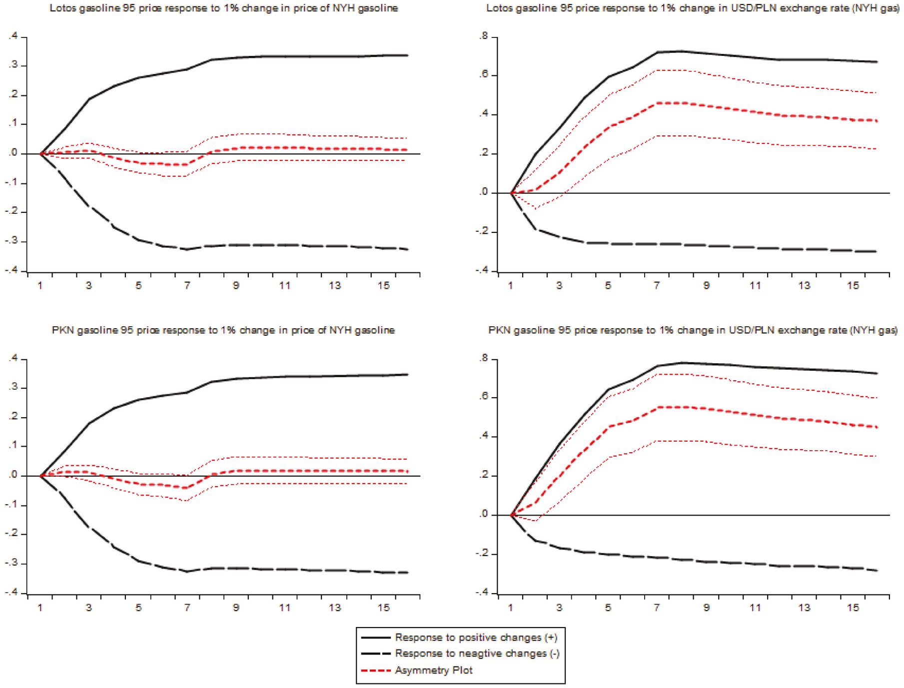


**Figure 6.** Dynamic multipliers—whole sample, wholesale Gasoline 95, and NYH_Gasoline.

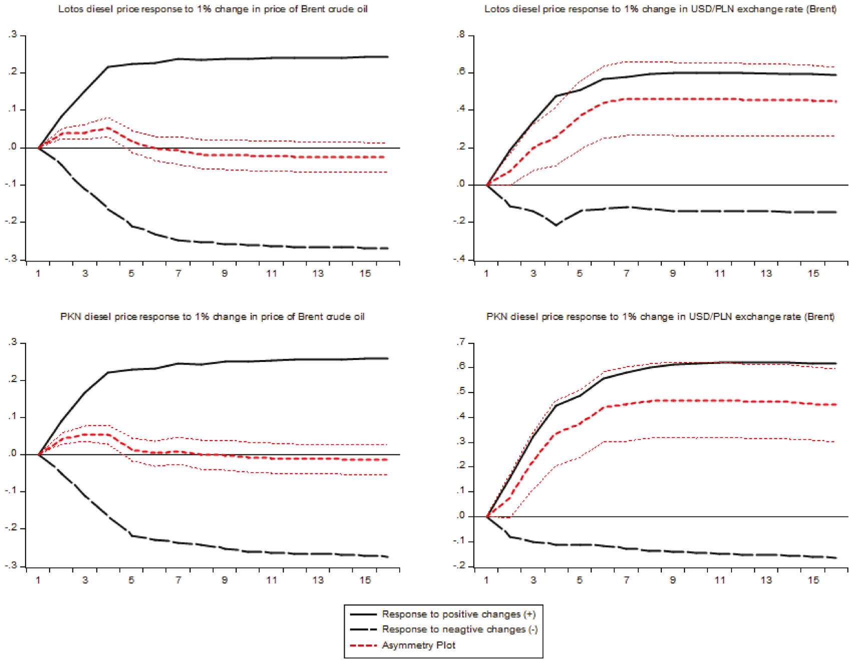


**Figure 7.** Dynamic multipliers—whole sample, wholesale diesel, and Brent crude.

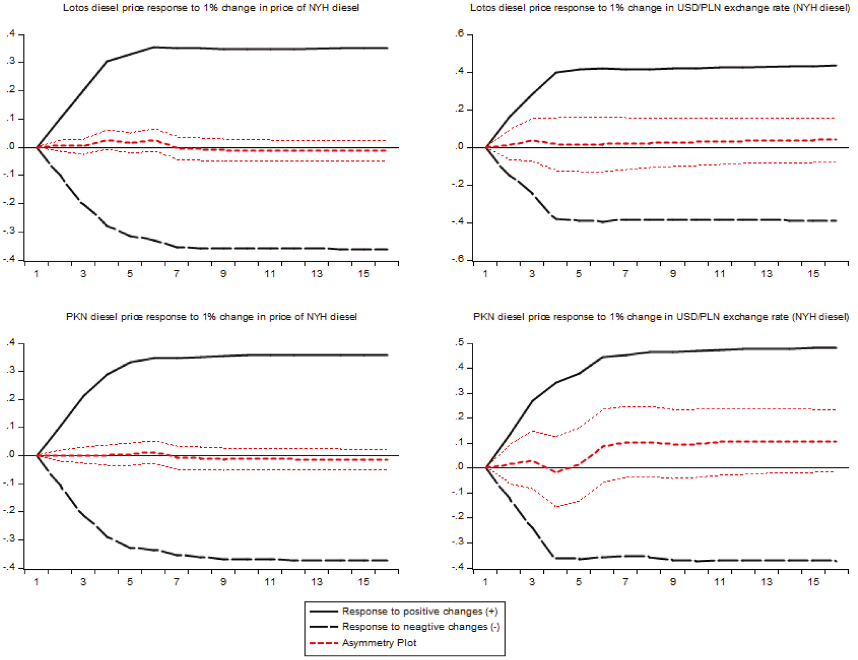


**Figure 8.** Dynamic multipliers—whole sample, wholesale diesel, and NYH_Diesel.

Tests of restrictions imposed on long-run multipliers associated with positive and negative changes in the regressor x and USD/PLN exchange rate shows that the difference between long-run multipliers of negative and positive changes is statistically significant in the case of the price of diesel oil (for both of the players). However, positive APT took place in the case of exchange rate pass-through, only. It means that, in the long run, Brent or NYH_Gasoline prices' reduction has a greater impact on wholesale prices than its increase, and, on the other hand, the reaction of wholesale prices to a depreciation of Polish national currency is significantly stronger than to appreciation. This result is similar to the findings in [47], where negative long-run asymmetry was found in the case of crude and a positive one in the case of the exchange rate. Figures 7 and 8 confirm the strong, positive asymmetric long-term impact of USD/PLN exchange rate in the case of Lotos and PKN when Brent price is the second regressor in a model and moderate positive asymmetry when NYH_Diesel price is in a model.

Given that the study is conducted on daily data, the short-term effects are more important than the long-term asymmetry. Taking the short-run asymmetric effects into account, one should analyze the results of W_SRa_u and W_SRa_x (additive symmetry) and W_SRi_u and W_SRi_x (impact symmetry) restrictions' tests.

Significant immediate asymmetric effect (impact) is detected in the case of wholesale Gasoline 95 price and Brent price (both players) and wholesale diesel oil price and Brent price (both players). As values of estimated, positive impact parameters $\pi_{x0}^{+}$ are greater than negative ones, and the asymmetry is positive. Additive short-run asymmetry is confirmed in the case of Gasoline 95 price and USD/PLN exchange rate (both players, with NYH_Gasoline price as a second regressor) and in the case of wholesale diesel oil price and USD/PLN exchange rate (both players, with Brent price as a second regressor). Table 7 exposes the type of additive short-run asymmetry.

**Table 7.** Aggregates of significant positive and negative short-run multipliers of USD/PLN exchange rate.

| | **Additive Asymmetry Cases** | | | |
|---|---|---|---|---|
| **Dependent Variable $y$** | **L_Gas9** | **O_Gas95** | **L_Diesel** | **O_Diesel** |
| **Regressor $x$** | **NYH_Gas** | **NYH_Gas** | **Brent** | **Brent** |
| $\sum_{j=0}^{q-1} \pi_{uj}^{-}$ | 0.1840 | 0.1302 | 0.0864 | 0.0813 |
| $\sum_{j=0}^{q-1} \pi_{uj}^{+}$ | 0.5716 | 0.5856 | 0.4416 | 0.4440 |

In the next step, APT examination in a subsample of the 2020 year is undertaken. The same methodology is utilized in that step to maintain comparability with the study of a whole sample, although with the limitation regarding the length of the sample. One-year sample and daily data are not sufficient to obtain reliable information about the long-term direction of adjustments. Therefore, the study of asymmetry in the short run was the main objective for the year 2020.

Table 8 shows the most important results of the estimation and testing phase for the year 2020, and Figures 9–12 contain multipliers' graphs for each of the players and wholesale price in a comparative form for the whole sample and for the year 2020.

**Table 8.** NARDL estimation results—subsample 2020.

| **Dependent Variable** | **L_Gas95** | | | **O_Gas95** | | |
|---|---|---|---|---|---|---|
| **Regressor *x*** | **Brent** | | | **Brent** | | |
| **Model Estimated** | **ARDL (6, 2, 5, 0, 3)** | | | **ARDL (6, 2, 5, 0, 1)** | | |
| **Parameter** | **Value** | **t-Statistic** | **Prob.** | **Value** | **t-Statistic** | **Prob.** |
| ρ | −0.0462 | 2.5828 | 0.0104 | −0.0486 | −2.9338 | 0.0037 |
| $\beta_x^+$ | 0.2495 | 3.3400 | 0.0010 | 0.2820 | 4.4925 | 0.0000 |
| $\beta_x^-$ | 0.2236 | 3.3332 | 0.0010 | 0.2504 | 4.4645 | 0.0000 |
| $\beta_u^+$ | 0.1881 | 0.3911 | 0.6961 | 0.0980 | 0.2375 | 0.8125 |
| $\beta_u^-$ | 0.3943 | 0.9253 | 0.3558 | 0.3418 | 0.9245 | 0.3563 |
| $\pi_{x0}^+$ | 0.0397 | 3.3883 | 0.0008 | 0.0526 | 4.7411 | 0.0000 |
| $\pi_{x0}^-$ | 0.0373 | 5.0291 | 0.0000 | 0.0246 | 3.5135 | 0.0005 |
| $\pi_{u0}^+$ | - | - | - | - | - | - |
| $\pi_{u0}^-$ | 0.4292 | 4.3122 | 0.0000 | 0.2263 | 2.4923 | 0.0134 |
| **Cointegration tests** | **Stat. Value** | | | **Stat. Value** | | |
| F_PSS | 2.9956 | | | 2.8553 | | |
| t_BDM | −2.5922 | | | −2.9338 | | |
| **Symmetry restrictions *** | **Stat. Value** | | **Prob.** | **Stat. Value** | | **Prob.** |
| W_SRa_x | −0.8379 | | 0.4030 | 0.09758 | | 0.9223 |
| W_SRa_u | 3.1099 | | 0.0021 # | - | | - |
| W_SRi_x | 0.1484 | | 0.8820 | 1.8299 | | 0.0686 |
| W_SRi_u | 4.3121 | | 0.0000 # | 2.4923 | | 0.0134 |
| **Dependent Variable** | **L_Gas95** | | | **O_Gas95** | | |
| **Regressor *x*** | **NYH_Gas** | | | **NYH_Gas** | | |
| **Model Estimated** | **ARDL (6, 4, 7, 7, 1)** | | | **ARDL (6, 7, 7, 7, 1)** | | |
| **Parameter** | **Value** | **t-Statistic** | **Prob.** | **Value** | **t-Statistic** | **Prob.** |
| ρ | −0.0855 | −4.6819 | 0.0000 | −0.0701 | −3.5041 | 0.0006 |
| $\beta_x^+$ | 0.3100 | 10.1975 | 0.0000 | 0.3428 | 7.4012 | 0.0000 |
| $\beta_x^-$ | 0.2536 | 9.0014 | 0.0000 | 0.2839 | 7.3037 | 0.0000 |
| $\beta_u^+$ | −0.3228 | −1.3753 | 0.1705 | −0.3067 | −1.1416 | 0.2550 |
| $\beta_u^-$ | 0.1429 | 0.7430 | 0.4583 | 0.1663 | 0.7544 | 0.4514 |
| $\pi_{x0}^+$ | 0.0452 | 3.3190 | 0.0011 | 0.0517 | 3.7601 | 0.0002 |
| $\pi_{x0}^-$ | 0.1022 | 10.8636 | 0.0000 | 0.0880 | 9.6893 | 0.0000 |
| $\pi_{u0}^+$ | 0.0112 | 0.1297 | 0.8969 | 0.0360 | 0.4404 | 0.6601 |
| $\pi_{u0}^-$ | 0.3345 | 3.5947 | 0.0004 | 0.1446 | 1.6596 | 0.0985 |
| **Cointegration tests** | **Stat. Value** | | | **Stat. Value** | | |
| F_PSS | 5.3190 | | | 3.8499 | | |
| t_BDM | −4.6819 | | | −3.5041 | | |
| **Symmetry restrictions *** | **Stat. Value** | | **Prob.** | **Stat. Value** | | **Prob.** |
| W_SRa_x | −2.1276 | | 0.0345 | −0.4210 | | 0.6742 |
| W_SRa_u | 1.8355 | | 0.0678 | 2.6802 | | 0.0080 |
| W_SRi_x | −2.9530 | | 0.0035 | −1.8721 | | 0.0626 |
| W_SRi_u | −2.2063 | | 0.0284 | −0.7883 | | 0.4314 |
| **Dependent Variable** | **L_Diesel** | | | **O_Diesel** | | |
| **Regressor *x*** | **Brent** | | | **Brent** | | |
| **Model Estimated** | **NARDL (4, 3, 6, 3, 0)** | | | **NARDL (2, 7, 6, 0, 0)** | | |
| **Parameter** | **Value** | **t-Statistic** | **Prob.** | **Value** | **t-Statistic** | **Prob.** |
| ρ | −0.0059 | −0.3117 | 0.7556 | −0.0155 | −0.8097 | 0.4190 |
| $\beta_x^+$ | −0.2080 | −0.1470 | 0.8833 | −0.1949 | −0.3417 | 0.7329 |
| $\beta_x^-$ | 0.0074 | 0.0086 | 0.9932 | −0.0605 | −0.1368 | 0.8913 |
| $\beta_u^+$ | 7.6790 | 0.3161 | 0.7523 | 3.5930 | 0.8075 | 0.4203 |
| $\beta_u^-$ | 4.9486 | 0.3098 | 0.7570 | 2.3159 | 0.7668 | 0.4440 |
| $\pi_{x0}^+$ | 0.0298 | 2.8343 | 0.0050 | 0.0263 | 2.3960 | 0.0174 |
| $\pi_{x0}^-$ | 0.0315 | 4.6786 | 0.0000 | 0.0377 | 5.3614 | 0.0000 |

**Table 8.** *Cont.*

| | | | | | | |
|---|---|---|---|---|---|---|
| $\pi_{u0}^{+}$ | 0.1649 | 2.1591 | 0.0319 | - | - | - |
| $\pi_{u0}^{-}$ | - | - | - | - | - | - |
| **Cointegration tests** | **Stat. Value** | | | **Stat. Value** | | |
| F_PSS | 3.1019 | | | 5.3472 | | |
| t_BDM | −0.3117 | | | −0.8097 | | |
| **Symmetry restrictions *** | **Stat. Value** | | **Prob.** | **Stat. Value** | | **Prob.** |
| W_SRa_x | −2.7660 | | 0.0062 | −3.0494 | | 0.0026 |
| W_SRa_u | 2.0877 | | 0.0380 # | - | | - |
| W_SRi_x | −0.1115 | | 0.9113 | −0.7400 | | 0.4601 |
| W_SRi_u | 2.1591 | | 0.0319 # | - | | - |
| **Dependent Variable** | **L_Diesel** | | | **O_Diesel** | | |
| **Regressor** $x$ | **NYH_Diesel** | | | **NYH_Diesel** | | |
| **Model Estimated** | **NARDL (3, 3, 3, 0, 0)** | | | **NARDL (3, 2, 4, 7, 0)** | | |
| **Parameter** | **Value** | **t-Statistic** | **Prob.** | **Value** | **t-Statistic** | **Prob.** |
| $\rho$ | −0.0654 | −2.8151 | 0.0053 | −0.0393 | −1.5343 | 0.1264 |
| $\beta_{x}^{+}$ | 0.4366 | 6.5535 | 0.0000 | 0.3249 | 2.7693 | 0.0061 |
| $\beta_{x}^{-}$ | 0.3764 | 8.2960 | 0.0000 | 0.3310 | 4.5467 | 0.0000 |
| $\beta_{u}^{+}$ | 0.4809 | 1.5299 | 0.1274 | 1.0687 | 1.2534 | 0.2114 |
| $\beta_{u}^{-}$ | 0.7260 | 2.2759 | 0.0238 | 0.9641 | 1.5069 | 0.1333 |
| $\pi_{x0}^{+}$ | 0.1241 | 7.0029 | 0.0000 | 0.1121 | 6.2631 | 0.0000 |
| $\pi_{x0}^{-}$ | 0.0716 | 5.3219 | 0.0000 | 0.0787 | 5.7187 | 0.0000 |
| $\pi_{u0}^{+}$ | - | - | - | 0.0035 | 0.0506 | 0.9597 |
| $\pi_{u0}^{-}$ | - | - | - | - | - | - |
| **Cointegration tests** | **Stat. Value** | | | **Stat. Value** | | |
| F_PSS | 3.8007 | | | 3.2311 | | |
| t_BDM | −2.8151 | | | −1.5343 | | |
| **Symmetry restrictions *** | **Stat. Value** | | **Prob.** | **Stat. Value** | | **Prob.** |
| W_SRa_x | 0.6069 | | 0.5445 | 6.5847 | | 0.0017 |
| W_SRa_u | - | | - | −0.1498 | | 0.8810 * |
| W_SRi_x | 1.9710 | | 0.0499 | 0.6839 | | 0.4947 |
| W_SRi_u | - | | - | 0.0506 | | 0.9597 * |

Notes: F_PSS, t_BDM: F-statistics of F_PSS and t-statistics of t_BDM bound testing approach; the critical values for Case 3 unrestricted intercept and no trend; k = 4 and usual significance levels: F-stat. I(0), I(1); t-stat. I(0), I(1), 1%: 3.74; 5.06; 1%: −3.43; −4.6; 5%: 2.86; 4.01; 5%: −2.86; −3.99; 10%: 2.45; 3.52; 10%: −2.57; −3.66. * For symmetry restrictions, hypothesis values of a Wald test t-statistics are reported. # For the null hypothesis that sum/value of short run parameters is equal to 0.

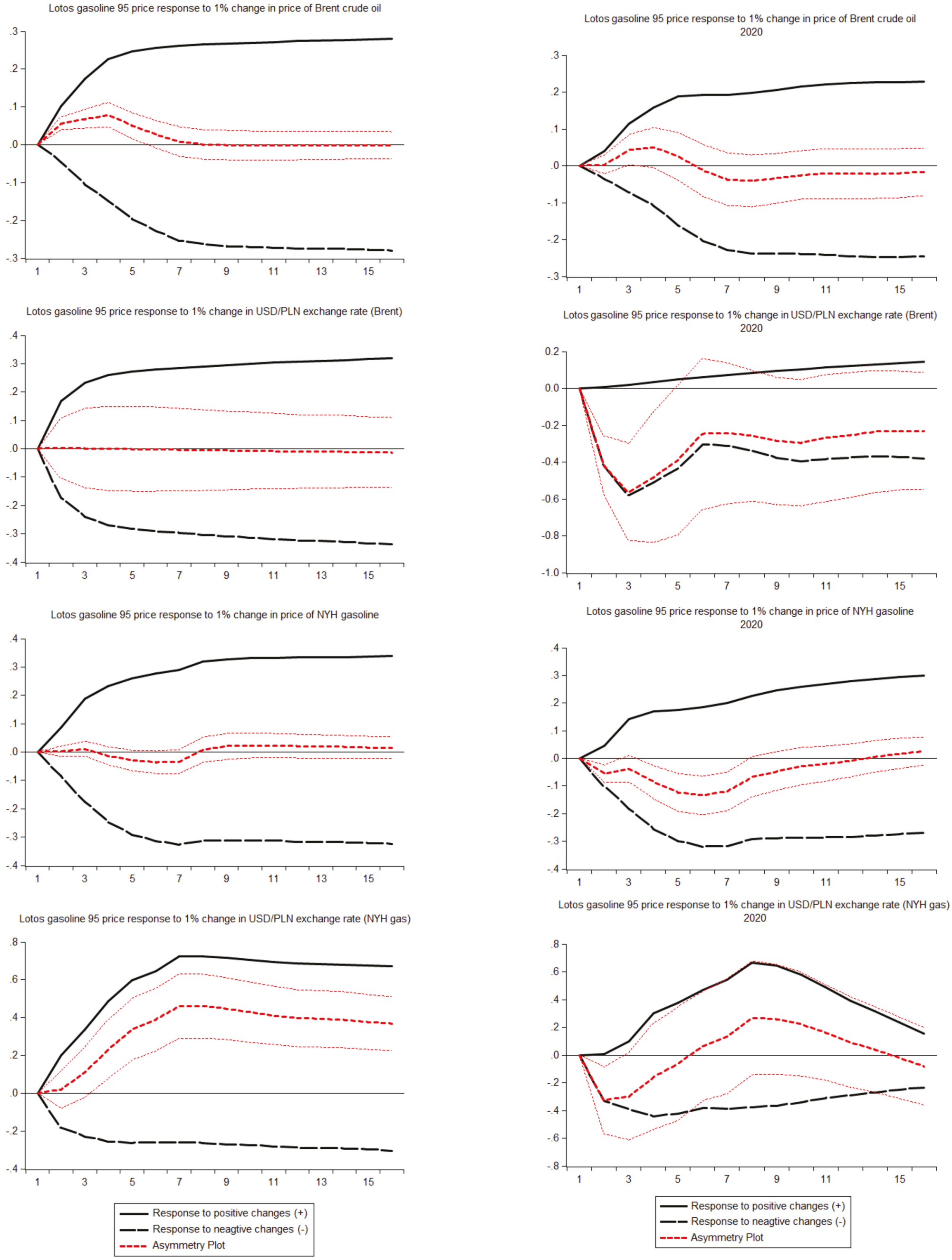
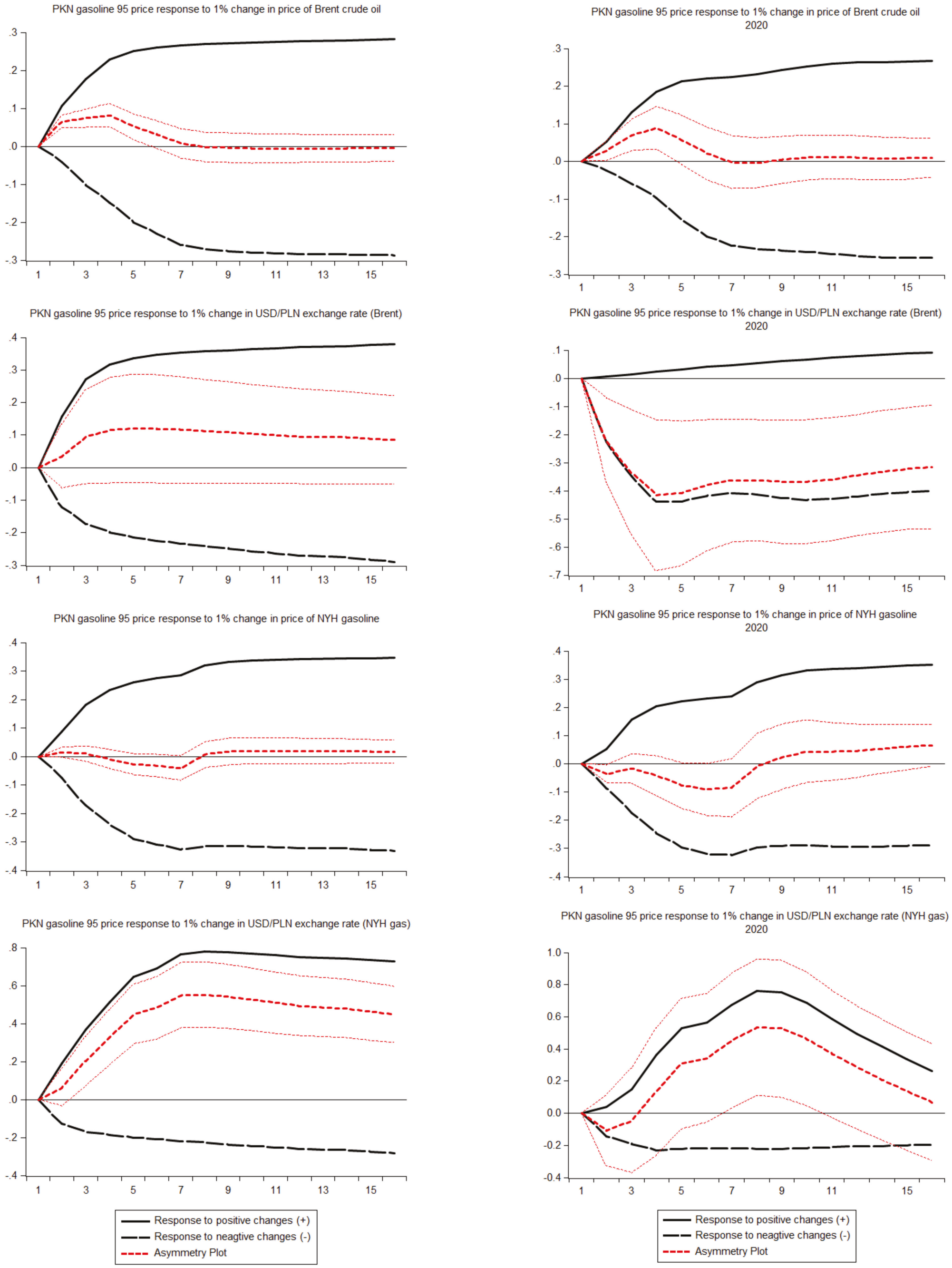
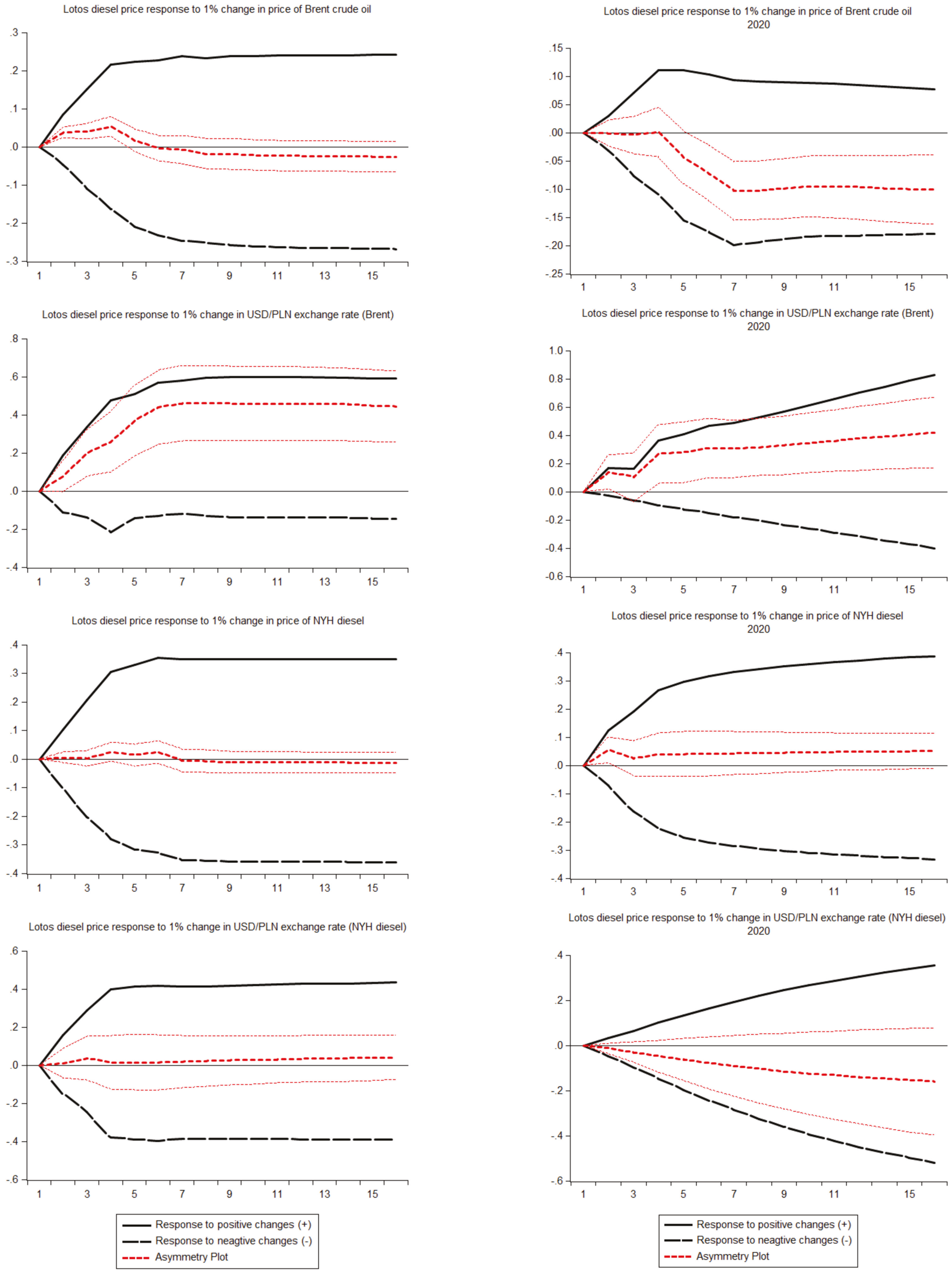


**Figure 9.** Dynamic multipliers for Lotos Gasoline 95 (**a**) whole sample; (**b**) year 2020.



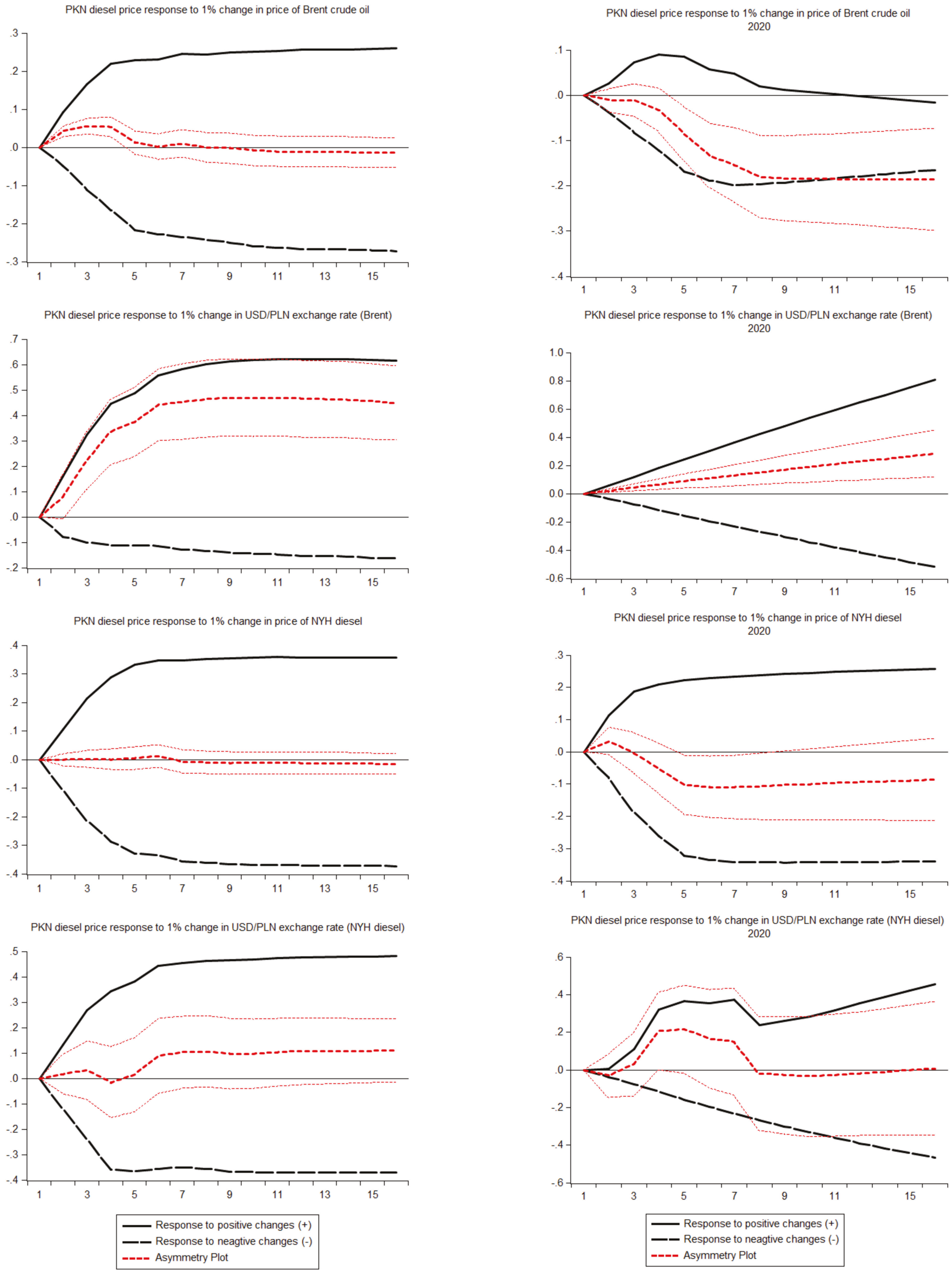
(**a**) (**b**)

**Figure 10.** Dynamic multipliers for PKN Orlen Gasoline 95 (**a**) whole sample; (**b**) year 2020.



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

**Figure 11.** Dynamic multipliers for Lotos Diesel (**a**) whole sample; (**b**) year 2020.



(**a**)

(**b**)

**Figure 12.** Dynamic multipliers for PKN Orlen Diesel (**a**) whole sample; (**b**) year 2020.

Analysis of Figures 9–12 starts the final step of stage two of the research, which is the comparison of APT in a whole sample and a subsample of the year 2020. In these figures, the multipliers for a specific type of product and player for the entire sample (panel a) and for the year 2020 (panel) are presented next to each other.

The analysis of the potential effects of the pandemic on APT is carried out simultaneously on the basis of Table 8 and Figures 9–12 and broken down by individual players to capture possible differences in price behavior. Only the differences in APT in the impact (next day effect) and short-run (few days) are assessed. In order to facilitate the evaluation of the research results, they are presented in tabular form. Table 9 summarizes the results.

**Table 9.** Comparison of the effects of impact and short-run APT—whole sample and 2020 subsample.

| Wholesale Price | Input | Whole Sample APT | The Year 2020 APT |
|---|---|---|---|
| L_Gas95 | Brent | Positive impact APT | No significant APT |
| L_Gas95 | USD/PLN (Brent) | No significant APT | Negative impact and additive APT |
| L_Gas95 | NYH_Gas | No significant APT | Negative impact and additive APT |
| L_Gas95 | USD/PLN (NYH_Gas) | Positive additive APT | Negative impact and additive APT |
| O_Gas95 | Brent | Positive impact APT | Positive impact APT |
| O_Gas95 | USD/PLN (Brent) | No significant APT | Negative impact APT |
| O_Gas95 | NYH_Gas | No significant APT | Negative impact APT |
| O_Gas95 | USD/PLN (NYH_Gas) | Positive additive APT | Positive additive APT |
| L_Diesel | Brent | Positive impact APT | Negative additive APT |
| L_Diesel | USD/PLN (Brent) | Positive additive APT | Positive impact and additive APT |
| L_Diesel | NYH_Diesel | No significant APT | Positive impact APT |
| L_Diesel | USD/PLN (NYH_Diesel) | No significant APT | No significant APT |
| O_Diesel | Brent | Positive impact APT | Negative additive APT |
| O_Diesel | USD/PLN (Brent) | Positive additive APT | No significant APT |
| O_Diesel | NYH_Diesel | No significant APT | Negative additive APT |
| O_Diesel | USD/PLN (NYH_Diesel) | No significant APT | No significant APT |

Note: The name of a second regressor is given in parenthesis for an exchange rate input.

Results contained in Table 9 show clearly that the outbreak of the pandemic did have an impact on a short-run APT and, hence, on competition in a wholesale fuel market in Poland. In 5 of the 16 analyzed cases, the positive asymmetry detected for the entire sample is replaced in 2020 by a negative asymmetry or no asymmetry. Moreover, in five cases, a negative asymmetry is detected in 2020, where there was no significant asymmetry in the entire sample. Only in three cases did positive APT remain unchanged, and in one case, positive impact asymmetry is detected in 2020 when there is no APT in a whole sample.

## 5. Discussion

The research shows that the first pandemic season of the year 2020 caused structural breaks, which were the most important in a sample period under consideration for almost all of the examined time series. Therefore, the question of the impact of the changes observed that year on the intensity of market competition is completely justified. The paper tries to answer that question on the basis of a well-established connection between positive APT and a possibility of anticompetitive behavior on a relevant market. The results of the research are obtained by an examination of APT in reference sample (whole sample period of 5 years) and comparison with the research done on the subsample of the year 2020. Individual price data of the two major players (with a cumulative market share of 90%) in a Polish market on a wholesale level of distribution are utilized.

Although this study has different goals than those previously encountered in the field of APT research, it is necessary to briefly discuss the results in the context of other studies of the relevant or similar market. In [18], the authors attempted to determine whether an APT can be identified in the Polish wholesale gasoline and diesel motor oil price data from the dominant player PKN Orlen. Using weekly data, they found that the wholesale price response to crude oil price increase was faster than the response to crude oil price decrease in every case. Wholesale price's response to the increase in the price of regular gasoline was found more intensive than to the decrease with a distinct maximum in the second week. The period of full adjustment was asymmetric in total length—in the case of upward movement of regular gasoline price, it lasted approximately three weeks. In the case of downward change, it lasted about five weeks. The study [30], encompassing the period 2006–2016, revealed significant short-run asymmetries in the transmission of all downstream price determinants and showed that the USD/PLN exchange rate was the main driver underlying a positive asymmetry in the wholesale prices' paths. In that work, dynamic price adjustment paths for the major players were also compared and common patterns detected (this kind of analysis was not a subject of the current paper). That suggests a strong possibility of parallel pricing, which supports the claim about competitions distortions on the market. The current examination of a whole sample (2015–2020) showed that positive long-term APT in a reference sample took place in a case of exchange rate pass-through. It means that, in the long horizon, reaction of wholesale prices to a depreciation of Polish national currency is significantly stronger than to appreciation. Figures 7 and 8 confirm a strong, positively asymmetric, long-term impact of USD/PLN exchange rate in the case of Lotos and PKN when Brent price is the second regressor in a model and moderate positive asymmetry in when NYH_Diesel price enters a model. It confirms the results of [30] and is in line with [46], where authors showed that Korean gasoline prices are more sensitive to exchange rate depreciations than to appreciations. The author's finding seems to confirm very clearly, using individual major players' price series, that positive asymmetry in a national currency exchange rate versus USD pass-through is a common pricing practice. This finding is coherent with the conclusion in [47] that fluctuation of an exchange rate is "less clearly perceived" and therefore may encourage players to use "rocket and feathers" pricing. It is further consistent with empirical results from [26]. The results of the study also confirm the existence of IPP price creation schema, as models with benchmarks (NYH_Gas and NYH_Diesel quotations) are slightly better fitted in terms of the Akaike criterion.

For the realization of the study's main objective, most important was the study of the reaction asymmetry in a short horizon. There are at least three reasons why short-run asymmetry is more important: At first, the comparative analysis with the subsample of 2020 was justified only for short-run asymmetry measures. Second, the wholesale price levels are announced publicly daily, which encourages exploring short-term price behavior. At third, using high-frequency data and concentrating on short-run pricing policy, one can eliminate justification of positive APT proposed in [13], saying that inventory policy may result in differences in pass-through. The author noticed that refineries might find it difficult to increase production in response to cost decreases, whereas the possibility to cut output through the accumulation of inventories can be implemented immediately. This mechanism, however, includes rather mid- or long-term reactions to change in demand–cost condition, not day-by-day pricing reactions according to some IPP schema.

In the present research, a significant positive impact asymmetric effect is detected analyzing a whole sample in a case of transmission of Brent price to Gasoline 95 price and transmission of Brent price to the wholesale diesel oil price. Additive short-run asymmetry is confirmed in the case of Gasoline 95 price and USD/PLN exchange rate (with NYH_Gasoline price as a second regressor) and in the case of wholesale diesel oil price and USD/PLN exchange rate (with Brent price as a second regressor). These results are in line with the results in [30].

The most important result of the study is the comparison of the 2020 subsample to the entire sample in terms of the presence of short-run APT. After positively verifying the hypothesis that significant structural changes in the analyzed processes (all except USD_PLN) were observed in 2020, it became reasonable to ask whether such turbulences, caused undoubtedly by the COVID-19 pandemic, contributed to the weakening or strengthening of competition on the market under examination. Assuming that positive asymmetry of price reduces end-user's welfare and could be connected with abuse of market power of the players, the study revealed (Table 9) that rapid changes in the economic environment observed at the beginning of the COVID-19 pandemic did mitigate this potential abuse of market power. The conclusion from this study could be stated as an implication: a significant positive APT had been observed in a history of a market; then, in the economic environment, major perturbations occurred, as a consequence of which the positive asymmetry of the reaction was largely eliminated. The word "consequence" should be treated with caution in this context, meaning correlative rather than causative effect. However, it must be stressed that the author's results showed the positive asymmetry is not the necessary element of price creation mechanism on the wholesale market, and, in some conditions (demand shocks, increased uncertainty in running a core business, global market instability), this positive APT could almost vanish. It implies that the market became more competitive. This conclusion is somehow similar to results presented in [29], where gasoline pricing in Hungary was investigated. At the wholesale level of the Hungarian market, there exists the dominant player MOL. The pricing practices of that player were investigated by Hungarian Competition Authority. During its investigation, the Hungarian Competition Authority scrutinized the market behavior of MOL under E.U. and Hungarian legal provisions on the prohibition of abuse of dominant position. Authors of [29] detected positive short-run APT in wholesale pricing of MOL in a period before the Authority's investigation. In a period directly after the conclusion of the investigation, the company's pricing on the wholesale market becomes more symmetric. Similar to this paper's results, it means that "rocket and feathers" pricing patterns are not an intrinsic property of the liquid fuel pricing mechanism and may be eliminated by external factors.

## 6. Conclusions

The empirical investigation of asymmetric pass-through in the Polish wholesale fuel market reveals a significant change in the short-run pass trough of inputs to wholesale prices in the first year of the COVID-19 pandemic. These changes may signal that players could not use market power, and the market became more competitive. Moreover, it means that downward sticky pricing patterns are not necessarily determined by the technological or business properties of the market but are maybe dependent on the deliberate pricing policy of the players. In the author's opinion, the results confirm a positive relationship between market power and pass-through asymmetry. From the policy perspective, there are two implications that are important. At first, as direct evidence of market power abuse is hard to obtain, such indirect markers as APT should be used to monitor the firms' behavior. Second, monitoring should be done frequently, especially whenever there are significant changes in the structure of a market or macroeconomic environment. This is especially true for the Polish refining industry at the moment, as there is the merger of PKN and LOTOS planned. The postmerger pricing behavior of the dominant player should be a subject of the subsequent study. This study should account for the retail level of the market as Orlen and Lotos are owners of about 30% of filling stations in Poland. The following open questions to consider are, "how persistent the players' change in behavior will be" and "what can be a theoretical mechanism generating such a change". The answers to these questions should be the subject of further studies, as well.

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# Analysis of Spatial Effects in the Relationship between $CO_2$ Emissions and Renewable Energy Consumption in the Context of Economic Growth

**Mateusz Jankiewicz * and Elżbieta Szulc**

Faculty of Economic Sciences and Management, Nicolaus Copernicus University, 87-100 Toruń, Poland; eszulc@umk.pl
* Correspondence: m.jankiewicz@umk.pl

**Abstract:** The paper presents a spatial approach to the analysis of the relationship between air pollution, economic growth, and renewable energy consumption. The economic growth of every country is based on the energy consumption that leads to an increase in national productivity. Using renewable energy is very important for the environmental protection and security of the earth's resources. Promoting environmentally friendly operations increases awareness of sustainable development, which is currently a major concern of state governments. In this study, we explored the influence of economic growth and the share of renewable energy out of total energy consumption on $CO_2$ emissions. The study was based on the classical environmental Kuznets curve (EKC) and enriched with the spatial dependencies. In particular, we determined the spatial spillovers in the form of the indirect effects of changes in renewable energy consumption of a specific country on the $CO_2$ emissions of neighboring countries. A neighborhood in this study was defined by ecological development similarity. The neighborhood matrix was constructed based on the values of the ecological footprint measure. We used the spatio-temporal Durbin model, with which the indirect effects were determined in relation to the spatially lagged renewable energy consumption. The results of our study also show the strength of the effects caused by imitating actions from the states with high levels of environmental protection. The study was conducted using data for 75 selected countries from the period of 2013–2019. Cumulative spatial and spatio-temporal effects allowed us to determine (1) the countries with the greatest impact on others and (2) the countries that follow the leading ones.

**Keywords:** economic growth; environmental Kuznets curve; renewable energy; spatio-temporal Durbin model; spatial spillovers

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## 1. Introduction

Caring for the natural environment should be an integral part of the economic development policy of each country. Unfortunately, state authorities have devoted too little attention to this issue so far, and the degradation of the environment caused by the over-exploitation of natural resources and an excessive desire to become wealthy has been extreme. High levels of consumption of non-renewable energy sources and environmental pollution cause an increase in greenhouse gas emissions, mainly carbon dioxide ($CO_2$). Increasingly more emissions have a negative effect on the composition of the atmosphere and global climate [1].

To protect nature, the concept of sustainable development was created, the goal of which is economic development with consideration for the well-being of the present and future generations [2]. The most popular definition of sustainable development is the one formulated by the Brundtland Commission, which describes it as meeting the needs of the present generation without limiting the possibilities of meeting them for future generations.

In particular, sustainable development addresses the problem of reducing the consumption of limited resources of the Earth as well as reducing environmental pollution [3].

The relationship between economic growth and the amount of environmental degradation is usually described by the environmental Kuznets curve (EKC) [4–7]. In the basic version, the curve expresses the dependence between these processes in the form of an inverted "U" shape, that is, an increase in the level of income of states leads to ever greater environmental degradation, and then, when wealth reaches a certain level, the relationship is reversed. In addition to economic development, renewable energy consumption also has an impact on the natural environment. Increases in the levels of renewable energy consumption, as well as its share of total energy consumption, promote environmental protection [8]. The influence of other factors on the state of the natural environment has also been considered in the literature, for example, the level of trade openness, fossil fuel energy consumption, and the degree of urbanization or population density [9–14].

In many countries, an increase in the share of energy from renewable sources out of the total energy consumption has been observed. Moreover, the actions of some countries in this direction have influenced changes to the structure of energy consumption in others. The improvement of environmental conditions resulting from the increase in using renewable energy sources causes an imitation effect.

The aim of this study was to explore the influence of economic growth and the share of renewable energy out of the total energy consumption on the $CO_2$ emissions for 75 selected countries of the world in the period of 2013–2019. Our concern, in particular, was the impact of changes in renewable energy consumption in a specific country on the air pollution in neighboring countries (the so-called spatial spillovers). In the investigation, we used the spatio-temporal Durbin model (STDM) as a re-specification of the equation based on the concept of the classical environmental Kuznets curve (EKC) and determined the indirect effects in relation to spatially lagged renewable energy consumption. A neighborhood in this study was defined by ecological development similarity. The neighborhood matrix was constructed based on the values of the ecological footprint measure.

The results of our study also show the strength of the effect caused by imitating actions from states with high levels of environmental protection. In particular, the study allowed us to determine the countries with the greatest impact on others as well as the countries that follow the leading ones.

In this study, the following research hypotheses were formulated: (1) The neighborhood, in the sense of ecological similarity, is significant for the analysis of dependence between $CO_2$ emissions, economic growth, and the consumption of energy from renewable sources. (2) The countries characterized by a high share of energy from renewable sources out of the total energy consumption have less of an impact on the state of the natural environment in other countries than those wealthier but with a lower use of renewable energy.

The paper is organized as follows. In Section 2, we present a review of the literature related to the subject of our research. Section 3 presents a discussion on the tools and models that were used in the empirical analysis performed. The data are discussed in Section 4, as are the spatial distributions of the variables considered. Section 5 contains the details of the empirical results, and Section 6 summarizes the main results and presents the general conclusions. Finally, suggestions for further studies are presented.

## 2. Literature Review

The relationship between energy consumption and the emissions of pollutants has been analyzed by many researchers. Issues related to the effects of increasing total energy consumption as well as increasing the share of energy consumption from renewable sources have been discussed. These studies show that increases in energy consumption result in increases in the emissions of pollutants. Özokcu and Özdemir [15] consider this relationship on the basis of the cubic Kuznets curve, which was estimated for two groups of countries—26 highly developed OECD countries and 52 developing ones. Other authors, such as Aydin and Esen [16], Piłatowska and Włodarczyk [17], Presno et al. [18], and

Yavuz and Yilanci [19] have also pointed out the negative impact of increased consumption energy on the environment. They used a nonlinear approach based on threshold analysis in their studies.

Studies that deal with the impact of renewable energy consumption on the environmental situation can be divided into two groups. The first group consists of studies in which the consumption of energy per capita was considered [20–23]; the second consists of those that considered the share of energy consumption from renewable sources [24]. In the work of Zoundi [25], 25 countries in the period of 1980–2012 were analyzed using the concept of co-integration. The same approach was presented by Zambrano-Monserrate et al. [26] with a discussion on the relationship in Brazil, by Jebli and Youssef [27], who considered the link between energy and the environment in Tunisia, as well as by Sahbi and Shahbaz [28], who focused on the countries of central-east and northern Africa. Similar analyses can be found in the works of Gill et al. [29], Sinha et al. [30], Dogan and Seker [31], and Bölük and Mert [32].

Despite the differences in the approaches to expressing energy consumption in the models used, the general results are the same. They show a positive effect of the increase in both the level and share of renewable energy consumption on the natural environment.

The research studies cited above were based on the environmental Kuznets curve, by which the role of the explanatory variable is played by an appropriate measure of economic growth. The models used were enriched with various additional explanatory variables. In a few works in this field, one can find a reference to the spatial connections between countries/regions. For example, Güçlü [33] incorporates spatial links into the Kuznets curve by analyzing the relationship between economic growth and environmental degradation for Turkish NUTS-3 regions in the years 2008–2013. The spatial environmental Kuznets curve was also used in the works by the following: Tan [34], Donfouet et al. [35], McPherson and Nieswiadomy [36], Burnett and Bergstrom [37], and Tevie et al. [38]. These researchers used simple spatial models, such as the spatial autoregressive model (SAR) and the spatial error model (SEM). In addition, Kang et al. [39], Wang et al. [40], Fong et al. [41], and Li et al. [42] used the spatial Durbin model (SDM). In their study, Li et al. [42] additionally determined the spatial direct and indirect effects resulting from changes in all explanatory variables included in the model.

In all of the above-mentioned studies, the significance of spatial connections for the relationship under investigation was indicated, and the authors formulated conclusions about the similarity of the environmental situation in the countries directly adjacent to each other. It should be emphasized that in these works, only the first-order neighborhood according to the common border criterion was considered.

## 3. Methodology

In the investigation, we used the models for pooled time series and cross-sectional data (TSCS), with particular reference to the spatial model. The basic space–time model was chosen, enriched only by spatial components, without any fixed or random effects that are characteristic of panel models. In this approach, we studied the heterogeneity of economies using the spatial trend, but for $CO_2$ emissions, it turned out to be statistically insignificant. We also considered the validity of using dynamic spatial models as well as dynamic spatial panel data models; however, given the insignificance of spatial effects and other diagnostics of these models, we decided to forgo them in further analysis. The justification for the use of the spatial models, that is, the models containing spatial lags of dependent or/and explanatory variables, comes from the specific interpretation of the parameters of these models, which measured the impact of changes in the variable values in neighboring observations/regions (i.e., $y_j$, $x_{kj}$) on the dependent variable observation $y_i$ [43] (p. 34).

In classical terms, based on the concept of the environmental Kuznets curve in the variant of the quadratic function, the model describing the relationship between $CO_2$

emissions and GDP per capita as well as the share of energy consumption from renewable sources out of the total energy consumption takes the following form:

$$\ln(CO_2)_{i,t} = \beta_0 + \beta_1 \ln(GDP)_{i,t} + \beta_2(\ln(GDP))^2_{i,t} + \beta_3 \ln(RE)_{i,t} + \varepsilon_{i,t}, \tag{1}$$

where $CO_2$ denotes the carbon dioxide emissions per capita, $GDP$ stands for the value of gross domestic product per capita, and $RE$ is the share of renewable energy consumption. In turn, $\beta_0$, $\beta_1$, $\beta_2$, and $\beta_3$ are the structural parameters of the model, and $\varepsilon$ is its random component. All the variables have been expressed in logarithms to stabilize the variance. Depending on the sign of the parameters $\beta_1$ and $\beta_2$, the Kuznets curve takes a different shape. Depending on their values, we explored the following situations:

(i) No relationship between GDP and $CO_2$ emissions ($\beta_1 = 0$ and $\beta_2 = 0$);
(ii) Linear relationship between GDP and $CO_2$ emissions ($\beta_1 \neq 0$ and $\beta_2 = 0$);
(iii) Inverse U-shaped relationship between GDP and $CO_2$ emissions ($\beta_1 > 0$ and $\beta_2 < 0$)—the classical Kuznets curve;
(iv) U-shaped relationship between GDP and $CO_2$ emissions ($\beta_1 < 0$ and $\beta_2 > 0$).

A turning point can be determined for the last two of the above-mentioned relationships, indicating the level of GDP per capita at which $CO_2$ emissions reach the maximum value (iii) or the minimum value (iv). It is determined according to the following formula:

$$GDP_{TP} = exp\left(-\frac{\beta_1}{2\beta_2}\right), \ \beta_2 \neq 0 \tag{2}$$

In order to verify the validity of introducing spatial connections to our analysis, first for all the variables considered in every year the values of Moran's $I$ have been calculated, using the following formula [44,45]:

$$I = \frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}} \cdot \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}[y_i - \overline{y}]\left[y_j - \overline{y}\right]}{\frac{1}{n}\sum_{i=1}^{n}[y_i - \overline{y}]^2} = \frac{n}{S_0} \cdot \frac{\mathbf{z}^T\mathbf{W}\mathbf{z}}{\mathbf{z}^T\mathbf{z}}, \tag{3}$$

where $y_i$ denotes an observed value of the phenomenon in the region $i$, $\mathbf{z}$ means a column vector with elements $z_i = y_i - \overline{y}$, $S_0 = \sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}$ is a sum of the corresponding elements of the weights' matrix $\mathbf{W}$, and $n$ stands for the number of regions. The matrix $\mathbf{W}$ of spatial connections in our study was defined based on the environmental development similarity of the countries.

The **W** matrix was derived from the 2017 ecological footprint value because this was the year for which the latest data was available. We decided to use the connectivity matrix constant in time due to the fact that in the period of 2013–2017, for the countries under consideration, there have been only minor changes in the ecological footprint values. Therefore, we concluded that this regularity was maintained in the following years. Thus, for the entire period of our study, the neighborhood structure remained unchanged.

The choice to use the ecological footprint as a criterion for determining the neighborhood of countries was dictated by its close relationship with the theory of sustainable development, in which special attention is paid to natural environmental protection. In addition, the level of $CO_2$ emissions, which was the subject of this study, is one of the main aspects of environmental pollution.

To construct the matrix **W,** we started by determining the distance between pairs of countries according to the following formula:

$$d_{ij} = \left|EF_i - EF_j\right|, \tag{4}$$

where $EF_i$ and $EF_j$ are indicators of the ecological footprint for countries $i$th and $j$th, respectively.

Then, the borderline level $g$ of similarity between the countries was determined as the fifteenth percentile of all distances. This avoided the problem of excessive density in the neighborhood matrix. A matrix too dense would blur the actual relations between neighbors.

Subsequently, the non-zero elements of the distance matrix **D** were inverted as follows:

$$d^{*}_{ij} = \begin{cases} \frac{1}{d_{ij}}, & i \neq j \wedge d_{ij} < g \\ 0, & i = j \vee d_{ij} > g \end{cases} \tag{5}$$

and row-standardized to one. Finally, a block matrix of cross-sectional and temporal links between various countries in the field of environmental development was created.

In order to confirm the validity of introducing the spatial effects to model (1) the Lagrange multiplier tests (LM), in the basic and robust versions, were used. Thus, the following spatio-temporal Durbin model specification was considered:

$$\begin{aligned} \ln(CO_2)_{i,t} = {} & \rho \textstyle\sum_{i \neq j} w_{ij,t} \ln(CO_2)_{j,t} + \alpha + \beta_1 \ln(GDP)_{i,t} + \beta_2 (\ln(GDP))^2_{i,t} + \beta_3 \ln(RE)_{i,t} \\ & + \theta \textstyle\sum_{i \neq j} w_{ij,t} \ln(RE)_{j,t} + \varepsilon_{i,t}. \end{aligned} \tag{6}$$

The models such as (6), thanks to the inclusion of spatial lags of the dependent variable and independent variables, allowed us to quantify the magnitude of the so-called direct and indirect effects in the short term [46] (p. 11). In this study, we were primarily interested in the indirect effects that were used to test the hypothesis whether in the area of the countries considered in terms of $CO_2$ emissions the spatial spillovers exist.

To see the way in which the mentioned effects were obtained, the general expression of the non-dynamic model was transformed into Equation (7)

$$\mathbf{Y}_{\mathrm{t}} = \rho \mathbf{W} \mathbf{Y}_{\mathrm{t}} + \alpha \boldsymbol{\iota}_N + \mathbf{X}_{\mathrm{t}} \boldsymbol{\beta} + \mathbf{W} \mathbf{X}_{\mathrm{t}} \boldsymbol{\theta} + \boldsymbol{\varepsilon}_{\mathrm{t}}. \tag{7}$$

By transforming the equation to the form the following:

$$\mathbf{Y}_{\mathrm{t}} = (\mathbf{I} - \rho \mathbf{W})^{-1} \alpha \boldsymbol{\iota}_N + (\mathbf{I} - \rho \mathbf{W})^{-1} (\mathbf{X}_{\mathrm{t}} \boldsymbol{\beta} + \mathbf{W} \mathbf{X}_{\mathrm{t}} \boldsymbol{\theta}) + (\mathbf{I} - \rho \mathbf{W})^{-1} \boldsymbol{\varepsilon}_{\mathrm{t}} \tag{8}$$

and excluding from the matrix $\mathbf{X}_t$ the vector regarding the variable $X_k$, that is, $\mathbf{X}_{kt}$, the following equation was obtained:

$$\mathbf{Y}_{\mathrm{t}} = (\mathbf{I} - \rho \mathbf{W})^{-1} \alpha \boldsymbol{\iota}_N + (\mathbf{I} - \rho \mathbf{W})^{-1} \left( \dot{\mathbf{X}}_{\mathrm{t}} \boldsymbol{\beta} + \mathbf{W} \dot{\mathbf{X}}_{\mathrm{t}} \boldsymbol{\theta} \right) + (\mathbf{I} - \rho \mathbf{W})^{-1} (\beta_k \mathbf{I}_N + \theta_k \mathbf{W}) \mathbf{X}_{kt} + (\mathbf{I} - \rho \mathbf{W})^{-1} \boldsymbol{\varepsilon}_{\mathrm{t}}, \tag{9}$$

where $\dot{\mathbf{X}}_{\mathrm{t}}$ stands for the matrix from which the $\mathbf{X}_{kt}$ has been removed.

The expression $(\mathbf{I} - \rho \mathbf{W})^{-1} (\beta_k \mathbf{I}_N + \theta_k \mathbf{W})$ allowed us to determine the direct and indirect effects of the *k*th explanatory variable $X_k$ on the dependent variable $Y$. In our study, the indirect effects were determined in relation to the share of energy from renewable sources out of the total energy consumption in the neighboring regions.

The short-term effects were designated as the matrix of partial derivatives of Y with respect to the *k*th explanatory variable of **X** in spatial unit 1 up to unit N at a particular point in time, as shown in the following equation:

$$\left[ \frac{\partial \mathrm{Y}}{\partial x_{1k}} \cdots \frac{\partial \mathrm{Y}}{\partial x_{Nk}} \right] = (\mathbf{I} - \rho \mathbf{W})^{-1} (\beta_k \mathbf{I}_N + \theta_k \mathbf{W}), \tag{10}$$

which denotes the effect of a change of a particular explanatory variable in a particular spatial unit on the dependent variable of all other units in the short term. Similarly, the long-term effects could be determined from the dynamic model, which takes into account the time delays of the dependent and/or independent variables [46] (p. 11).

The diagonal elements of the matrix $(\mathbf{I} - \rho \mathbf{W})^{-1} (\beta_k \mathbf{I}_N + \theta_k \mathbf{W})$ define the direct impacts of change in *i*th observation $x_k$ (denoted by $x_{ik}$) on $y_i$, that is, on the values of the dependent variable in the same *i*th spatial unit. The average of the sum across the *i*th row of this matrix represents the average impact on the individual observation $y_i$ resulting from changing the *k*th explanatory variable by the amount across all observations—the average impact to an observation. In turn, the average of the sum in the $j$th column of the matrix yields the average impact over all $y_i$ observations from changing the $k$th explanatory variable by an amount in the $j$th observation—the average impact from an observation [43] (p. 37). To sum up, indirect effects as spatial spillovers were identified based on the non-diagonal elements of the matrix considered.

## 4. Data

The data used in the analysis came from three databases. First, the Our World in Data website (https://ourworldindata.org (accessed on 17 May 2021)) provided the data on $CO_2$ emissions per capita $(CO_2)$ and the share of energy from renewable sources out of the total energy consumption $(RE)$. Second, the World Bank (https://data.worldbank.org (accessed on 17 May 2021)) provided the GDP per capita $(GDP)$. Third, the Global Footprint Network (https://data.footprintnetwork.org (accessed on 17 May 2021)) provided the ecological footprint by countries used to create a neighborhood matrix. All calculations and drawings were made in the program R-CRAN (version 4.0.2).

Figure 1 presents the spatial distributions of carbon dioxide per capita in 2013 and 2019. In both years, the $CO_2$ values were distributed almost identically in the studied area. The lowest $CO_2$ emission values can be observed in the countries of South America, the southern part of Asia (on the Indian Peninsula and Indonesia), as well as in Southern Europe and the countries of Northern Africa. The highest values can be observed in North America (the US and Canada), northern and eastern parts of Asia, in Arab countries, as well as in Australia and New Zealand. Mostly, they are the relatively high development countries, which have a great impact on the world economy.

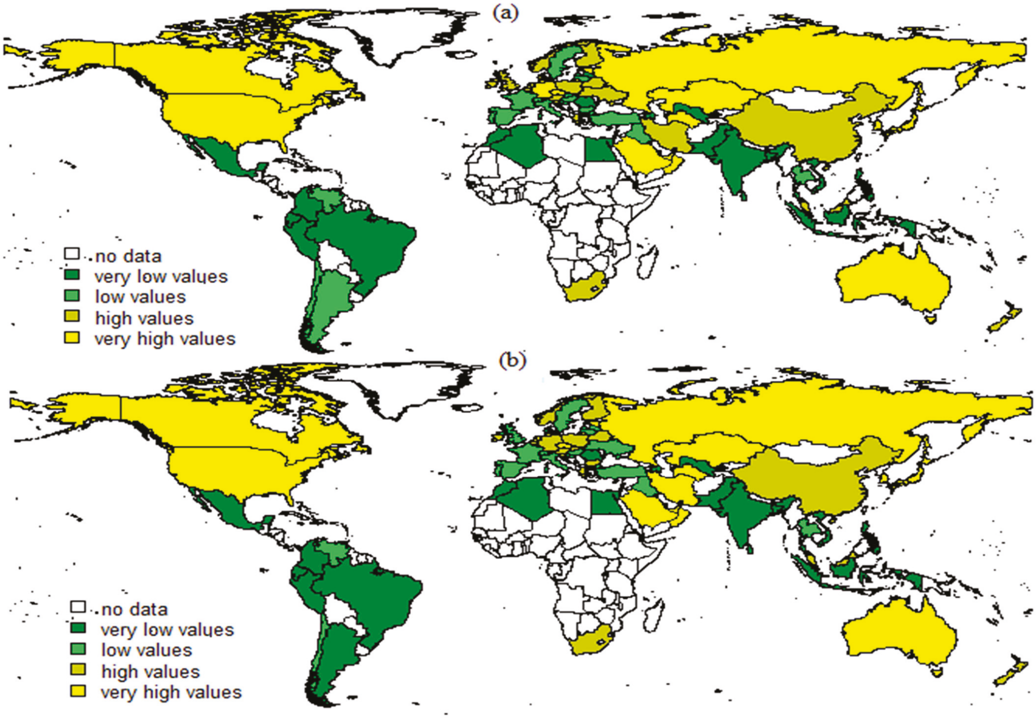

**Figure 1.** Spatial distribution of the per capita $CO_2$ emissions in (**a**) 2013 and (**b**) 2019.

Figure 2 shows the spatial distributions of the share of energy from renewable sources out of the total energy consumption in 2013 and 2019. The greatest share of renewable energy consumption characterized countries of both North and South America (excluding Mexico), most European countries (without Central and Eastern Europe), and China, Australia, and New Zealand. The lowest values were observed in Africa and in North and West Asia. By comparing the distributions of the variables under consideration in Figures 1 and 2, it can be assumed that there is an inverse relationship between renewable energy consumption and $CO_2$ emissions in the areas of the surveyed countries. An exception may be highly developed countries, such as Canada, the United States, Australia, and China (in these countries, both variables have relatively high values), as well as less developed countries, such as Egypt, Morocco, and Algeria (in these countries, both variables are characterized by relatively low values).

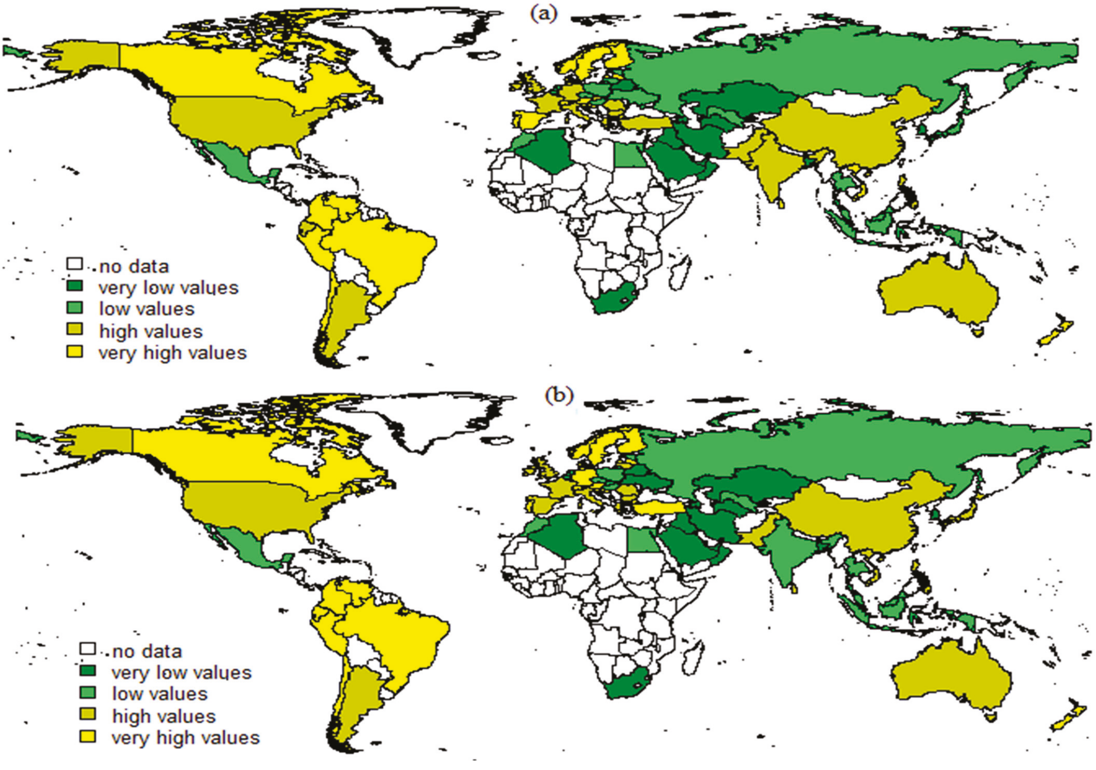

**Figure 2.** Spatial distribution of the share of energy from renewable sources in total energy consumption in (**a**) 2013 and (**b**) 2019.

## 5. Empirical Results

### *5.1. Spatial Autocorrelation*

The empirical analysis began with testing the spatial autocorrelation for the variables under consideration with established connections between countries based on the level of environmental development (ecological footprint). The level of significance was 0.05. Table 1 presents the values of Moran statistic (Moran's *I*) and the assessment of its statistical significance in the years 2013–2019.

**Table 1.** Spatial autocorrelation tests for the variables considered in years 2013–2019.

| Year | $l\_CO_2$ | | l_RE | | l_GDP | |
|---|---|---|---|---|---|---|
| | Moran's *I* | *p*-Value | Moran's *I* | *p*-Value | Moran's *I* | *p*-Value |
| 2013 | 0.6733 | 0.0000 | −0.0747 | 0.2499 | 0.6298 | 0.0000 |
| 2014 | 0.6554 | 0.0000 | −0.0749 | 0.2486 | 0.6316 | 0.0000 |
| 2015 | 0.6563 | 0.0000 | −0.0719 | 0.2602 | 0.6282 | 0.0000 |
| 2016 | 0.6624 | 0.0000 | −0.0840 | 0.2184 | 0.6270 | 0.0000 |
| 2017 | 0.6659 | 0.0000 | −0.0885 | 0.2027 | 0.6282 | 0.0000 |
| 2018 | 0.6587 | 0.0000 | −0.0801 | 0.2303 | 0.6295 | 0.0000 |
| 2019 | 0.6484 | 0.0000 | −0.0810 | 0.2257 | 0.6291 | 0.0000 |

Positive and statistically significant values of the spatial autocorrelation coefficient for the per capita carbon dioxide emission and the per capita GDP (expressed in natural logarithms and marked as $l\_CO_2$ and l_GDP, respectively) have been recorded for all the years. The positive spatial autocorrelation indicates similarity, in terms of $CO_2$ emissions as well as GDP, of countries with a similar level of environmental protection. The values of the Moran's *I* prove the strong links between countries with comparable levels of environmental development.

The situation is different in the case of the share of energy from renewable sources in total energy consumption (l_RE). The Moran statistics are statistically insignificant and indicate the lack of links, in this respect, between "neighboring" countries.

The results of spatial autocorrelation testing for the considered variables were the initial motivation for incorporating the spatial effects into the model of $CO_2$ emissions relative to GDP and renewable energy consumption using the Kuznets curve additionally.

### *5.2. Empirical Models*

First, the space–time model (LM_pooled) in the form of Equation (1) was estimated and verified. The results obtained are presented in Table 2. The *p*-values for the parameters $\beta_1$ and $\beta_2$ indicate the significance of the impact of GDP per capita as well as its squares on $CO_2$ emissions. Moreover, the signs of the parameters ($\beta_1 > 0$ and $\beta_2 < 0$) allow us to conclude an inverse U-shaped relationship between GDP and $CO_2$ emissions. Thus, the considered relationship for selected countries of the world takes a classic shape of the Kuznets curve.

**Table 2.** The results of estimation and verification of the TSCS model for the squared Kuznets curve.

| Parameter | Estimate | Std. Error | t-Statistic | *p*-Value |
|---|---|---|---|---|
| $\alpha$ | −12.5434 | 1.1672 | −10.7470 | 0.0000 |
| $\beta_1$ | 2.5715 | 0.2500 | 10.2840 | 0.0000 |
| $\beta_2$ | −0.1085 | 0.0133 | −8.1750 | 0.0000 |
| $\beta_3$ | −0.1720 | 0.0081 | −21.2050 | 0.0000 |
| $GDP_{TP}$ | 139,658.40 | | | |
| $R^2$ | 0.7472 | | | |
| $F$ | 513.4000 (0.0000) | | | |
| $JB$ | 5.3284 (0.0697) | | | |
| Moran test | −0.0483 (0.0953) | | | |
| $LM$ tests | $LM_{SE}$: 2.0105 (0.1562)<br>$LM_{SAR}$: 12.2105 (0.0005)<br>$RLM_{SE}$: 13.4241 (0.0002)<br>$RLM_{SAR}$: 23.6242 (0.0000) | | | |

Note: *JB* means the Jarque'a–Bery test (for normality of the distribution of residuals); figures in brackets refer to the *p*-values.

The negative and statistically significant value of the $\beta_3$ parameter indicates an inverse relationship between renewable energy consumption and $CO_2$ emissions. Thus, an increase in the share of energy consumption from renewable sources in individual countries leads to improvement in their environmental situation. Based on the estimated Kuznets curve, its turning point was determined, amounting to $139,658.40 per capita. Taking into account the values of GDP per capita, it should be stated that none of the countries reached this ceiling during the period considered. Therefore, all the countries are on the path leading to the turning point, which may indicate a greater focus on economic development than on care for the natural environment. Figure 3 shows the shape of the Kuznets curve determined on the basis of model (1).

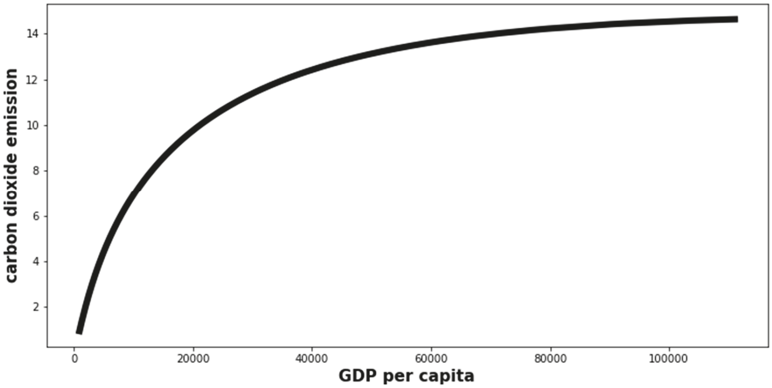

**Figure 3.** The shape of the Kuznets curve for the considered countries in the period of 2013–2019 (determined based on model (1)).

The Lagrange multiplier tests (the basic versions—$LM_{SE}$, $LM_{SAR}$, and the robust ones—$RLM_{SE}$, $RLM_{SAR}$) indicate the legitimacy of supplementing model (1) with spatial connections between the countries. Therefore, the spatio-temporal Durbin model was specified (see Equation (6)). The results of estimation and verification of the model are reported in Table 3.

**Table 3.** The results of estimation and verification of the spatio-temporal Durbin model for the squared Kuznets curve.

| Parameter | Estimate | Std. Error | z-Statistic | *p*-Value |
|---|---|---|---|---|
| $\alpha$ | −13.1261 | 1.2111 | −10.8380 | 0.0000 |
| $\beta_1$ | 2.7745 | 0.2627 | 10.5607 | 0.0000 |
| $\beta_2$ | −0.1226 | 0.0138 | −8.8546 | 0.0000 |
| $\beta_3$ | −0.1725 | 0.0076 | −22.8059 | 0.0000 |
| $\theta$ | −0.1042 | 0.0133 | −7.8316 | 0.0000 |
| | | $\rho$ : 0.0589 (0.0386) | | |
| $GDP_{TP}$ | | 82,138.04 | | |
| $pseudo - R^2$ | | 0.7805 | | |
| *Wald* statistics | | 4.9215 (0.0265) | | |
| Log likelihood | | −242.2354 | | |
| *JB* | | 1.7206 (0.4230) | | |
| *Moran* test | | −0.0144 (0.3624) | | |

The values of the $\beta_1$ and $\beta_2$ parameters, as in the case of the model without spatial effects, indicate an inverse U-shaped relationship between GDP and $CO_2$ emissions. Importantly, these parameters are statistically significant. Moreover, the sign of the parameter $\beta_3$ has not changed, which, as in the previous model, indicates a positive impact of renewable energy consumption on carbon dioxide emissions. Likewise, a negative and statistically significant parameter $\theta$ describing the effects of changes in renewable consumption in "neighboring" countries (with a similar level of environmental development) shows that its increase results in lower $CO_2$ emissions in a given country.

Compared to model (1), the GDP value at which $CO_2$ emissions started to decline decreased. In this case, the threshold value was estimated at $82,138.04. This is further evidence of a positive influence of pro-ecological neighbors' behavior on the environmental situation in a given country. It is worth emphasizing that only two countries have reached the threshold point, namely Luxembourg and Norway. The shape of the Kuznets curve, determined based on model (6), is presented in Figure 4.

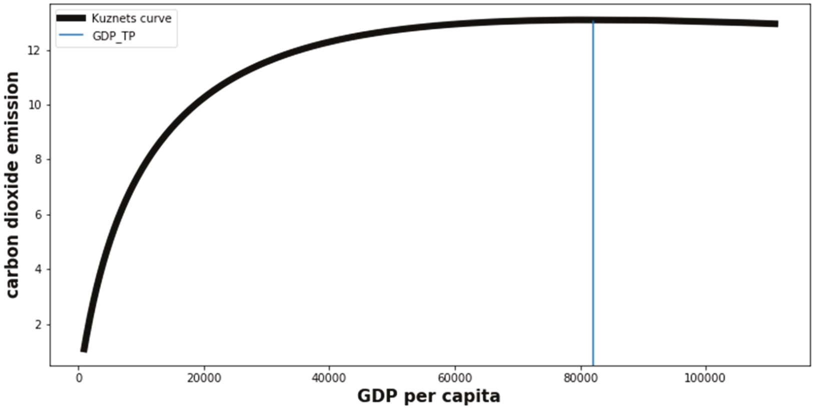

**Figure 4.** The shape of the Kuznets curve for the considered countries in the period of 2013–2019 (determined based on model (6)).

The positive and statistically significant value of the autoregression parameter $\rho$ proves a similar level of $CO_2$ emissions in countries with a similar level of environmental development.

### 5.3. Spatial Spillovers

In this subsection, we present the results of the empirical indirect effects analysis for the years of the examined period, carried out on the basis of the following transformation of model (6), with respect to the spatially lagged renewable energy consumption, expressed in natural log $\mathbf{W}\mathbf{ln}(\boldsymbol{RE})$, that is, as the following formula:

$$\begin{aligned}\mathbf{ln}(\boldsymbol{CO_2})_t = {} & (\mathbf{I}-\rho\mathbf{W})^{-1}\alpha\iota_N + (\mathbf{I}-\rho\mathbf{W})^{-1}\beta_1\mathbf{ln}(\boldsymbol{GDP})_t + (\mathbf{I}-\rho\mathbf{W})^{-1}\beta_2(\mathbf{ln}(\boldsymbol{GDP}))_t^2 \\ & +(\mathbf{I}-\rho\mathbf{W})^{-1}(\beta_3\mathbf{I}_N+\theta\mathbf{W})\mathbf{ln}(\boldsymbol{RE})_t\end{aligned} \tag{11}$$

The indirect effects were determined in the form of the average values in the cross-section of rows and, separately, in the cross-section of columns of the $(\mathbf{I}-\rho\mathbf{W})^{-1}(\beta_3\mathbf{I}_N+\theta\mathbf{W})$ matrix, excluding diagonal elements. In this way, measurements of the average impacts (in terms of the analyzed variables) of individual countries on a given country, and of a given country on other countries, respectively, were obtained. Due to the stability of the spatial connectivity matrix over time, the spillover effects were the same in each of the analyzed years.

Figure 5 presents spatial distributions of indirect effects obtained. The first map in Figure 5 shows the distribution of average inflows via the share of energy consumption from renewable sources out of the total energy consumption in individual countries on the $CO_2$ emissions in a given country.

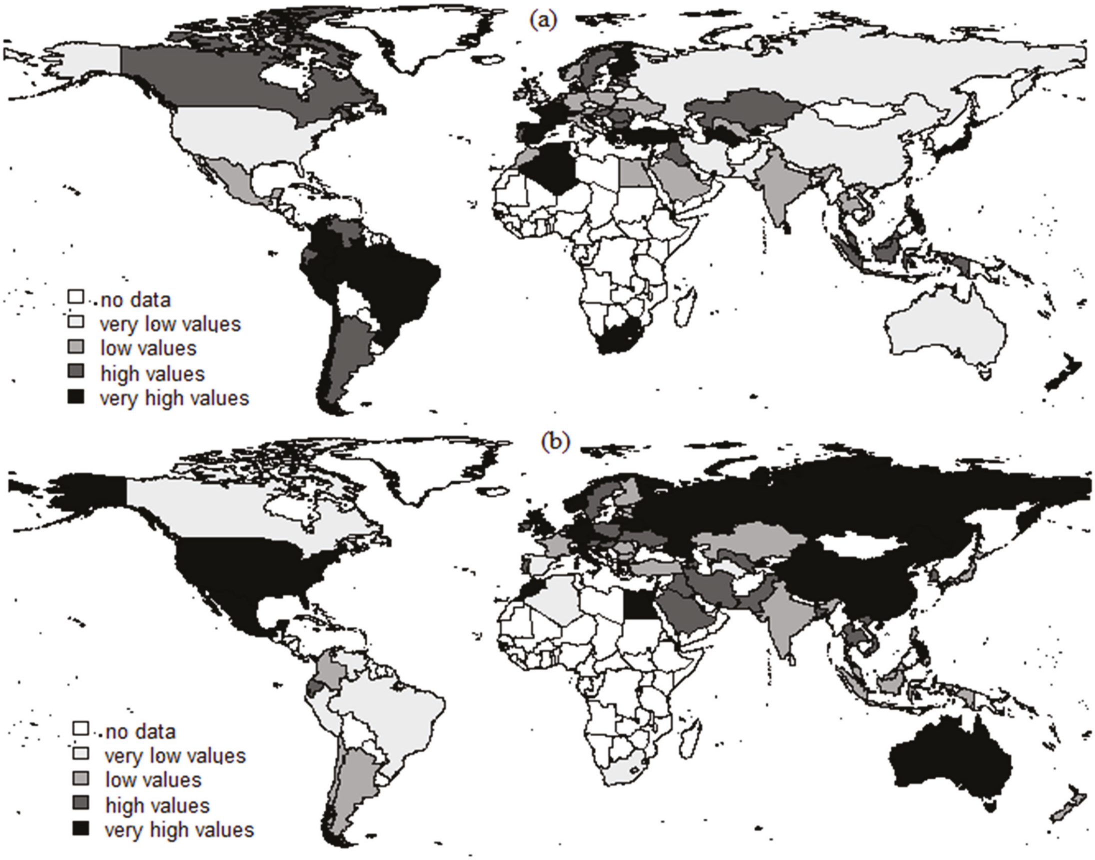

**Figure 5.** The distribution of the average impacts of (**a**) the spatially lagged renewable energy consumption on the $CO_2$ emissions in individual economies and (**b**) a change of the share of energy from renewable sources out of the total energy consumption in a particular economy on the $CO_2$ emissions in all other economies.

We can see that the countries of South America were among the ones that received transmission impulses from other countries with the highest strength. It should be noted that these countries were characterized by the lowest $CO_2$ emissions and the highest share of renewable energy consumption. The countries that were least affected by all other countries through the transmission of renewable energy consumption included the United States, China, Russia, and Australia—the relatively highly developed economies.

The second map in Figure 5 shows the distribution of the average impacts of a given country's share of energy from renewable sources out of the total energy consumption on the $CO_2$ emissions in all other economies. It is worth noting that countries that were the least influenced by others were the ones that most strongly affected other countries. Thus, renewable energy consumption in the United States, China, Russia, and Australia most strongly affected the $CO_2$ emissions in other countries. Among the economies whose impact on other economies was the largest, there were also those of Italy and Norway. On the other hand, among the countries whose impact (through changes in the structure of energy consumption) on environmental pollution in other countries was the lowest, were Brazil, Algeria, Peru, and Venezuela.

Figure 6 shows the impacts of two selected countries on other countries in the range of the variables considered. The maps in this figure present transmission impulse distributions resulting from changes in the structure of energy consumption in countries with the highest share of energy consumption from renewable sources, namely Norway and Brazil.

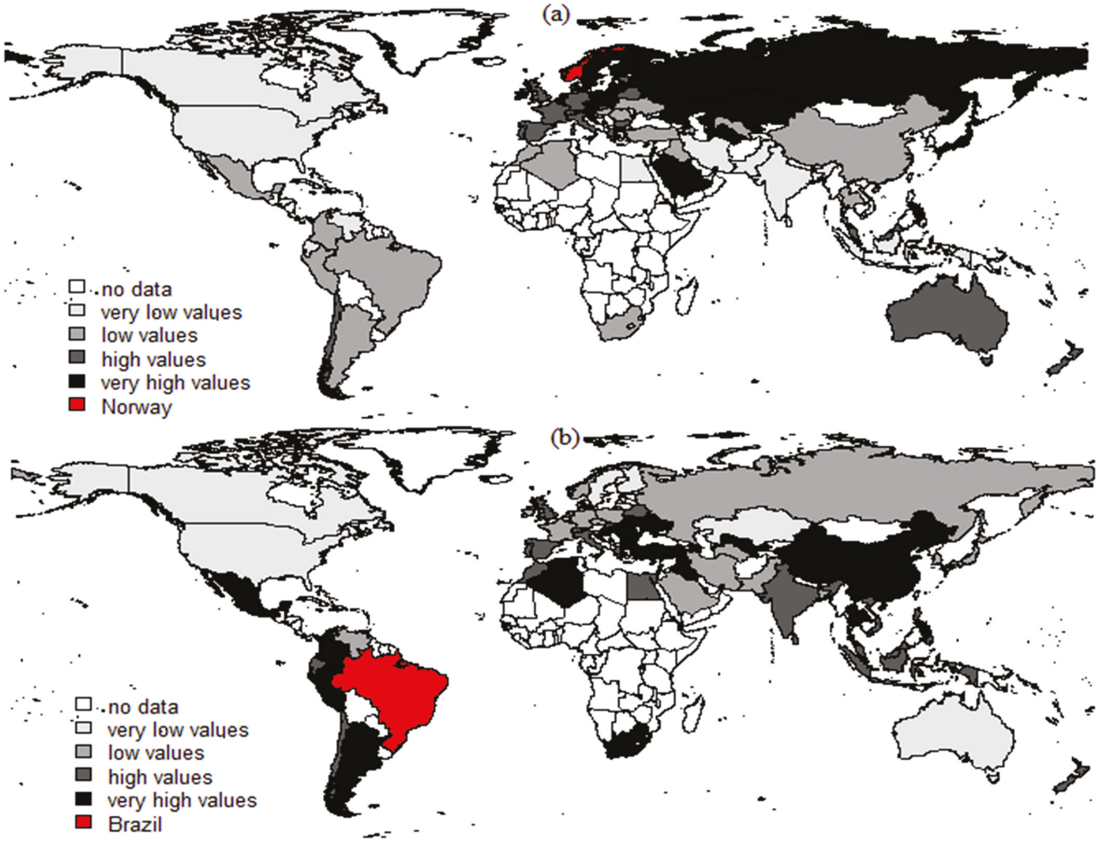

**Figure 6.** Dependence of the $CO_2$ emissions of all other countries on the share of energy from renewable sources out of the total energy consumption in (**a**) Norway and (**b**) Brazil.

A change in the share of renewable energy in Norway had the strongest impact on environmental pollution in other Scandinavian countries, as well as in Central European countries and Russia. It can be assumed that this was due to the high degree of energy dependence on Norway of countries located close to each other in geographical space. In contrast, the countries of both North and South America, as well as South Asia, were least influenced by the changes in Norway.

Changes in the share of renewable energy out of the total energy consumption in Brazil had the strongest impact on environmental pollution in most of other South American countries, China and Mexico, as well as in most Mediterranean countries. The reason for such dependencies may be the comparable, equatorial climate of the countries, where changes in the structure of energy consumption result in similar changes in terms of $CO_2$ emissions. The least sensitive (from the environmental aspect) to changes in renewable energy consumption in the country were the United States, Canada, Norway, and Finland.

Figure 7 presents the distributions of the average impacts of changes in the structure of energy consumption in countries with the strongest impact on others in terms of $CO_2$ emissions. Based on the results obtained, it was established that such countries were Italy and China.

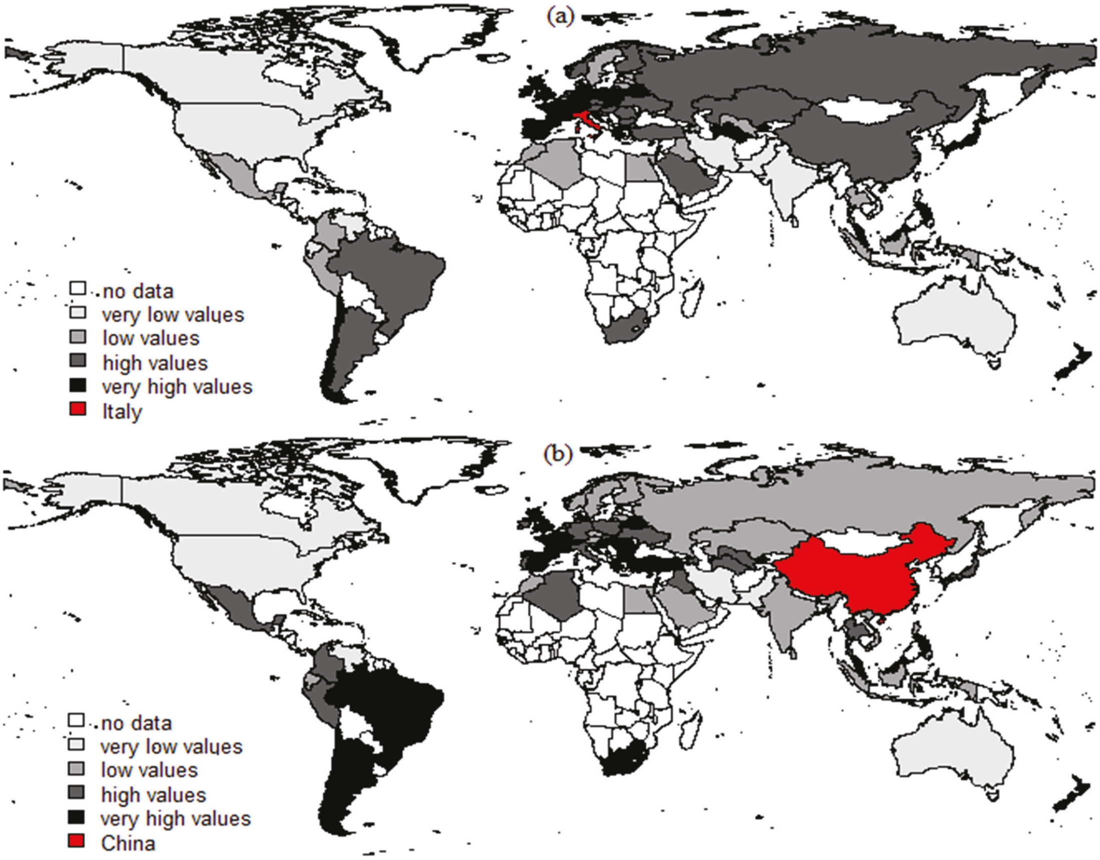

**Figure 7.** Dependence of $CO_2$ emissions of all other countries on the share of energy from renewable sources out of the total energy consumption in (**a**) Italy and (**b**) China.

In the cases analyzed, we found that a change in the share of renewable energy out of the total energy consumption in Italy had the strongest impact on the levels of $CO_2$ emissions in most of the European economies taken into account, as well as in Chile. The North and East Asia countries, as well as Brazil and Argentina, were among the ones slightly less affected by Italy, whereas the smallest transmission impulses from Italy were received by the United States, Canada, Australia, and India.

China, in turn, had the strongest impact on Argentina, Brazil, Malaysia, as well as on most of the European Mediterranean countries. As with the impulses from Italy, the group of countries least sensitive to changes in the structure of energy consumption in China included the United States, Canada, and Australia.

Finally, it is worth emphasizing the similarity of the strength of influence of Italy and China on environmental pollution in South American countries as well as in most European countries. It is also worth noting the weak dependence of the level of environmental protection in the United States on changes in the structure of energy consumption in other considered world economies.

## 6. Conclusions

The results of this study underline the role of changes in the structure of energy consumption in the world economies for the improvement of the environmental situation.

Environmental protection has become an increasingly important element of the economic development of countries, which is reflected in the contemporary concept of sustainable development. Its purpose is to improve the state of the national economy while reducing the consumption of scarce resources.

The Kuznets curve determined for the selected countries pointed to the inverse U-shaped relationship between the per capita GDP and $CO_2$ emission. Including the share of energy from renewable sources in the total energy consumption as an additional explanatory variable in the models constructed confirmed the conclusions of other researchers that with the increase in this share, there was an improvement in the environmental situation, that is, the carbon dioxide emissions were reduced. Moreover, the inclusion of spatially lagged variables (i.e., the $CO_2$ emissions and energy from renewable sources consumption in "neighboring" countries) in the final model showed to what extent the pro-ecological actions of some economies affect others. Additionally, it can be seen that the impact of these variables on the dependent variable is smaller than their impact within a given territorial unit.

The spatial indirect effects determined based on the spatio-temporal Durbin model allowed us to identify, firstly, the countries that are most susceptible to the influence of other countries, and secondly, those with the strongest impact on others.

It is worth noting that relatively highly developed countries were among those in which the change in energy from renewable sources consumption had the greatest impact on the $CO_2$ emissions in other countries. This is mainly due to the fact that most of the economies failed to reach the turning point, that is, the level of GDP per capita at which the $CO_2$ emissions start to decline. The economies are still at a stage where the main focus is on economic development.

At the same time, the highly developed countries were minorly influenced by other countries in terms of the variables under consideration. The case of the United States should be distinguished as an economy independent of most others.

Undoubtedly, the positive impact of the changes taking place in the countries with a higher level of environmental development on the state of the environment in other countries was observed. This thesis was confirmed by the decline in GDP per capita at the turning point when relationships between neighbors were incorporated into the model.

The analysis of the spatial distributions of the impact of changes in the structure of energy consumption in Norway, Italy, Brazil, and China on air pollution in other countries leads to interesting conclusions. The mentioned European countries have a major influence on the others within the same continent, whereas impulses from economies such as Brazil and China, located on other continents, have a wider geographical scope. The countries influenced by them are not located in one cohesive area.

The results of the research show the importance of pro-ecological activities not only within a given country. The spatial spillovers in this regard are also significant.

The spatio-temporal Durbin model used in our study is only one of the possible specifications that turned out to be useful for the analysis of the phenomenon under consideration. Other model specifications should be used in further studies. Additionally, the use of other connectivity matrices should be verified. It is also worth determining the indirect effects in relation to other explanatory variables and establishing appropriate spatial regimes with regard to the wealth of the analyzed economies.

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# Between Poverty and Energy Satisfaction in Polish Households Run by People Aged 60 and Older

**Marlena Piekut**

College of Economics and Social Sciences, Warsaw University of Technology, Plac Politechniki 1, 00-661 Warsaw, Poland; marlena.piekut@pw.edu.pl

**Abstract:** The household sector contributes significantly to a country's energy consumption. Energy carrier expenses are the highest expenditures in Polish household budgets. Households run by individuals aged 60 and older are heavily burdened with energy expenditures. The scientific aim of the research is to present and assess housing conditions, with particular emphasis on energy poverty in households run by individuals aged 60 and older. Multivariate statistical analyses were used to conduct the research objectives (cluster methods, variance methods, regression methods). This paper identifies a new index—one that has been applied to the situation in Poland. Households that consist of elderly people are strongly diversified in terms of housing conditions (including energy conditions). There are concerns that some households are not able to access energy services that are required to satisfy basic human needs, particularly individuals with low levels of education, living on social benefits, with low disposable incomes, or living in the countryside. Households represented by men aged 60 and older have better energy supply than households run by women. The older the individual representing the household, the greater the likelihood that his/her energy service needs are not met.

**Keywords:** aging population; elderly; older people; poverty of energy; comfort of energy; consumption; household

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## 1. Introduction

The article focuses on energy consumption in households. Household expenditures involve many categories, including consumer goods and services (including food and non-alcoholic beverages, housing maintenance and equipment, educational, and recreational and cultural services); energy carrier expenditures are one of the largest shares of total consumption expenditures (Poland, Germany) [1,2]. The paper examines households run by people aged 60 and older, i.e., the group that is the most burdened with energy expenditures [3,4]. A high share of the above-mentioned expenditures may, in the case of a notable group of households, lead to unmet heat-related needs, which in turn causes energy deprivation and energy poverty [5–7].

The topic (energy consumption in households) considered in this article is important, due to theoretical and practical reasons, taking into account the functioning of the housing market and investor decisions [8,9]. On the theoretical level, it is important to diagnose the housing situations of the elderly and any existing problems [10], both at a national level [11,12] and throughout Europe [13–15]. On the practical level, it is important to find solutions that serve both seniors in their everyday lives (e.g., removing inconveniences in apartments) as well as investors, so that new housing products can meet the actual needs of seniors. Recognizing housing conditions, e.g., ensuring that there is heat in the apartment and finding energy impoverished households, is important, from the point of view from a country's social policies, and in accordance with social policy forecasts [16,17]. Energy poverty impacts one's standard of living and health. These issues are important to politicians and other healthcare managers [18–21]. Energy used in households is also a significant problem, particularly concerning responsible consumption [22]. For sectors dealing with the modernization of residential buildings—the standard of buildings and the related satisfaction of living conditions is interesting [23–25]. The problem addressed is valid from the point of view of the United Nations sustainable development goals [26,27].

Household energy spending is a global problem, where the globalization process [28–30], especially in the case of EU member states [31–33], has intense influence on convergence tendencies, in terms of the expenditure amounts and the energy carriers used in the households. Systematic development of the globalization process has contributed to the creation of a new institutional order; thus, it is necessary to consider the energy transformation of countries and social consequences [33–36]. The globalization process has led to the emergence of interdependencies between economies, in terms of various socioeconomic aspects [35–40], including those related to household consumption structures [41–43]. They also translate into purely economic aspects, contributing to a higher level of innovation and competitiveness of economies [34,35], which, in turn, increases the level of innovation and competitiveness of these economies [44–48]. Undoubtedly, the globalization process is responsible for economic convergence in a selected group of countries, including EU member states [49,50]. Economic convergence affects the structures of households and their main characteristics, mainly related to the increase in wealth or the types of employment of the household members [51–59]. Thus, the globalization process and the ongoing economic convergence of countries have contributed to a permanent change in household approaches to consumption, especially in terms of energy consumption [60–63].

Analyzing selected groups of households is challenging, when considering the ongoing energy transformation of countries, the possibility of using various energy and heat carriers, the possibility of purchasing energy from different suppliers, changing consumer attitudes, and changes in the structures of households. The article analyzed household energy carrier expenditures in Poland. The scientific objective of the research is to present and assess housing conditions, with particular emphasis on energy poverty in households comprised of people aged 60 and older. The paper presents an assessment method applied to Polish households, and a specific target group of residents—individuals aged 60 and older. In particular, this work aims to provide a deep analysis and assessment of housing conditions in Poland, particularly linked to energy poverty, and households run by older individuals.

Poland is an interesting object of analysis due to the growing similarity of Polish consumption patterns with those observed in Western Europe, as well as a specific imitation of consumption patterns pertaining to countries with a higher standard of living [64]. The processes taking place in Poland—as in other countries in Central and Eastern Europe [65]—can be a good prognostic example regarding changes in the behavioral patterns of households in countries with lower standards of living.

This study will be used to evaluate the relationship between the risk of energy poverty and particular sociodemographic/economic features of the household representatives.

Energy is a key area of action in sustainable development. The Agenda for Sustainable Development adopted by the United Nations includes, inter alia, such tasks as ensuring universal access to affordable, reliable, and modern energy services [66]. The household sector contributes significantly to a country’s energy consumption, although its share in total consumption decreases each year. In Poland, in 2019, households represented an estimated 26.3% of final energy consumption; three years prior, it was 30.5%; in 2006, it was 34.2% [67].

In 2019, Polish households, on average, spent 10.2% of their total expenditures on consumer goods and services, in regard to energy carriers (coal, gas, and other fuels). This high value may affect the existence of a significant group of people (i.e., households unable to access energy services required to satisfy basic human needs) and may undoubtedly lead to energy deprivation and poverty. The literature review [10,68–70] and the statistical analysis [71] indicate that households comprised of individuals 60 and older are the groups overloaded with energy carrier costs. In Poland in 2018, expenditures on energy, gas, and other fuels consumed 11% of disposable income (used interchangeably with available income) of a 60 and older household, while in households with younger persons, it was 6.0–8.1% of their disposable income (Figure 1).

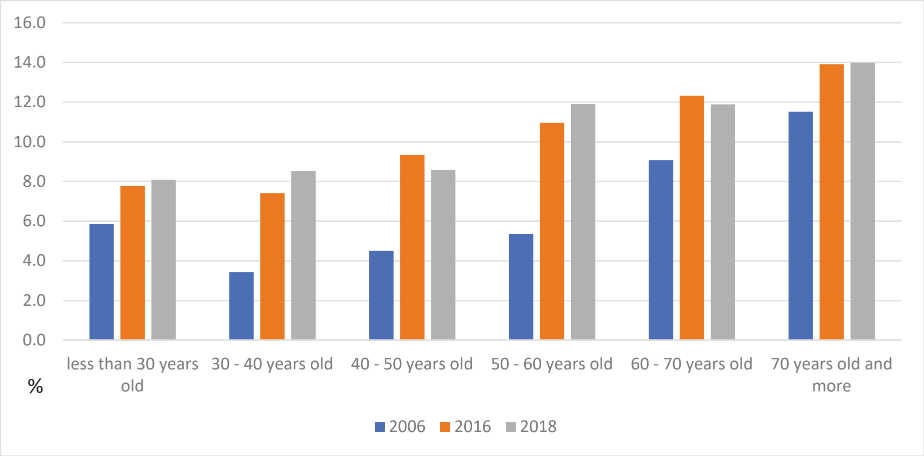

**Figure 1.** Share of energy expenditure in disposable income in households by age of the person running the household in Poland in 2006, 2016, and 2018. Source: own elaboration based on data from [72–74].

The number of 60 and older households is continuously increasing, in both relative and absolute values, and this trend is projected [71] to grow. For the purpose of the described research, the expression "energy poverty" is explained as the scarcity of affordable energy and lack of satisfaction of household energy necessities. It is worth noting that the smaller possibility of getting economically viable energy is related to a higher share of energy expenses (over 20%) in available income [1]. The paper deals with the issues of energy poverty among the elderly, but it should be kept in mind that energy poverty has wider boundaries, and is not simply associated to a targeted age range.

## 2. Literature Review

### 2.1. Housing Conditions and Their Roles in the Lives of Older People

In the scientific literature, issues related to old age receive a lot of attention, mainly due to the increase of aging societies. The above-mentioned issue, of aging societies, affects Poland as well. The size of the population in the 60 years and older age group is characterized by the highest growth dynamics. In Poland, in the 1990s, this group accounted for about 15% of the entire population; in the second decade of the 21st century, the number was estimated at more than 20%. According to forecasts, in 2035, elderly people will constitute over 28%, and in 2050—over 40% of the entire Polish society [55]. Longevity, i.e., extending the duration of human life, is—on the one hand—perceived as a civilization achievement, and on the other hand, it generates a number of challenges in the economic, social, and cultural spheres. The housing infrastructure problem is not adapted to the needs of older people, which constitutes a major challenge. In particular, this concerns the needs related to the shaping of the broadly understood housing conditions, which have a significant impact on the quality of life of older people [75–77].

Housing conditions are one of the indicators related to quality of life—understood as an objective assessment related to satisfying human needs [78]. Meeting housing needs, i.e., housing standards depends on the technical conditions of the building or flat (standard of goods, construction standards), as well as the manner of use and the population (standard of use). The first one determines the level of satisfaction of needs in relation to the usable space, interior finishing, and furnishing of a building or apartment [79]. The second one is associated with the number of people per flat or room and the average floor space per flat, household, or person.

The above-mentioned, alongside the ages of the individuals in the home, and their progressing disabilities, it may turn out that the current flat has many architectural barriers or does not meet the other needs of older people (e.g., it is too large). In such a case, it is important to help elderly people adapt to changing conditions so that they maintain their wellbeing and independence in their daily activities longer [80]. It is also important that older people have the right to choose their residences freely and that they have the option to live in their flats for as long as possible. This is reflected in many international documents, including in the Vienna International Plan of Action on Aging, adopted in 1982 by the World Assembly on Aging, and in the UN Principles for Older Persons, adopted in 1991. The directives and resolutions define the rights of seniors in relation to, inter alia, choosing the form of residence and receiving support, enabling implementation of this entitlement. The above-mentioned (and other rights) surround the principles of independence, participation, care, self-fulfillment, and dignity. In addition, the Revised European Social Charter (Article 23) indicates the need to let the elderly freely choose their way of life, and to live independently in a familiar environment for as long as they wish (and are capable to do so), as one of the guiding principles for full participation in society. The implementation of this right should be executed, inter alia, by providing housing adapted to the needs of older people and their health conditions, and by providing appropriate assistance in adapting housing to their needs.

Housing conditions that are in the comfort zone can positively affect the health and well-being of aging individuals [81]. Simultaneously, conditions that extend beyond the comfort zone are known to cause a number of health complications, as the elderly tend to be more vulnerable to the inconvenience of a home environment [82]. The comfort zone includes, among others, ensures proper temperature in the living quarters. "Thermal comfort" is defined by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) as "*the state of mind which ex-presses satisfaction with the thermal environment*" [83]. For every individual, the home is the basic point of reference. For older people, it is of particular importance, as it is a place where most needs are met. Reduced physical and mental capacity, increased limitations resulting from disabilities, difficulties, in terms of spatial mobility, and a sense of threat to public safety, mean that older people spend more time in their lodgings and their immediate vicinities. Therefore, an important issue in this context is whether the dwellings occupied by older people meet their needs, providing conditions that make it possible for them to live independent and dignified lives. When considering the housing situation of older people, two crucial aspects should be focused on. The first is objective housing conditions, measured with the use of indicators, such as the area of the flat, the standard of the flat, the amount of expenditure on energy carriers. Qualitative, non-measurable aspects also play a significant role, and they are frequently more important for older people than the quantitative aspects described above. They include, among others, the level of satisfaction with meeting the needs, for example, thermal conditions in the apartment.

The standard of the apartment, as well as its amenities, are the main factors that influence housing satisfaction and overall life satisfaction. In a recent study examining the situation of the elderly in Vietnam [25], it was shown that housing satisfaction has a strong positive effect on life satisfaction. Housing is an important area of life and, therefore, housing satisfaction is a strong predictor rating for life satisfaction and the quality of life. People invest their resources in their homes and their welfare increases as a result. Policies and programs to help poor families and improve housing facilities can improve the quality of life of poor, elderly people [25]. Taking effective actions to improve the housing conditions of the elderly requires, first, knowledge on how they live and how they evaluate their housing situations.

Zrałek [84] points to the improvement of the housing conditions of elderly people in Poland, as evidenced by, inter alia, the indicators characterizing the degree of the housing population. Households of retirees have the largest usable floor space per person (35.1 m$^2$), while the average floor area of a flat in Poland is 25.4 m$^2$ per person. This is due to changes of the compositions of households of older people—children leaving their family homes or widowhood. Although the population norm, applicable at the time of the settlement of the apartment, was designed for two-generation families, and was characterized by a relatively small area, due to the current size of households of elderly people, these apartments provide larger areas per person. In general, the older the head of a one-person household is, the less often the apartment is overcrowded. In the case of multi-person households with an elderly person as the head of the household, the situation is much less favorable, as almost 30% of these households live in densely populated apartments [84].

It is also indicated that the elderly, living in small households or alone, live in flats that are too large and too expensive [1], which they do not want or cannot leave. An objective factor limiting the possibility of switching flats is the limited supply of small flats. Such flats are very popular because they are attractive to young people due to their price, but often too expensive in relation to the financial possibilities of old people [84]. The research findings show that the elderly are passive when it comes to modernizing their apartments [85]. Seniors, regardless of their living conditions, rarely decide to replace their current apartments with smaller ones, which may be cheaper to maintain and more modern. Among seniors, the attachment to the housing environment appears very strong [86]. This fact is indicated not only by studies carried out in Poland, but also by research conducted in Germany [87], Hong Kong [88], Ireland [89], Spain [90], and the Netherlands [91].

Another problem related to the housing conditions of older people is energy poverty. In Poland, it particularly affects the elderly in large houses in the countryside [1,92].

### *2.2. Influence of Demographic and Socioeconomic Determinants of Elderly People on Housing Conditions and Satisfaction with Housing*

Providing appropriate housing conditions, including thermal comfort and satisfaction, is related to the financial situation of the household [1]. Households with a lower affluence ratio are more likely to suffer from energy poverty because their income cannot cover their energy expenditure. Households that inhabit individuals with low wages or benefits are unable to spend more to access the right amount of energy [93]. Insufficient amounts allocated to housing, including heating, lead to lower satisfaction with housing conditions. Research shows that people in higher-income households are generally more satisfied with housing, have more financial resources to live in better homes, and could afford better interior furnishings. Thus, higher income has a positive effect on respondent satisfaction with housing [94–99], although there are reports showing that income has a negative impact [100] or does not have a significant impact on satisfaction with housing conditions [101]. The latter is caused by the fact that people with higher incomes tend to aspire higher, compared to their current housing standards, which in turn may reduce their satisfaction with housing [25,102,103].

Age is another factor that influences living conditions. For example, elderly people prefer different thermal conditions than younger people [104–109], although there are studies that show no differences between older and younger people in this respect [110–114]. One may observe that, in everyday life, the elderly may be less active; therefore, they prefer higher ambient temperatures [112]. Age is important, not only in terms of the subjective perception of satisfaction with housing conditions, but it also constitutes an important determinant of multidimensional energy poverty. Moreover, it has emerged that senior age increased energy sensitivity [93].

Analyzing the role of gender, some researchers indicated that women are more satisfied with their homes than men [1,96,115], while other studies [99,100,116–118] did not show the influence of gender on satisfaction with housing. However, in relation to elderly people, the research findings have indicated that gender plays a significant role in the perception of the thermal environment. The thermal conditions preferred by the elderly and women differed from those preferred by younger adults and men. Women were more sensitive to cold and deviations from individual optimal conditions than men. Moreover, women often preferred higher temperatures [119–122]. Households with a woman as the main breadwinner were also at a higher risk of multi-dimensional energy poverty. In this context, it is important to emphasize that there is a gender imbalance in employment opportunities and the level of remuneration. Women generally receive lower wages than men, which negatively affects the living conditions in their households [93].

It was also found that education is an important determinant of housing satisfaction. However, the impact of education on satisfaction with housing tends to be perceived as ambiguous. The relationship between education and housing satisfaction was found to be positive in Taiwan [123] and China [124], but negative in Ghana [125]. Moreover, studies [126] revealed that, although the level of education contributed significantly to the housing satisfaction of Asians, there was no correlation in the case of white individuals. Regarding thermal comfort, previous studies [1] showed that the level of education is a very important determinant among those who run the households. People with higher education were less likely to experience energy poverty, and their needs, in terms of thermal comfort, were satisfied to a higher degree. However, in the case of some older people, apart from the favorable objective characteristics of their households (the level of disposable income, the share of energy expenditure in disposable income, the technical and sanitary condition of buildings), problems occurred with fully satisfying energy-related needs (in subjective terms). This may be related to the higher aspirations of more educated individuals.

Another feature related to housing conditions and satisfaction is the number of people in the household. The larger the household, the more dissatisfied with the housing conditions individuals tend to be [94,123,127,128]. Compared to smaller families, larger families were also more prone to suffer from energy poverty [93].

Health status is another factor that significantly influences housing satisfaction. The better the health of the individuals, the more satisfied with the housing conditions they tend to be [95]. The literature on the subject also shows that the level of housing satisfaction is mainly determined by a number of physical characteristics of the residential and neighborly environment [94,100,125,129–133]. Larger apartment sizes, better internal structure of the apartment, type of housing (better homes), location, and surroundings of the apartment building were positively associated with housing satisfaction. Moreover, many studies have found a positive relationship between the length of stay in a given place and housing satisfaction [100,127,134], while other studies have shown the negative effects of such circumstances [135]. It was also noted [93] that multi-dimensional energy poverty was more common in rented housing than in the dwellings owned by household members.

To summarize, the size of the house, homeownership status, place of residence, household financial situation, age, gender, education, occupation, and marital status of the head of the household, as well as the size of the household, were significant determinants of energy poverty in households. It was noticed that, in most cases, these features were both overlapping and interdependent. Therefore, when studying the influence of specific features on examined phenomena, their multidimensional relationship should be taken into account. All the accumulated assets or earnings determine the nature of employment, which in turn determines the level of education. No single socioeconomic variable causes or determines multidimensional energy poverty; it a combination of many of these variables leading to a specific outcome [1,93].

## 3. Methods of the Research

### *3.1. Data Sources and Study Design*

The research concerns Polish households with people aged 60 and older. The research material was from Statistics Poland data. The data covered 36,000 to 37,000 cases (households). There were 10,114 (27.0% of all respondents) in 2006, 13,859 (37.8%) in 2016, and 14,461 (40.0%) in 2018, regarding households of people aged 60 and older [136].

Implementing the research goal required examining the following research problems:

- Constructing an aggregate index of energy poverty;

- Identifying the types of households run by people aged 60 and older who were at risk of energy poverty;
- Distinguishing the types of households of people 60 and older, according to the characteristics describing the expenses needed to maintain a flat, as well as housing conditions.

The following research procedure was adopted.

Research task no. 1. The author designed an aggregate indicator as a measure to identify the types of households run by people aged 60 and older, considering their exposure to energy poverty. The created indicator was verified by analyzing the correlation between its components. The aggregate indicator was created based on the concept presented in the author's earlier work [1], but it was adapted to the needs of the study presented in this paper and the statistical data available. The decision to build an aggregate index was supported by an analysis of the literature on energy poverty [137–144].

The aggregate indicator consisted of two components, i.e., (a) the component describing the objective housing situation of older people (their housing conditions), and (b) the component describing their subjective satisfaction with their apartment/home.

Undoubtedly, energy poverty—apart from the fact that it concerns the energy circumstances of households—is strongly associated with poverty construed economically as deprivation of access to material goods and resources. Therefore, the components of the aggregate index of energy poverty include such variables as the financial situation of a household and the level of satisfaction of the primary needs of their members, such as food.

Research task no. 2. For the delimitation of households of people aged 60 and older, the following steps were adopted:

1. Applied the k-means cluster analysis with the application of data mining techniques. K-means cluster is described, among others, in the books: L. Kaufman, P. Rousseeuw [145], and A. Kassambara [146], and in papers [147–149]. Clustering is a process of partitioning a set of data objects from one set into multiple classes. Finding groups (clusters) in the data was the aim of the analysis. Data points are clustered based on feature similarity [150].
2. Calculated the average values for each cluster using the arithmetic mean (e.g., expenditure on energy, gas, and other fuels), horizontal distributions of socioeconomic and demographic features for each cluster (e.g., gender).
3. Compared the differences in mean values of the parameters associated to energy carriers between the clusters using the analysis of variance and post hoc tests (the Tukey's range test (HSD) or Scheffe test [151]). The alpha level of 0.05 was used in the article.

### *3.2. Test Method and Preliminary Research Results*

In order to achieve research objective no. 1, the author used an aggregated indicator that was adapted to this research, and took into account variables related to energy expenses, the degree of satisfaction of the needs related to using energy carriers, and the standard of a flat or a house (Table 1). It is worth mentioning that the building characteristics may have a strong influence in addition to income status and the other parameters considered. The role of the building system (construction quality and level of efficiency) is quite relevant in concurring to fall in energy poverty [152–154]. However, it is not fully translated into the investigated variables within the adopted methodology.

The division into groups of households, according to the share of expenditure on energy carriers (less than 10%, 10–20%, and above 20%), results from the adopted thresholds described in the literature. According to the first official British definition from 1991, created by B. Boardman, and applied by researchers and practitioners in other countries, it is assumed that "a household is fuel poor if it has to spend more than 10% of its income on fuel to maintain an adequate level of heat" [155].

**Table 1.** Aggregate index of energy poverty (thermal comfort) for households of people aged 60 and older in Poland.

| Variables | Possible Answers and Evaluative Loads | Maximum Number of Points in 2018 |
|---|---|---|
| **Objective variables** | | |
| Share of expenses on energy carriers in disposable income (%) | Less than 10%—2; 10% to 20%—1; Above 20%—0 | 2 |
| Access to hot running water | Yes—1; No—0 | 1 |
| The period of construction of the building | Until 1960—0; in the years 1961–1995—1; in the years 1996–2011—2; after 2011—3. | 3 |
| Leaking roof, damp walls, floors, rotting windows or floors | Yes—1; No—0 | 1 |
| The amount of expenditures associated with maintaining the apartment above the subsistence level (340 PLN) | Yes—1; No—0 | 1 |
| The level of disposable income by quintile groups | 1st quintile group—1; 2nd quintile group—2; . . . ; 4th quintile group—4 | 4 |
| **Subjective variables** | | |
| The flat is cool enough in summer | Yes—1; No—0 | 1 |
| The flat is warm enough in winter | Yes—1; No—0 | |
| Assessment of meeting the needs of: | | |
| - Food;<br>- Timely payment of housing fees;<br>- Healthcare. | Good—4; Rather good—3; On average—2; Rather bad—1; Very bad—0 | 12 |

To design the indicator, the variables were transformed so that they were all stimulants (larger values of a given variable associated with a more advantageous comfort of energy). The details are described in paper [1]. The values of the descriptive statistics of the aggregate indicators for households of people aged 60 and older are presented in Table 2.

**Table 2.** The values of descriptive statistics of the aggregate index for households of people aged 60 and older.

| Specification | Indicator Values |
|---|---|
| Means | 20.2 |
| Median | 20.0 |
| Standard deviation | 3.44 |
| Modal | 22.0 |
| Kurtosis | −0.05 |
| Minimum | 4.0 |
| Maximum | 29.0 |
| The first decile | 18.0 |
| The ninth decile | 23.0 |
| Coefficient of variation | 17.0 |
| Coefficient of asymmetry | −0.42 |

Source: own elaboration based on data from [136].

The distribution of the aggregate indicator turned out to be similar to the normal distribution, although the Lilliefors distribution normality test formally rejected the normality hypothesis. The distribution of the index was characterized by a slight left-hand asymmetry (a slightly larger number of households are above the average) (Figure 2).

### *3.3. Types of Households according to Housing Conditions and Apartment Satisfaction*

Research task no. 2. To identify clusters of households, the author used cluster analysis (k-means method) with the application of data mining techniques. The V-fold cross-validation test used the selection of the optimal number of groups (number of trials—10). The optimal number of clusters was assumed to be 5, according to the diagram titled "Cost sequence chart" (Figure 3).

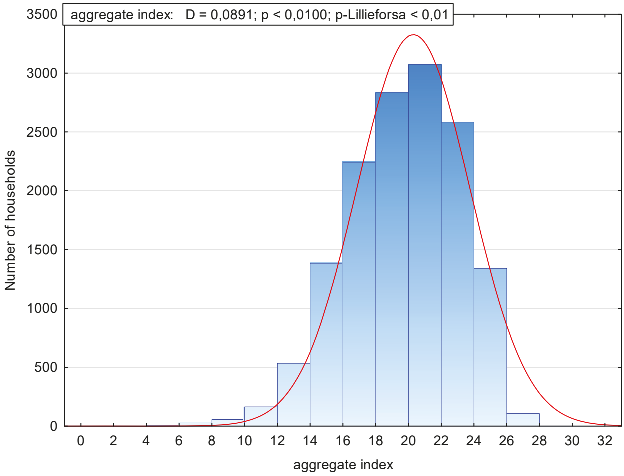

**Figure 2.** Distribution of the aggregate indicator for households of people aged 60 and older in 2018. Source: own elaboration based on data from [136].

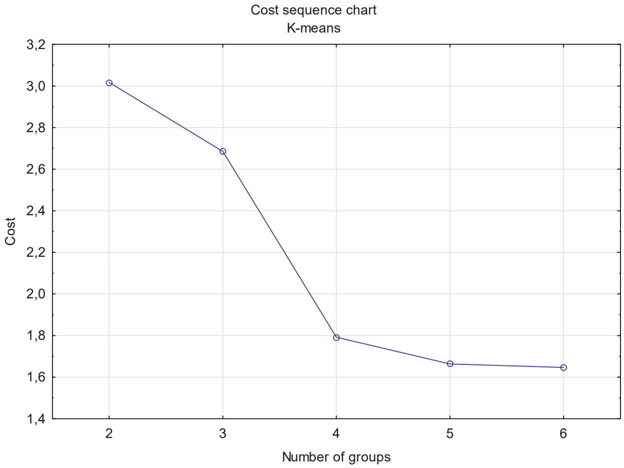

**Figure 3.** Cost sequence chart for k-means classification for households of people aged 60 and older in 2018. Source: own elaboration based on data from [136].

## 4. Results

### 4.1. Housing Conditions in Polish Households of People Aged 60 and Older, and Younger, in 2006, 2016, and 2018

Housing conditions positively affect the health and well-being of individuals. When analysts compare the conditions related to access energy carriers in households of people up to 60 years of age, and over 60 years of age, the conditions of the younger age group tend to be assessed as better. A larger percentage of households of people aged 60 and older (in 2018—the level was estimated at about 14%) compared to younger ones (less than 13%) reported problems connected with not meeting the needs related to maintaining the proper temperatures in the living spaces.

Together, with the transition to the next age group, a higher percentage of households had a higher share of expenses in energy, gas, and other fuels in their available income. In 2018, the share of households of people up to 60 years of age, in which 10% or more of their disposable income was spent on energy carriers, amounted to about 22%, while in the case of households of people over 60, depending on the age group, the percentage ranged from 38 to 46%.

A larger percentage of elderly households were also equipped with solid fuel stoves, e.g., coal-fired stoves, which are less convenient than central heating. In the case of younger people, about 10% of households were equipped with such stoves, while among the households of older people—the share was estimated at 12–16%.

By comparing the changes, which took place over time, it should be noted that the conditions with regard to energy carriers in households of the elderly improved. In the years 2006–2018, the percentage of households with a high, i.e., 20% and more, share of expenses of energy, gas, and other fuels, of available income, decreased. For example, in households of people aged 60–70, this percentage decreased by 9.2 pp (percentage points) and in the oldest age group, i.e., 80 years and more—by 10.2 pp. The share of households equipped with a solid fuel-fired furnace also decreased. In the case of people aged 60–70, this percentage decreased by 6.9 pp, and in the case of people aged 80 and older, by 19.9 pp. Regarding thermal comfort in a flat, the lack of statistical data for 2006 made it impossible to carry out a comparative analysis of this feature in examined households. However, it was noticed that in the years 2016–2018, the percentage of households with problems regarding thermal comfort in the apartment decreased slightly, albeit more in the case of households of younger people, up to 60 years of age, than in those of older people (Table 3).

**Table 3.** Comparison of conditions in terms of energy carriers in households by age of the person running the household in 2006, 2016 and 2018.

| Household Characteristics | Year | People under 60 Years of Age | People Age 60–70 | People Age 70–80 | People Aged 80 and Over |
|---|---|---|---|---|---|
| Unfulfilled needs related to thermal comfort in the apartment (warm in winter, cool in summer) (% households) | 2016 | 17.4 | 15.8 | 15.7 | 14.8 |
| | 2018 | 12.7 | 14.0 | 13.5 | 14.6 |
| Changes in percentage points | | −4.7 | −1.8 | −2.2 | −0.2 |
| Share of expenditure on energy carriers in disposable income above 20% (% households) | 2006 | 13.4 | 19.8 | 22.3 | 24.0 |
| | 2016 | 8.3 | 14.3 | 14.9 | 15.7 |
| | 2018 | 6.2 | 10.6 | 12.0 | 13.8 |
| Changes in percentage points | | −7.2 | −9.2 | −10.3 | −10.2 |
| Share of expenditure on energy carriers in disposable income between 10 and 20% (% households) | 2006 | 27.9 | 31.4 | 31.4 | 26.9 |
| | 2016 | 19.9 | 29.1 | 33.9 | 33.2 |
| | 2018 | 15.6 | 27.0 | 32.1 | 32.0 |
| Changes in percentage points | | −12.3 | −4.4 | 0.7 | 5.1 |
| The apartment is heated with a solid fuel stove, e.g., coal, wood (% households) | 2006 | 17.1 | 18.8 | 25.7 | 35.6 |
| | 2016 | 8.8 | 10.3 | 10.9 | 14.8 |
| | 2018 | 9.9 | 11.9 | 11.8 | 15.7 |
| Changes in percentage points | | −7.2 | −6.9 | −13.9 | −19.9 |

Source: own elaboration based on data from [136].

### 4.2. Economic and Sociodemographic Factors Influencing Energy Conditions in Households of the Elderly

Housing conditions, including appropriate conditions related to heat and electricity, are determined by many characteristics of households and the technical conditions of their flats. Age is a factor that significantly differentiates the level of the energy poverty index in Polish households maintained by people aged 60 and older. The conducted analysis revealed that the situations of people aged 60 and older, related to providing the above-mentioned housing conditions, was worse, compared to younger people, and it was the case of a statistically significant difference ($p < 0.005$). The aggregate index in households of people up to 60 years of age was the highest and amounted to 21.1, while in households of people aged 60–70, it was estimated at 20.4, and it decreased with age, reaching 19.8 in the case of households run by people aged 80 and older (Figure 4). However, in the last two age groups, i.e., 70–80 and 80 and older, no statistically significant differences were found in the level of the aggregate index of energy poverty.

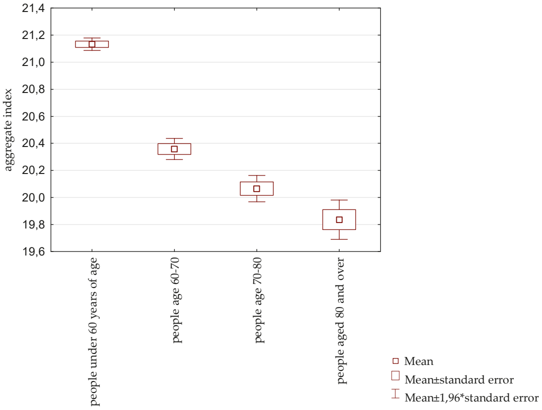

**Figure 4.** The level of the aggregate indicator in 2018 by age of the person running the household. Source: own elaboration based on data from [136].

The level of the aggregate index of energy poverty depends on the available income level. Thus, for the poorest households, this level is significantly higher ($p < 0.05$) in statistical terms than for households with higher income. In 2018, for 25% of the 60 and older households forming the first income group (the poorest), the level of the aggregate index was 16.8, whereas for other income groups, it ranged between 18.9 and 23.5 (Figure 5). The mean of the aggregate indicator increased with the higher income groups, the aggregate ratio increased from 2.1 to 2.5. The income situation is inherently associated with energy affordability. In the group of poorest households, this situation tends to improve, but, unfortunately, this improvement is the slowest.

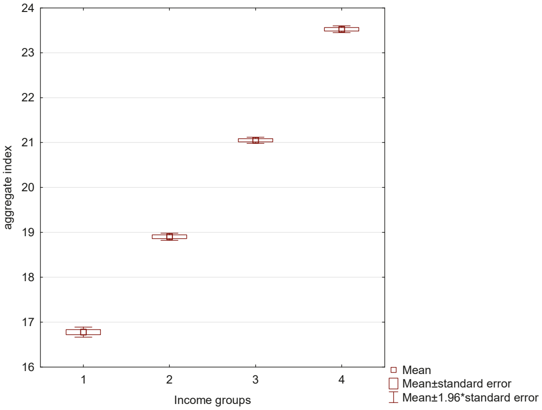

**Figure 5.** The level of the aggregate indicator in 2018 by income groups for households of people aged 60 and older Comment: the groups of households were divided into four equal groups. In the first quintile group, there were 1/4 of households with the lowest levels of disposable income. Source: own elaboration based on data from [136].

The household location is a determinant that significantly differentiates the value of the aggregate index in households of people over 60 years of age ($p = 0.0000$). The research made it possible to distinguish three groups of households of older people, with a statistically significant difference between them, due to the level of the analyzed indicator. The first group with the highest indicator covered households located in cities with over 100,000 inhabitants, the second group represented by households from cities with over 20,000 up to 99,000 inhabitants, and a third covering rural households. The highest index was characteristic for households located in the largest cities, i.e., 100,000 and more inhabitants (20.9–21.3), and the lowest for rural residents (19.4). A graphical presentation of the distributions of the aggregate indicator values, according to the household location, in households of people 60 and older in 2018, is shown in Figure 6.

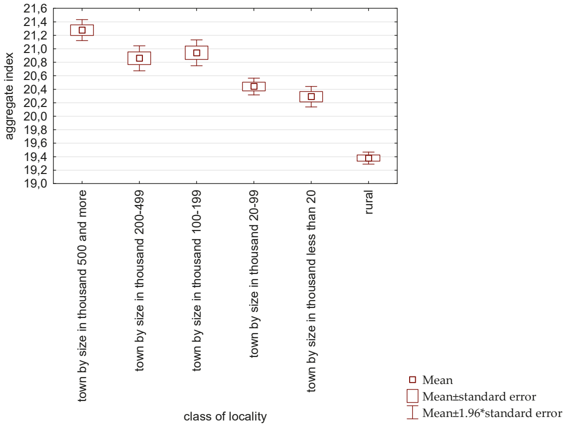

**Figure 6.** The level of the aggregate indicator in 2018 by household location for households of people aged 60 and older. Source: own elaboration based on data from [136].

Based on the analysis of the values of the aggregate index, depending on the number of people in the household, it can be concluded that there is one category of a household that is statistically different from the others ($p < 0.05$). The best situation was recorded in the case of two-person households and this category had a statistically significant higher level of the aggregate indicator than the other categories of households. The value of the analyzed index was 20.7 in the case of two-person households and 19.3–19.9 in other households (Figure 7).

The results also showed that women running households of people aged 60 and older (20.7) had lower thermal comfort than men (19.6). A graphical presentation of the distributions of the aggregate indicator values, according to the sex of the person representing the household of people aged 60 and older in 2018, is shown in Figure 8.

The level of education clearly affects the average level of the aggregate indicator in households of people aged 60 and older, and this correlation appears statistically significant ($p < 0.05$). The mean of the aggregate indicator increased with the higher education level, and the highest increase (by 1.0 percentage point) was observed when moving from secondary to higher level education, i.e., from 20.8 to 22.6. The value of the aggregate index of energy poverty for people with lower secondary and primary education was established at 18.1, while for people with basic vocational education, it amounted to 19.8 (Figure 9).

When considering the aggregate index according to socioeconomic groups, it was noticed that the highest value was recorded for households of non-manual workers and self-employed persons (22.8. and 22.6) and these values were statistically significantly higher than the other indicators ($p < 0.05$). In households referred to as “other”, including households of people over 59 years of age, living on social benefits, other than pensions or retirement pays, and other non-profit-making sources of income, the average value of the aggregate indicator was estimated at 16.5. Farmers' households (20.1) recorded levels of the aggregate index that were similar to the households of blue-collar workers (20.2) and retirees (20.2) (Figure 10).

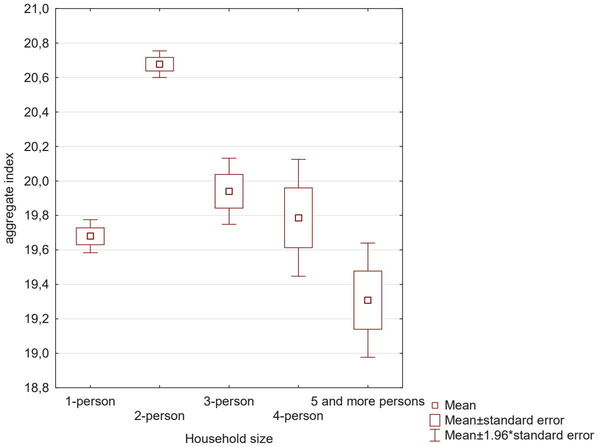

**Figure 7.** The level of the aggregate indicator in 2018 by household size for households of people aged 60 and older. Source: own elaboration based on data from [136].

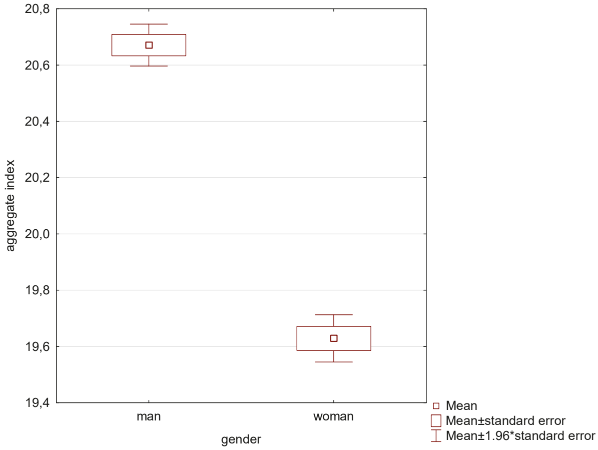

**Figure 8.** The level of the aggregate indicator in 2018 by sex of the person representing the household of people aged 60 and older. Source: own elaboration based on data from [136].

The marital status of a person running a household is another variable that appears to be statistically significant when differentiating the level of the aggregate indicator ($p < 0.05$). The highest analyzed index was recorded in households of married persons (20.9), and the lowest among people who were never married (19.0). The latter category of households was distinguished by a statistically significantly higher level of the analyzed index among other household categories (Figure 11).

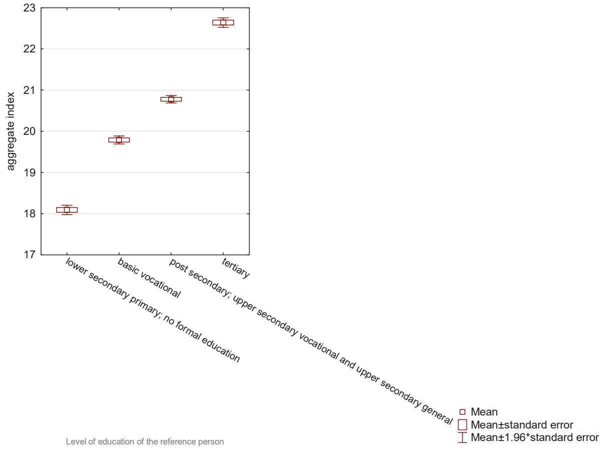

**Figure 9.** The level of the aggregate indicator in 2018 according to the education level of the person representing the household of people aged 60 and older. Source: own elaboration based on data from [136].

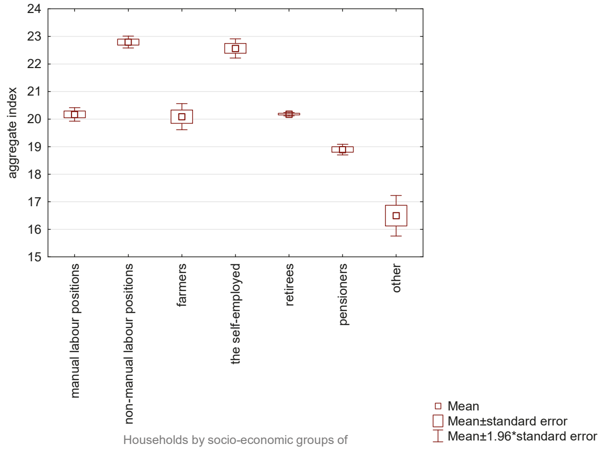

**Figure 10.** The level of the aggregate indicator in 2018 according to the socioeconomic group of households of people aged 60 and older. Source: own elaboration based on data from [136].

Interesting results were also obtained when comparing the value of the aggregate index depending on the method of heating a house/flat. People whose houses/flats were equipped with central heating (20.5), or which were heated with an electric, gas, or tiled stove with a heater (20.4), indicated the greatest energy comfort. The lowest values of the aggregate index were found in households heated with, e.g., coal, oil, or wood heating stoves (17.4), and only these households differed statistically from the others in terms of the level of the analyzed index. On the other hand, households of older people, where the rooms were heated in a different way, i.e., with portable oil stoves or blowers, showed a large variation in the energy poverty index, and its average value amounted to 19.6 (Figure 12).

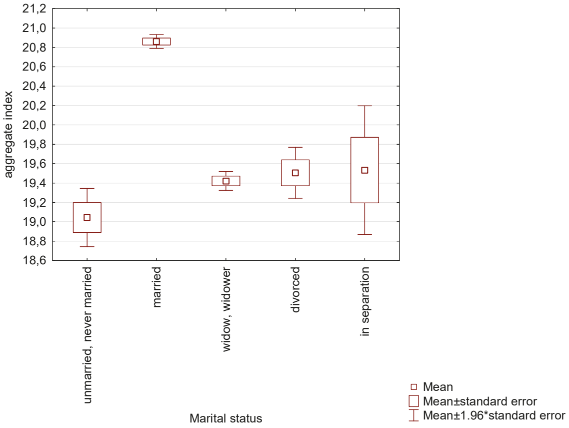

**Figure 11.** The level of the aggregate indicator in 2018 by marital status of a person representing the household of people aged 60 and older. Source: own elaboration based on data from [136].

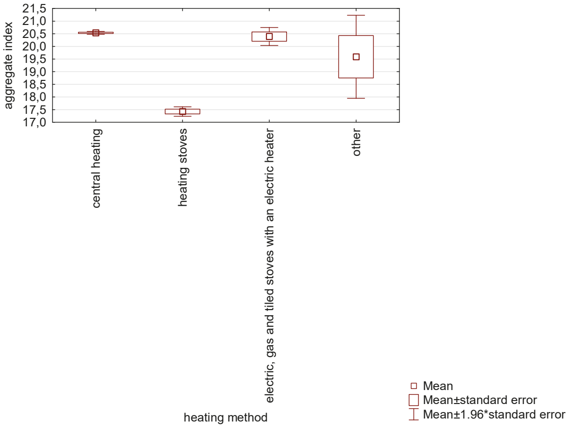

**Figure 12.** The level of the aggregate indicator in 2018 according to the household heating method of people aged 60 and older. Source: own elaboration based on data from [136].

To summarize, the lowest level of the aggregate indicator concerned the following households: people living on social benefits, with low available income, people with primary or lower secondary education, and houses heated by a solid fuel stove. The level of the aggregate indicator did not exceed 18.1 points.

High aggregate values of the indicator were received in households with the highest levels of income, earning their living from non-manual positions or self-employment, houses run by individuals with higher education, and people living in larger cities (500,000 and more inhabitants). In these types of households, the level of the aggregate indicator was estimated at 21.3 points or more.

### *4.3. Types of Households (of People Aged 60 and older), According to Energy Conditions*

As a result of grouping households run by people aged 60 and older, the author distinguished five clusters representing five types of households. The first and largest group, called "moderately energy-satisfied", included households of people with relatively low expenditures on energy carriers and their lowest share in disposable income (6.1%). A relatively low percentage of households, i.e., 1.8% of households, indicated the share of expenditure on energy carriers, which was established at above 20% of their disposable income. The basic method of heating a flat/house in this group was central heating. In these farms, over 1/5 of the disposable income was spent on food and non-alcoholic beverages. In the households from the first group (group I), nearly every 10th household did not have appropriate technical and sanitary conditions. Individuals who made up these households had relatively large flats, slightly larger than the average for all respondents. The average usable floor space of a flat in the first cluster was 78.4 m$^2$, and the average number of rooms was estimated at 3.0. People representing households from the first cluster (cluster I) constituted the smallest share of all clusters among those who indicated architectural barriers in their residential buildings. The percentage of households pointing to difficulties with the timely payment of housing fees was close to the average value for all respondents, amounting to 1.6%. Low and very low levels of satisfaction, in terms of the many needs reported by people forming cluster I, remained at an average level, i.e., close to the average level for all surveyed households, lower than in the case of clusters III and V, and higher compared to groups II and IV. As far as satisfying healthcare needs, 6.3% of the surveyed households indicated a low or very low level of satisfaction of these needs. On the other hand, nearly every fourth household indicated low or very low satisfaction of needs related to culture and recreation, and more than 1/3—those connected with tourism and rest (Table 4).

**Table 4.** Patterns of consumption of energy carriers of the types of households of people aged 60 and older in Poland in 2018.

| Characteristics | 1st Group Modest, Energy-Satisfied | 2nd Group Energy-Satisfied | 3rd Group Energy Dissatisfied | 4th Group Energy Comfort | 5th Group Energy Poor | Total Number |
|---|---|---|---|---|---|---|
| Number of households | N = 8434 | N = 5458 | N = 213 | N = 174 | N = 63 | N = 14342 |
| Aggregate index | 7.6 | 8.6 | 4.1 | 9.7 | 3.2 | 7.9 |
| The level of expenditure on energy carriers (PLN) | 104 | 340 | 76 | 225 | 450 | 197 |
| Share of households where expenditure on energy carriers in available income is 10% or more/20% or more (%) | 19.8/1.8 | 44.4/26.1 | 22.5/0.0 | 12.6/29.9 | 19.1/81.0 | 29.3/11.5 |
| The share of expenditure on energy carriers in disposable income (%) | 6.1 | 16.0 | 6.6 | 8.9 | 39.7 | 9.8 |
| The share of expenditure on energy carriers in consumer expenditure (%) | 9.5 | 20.4 | 9.9 | 13.5 | 36.3 | 14.2 |
| Available income per person (PLN) | 1676 | 2155 | 1152 | 2390 | 1088 | 1857 |
| Expenditure on consumer goods and services in available income (%) | 63.9 | 78.7 | 66.7 | 65.5 | 109.3 | 69.4 |
| The share of expenditures on food in available income (%) | 21.1 | 19.4 | 26.9 | 16.8 | 29.7 | 20.5 |
| The apartment does not have the appropriate technical and sanitary conditions—(sewage, water, electricity, gas, heating installations; good condition of the roof, walls, floors, windows) (%) | 9.4 | 7.0 | 84.5 | 4.6 * | 88.9 | 1423 |
| The apartment does not provide thermal comfort (the apartment is not cool enough in the summer and not warm enough in the winter) (%) | 13.6 | 12.2 | 52.6 | 0.0 | 57.1 | 1965 |
| There is no hot running water in the apartment (%) | 0.0 | 0.0 | 100.0 | 0.0 | 100.0 | 276 |

**Table 4.** *Cont.*

| Characteristics | 1st Group Modest, Energy-Satisfied | 2nd Group Energy-Satisfied | 3rd Group Energy Dissatisfied | 4th Group Energy Comfort | 5th Group Energy Poor | Total Number |
|---|---|---|---|---|---|---|
| Usable floor area of the apartment (m2) | 78.4 | 70.4 | 54.6 | 91.1 | 52.7 | 75.0 |
| Number of rooms (mean number) | 3.0 | 2.8 | 1.8 | 3.3 | 1.7 | 2.9 |
| The apartment is located in a building with architectural barriers that makes it difficult to access the apartment (e.g., no elevator, stairs without driveway, high thresholds, or no handrails) (%) | 27.9 | 34.6 | 30.5 | 35.1 | 39.7 | 4395 |
| The method of heating the apartment (% from the cluster) | | | | | | |
| Central heating (e.g., from a combined heat and power plant, local, or individual boiler room) | 85.8 | 89.6 | 6.6 | 88.5 | 9.5 * | 12,300 |
| A solid fuel stove | 11.2 | 6.3 | 87.3 | 5.8 * | 84.1 | 1537 |
| Electric stove | 2.9 | 4.0 | 5.6 | 4.6 * | 4.8 * | 483 |
| Other heating | 0.2 | 0.1 * | 0.5 * | 1.2 * | 1.6 * | 22 |
| Satisfying consumer needs | | | | | | |
| Bad and rather bad satisfaction of timely payment of housing fees (fixed fees, rent, rental costs, etc.) (% from the cluster) | 1.6 | 1.5 | 8.9 | 0.0 | 17.5 | 1.7 |
| Bad and rather bad satisfaction of culture and recreation needs (% from the cluster) | 24.3 | 22.9 | 40.4 | 14.9 | 61.9 | 24.0 |
| No need for culture and recreation | 16.9 | 14.0 | 39.4 | 11.5 | 28.6 | 16.1 |
| Bad and rather bad satisfaction of tourism and leisure needs (% from the cluster) | 34.5 | 30.2 | 49.8 | 21.3 | 58.7 | 33.0 |
| No need for tourism and leisure | 19.4 | 16.8 | 41.3 | 14.9 | 38.1 | 18.7 |
| Bad and rather bad satisfaction of healthcare needs (% from the cluster) | 9.4 | 10.1 | 19.7 | 4.6 | 39.7 | 9.9 |
| Bad and rather bad satisfaction of clothing and footwear needs (% from the cluster) | 6.3 | 6.7 | 25.8 | 2.9 | 36.5 | 6.8 |
| Bad and rather bad satisfaction of food needs (% from the cluster) | 1.5 | 1.6 | 8.0 | 0.6 | 14.3 | 1.7 |
| The period of construction of the building (% from the cluster) | | | | | | |
| Before 1946 | 18.7 | 16.5 | 56.8 | 15.5 | 61.9 | 2664 |
| In the years 1946–1960 | 13.7 | 11.8 | 26.8 | 10.9 | 27.0 | 1895 |
| In the years 1961–1980 | 42.5 | 43.9 | 11.7 | 35.1 | 9.5 * | 6074 |
| In the years 1981–1995 | 18.9 | 19.7 | 4.2 * | 27.6 | 0.0 | 2724 |
| In the years 1996–2006 | 5.3 | 7.1 | 0.5 * | 9.2 | 0.0 | 851 |
| In the years 2007–2011 | | | | | | |
| after 2011 | 0.9 | 1.0 | 0.0 * | 1.7 * | 1.6 * | 134 |

Comment: the percentages for individual clusters are presented horizontally, i.e., the summed results in the rows should give 100%; * statistically insignificant result. Source: own work.

The characteristics of the demographic and socioeconomic profiles of the households in cluster I indicated that, more often than in other clusters, these households were created by men (62%). These households were relatively the largest, the average number of people, in this case, was estimated at 2.1. The household members of the first group were relatively the youngest, and the average age was 69.6 years; they were married more often than the representatives of other groups examined in the study—the average share amounted to 66%. The level of disposable income in these households reflected an average financial situation, although it was still below the average for all surveyed households. More than 1/3 of the representatives of households in the first cluster were people with primary and vocational education, and less than 1/3 of the respondents declared having secondary education. On the other hand, nearly every fourth person had lower secondary or lower education. People representing the first type were mainly retired (76%), but also working in blue-collar positions more often than in the case of other clusters (6.5%). Nearly half of these households were located in the countryside and slightly more than 30% in towns with less than 100,000 residents (Table 5).

**Table 5.** Economic and sociodemographic characteristics of the types of households of people aged 60 and older in Poland in 2018 (as a percentage of a given cluster).

| Characteristics | 1st Group Modest, Energy-Satisfied | 2nd Group Energy-Satisfied | 3rd Group Energy Dissatisfied | 4th Group Energy Comfort | 5th Group Energy Poor | Total Number |
|---|---|---|---|---|---|---|
| Number of households | N = 8434 | N = 5458 | N = 213 | N = 174 | N = 63 | N = 14342 |
| Available income per person (PLN) | 1676 | 2155 | 1152 | 2390 | 1088 | 1857 |
| Expenditure on consumer goods and services in available income (%) | 63.9 | 78.7 | 66.7 | 65.5 | 109.3 | 69.4 |
| The share of expenditures on food in available income (%) | 21.1 | 19.4 | 26.9 | 16.8 | 29.7 | 20.5 |
| Sex | | | | | | |
| Male (%) | 61.9 | 43.2 | 46.0 | 62.6 | 41.3 | 7808 |
| Female (%) | 38.1 | 56.8 | 54.0 | 37.4 | 58.7 | 6534 |
| Number of people | 2.1 | 1.5 | 1.7 | 1.9 | 1.5 | 1.9 |
| The average age of the person | 69.6 | 70.8 | 72.3 | 69.4 | 72.3 | 70.1 |
| Marital status | | | | | | |
| Unmarried, never married (%) | 4.2 | 5.1 | 17.4 | 2.9 * | 20.6 | 690 |
| Married (%) | 66.3 | 37.9 | 27.7 | 63.8 | 14.3 * | 7843 |
| Widow, widower (%) | 25.1 | 46.7 | 48.4 | 23.0 | 52.4 | 4837 |
| Divorced (%) | 3.8 | 9.4 | 5.6 | 6.9 | 12.7 * | 867 |
| In separation (%) | 0.6 | 0.9 | 0.9 * | 3.5 * | 0.0 | 105 |
| Level of education of the personal | | | | | | |
| Lower secondary, primary, no formal education (%) | 24.3 | 15.1 | 67.6 | 9.8 | 65.1 | 3074 |
| Basic vocational (%) | 34.0 | 24.1 | 23.5 | 21.8 | 22.2 | 4284 |
| Post-secondary, upper secondary vocational, upper secondary general (%) | 30.2 | 39.0 | 8.5 | 40.2 | 11.1 | 4767 |
| Tertiary (%) | 11.6 | 21.8 | 0.5 * | 28.2 | 1.6 * | 2217 |
| Socioeconomic groups | | | | | | |

**Table 5.** *Cont.*

| Characteristics | 1st Group Modest, Energy-Satisfied | 2nd Group Energy-Satisfied | 3rd Group Energy Dissatisfied | 4th Group Energy Comfort | 5th Group Energy Poor | Total Number |
|---|---|---|---|---|---|---|
| Households of employees in manual labor position (%) | 6.5 | 3.0 | 4.7 * | 4.6 * | 1.6 | 728 |
| Households of employees in non-manual labor position (%) | 4.7 | 5.6 | 0.5 * | 10.9 | 3.2 * | 718 |
| Households of farmers (%) | 1.7 | 0.5 | 1.4 * | 0.0 | 1.6 * | 179 |
| Households of self-employed (%) | 2.0 | 1.8 | 0.5 * | 4.6 * | 0.0 | 271 |
| Households of retirees (%) | 76.1 | 78.0 | 67.6 | 73.0 | 60.3 | 10,986 |
| Households of pensioners (%) | 7.8 | 10.3 | 18.8 | 6.3 | 17.5 | 1283 |
| Households living on supplementary welfare allowance (%) | 1.0 | 0.3 | 6.6 | 0.6* | 14.3* | 127 |
| Households having income from other sources (%) | 0.3 | 0.5 | 0.0 | 0.0 | 1.6* | 50 |
| Place of location | | | | | | |
| Urban area, ≥500,000 inhabitants (%) | 8.2 | 17.8 | 2.8 * | 19.0 | 3.2 * | 1707 |
| Urban area, 200,000–499,000 inhabitants (%) | 6.9 | 12.6 | 3.8 * | 10.9 | 9.5 * | 1303 |
| Urban area, 100,000–199,000 inhabitants (%) | 7.4 | 10.9 | 5.2 | 9.2 | 7.9 * | 1250 |
| Urban area, 20,000–99,000 inhabitants (%) | 18.0 | 23.0 | 8.5 | 20.1 | 11.1 * | 2831 |
| Urban area, <20,000 inhabitants (%) | 12.4 | 12.0 | 9.9 | 10.3 | 3.2 * | 1744 |
| Rural area (%) | 47.0 | 23.8 | 70.0 | 30.5 | 65.1 | 5507 |

Comment: the percentages for individual clusters are presented horizontally, i.e., the summed results in the rows should give 100%; * statistically insignificant result. Source: own work.

In the second group, which is referred to as "energy-demanding", the analysis showed relatively high expenditure on energy carriers and its high share in disposable income (16%). Over a quarter of households indicated an over 20% share of expenses on energy, gas, and other fuels in their available income, and 44% spent 10 to 20% of their disposable income on energy carriers. Nearly 90% of the flats/houses from the second cluster used central heating. The disposable income in these households was higher than in clusters I, III, and V, but lower than in cluster IV. A relatively low percentage of people creating these households reported problems related to the technical and sanitary conditions of the rooms (7.0%); however, over 1/3 of the respondents indicated architectural barriers hindering access to housing. The average living space was estimated at over 70 m$^2$. In these households, a similar share of respondents, as in the case of cluster I, reported a low or very low level of satisfaction of their consumption needs.

Households in the second cluster were more frequently represented by women (56.8%) than by men, but the difference was not significant. The average age of the respondents was 70.8 years. These households were most often established by people who lost their spouses (nearly 47% of widowed individuals). The financial situations of these households were relatively favorable. More than a quarter of individuals representing households from the second cluster declared having higher education, which was regarded as a relatively high level in comparison to other groups. People representing the group in question were mainly retirees (78%) or pensioners (10%). A relatively small share of these households was located in the countryside (23.8%), and a relatively large group of survey participants lived in larger cities, with more than 199,000 inhabitants (30.4%).

In households from the first and second cluster, the technical and sanitary conditions (access to water supply, flushing toilet, bathroom, hot running water, gas, central heating), as well as the heating methods were comparable. However, in the second cluster, energy carrier expenditures were at a much higher level, which may suggest different preferences in terms of the comfort of people from both types of households. Perhaps this fact was influenced by the gender of the respondents. The households from the second cluster were more often represented by women, who, according to the literature review, frequently prefer higher temperatures than men.

The next three clusters are groups with considerably fewer cases of households than the previous ones. The third group, referred to as "energy-unsatisfied", are households with the lowest levels of expenditures on energy carriers and the lowest share in disposable income (6.6%). The main methods of heating in these households were stoves fired with solid fuels, e.g., coal, wood. In more than half of these households, the respondents reported problems with ensuring the maintenance of adequate heat comfort in living quarters in the winter and summer. In nearly 31% of households, the survey participants indicated architectural access barriers to housing. The usable areas of flats were relatively small (approximately 55 m$^2$). In nearly 9% of households, the respondents reported problems with the timely payment of residential rents and other housing fees. In a relatively high share of households, the residents also indicated a problem with meeting other consumption needs. For example, in more than 40% of households, the research indicated a low or very low satisfaction of needs related to culture and recreation, and the needs of tourism and leisure were not satisfied in almost half of the surveyed households. In every fifth household, low and very low satisfaction of healthcare needs was reported; in every fourth household, clothing and footwear needs remained largely unsatisfied (Table 4).

Households included in cluster III—similarly to cluster V—were composed of relatively older people (72.3 years) than in other clusters. About half of these households were managed by widows. The disposable income in the analyzed households was, next to the households from cluster V, the lowest income per person, which indicates a modest financial situation. First, individuals representing this group had the lowest level of education (67.6%), or the basic vocational education level (23.5%). Here, the groups of individuals with secondary (8.5%) and higher education constituted the smallest shares among all the clusters. Retirees (68%) and disability pensioners (20%) were the two largest socioeconomic groups represented in this cluster. Moreover, the largest percentage of households from cluster III, compared to other clusters, was located in the countryside (70%) (Table 5).

The presented characteristics of households, in terms of conditions related to heat and electricity in households, indicate the possibility of energy deprivation of household members from the third cluster. Despite the low percentage of households spending more than 20% of their disposable income on energy carriers, the unfavorable financial situation, poor technical and sanitary conditions, as well as high percentages of households with unmet consumer needs, including thermal comfort, prove a lack of energy comfort. The characteristics of this cluster also show that taking into account only objective features in the field of energy expenditure, such as the share of energy expenditure in disposable income (low in the analyzed cluster), does not provide a full picture, in terms of meeting energy needs. Therefore, it is advisable to create aggregate indicators of energy poverty that take into account both the objective and subjective evaluation of the situation of the respondents.

In the fourth group, which is referred to as "energy comfort", the highest level of the aggregate energy poverty index was recorded, and it amounted to 9.7. These households incurred the expenditure on energy carriers, which is slightly higher than average, with the share that does not exceed 10% of the household's disposable income. The main method of heating in these households was central heating (89%). These households were characterized by the most favorable financial situations among all of the examined groups. Moreover, in this group, the share of food expenditure in disposable income was evidence of a better standard of living than in the case of other clusters. These households had the largest usable dwelling areas (91.1 m$^2$). More than 35% of members representing these households pointed to architectural barriers in their residential building that hinder access to housing. This appears to be a relatively serious problem, similar to the circumstances indicated in the case of cluster I. In these households, the lack of satisfaction of consumption needs was reported relatively least frequently among all clusters. Moreover, 15% of the household representatives complained about the low and very low levels of satisfaction of needs related to culture and recreation, while 21% complained about unsatisfied needs with regard to tourism and recreation. Less than 5% of respondents indicated that their healthcare needs were not met to a sufficient degree.

As far as the demographic and socioeconomic profiles of cluster IV—households represented by men accounted for nearly 63% of the group and it was the highest percentage of all surveyed clusters. These individuals, first, were married—64%; more often than in other cases, declared having higher education—28% or secondary education—40%. People with the lowest levels of education represented the smallest share, i.e., 10% among all of the analyzed clusters These households were located mainly in larger cities with more than 199,000 inhabitants (30%) and in villages (31%).

Cluster V, which constituted the smallest group, including 63 households, was called "energy-poor". These households indicated a high level of expenditure on energy carriers and a very high percentage of such costs in their disposable income (40%). Residential buildings were heated mainly with solid fuels, such as coal or wood. In these households, it was observed that the level of consumer spending exceeded the level of their disposable income, which may be related to the indebtedness of the analyzed households. This fact may also reflect the tendency for income to be underestimated by some representatives of households; therefore, analyzing the expenses of households may prove to be more effective as an indication of their actual circumstances.

The level of disposable income in these households was the lowest among all clusters, and the percentage of food expenditure was the highest among all the examined clusters. It is worth mentioning that over 14% of these households indicated the unmet needs related to food consumption. Among other problems that appeared in the households from the fifth cluster, the respondents indicated architectural barriers in residential buildings that made access to housing difficult. In this case, the issue was pointed out by the largest share of households from all groups, i.e., nearly 40%. These households occupied the smallest usable floor space of a flat, i.e., 52.7 $m^2$.

Households in the fifth cluster were represented by women more often than in other clusters (59%), and more than half of the households included individuals who lost their spouses (widows and widowers). These people declared having a low level of education, i.e., lower secondary and lower level of education (65%) and vocational education was pointed out by 22% of the share. People who make up these households lived mainly in the countryside (65%). It was also noticed that in cluster V, similar to cluster III, people representing households were the oldest, i.e., they were over 72 years old, compared to 69–70-year-old individuals in other clusters.

Households from clusters III and V lived in older residential buildings. In these clusters, high percentages of respondents indicated a poor technical and sanitary condition of the dwellings they occupied. In cluster V, a large percentage of respondents pointed to architectural barriers hindering access to the residential building.

## 5. Discussion

Housing conditions, including those related to energy carriers, in Polish households run by older people appear to be improving. However, the studies conducted by other authors do not clearly indicate a consistent improvement in the field of energy poverty: in some countries, the percentage of households affected by this problem seems to be decreasing [155], while in other countries, energy poverty is spreading [156].

In households managed by elderly people, the living conditions in terms of ensuring an adequate energy standard are still worse than in households of younger people. Research shows [157] that seniors—due to physiological changes occurring with age—are more exposed to very low and very high temperatures. It's worth adding, physiological changes in the organisms of the elderly, and the more difficult financial situations of this group, often lead to insufficient provision of adequate thermal conditions in the apartment, which is confirmed by own research and other studies [158]. Research emphasizes that the elderly population is more exposed to extreme temperatures in both winter and summer [159,160].

Research from Australia has shown that elderly people with low incomes much less frequently used devices, such as air conditioners, to improve their quality of life than younger people [161]. The study by A.C. Sadath and R.H. Acharya [162] finds that income poverty and energy poverty are commensurate with each other. The research [163] also draws attention to the ineffectiveness of heating systems in many apartments occupied by the elderly. The study emphasizes the need to improve energy policy in order to align the requirements for the thermal performance of buildings with the wider healthcare plan and the specific needs of older people.

The conducted research showed that people living in the countryside, in multi-person households, with a low level of education, and heating their homes with obsolete heating equipment, have a greater chance of remaining at risk of energy poverty than people living in other types of households. These results are consistent with analyses from other countries where the authors emphasize that, in rural areas, individuals face a greater risk of energy poverty than those living in urban areas [155,164].

Other studies [1] confirm the positive impact of higher education on energy satisfaction. However, research [165] shows that the education level of households does not have any significant effect on energy poverty, although, on the other hand, in households with persons having higher education, their awareness of energy conservation measures is linked to a reduction in energy poverty, particularly in households having lower income.

People experiencing energy poverty often have to choose between warmth and food [166,167]. Satisfying other consumption needs also means deprivation in the analyzed households. In some of the surveyed households, it was found that the needs in terms of culture and recreation, tourism and leisure, healthcare, clothing, and footwear were poorly (or very poorly) met. The research findings also show that, in other households these needs do not exist at all. Thus, the results of other studies [162,163] have confirmed that energy poverty also has an impact on the health of residents.

Many studies show a link among gender, energy, and poverty. It turns out that women are more exposed to energy poverty [159,168–172].

In the third and fifth cluster, high percentages of households equipped with a solid fuel stove, additionally indicating an unfavorable financial situation, indicate the phenomenon of energy deprivation, which may lead to adverse health effects [173]. Heating your home with a coal and wood stove poses a greater risk of lung disease, especially among energy-poor people. Inefficient heat sources increase indoor air pollution. Nearly 40% of people who have a coal or wood stoves suffer from respiratory diseases (including asthma and bronchitis). Moreover, energy-poor people who heat their apartments with a solid fuel stove in a flat area have a 27% higher risk of getting a respiratory disease than energy-poor people whose apartments are connected to the heating network [174]. It should also be noted that heating with a solid fuel stove (coal, wood) is more burdensome. Manual heating and maintaining a stable temperature require storage and systematic refilling of fuel. Individual heating also requires effort: getting up at night, carrying fuel, cleaning the stove, as well as the use of additional equipment—heat guns, moisture absorbers, or air purifiers. It is also associated with additional energy consumption and higher costs, which is particularly burdensome for pensioners' household budgets. It probably also has a significant impact on lowering the standard of living of these people [174]. In Poland, the use of hard coal stoves in rural areas is very high [175].

Households from clusters with the least favorable financial situations lived in older residential buildings. In these clusters, relatively high of respondents indicated a poor technical and sanitary condition of the dwellings they occupied. The respondents also pointed to architectural barriers hindering access to the residential building. As a rule, new homes are usually safer and healthier because they are built in accordance with modern building standards, technologies, and regulations—as well as with (constantly changing) consumer expectations [176,177]. However, they are usually inhabited by younger people. With this in mind, appropriate support programs should be targeted at residents of older homes, especially those who are elderly and whose disposable incomes do not allow for investments in the modernization of housing premises. It is also worth conducting initiatives to support these households (i.e., with installations using renewable energy sources) [178].

## 6. Conclusions

Households consisting of elderly people are strongly diversified (i.e., in terms of housing conditions, including energy conditions). Research carried out in Poland shows that a minor percentage of households of people aged 60 and older are in a very difficult situation, in terms of having their needs satisfied, in relation to energy carriers. These are mainly people with low levels of education, living on social benefits, with low levels of disposable income, living in the countryside.

Therefore, the energy deprivation of Polish households, of people aged 60 and older, seems to occur mainly among specific socio-professional clusters, consisting of households with persons with lower education, people with low income, as well as those living in the countryside. The conducted research—similar to the previous work [1]—exposed that the possibility of perceive energy poverty solely through the prism of income-based indicators may result in the failure to detect all energy-impoverished persons. The age and gender of the person representing the household are important demographic determinants of energy poverty. It was noticed that households represented by men aged 60 and older have a better energy supply than households run by women. Households with people aged 60 and over, in which a woman is the head of the household, are more likely to suffer from energy poverty. Similarly, the older the person representing the household, the greater the likelihood of reporting that the energy comfort needs are not met. It seems that these features are related, inter alia, to the physiology of these people. Women need higher ambient temperatures. With age, people move less, which also affects the problem of thermal discomfort experienced in the immediate environment.

Polish households of people aged 60 and older were classified into five groups according to the spending on energy, gas, and other fuels and meeting their needs related to thermal conditions (moderately energy-satisfied, energy-demanding, energy-unsatisfied, energy-comfort, and energy-poor). The identified groups are heterogeneous in terms of the variables under consideration.

The research indicated the existence of varied patterns of consumption of energy carriers in households of people aged 60 and older in Poland and dissimilarities in terms of the reasons for energy poverty among households, of people aged 60 and older. The most important factors influencing energy poverty in the households of people aged 60 and older involved income situations and social and professional characteristics.

Research findings provide critical implications for policymakers whose goal is to alleviate energy poverty. Households of people aged 60 and over often have low income, which prevents them from covering their energy expenditures and ensuring adequate housing conditions. Until their incomes rise, they will not be able to spend more on access to energy services, and their deprivation will continue. Thus, it is necessary to raise income levels or introduce appropriate legal solutions (support programs) that will enable people from these households to have access to an adequate amount of energy. This applies especially to people living in the countryside, who support themselves using social benefits. Income from social benefits for older people is usually low and is not sufficient to cover basic needs. Obsolete heating solutions do not ensure proper energy comfort in these households. Expenditures on electricity and fuel accounts for a significant share of household income, leaving limited funds to be spent on other necessities and services. Reliance on traditional fuels, such as hard coal, is a major problem in rural areas. It is, therefore, necessary to extend the gas pipeline network, so that residents in rural areas can use natural gas as well.

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# Nonlinear Causality between Crude Oil Prices and Exchange Rates: Evidence and Forecasting

**Witold Orzeszko**

Department of Applied Informatics and Mathematics in Economics, Faculty of Economic Sciences and Management, Nicolaus Copernicus University in Torun, ul. Gagarina 13a, 87-100 Torun, Poland; witold.orzeszko@umk.pl

**Abstract:** The relationships between crude oil prices and exchange rates have always been of interest to academics and policy analysts. There are theoretical transmission channels that justify such links; however, the empirical evidence is not clear. Most of the studies on causal relationships in this area have been restricted to a linear framework, which can omit important properties of the investigated dependencies that could be exploited for forecasting purposes. Based on the nonlinear Granger causality tests, we found strong bidirectional causal relations between crude oil prices and two currency pairs: EUR/USD, GBP/USD, and weaker between crude oil prices and JPY/USD. We showed that the significance of these relations has changed in recent years. We also made an attempt to find an effective strategy to forecast crude oil prices using the investigated exchange rates as regressors and vice versa. To this aim, we applied Support Vector Regression (SVR)—the machine learning method of time series modeling and forecasting.

**Keywords:** crude oil prices; exchange rates; nonlinear causality; forecasting; support vector regression; machine learning

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## 1. Introduction

The crucial role of crude oil in the world economy has implied a discussion on links between oil prices and other macroeconomic and financial variables. Both theoretical and empirical research have pointed out some sources and potential consequences of these links (cf. [1]). It has been noticed that one of the most important factors connected with crude oil prices is exchange rates. The relation between oil prices and exchange rates has always been of interest to academics and policy analysts. Theory indicates various mechanisms which explain this relationship. They refer not only to direct ways how both variables affect each other but also to indirect transmission channels referring to specific macroeconomic or financial factors [2]. It should be noted that both directions of causation are well-founded. On the one hand, crude oil prices affect exchange rates. Crude oil is the most important source of energy in the world, and its price does not offer a substantial arbitrage opportunities. On the other hand, exchange rate connects the internal and external economies, hence in market-oriented and open economies crude oil prices exert on exchange rates [3]. More specifically, three direct transmission channels of oil prices to exchange rates can be indicated: the terms of the trade channel, the wealth effect channel, and the portfolio reallocation channel [4]. On the other hand, reverse causality from exchange rates to crude oil prices is also theoretically motivated. The main reason for this fact is that oil prices are denominated in USD. An appreciation of the U.S. dollar increases the price of oil in domestic currencies for countries besides the U.S., which directly affects the oil supply and demand. Moreover, exchange rates can also affect oil prices directly through financial markets or indirectly via other financial assets, and through portfolio rebalancing and hedging practices in particular [5].

The relationships between crude oil prices and exchange rates have been the topic of a rapidly growing body of empirical literature over the past two decades (cf. [1,3,6–9]). The general literature on this issue can be divided into four main research areas: links between exchange rates and imported crude oil prices, causality analysis, variance decomposition and impulse response, and the influence of crisis [7]. The obtained results showed that the relations between crude oil prices and exchange rates can differ in time length. Many studies found long-run connections between oil prices and exchange rates. There is also much weaker evidence for short-run linkages and spillovers between both variables at daily and monthly frequencies (cf. [1,3]). Moreover, it has been shown that the detected relationships are time-varying, which can be the effect of their nonlinear or asymmetric mechanism [3].

The main purpose of our paper was to test for bidirectional Granger causality between crude oil prices and selected exchange rates, namely, EUR/USD, GBP/USD, and JPY/USD, and to analyze its stability. In econometrics, Granger causality is one of the most popular concepts of causality. It provides not only a strong insight into the mechanism of the relationships, but most of all indicates the potential ability to predict investigated time series. In the economic literature, Granger causality is usually tested in the framework of linear dependencies, represented by VAR models (cf. [10]). In particular, linear Granger causality between crude oil prices and exchange rates has been studied by [2,7,9,11–16]. The obtained results are not so clear on the direction of the causal relationship between these two variables; however, some authors found evidence for bidirectional causality (see [1,9]). On the other hand, it has been generally noted that the linear approach is not sufficient in the case of nonlinear relations (e.g., [17–19]). Many studies have confirmed the nonlinear dynamics of financial and economic systems, which indicates the need for including nonlinear causality tests in studies. Otherwise, one can omit important properties of the investigated dependencies that could be exploited for forecasting purposes (cf. [10]). The nonlinear analysis of the relationships between crude oil prices and exchange rates has been performed much more rarely than the linear one, but the obtained results show that it can give a better insight into the mechanism of the investigated dependencies (e.g., [8,20–24]). It has been argued that the nonlinear causality behavior between oil prices and exchange rates can be explained by asymmetric responses of economic activity to oil price shocks [25–27], the negative effects of oil price uncertainty on economic activity [28], structural breaks, persistence and discontinuity in the adjustment (cf. [21]).

For these reasons, in our study, we tested for nonlinear causality, using two nonlinear causality tests, introduced by Hiemstra and Jones [18] and Diks and Panchenko [29]. Moreover, we divided the analyzed period into two subperiods in order to verify if the existing causalities were stable over time.

It has been concluded in the literature that the frequent finding that exchange rates and oil prices move together (especially over the long-run) does not necessarily imply that one is useful when forecasting the other. The reason is that past relationships do not necessarily hold in the future and the link between in-sample and out-of-sample is often rather weak [1]. That is why the purpose of our study was not limited only to detecting causality between the investigated series, but additionally to make an attempt to exploit these relations for effective forecasting. As the predictor, we applied Support Vector Regression (SVR)—the machine learning method of time series modeling and forecasting. In recent years, specific machine learning techniques have been successfully applied for forecasting purposes. They are data-driven, self-adaptive methods requiring very few assumptions concerning the investigated data. The support vector regression model [30] is based on the support vector machine method [31], which was originally introduced to solve classification problems. It is designed to have a good power of generalization and an overall stable behavior, which implies a good out-of-sample performance. Many studies in the literature have shown that SVR models can give more accurate forecasts than alternative machine learning methods and can be successfully used to forecast financial time series, such as stock indices, stock prices, future contracts, or exchange rates (see, e.g., [32–35]). SVR and SVR-based models have also been applied to forecast crude oil prices [36–41] or exchange rates [42–46]. However, it should be noted that most of these models were autoregressive. In particular, to the best of our knowledge, there has not been an attempt to incorporate crude oil prices and exchange rates jointly to the SVR model, using one of these variables as the regressor for the second one. In our study, we construct and analyzed such SVR models to verify if potential predictability (ensured by the existence of Granger causality) really can result in more accurate forecasts.

The paper has three main contributions:

- First, we found strong nonlinear causal relationships between crude oil prices and most investigated exchange rates;
- Second, we showed that the significance of the detected relationships has changed in recent years;
- Third, we applied SVR models of different kernels and regressors to verify if it is possible to exploit the detected relationships for effective forecasting.

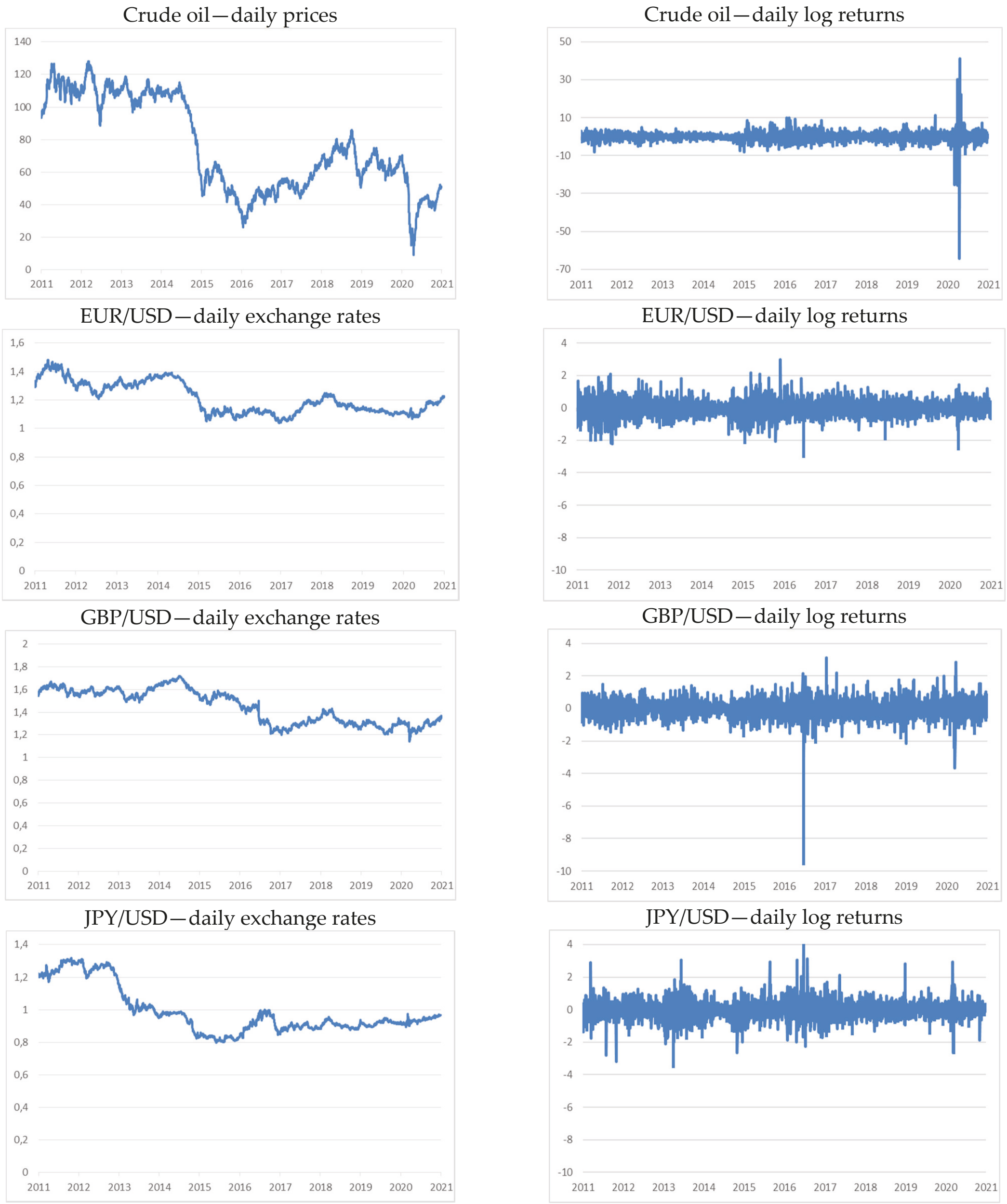
The rest of the paper is organized in the following way. In Section 2, we introduce data and describe the applied methods. Section 3 provides the results of our research. Finally, in the last section, we discuss and conclude our findings.

## 2. Materials and Methods

### 2.1. Data

Our dataset consisted of the Brent spot prices' FOB (published by the United States Energy Information Administration (EIA)) and the exchange rates of three most heavily traded currency pairs in the forex market, namely EUR/USD, GBP/USD, and JPY/USD. We analyzed the daily data from 3 January 2011 to 31 December 2020. However, in order to verify if the existing causalities were stable over time, we divided the analyzed period into two separate subperiods. For comparison purposes (i.e., to preserve the same power of the applied tests), we considered two subperiods of the same length—from 3 January 2011 to 31 December 2015 (Period 1) and from 4 January 2016 to 31 December 2020 (Period 2). All data were transformed to log returns using the formula $r_t = 100 \ln(p_t / p_{t-1})$, where $p_t$ is the price at time $t$. The investigated time series are presented in Figure 1. One can see differences between both subperiods under study. There was a strong decline in crude oil prices at the end of Period 1, which was the effect of the decisions of the U.S. and OPEC countries to increase production, resulting in oversupply of crude oil compared to demand. The crude oil prices were stabilized at clearly lower levels in Period 2. On the other hand, the plot for daily log returns showed that the volatility of crude oil prices increased in Period 2. This conclusion is confirmed by the descriptive statistics in Table 1.

For all investigated series, the calculated means were negative in the whole period and in Period 1. Other statistics showed noticeable differences between crude oil and exchange rates; crude oil proved to be much more volatile than the exchange rates (especially in Period 2). As a consequence, it was characterized by the highest absolute values of the minimum and maximum returns and a very high standard deviation. Moreover, the distribution of crude oil returns exhibited the strongest skewness (except Period 1) and the highest kurtosis. According to the results of the Ljung–Box test, only the returns for crude oil were autocorrelated.



Crude oil—daily prices

Crude oil—daily log returns

EUR/USD—daily exchange rates

EUR/USD—daily log returns

GBP/USD—daily exchange rates

GBP/USD—daily log returns

JPY/USD—daily exchange rates

JPY/USD—daily log returns

**Figure 1.** Investigated time series from the period 3 January 2011–31 December 2020.

**Table 1.** Descriptive statistics of the investigated returns.

| | **Mean** | **Min** | **Max** | **SD** | **Skew** | **Kurt** | **LB(10)** |
|---|---|---|---|---|---|---|---|
| 3 January 2011–31 December 2020 | | | | | | | |
| Crude oil | −0.024 | −64.370 | 41.202 | 2.920 | −3.270 | 121.79 | 0.000 |
| EUR/USD | −0.002 | −2.948 | 2.962 | 0.526 | −0.087 | 2.123 | 0.382 |
| GBP/USD | −0.005 | −9.505 | 3.130 | 0.572 | −1.809 | 31.663 | 0.263 |
| JPY/USD | −0.009 | −3.466 | 4.136 | 0.564 | 0.113 | 5.298 | 0.655 |
| 3 January 2011–31 December 2015 (Period 1) | | | | | | | |
| Crude oil | −0.074 | −8.245 | 8.508 | 1.696 | −0.062 | 3.175 | 0.051 |
| EUR/USD | −0.015 | −2.230 | 2.962 | 0.595 | −0.012 | 1.524 | 0.485 |
| GBP/USD | −0.003 | −1.649 | 1.490 | 0.462 | −0.085 | 0.562 | 0.250 |
| JPY/USD | −0.031 | −3.466 | 3.032 | 0.577 | −0.221 | 4.110 | 0.402 |
| 4 January 2016–31 December 2020 (Period 2) | | | | | | | |
| Crude oil | 0.026 | −64.370 | 41.202 | 3.756 | −3.081 | 87.576 | 0.000 |
| EUR/USD | 0.010 | −2.948 | 1.803 | 0.448 | −0.186 | 2.507 | 0.718 |
| GBP/USD | −0.007 | −9.505 | 3.130 | 0.664 | −2.271 | 34.228 | 0.339 |
| JPY/USD | 0.013 | −2.653 | 4.136 | 0.551 | 0.503 | 6.583 | 0.244 |

Note: Mean denotes the arithmetic mean, Min—minimum, Max—maximum, SD—standard deviation, Skew—skewness, Kurt-excess kurtosis, LB(10)—the *p*-value of the Ljung–Box test for autocorrelation (with 10 lags).

### 2.2. Nonlinear Causality Tests

The most general definition of Granger causality is formulated in terms of conditional probability distributions [47]. It states that $X_t$ does not Granger-cause $Y_t$ if:

$$F(Y_t|(X_{t-1}, X_{t-2}, \ \ldots; Y_{t-1}, Y_{t-2}, \ldots)) = F(Y_t|(Y_{t-1}, Y_{t-2}, \ \ldots)), \tag{1}$$

where $(X_t, Y_t)$ is a strictly stationary bivariate stochastic process and $F$ denotes the conditional cumulative distribution function. According to the definition, when Equation (1) is not satisfied, we say that $X_t$ is a Granger cause of $Y_t$ (denoted: X→Y).

In causality testing, it is assumed that the lags of the processes $X_t$ and $Y_t$ are finite; hence, the null hypothesis of noncausality is expressed by the formula:

$$F\left(Y_t\middle|\left(X_{t-1}, \ \ldots, X_{t-lx}; Y_{t-1}, \ \ldots, Y_{t-ly}\right)\right) = F\left(Y_t\middle|\left(Y_{t-1}, \ \ldots, Y_{t-ly}\right)\right) \tag{2}$$

for given $lx \geq 1$, $ly \geq 1$. It is convenient to reformulate Condition (2) using the lagged vectors of $X_t$ and $Y_t$, i.e., $\overset{\wedge\, lx}{X_t} = (X_t, X_{t-1}, \ldots, X_{t-lx+1})$ and $\hat{Y}_t^{ly} = \left(Y_t, Y_{t-1}, \ \ldots, \ Y_{t-ly+1}\right)$. In this notation, it takes the form:

$$F\left(Y_t\middle|\left(\hat{X}_{t-1}^{lx}, \hat{Y}_{t-1}^{ly}\right)\right) = F\left(Y_t\middle|\hat{Y}_{t-1}^{ly}\right). \tag{3}$$

Due to its generality, Equation (3) is not easy to verify in practice. Therefore, it is often reduced to the equality of the means of both conditional distributions and considered in the linear framework using VAR models. However, this approach has low power against many nonlinear alternatives. For this reason, Baek and Brock [17] introduced the alternative definition and the test for nonlinear Granger causality, using the correlation integrals. Formally, for a multivariate random vector $W$, the associated correlation integral $C_W(\varepsilon)$ is the probability of finding two independent realizations of the vector at a distance smaller than (or equal to) $\varepsilon$, i.e.,

$$C_W(\varepsilon) = P\left\{\| \ \bar{W} - \widetilde{W} \ \| < \varepsilon\right\} = \int \int \ I_\varepsilon(s_1, s_2) f_W(s_1) f_W(s_2) ds_2 ds_1, \tag{4}$$

where $\overline{W}, \widetilde{W}$ are independent copies of $W$, $\| \, . \, \|$ is the supremum norm, and $I_\varepsilon(s_1, s_2)$ denotes the indicator function that equals 1 when $s_1$ and $s_2$ are within the supremum-norm distance $\varepsilon$ of each other, and 0 otherwise. In the concept of Baek and Brock, $X_t$ does not nonlinearly Granger-cause $Y_t$ if:

$$P\Big\{\| Y_t - Y_s \| < \varepsilon \Big| \Big(\| \hat{Y}^{ly}_{t-1} - \hat{Y}^{ly}_{s-1} \| < \varepsilon, \| \hat{X}^{lx}_{t-1} - \hat{X}^{lx}_{s-1} \| < \varepsilon\Big)\Big\} = P\Big\{\| Y_t - Y_s \| < \varepsilon \Big| \| \hat{Y}^{ly}_{t-1} - \hat{Y}^{ly}_{s-1} \| < \varepsilon\Big\}. \tag{5}$$

Equation (5) states that the conditional probability that $Y_t$ and $Y_s$ are within the distance $\varepsilon$, given that the corresponding lagged vectors $\hat{Y}^{ly}_{t-1}$ and $\hat{Y}^{ly}_{s-1}$ are $\varepsilon$-close, remains the same as when, in addition, one also conditions on the vectors $\hat{X}^{lx}_{t-1}$ and $\hat{X}^{lx}_{s-1}$ being $\varepsilon$-close. This means that $lx$ lags of $X_t$ do not incrementally help to predict the next period's value of $Y_t$, given $ly$ lags of $Y_t$.

Note that based on the definition of the conditional probability, the null hypothesis of Granger nonlinear noncausality given by (5) may be expressed as follows:

$$\frac{C1}{C2} = \frac{C3}{C4}, \tag{6}$$

where $C1$, $C2$, $C3$, and $C4$ are the correlation integrals of the form:

$$C1 = P\Big\{\| \hat{Y}^{ly+1}_{t} - \hat{Y}^{ly+1}_{s} \| < \varepsilon, \| \hat{X}^{lx}_{t-1} - \hat{X}^{lx}_{s-1} \| < \varepsilon\Big\}, \tag{7}$$

$$C2 = P\Big\{\| \hat{Y}^{ly}_{t-1} - \hat{Y}^{ly}_{s-1} \| < \varepsilon, \| \hat{X}^{lx}_{t-1} - \hat{X}^{lx}_{s-1} \| < \varepsilon\Big\}, \tag{8}$$

$$C3 = P\Big\{\| \hat{Y}^{ly+1}_{t} - \hat{Y}^{ly+1}_{s} \| < \varepsilon\Big\}, \tag{9}$$

$$C4 = P\Big\{\| \hat{Y}^{ly}_{t-1} - \hat{Y}^{ly}_{s-1} \| < \varepsilon\Big\}. \tag{10}$$

Given time series $x_t$ and $y_t$ of $n$ realizations on $X_t$ and $Y_t$, Equation (6) is verified using the estimators of the correlation integrals (7)–(10):

$$C1(N) = \frac{2}{N(N-1)} \sum_{t<s}\sum I_\varepsilon(\hat{y}^{ly+1}_{t}, \hat{y}^{ly+1}_{s}) I_\varepsilon\Big(\hat{x}^{lx}_{t-1}, \hat{x}^{lx}_{s-1}\Big), \tag{11}$$

$$C2(N) = \frac{2}{N(N-1)} \sum_{t<s}\sum I_\varepsilon(\hat{y}^{ly}_{t-1}, \hat{y}^{ly}_{s-1}) I_\varepsilon\Big(\hat{x}^{lx}_{t-1}, \hat{x}^{lx}_{s-1}\Big), \tag{12}$$

$$C3(N) = \frac{2}{N(N-1)} \sum_{t<s}\sum I_\varepsilon(\hat{y}^{ly+1}_{t}, \hat{y}^{ly+1}_{s}), \tag{13}$$

$$C4(N) = \frac{2}{N(N-1)} \sum_{t<s}\sum I_\varepsilon(\hat{y}^{ly}_{t-1}, \hat{y}^{ly}_{s-1}), \tag{14}$$

where $t, s = \max(lx, ly) + 1, \ldots, n$, $N = n - \max(lx, ly)$.

Hiemstra and Jones [18] modified the test introduced by Baek and Brock by relaxing its assumptions. According to their testing procedure (H-J test), for the given values of $lx \geq 1$, $ly \geq 1$, and $\varepsilon > 0$, under the assumptions that $X_t$ and $Y_t$ are strictly stationary, weakly dependent, and satisfy the mixing conditions of Denker and Keller [48], if $X_t$ does not strictly Granger-cause $Y_t$ then:

$$\sqrt{N}\left(\frac{C1(N)}{C2(N)} - \frac{C3(N)}{C4(N)}\right) \sim N\Big(0, \sigma^2(lx, ly, \varepsilon)\Big), \tag{15}$$

where the definition and the estimator of $\sigma^2(lx, ly, \varepsilon)$ were given in the Appendix of Hiemstra and Jones [18].

It was noted by Diks and Panchenko [49] that the H-J test is not fully compatible with the definition of Granger causality; hence, it may lead to over-rejection of the null hypothesis of noncausality. Therefore, they proposed an alternative test (D-P test) which overcomes these inadequacies [29]. Their test statistics takes the form:

$$T_N(\varepsilon) = \frac{(2\varepsilon)^{-lx-2ly-1}}{N(N-1)(N-2)} \sum_i \left[ \sum_{k \neq i} \sum_{j \neq i} \left( I_{ik}^{XYZ} I_{ij}^{Y} - I_{ik}^{XY} I_{ij}^{YZ} \right) \right], \tag{16}$$

where $I_{ij}^{W} = I_\varepsilon(W_i, W_j)$ and $XYZ = \left(\hat{X}_{t-1}^{lx}, \hat{Y}_{t-1}^{ly}, Y_t\right)$. In the case of $lx = ly = 1$, Diks and Panchenko proved that their test statistics is asymptotically distributed as standard normal and diverges to positive infinity.

It should be noted that the value of the test statistics in both the H-J and D-P tests depends on the parameters $lx, ly$, and $\varepsilon$. In practice, lags $lx = ly = 1, 2, \ldots, l_{max}$ are considered, where $l_{max}$ is a fixed natural number. In the studies presented in the literature, the value of a distance measure $\varepsilon$ between 0.5 and 1.5 is recommended for consideration (cf. [18,29,50]).

### 2.3. Support Vector Regression

Consider the regression model:

$$y = r(\mathbf{x}) + \delta, \tag{17}$$

where $r(\mathbf{x})$ is the unknown regression function, $y$ is the dependent variable, $\mathbf{x}$ is the vector of explanatory variables, and $\delta$ is an additive zero-mean noise with variance $\sigma^2$. The general purpose of SVR is to use a training dataset $\{(\mathbf{x}_t, y_t)\}_{t=1,\ldots n}$ to approximate $r(\mathbf{x})$ by a function $f(\mathbf{x})$, which has, at most, $\varepsilon$ deviation from the outputs $y_t$ and is as flat as possible [51]. To construct the SVR function $f(\mathbf{x})$, the vectors $\mathbf{x}$ are mapped onto a high-dimensional space using some specific nonlinear transformation, and next, the coefficients of the linear model:

$$f(\mathbf{x}) = \sum_{i=1}^{d} \omega_i \varphi_i(\mathbf{x}) + b \tag{18}$$

are estimated, where $d$ is the space dimension, $\varphi_i(\mathbf{x})$ are the transformation functions, $\omega_i$ denote the model coefficients, and $b$ is the bias term [52,53]. In order to estimate $\omega_i$ and $b$, the $\varepsilon$-insensitive loss function:

$$L_\varepsilon(y, f(\mathbf{x})) = \begin{cases} 0, \ |y - f(\mathbf{x})| \leq \varepsilon, \\ |y - f(\mathbf{x})| - \varepsilon, \ \text{otherwise} \end{cases} \tag{19}$$

has been proposed [31]. By its construction, $L_\varepsilon$ does not penalize errors below some $\varepsilon > 0$, chosen a priori. This means that training points within the $\varepsilon$-margin have no loss; hence, only points located outside the $\varepsilon$-margin are used as the support vectors to estimate the model. However, the accuracy of the approximation (measured by the function $L_\varepsilon$) is not the only postulate taken into account in SVR. Besides it, SVR tries to reduce the model complexity by minimizing the formula $\| \boldsymbol{\omega} \|^2 = \boldsymbol{\omega}^T \boldsymbol{\omega}$, where $\boldsymbol{\omega} = (\omega_1, \omega_2, \ldots, \omega_d)^T$. In many cases, it is not possible to approximate all observations in the training set with an error below $\varepsilon$ (cf. [54]). Therefore, in order to allow for greater errors, one incorporates nonnegative slack variables $\xi_t$ and $\xi_t^*$, which represent the upper and lower constraints, s.t.:

$$y_t - f(\mathbf{x}_t) \leq \varepsilon + \xi_t^*, \tag{20}$$

$$f(\mathbf{x}_t) - y_t \leq \varepsilon + \xi_t, \tag{21}$$

for all $t = 1, 2, \ldots, n$. Finally, the function $f(\mathbf{x})$ is indicated as the minimum of the functional:

$$\Phi(\boldsymbol{\omega}, \boldsymbol{\xi}) = \frac{1}{2} \| \boldsymbol{\omega} \|^2 + C \sum_{t=1}^{n} (\xi_t + \xi_t^*), \tag{22}$$

where $C$ is some prespecified positive value (cf. [55]). The first term of $\Phi(\boldsymbol{\omega}, \boldsymbol{\xi})$ penalizes large coefficients $\omega_i$ in order to maintain the flatness of the function $f(\mathbf{x})$, whereas the second one penalizes training errors by using the $\varepsilon$-insensitive loss function [56]. The hyperparameter $C$ helps to prevent overfitting by determining the penalty imposed on data that lie outside the $\varepsilon$-tube.

However, the minimization problem above can be simplified by considering a corresponding dual problem, where the solution is given by:

$$f(\mathbf{x}) = \sum_{t=1}^{n_{SV}} (\alpha_t - \alpha_t^*) K(\mathbf{x}_t, \mathbf{x}), \text{ s.t. } 0 \le \alpha_t \le C,\ 0 \le \alpha_t^* \le C, \tag{23}$$

where $\alpha_t$ and $\alpha_t^*$ denote the Lagrange multipliers, $n_{SV}$ is the number of support vectors, and $K$ is the kernel function of the form:

$$K(\mathbf{x}_t, \mathbf{x}) = \sum_{i=1}^{d} \varphi_i(\mathbf{x}) \varphi_i(\mathbf{x}_t). \tag{24}$$

In practical applications, the following kernel functions are the most popular:

- Linear: $K(\mathbf{x}_t, \mathbf{x}) = \mathbf{x}_t{}^T \mathbf{x}$;
- Radial Basis Function (RBF): $K(\mathbf{x}_t, \mathbf{x}) = \exp\left(-\gamma \| \mathbf{x_t} - \mathbf{x} \|^2\right)$;
- Polynomial: $K(\mathbf{x}_t, \mathbf{x}) = \left(1 + \mathbf{x}_t{}^T \mathbf{x}\right)^p$; $p = 2, 3, \ldots$

## 3. Results

### 3.1. Nonlinear Granger Causality Testing

We tested for nonlinear Granger causality by applying the H-J and D-P tests. Eight values of lags: $lx = ly = 1,\ 2, \ldots,\ 8$ and two distance measures $\varepsilon = 1$ and $\varepsilon = 1.5$ were used. We analyzed two directions of causality—from crude oil to exchange rates and vice versa—and two subperiods—Period 1 and Period 2.

The obtained results are summarized in Tables 2–4. Each cell in the table contains $p$-values of both tests. We bolded the values smaller than 0.05, indicating the rejection of the null hypothesis of noncausality.

In Period 1 we found strong bidirectional causalities between crude oil and two currency pairs: EUR/USD and GBP/USD. The relations between crude oil and JPY/USD in this period were less evident, since they were detected only for the distance measure $\varepsilon = 1$. Moreover, causality from crude oil to JPY/USD was detected only by the H-J test.

Different results were obtained for Period 2. First of all, one can see the lack of causality between EUR/USD and crude oil (in both directions). Additionally, the results for GBP/USD and crude oil were not so univocal as in Period 1. Although the final conclusions in this case were the same (i.e., bidirectional causalities were detected), one can see that only some value of the lags applied in the testing procedure led to rejection of the null hypothesis. In the case of the relation between crude oil and JPY/USD, the results also changed in comparison to Period 1. First, the $p$-values for the direction JPY/USD→Brent clearly decreased, strongly confirming this causality. Additionally, the results for the opposite direction (Brent→JPY/USD) were also slightly different than before. Both conducted tests led to the same conclusion, confirming the existence of causality; however, this conclusion was derived only from small values of lags ($lx = ly = 1$), which suggests that the JPY/USD exchange rate reacted to changes in crude oil prices much faster than before.

**Table 2.** Results of nonlinear Granger causality testing for crude oil and EUR/USD.

| $\varepsilon$ | **Test** | **Number of Lags** $lx = ly$ | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
| | | Brent→EUR/USD (Period 1) | | | | | | | |
| 1 | H-J | **0.0000** | **0.0000** | **0.0000** | **0.0000** | **0.0000** | **0.0000** | **0.0000** | **0.0000** |
| | D-P | **0.0001** | **0.0000** | **0.0004** | **0.0022** | **0.0039** | **0.0055** | **0.0170** | **0.0257** |
| 1.5 | H-J | **0.0005** | **0.0000** | **0.0000** | **0.0000** | **0.0000** | **0.0000** | **0.0000** | **0.0000** |
| | D-P | **0.0007** | **0.0000** | **0.0000** | **0.0000** | **0.0000** | **0.0000** | **0.0000** | **0.0002** |
| | | Brent→EUR/USD (Period 2) | | | | | | | |
| 1 | H-J | 0.1128 | 0.3092 | 0.1869 | 0.3024 | 0.3411 | 0.1714 | 0.1495 | 0.1228 |
| | D-P | 0.1183 | 0.3502 | 0.2668 | 0.4334 | 0.5253 | 0.2647 | 0.3567 | 0.2685 |
| 1.5 | H-J | 0.0724 | 0.2511 | 0.1410 | 0.2270 | 0.2121 | 0.2871 | 0.2542 | 0.2738 |
| | D-P | 0.0737 | 0.2548 | 0.1481 | 0.2267 | 0.2526 | 0.3231 | 0.2894 | 0.2821 |
| | | EUR/USD→Brent(Period 1) | | | | | | | |
| 1 | H-J | **0.0017** | **0.0000** | **0.0000** | **0.0000** | **0.0000** | **0.0000** | **0.0000** | **0.0000** |
| | D-P | **0.0028** | **0.0000** | **0.0015** | **0.0013** | **0.0031** | **0.0192** | **0.0175** | **0.0175** |
| 1.5 | H-J | **0.0242** | **0.0001** | **0.0000** | **0.0000** | **0.0000** | **0.0000** | **0.0000** | **0.0000** |
| | D-P | **0.0240** | **0.0001** | **0.0000** | **0.0000** | **0.0000** | **0.0001** | **0.0001** | **0.0003** |
| | | EUR/USD→Brent(Period 2) | | | | | | | |
| 1 | H-J | 0.2438 | 0.0659 | 0.2864 | 0.3981 | 0.6039 | 0.4586 | 0.5040 | 0.4584 |
| | D-P | 0.2785 | 0.0811 | 0.3206 | 0.4528 | 0.5708 | 0.4194 | 0.5161 | 0.4944 |
| 1.5 | H-J | 0.0812 | 0.0564 | 0.3510 | 0.2544 | 0.4281 | 0.3952 | 0.4743 | 0.5211 |
| | D-P | 0.0798 | 0.0665 | 0.3918 | 0.2936 | 0.4838 | 0.4705 | 0.5652 | 0.5735 |

**Table 3.** Results of nonlinear Granger causality testing for crude oil and GBP/USD.

| $\varepsilon$ | **Test** | **Number of Lags** $lx = ly$ | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
| | | Brent→GBP/USD (Period 1) | | | | | | | |
| 1 | H-J | **0.0154** | **0.0017** | **0.0006** | **0.0000** | **0.0000** | **0.0002** | **0.0003** | **0.0089** |
| | D-P | **0.0200** | **0.0059** | **0.0079** | **0.0064** | **0.0138** | **0.0290** | **0.0474** | 0.1421 |
| 1.5 | H-J | 0.1482 | **0.0029** | **0.0026** | **0.0000** | **0.0000** | **0.0000** | **0.0000** | **0.0000** |
| | D-P | 0.1692 | **0.0047** | **0.0069** | **0.0012** | **0.0009** | **0.0003** | **0.0002** | **0.0009** |
| | | Brent→GBP/USD (Period 2) | | | | | | | |
| 1 | H-J | **0.0132** | 0.2492 | 0.1748 | **0.0290** | **0.0134** | **0.0075** | **0.0130** | 0.0657 |
| | D-P | **0.0154** | 0.3152 | 0.2010 | **0.0493** | **0.0344** | **0.0410** | **0.0453** | 0.1207 |
| 1.5 | H-J | **0.0047** | **0.0308** | **0.0162** | **0.0023** | **0.0015** | **0.0005** | **0.0003** | **0.0006** |
| | D-P | **0.0046** | **0.0399** | **0.0192** | **0.0028** | **0.0023** | **0.0012** | **0.0008** | **0.0020** |
| | | GBP/USD→Brent(Period 1) | | | | | | | |
| 1 | H-J | **0.0477** | **0.0017** | **0.0030** | **0.0007** | **0.0014** | **0.0079** | **0.0140** | **0.0206** |
| | D-P | 0.0574 | **0.0041** | **0.0130** | **0.0166** | **0.0339** | 0.0544 | 0.0562 | 0.0785 |
| 1.5 | H-J | 0.0669 | **0.0026** | **0.0087** | **0.0006** | **0.0012** | **0.0033** | **0.0061** | **0.0029** |
| | D-P | 0.0716 | **0.0027** | **0.0129** | **0.0035** | **0.0069** | **0.0163** | **0.0235** | **0.0149** |
| | | GBP/USD→Brent(Period 2) | | | | | | | |
| 1 | H-J | **0.0186** | 0.1343 | 0.5399 | 0.1944 | 0.1731 | 0.1291 | 0.0985 | 0.1465 |
| | D-P | **0.0212** | 0.1805 | 0.5493 | 0.2012 | 0.1657 | 0.1406 | 0.1829 | 0.2603 |
| 1.5 | H-J | **0.0315** | 0.0628 | 0.4332 | 0.1904 | 0.2265 | 0.1261 | **0.0164** | **0.0104** |
| | D-P | 0.0311 | 0.0644 | 0.4081 | 0.1787 | 0.2515 | 0.1579 | **0.0269** | **0.0181** |

**Table 4.** Results of nonlinear Granger causality testing for crude oil and JPY/USD.

| $\varepsilon$ | Test | Number of Lags $lx = ly$ | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
| Brent→JPY/USD (Period 1) | | | | | | | | | |
| 1 | H-J | 0.3999 | 0.3858 | 0.6696 | 0.3276 | 0.2312 | 0.0538 | **0.0321** | **0.0092** |
| | D-P | 0.4608 | 0.3947 | 0.6248 | 0.2041 | 0.2074 | 0.1337 | 0.0980 | 0.0925 |
| 1.5 | H-J | 0.5198 | 0.6875 | 0.8965 | 0.9217 | 0.9594 | 0.8297 | 0.5170 | 0.3306 |
| | D-P | 0.5192 | 0.7003 | 0.9109 | 0.9355 | 0.9686 | 0.8229 | 0.4534 | 0.3344 |
| Brent→JPY/USD (Period 2) | | | | | | | | | |
| 1 | H-J | **0.0405** | 0.3544 | 0.3852 | 0.4075 | 0.3559 | 0.4972 | 0.7010 | 0.7573 |
| | D-P | 0.0579 | 0.4407 | 0.5160 | 0.5377 | 0.4822 | 0.5730 | 0.6791 | 0.6939 |
| 1.5 | H-J | **0.0293** | 0.2695 | 0.2326 | 0.1326 | 0.1741 | 0.3503 | 0.5965 | 0.5193 |
| | D-P | **0.0328** | 0.3097 | 0.2666 | 0.1528 | 0.2097 | 0.3706 | 0.6288 | 0.5560 |
| JPY/USD→Brent(Period 1) | | | | | | | | | |
| 1 | H-J | 0.5404 | 0.7095 | 0.5646 | 0.1271 | **0.0053** | **0.0042** | **0.0066** | **0.0039** |
| | D-P | 0.5813 | 0.6788 | 0.4553 | 0.1219 | **0.0326** | **0.0267** | **0.0437** | 0.0567 |
| 1.5 | H-J | 0.5028 | 0.8275 | 0.8776 | 0.5392 | 0.3383 | 0.3392 | 0.2614 | 0.1260 |
| | D-P | 0.5102 | 0.8482 | 0.8728 | 0.4764 | 0.2832 | 0.2534 | 0.1995 | 0.1070 |
| JPY/USD→Brent(Period 2) | | | | | | | | | |
| 1 | H-J | **0.0133** | **0.0027** | **0.0136** | 0.1000 | 0.2297 | 0.4628 | 0.2631 | 0.1618 |
| | D-P | **0.0192** | **0.0049** | **0.0242** | 0.1400 | 0.2772 | 0.4756 | 0.2513 | 0.1392 |
| 1.5 | H-J | **0.0042** | **0.0004** | **0.0002** | **0.0008** | **0.0034** | **0.0129** | **0.0141** | **0.0142** |
| | D-P | **0.0037** | **0.0003** | **0.0002** | **0.0006** | **0.0034** | **0.0160** | **0.0207** | **0.0239** |

### 3.2. Forecasting

The results of nonlinear causality testing showed that most of the investigated series were linked by causal relationships. This means that there is a potential possibility to use lagged crude oil returns as the regressor for the exchange rates' returns and vice versa. However, the crucial question is if it is really feasible to find a forecasting method that can exploit these potential possibilities to generate accurate forecasts. It should be noted that both tests for nonlinear Granger causality applied in the study are nonparametric, which means that they test the null hypothesis of noncausality against an unspecified alternative. This fact is beneficial since it allows detecting causal relations of a different type—linear and nonlinear ones. On the other hand, a shortcoming of this approach is that the rejection of the null hypothesis gives no information about the functional form of the model that can be used to exploit the detected relationship for forecasting purposes [10]. However, there are many forecasting techniques that do not impose assumptions about the form of the modeling dependencies and, as a consequence, are flexible with respect to different types of dependencies, including nonlinear ones. It has been shown that SVR satisfies these requirements, combining the training efficiency and simplicity of linear methods with the prediction accuracy of the best nonlinear algorithms. Moreover, SVR copes with high-dimensional or incomplete data and is robust to outliers [40,57,58].

In our study, we applied two alternative approaches to the SVR models' specification. In the first one, we used only lagged dependent variables as the regressors, which means that the constructed models are autoregressive, i.e.,:

$$y_{t+1} = f\left(y_t, y_{t-1}, \ldots, y_{t-ly+1}\right), \tag{25}$$

where $ly$ is the lag length. In the second approach, we additionally incorporated the second lagged variable as the regressor:

$$y_{t+1} = f\left(y_t, y_{t-1}, \ldots, y_{t-ly+1}, x_t, x_{t-1}, \ldots, x_{t-lx+1}\right), \tag{26}$$

where $lx$ and $ly$ are the lag lengths. This means that if the dependent variable $y$ denotes the crude oil returns, then $x$ denotes the exchange rates' returns and vice versa. According to the purpose of our study, we intended to assess if the extended model of the form (26) outperformed the autoregressive model (25) in terms of its predictive power.

We determined the lag lengths $lx$ and $ly$ in the SVR models based on the results of the nonlinear causality tests presented in Tables 2–4 (assuming $lx = ly$ as in the applied tests). For a better comparison, we decided to choose the same lag for Period 1 and Period 2 (separately for each modeled relationship). In the autoregressive model (25), we used the same $ly$ as in the corresponding model (26). The chosen lag lengths are summarized in Table 5.

**Table 5.** Lag lengths in the constructed SVR models.

| Modeled Relationship | $lx = ly$ |
|---|---|
| Brent→EUR/USD | 3 |
| EUR/USD→Brent | 2 |
| Brent→GBP/USD | 6 |
| GBP/USD→Brent | 8 |
| Brent→JPY/USD | 8 |
| JPY/USD→Brent | 8 |

Before estimating the SVR models, the regressors were standardized, i.e., centered by subtracting their mean and divided by the standard deviation. The kernel and the values of the model hyperparameters $\varepsilon$, $C$ (and $\gamma$ in case of the RBF kernel) must be specified before estimation as well. In the study, we constructed the SVR models with two different kernels: the linear and RBF ones. There are competitive propositions in the literature of how to tune the hyperparameters in SVR models (e.g., [52,59–61]), but previous studies did not prove the convincing superiority of any of them. To this purpose, we applied Bayesian optimization, which is a method for performing global optimization of unknown "black box" objectives and is particularly appropriate when objective function evaluations are expensive (in any sense, such as time or money [62]).

Finally, for each investigated pair of time series, we considered four variants of the SVR models:

1. The autoregressive model of type (25) with the linear kernel (SVR_ar_lin);
2. The autoregressive model of type (25) with the RBF kernel (SVR_ar_rbf);
3. The extended model of type (26) with the linear kernel (SVR_reg_lin);
4. The extended model of type (26) with the RBF kernel (SVR_reg_rbf).

To estimate the SVR models, we used a rolling window in the following way. For the starting three-year sample (i.e., from 3 January 2011 to 31 December 2013 for Period 1, and from 4 January 2016 to 31 December 2018 for Period 2), we estimated the models and calculated one-day-ahead forecasts. Consecutively, we changed the estimation sample by adding one new observation while removing the oldest one. For each estimation sample, we determined the optimal hyperparameters $\varepsilon$, $C$, and $\gamma$, re-estimated the models, and forecasted. We repeated this procedure until we obtained forecasts for the whole two-year period (i.e., from 2 January 2014 to 31 December 2015 for Period 1 and from 2 January 2019 to 31 December 2020 for Period 2).

In order to assess the predictive power of the models, two primary measures of the forecasts' accuracy, namely the Mean Squared Error (MSE) and the Mean Absolute Error (MAE), were applied. They are defined as:

$$\mathrm{MSE} = \frac{1}{T}\sum_{t=1}^{T}\left(y_t - y_{f,t}\right)^2,$$

$$\mathrm{MAE} = \frac{1}{T}\sum_{t=1}^{T}\left|y_t - y_{f,t}\right|$$

where $y_{f,t}$ is the forecast of $y_t$ at time $t$ and $T$ is the number of forecasts. As the benchmarks, we applied the white noise models, where the forecasts $y_{f,t}$ were calculated as the mean of the observations from the previous three-year sample (used to estimate the corresponding SVR models). The obtained results are given in Table 6. For each modeled relationship (and each period), the smallest values of the MAE and MSE are bolded.

**Table 6.** Accuracy measures of the forecasts from the constructed SVR models.

| Modeled Relation | Period | Model | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | WN | | SVR_ar_lin | | SVR_ar_rbf | | SVR_reg_lin | | SVR_reg_rbf | |
| | | MAE | MSE | MAE | MSE | MAE | MSE | MAE | MSE | MAE | MSE |
| Brent→EUR/USD | Period 1 | **0.430** | **0.352** | 0.434 | 0.363 | 0.431 | **0.352** | 0.431 | 0.353 | 0.431 | 0.353 |
| | Period 2 | 0.304 | 0.162 | 0.308 | 0.164 | **0.303** | **0.161** | 0.313 | 0.180 | **0.303** | **0.161** |
| EUR/USD→Brent | Period 1 | **1.353** | **3.924** | 1.359 | 3.943 | 1.359 | 3.943 | 1.359 | 3.943 | 1.359 | 3.943 |
| | Period 2 | 2.512 | 27.948 | 2.513 | **27.616** | **2.501** | 27.749 | 2.519 | 28.540 | 2.515 | 27.934 |
| Brent→GBP/USD | Period 1 | 0.332 | **0.202** | 0.332 | 0.203 | **0.331** | **0.202** | 0.345 | 0.217 | **0.331** | **0.202** |
| | Period 2 | 0.453 | 0.389 | **0.452** | 0.389 | 0.453 | **0.388** | 0.466 | 0.450 | 0.455 | 0.391 |
| GBP/USD→Brent | Period 1 | **1.353** | **3.924** | 1.360 | 3.972 | 1.361 | 3.929 | 1.371 | 4.041 | 1.361 | 3.958 |
| | Period 2 | **2.512** | 27.948 | 2.526 | **27.925** | 2.529 | 28.096 | 2.558 | 29.170 | 2.518 | 27.987 |
| Brent→JPY/USD | Period 1 | **0.358** | **0.250** | 0.360 | 0.256 | 0.360 | 0.252 | 0.368 | 0.269 | 0.359 | 0.251 |
| | Period 2 | **0.303** | **0.221** | 0.326 | 0.341 | 0.305 | 0.222 | 0.323 | 0.264 | 0.304 | 0.222 |
| JPY/USD→Brent | Period 1 | **1.353** | **3.924** | 1.369 | 3.997 | **1.353** | 3.933 | 1.358 | 3.962 | 1.356 | 3.944 |
| | Period 2 | 2.512 | 27.948 | **2.504** | 27.846 | 2.717 | 41.748 | 2.513 | **27.834** | 2.599 | 30.809 |

The results showed that the constructed SVR models did not differ significantly from each other in terms of the forecasts' accuracy. What is most important is that the results did not support the hypothesis that extended SVR models outperform the autoregressive ones. This means that lagged crude oil returns used as regressors do not help to calculate more accurate forecasts of the exchange rates' returns and vice versa. Moreover, we showed that none of the applied kernels had an advantage over the second one. Finally, the results implied that the constructed SVR models do not outperform the benchmark white noise model.

## 4. Discussion

In our study, we tested for bidirectional causal relationships between crude oil prices (Brent spot prices' FOB) and the most important exchange rates (EUR/USD, GBP/USD, and JPY/USD). To this purpose we applied two tests for nonlinear Granger causality, introduced by Hiemstra and Jones and Diks and Panchenko. In order to analyze stability of the investigated relations, we divided the analyzed period into two subperiods: Period 1—from 3 January 2011 to 31 December 2015 and Period 2—from 4 January 2016 to 31 December 2020. Due to the fact that we analyzed daily data, our study was concentrated on short-term relationships.

We found that most of the investigated series were linked by causal relationships. However, our study revealed some differences between both analyzed subperiods. Generally, EUR/USD and GBP/USD proved to be more strongly related to crude oil in the earlier period (Period 1) than in the later one (Period 2). One can even see that the bidirectional causality between EUR/USD and crude oil, which was strongly indicated by both tests in Period 1, vanished in Period 2. Moreover, in Period 1, JPY/USD was linked to crude oil (in both directions) much more weakly than EUR/USD and GBP/USD. However, the opposite situation took place in Period 2, where the unidirectional causality from JPY/USD to crude oil was stronger in comparison to both other currency pairs.

There are many empirical studies concentrating on the detection of causality between crude oil price and exchange rates, and their results are mixed [21]. The inclusiveness of the causation between exchange rates and oil price may depend on the choice of the exchange rate measure, the time-varying causality patterns, or others [7]. Moreover, it should be noted that most of previous investigations have been restricted to linear framework, ignoring the possible nonlinear behaviors, which may be caused by asymmetry, persistence, or structural breaks [21]. The nonlinear Granger causality tests were applied to detect the relationships between crude oil price and exchange rates by [8,22–24,63]. The results of these studies were also mixed. Bayat et al. [63] analyzed three transition countries, namely the Czech Republic, Hungary, and Poland. Based on the D-P test, they found that neither oil price shocks, nor exchange rate fluctuations affect each other. This conclusion was confirmed by Drachal [22], who also applied the D-P test to CEE countries, namely the Czech Republic, Hungary, Poland, Romania, and Serbia, and found no causal relations between the exchange rates and oil prices. According to the results of the H-J and D-P tests, Wen et al. [8], pointed out sufficient statistical evidence in favor of nonlinear Granger causality from the crude oil prices to the USD exchange rate and much weaker for causation in the opposite direction. Kumar [23] tested for causality between oil prices and exchange rate in the Indian context and found that the H-J test strongly rejected the hypothesis of no causality in both directions. Ajala et al. [24] investigated the impact of oil prices on the exchange rates in Nigeria and found that oil prices significantly affected the exchange rates. All of the mentioned studies were performed for monthly data, except Wen et al. [8], who applied weekly data. We conducted our analysis for daily data, which means that the relationships we detected can be regarded as more short-term. Our results, confirming causal relationships between crude oil price and exchange rates, have practical implications for policymakers in the field of monetary policies and strategic risk management. However, due to the short-term character of the detected relationships, they should be taken into consideration primarily by market participants, such as investors, financial managers, and traders, to create effective investment portfolios and risk-hedging strategies (cf. [7,23]).

The revealed existence of bidirectional causal relations between crude oil and exchange rates' returns implies the potential possibility of using lagged values of one of these variables as the regressor for the second one. However, the applied tests are nonparametric, which means that they give no information about the model that can describe the detected relations. Therefore, it causes a question about the forecasting method that can be successfully applied to investigated time series. That is why in the second part of our study, we verified if the support vector regression model can be used for this purpose.

Generally, the obtained results did not support the hypothesis that SVR can be effectively used to forecast the investigated time series. First of all, the constructed models, regardless of the applied kernel and regressors, did not significantly outperform the benchmark white noise model. Secondly, we found that including the lagged crude oil returns to the SVR models of the exchange rates' returns (and vice versa) did not significantly improve the accuracy of the obtained forecasts. This shows that the applied models were not able to exploit the dependencies detected by the Granger causality tests.

This finding seems consistent with previous studies performed using other forecasting methods. It has been concluded in the literature that the fact that exchange rates and crude oil prices are linked to each other does not necessarily imply that one is useful when forecasting the other. The reason is that past relationships do not necessarily hold in the future, and the link between in-sample and out-of-sample is often rather weak [1]. Chen et al. [64] showed that exchange rates of commodity exporters have robust power in predicting global commodity prices. Their explanation was that exchange rates embody information about future movements in commodity export markets. However, based on comprehensive literature studies, Alquist et al. [65] derived the general conclusion that trade-weighted exchange rates have no significant predictive power for the nominal price of oil. On the other hand, they noted that this does not necessarily mean that all exchange rates lack predictive power and found evidence that the Australian exchange rate has significant predictive power for the sign of the change in the nominal price of oil at certain horizons. When analyzing the opposite direction models, one cannot find systematic evidence that oil price is useful for exchange rates' predictions. Chen et al. [64] noted that the problem with effective exchange rates' forecasting can result from the fact that exchange rates are strongly forward-looking, whereas commodity price fluctuations are typically more sensitive to short-term demand imbalances. The literature on fundamental exchange rate models is vast, starting from the seminal work of Meese and Rogoff [66], which showed that such models do not outperform the benchmark random walk model. Contemporarily, it has been argued that the forecasting performance of exchange rate models based on economic fundamentals can depend on the choice of predictor, forecast horizon, sample period, model, and forecast evaluation method [67].

Future research might extend this study by considering SVR models with other lags of regressors. Moreover, alternative machine learning methods of forecasting such as neural networks or hybrid models could be applied.

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Article

# Evaluation of Energy Transition Scenarios in Poland

**Ewelina Kochanek**

Faculty of Social Sciences, Institute of Politics and Security Sciences, University of Szczecin,
71-017 Szczecin, Poland; ewelina.kochanek@usz.edu.pl

**Abstract:** Long-term energy scenarios form the basis of energy policy-making. In practice, the use of energy scenarios for the effective creation of energy policy differs in each country. Therefore, the aim of this study is to present two possible scenarios for the development of the Polish energy sector, resulting from the current national policy and international commitments of Poland. The study examined the development of the energy mix in Poland in the 2040 perspective, in accordance with the strategic document Energy Policy of Poland (PEP 2040). The analysis took into account four diagnostic features: electricity production, electricity price, the share of renewable energy sources (RES) in final energy consumption, and $CO_2$ emission reduction. In addition, the analysis allowed for the presentation of the implications for the Polish economy and society after the application of the diversified variant with nuclear energy and the diversified variant with natural gas. Both scenarios assume too slow development of RES, and the ambivalent attitude of the Polish political elite towards zero-emission energy sources significantly hinders the development of some of its forms (e.g., onshore wind energy). Unfortunately, both the first and second variants entail a large increase in electricity prices, which will affect the entire economy and increase the level of energy poverty among Poles. The study provides strategic insights on the consequences of Poland's choice of a specific energy transformation scenario. The results may serve as a starting point for understanding Poland's restraint towards achieving zero emissions and contribute to the discussion of the direction of development of the Polish energy sector.

**Keywords:** energy transition; energy scenarios; energy policy; polish energy transformation

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## 1. Introduction

Climate protection issues have now moved to the top of the political agenda. The popularization of transformational actions in the energy sector started after the adoption of the Climate Change Agreement at the Paris Climate Conference (COP21) in 2015. Almost 190 countries, signatories to the agreement there, committed themselves to the climate target of keeping the temperature increase below 2 °C and preferably at 1.5 2 °C [1]. As a result, the countries of the European Union (EU), have begun to look for solutions that would significantly reduce greenhouse gas emissions by 2030 and achieve climate neutrality by 2050. The European Green Deal is a new growth strategy proposed and adopted by the European Commission in December 2019. Its aim is for the European Community to achieve climate neutrality, i.e., zero net greenhouse gas emissions, by 2050. It is worth adding that by 2030 gas emissions are to be reduced by 50–55% compared to 1990 [2].

Despite an uneasy starting point, Poland has begun the transformation of its energy system. Decarbonizing the Polish economy is a huge challenge. The country does not have many rivers on which hydroelectric power plants could be built, and the number of hours of sunshine is 1300–1900 per year, which is fifty percent less than in southern Europe [3]. Natural gas resources are low and geopolitical factors make importing this raw material on an appropriate scale a challenge. The Baltic Sea allows the development of offshore wind energy in the north of the country, but it is in the south where the most energy-consuming areas are found. Poland also does not have a nuclear power plant, unlike other EU countries from the former Eastern bloc, such as Bulgaria, the Czech Republic, Hungary, Romania, or Slovakia. Energy is largely based on coal [4].

The purpose of this article is to assess the scenarios for the development of the Polish energy sector resulting from the current national policy and Poland's international commitments. The analysis will present the economic and social implications for Poland of the implementation of each of the discussed energy transformation scenarios. The following research questions are aimed at achieving the assumed objective:

1. What are the real scenarios for the development of the energy mix for Poland in the 2040 perspective?
2. How will the energy mix develop in the described scenarios?
3. What will be the impact of each of the proposed energy transformation scenarios on the Polish economy and society?

The article consists of five parts. After the introduction, the theoretical background of creating scenarios for energy sector development is presented. The third section presents the methods used in writing the article and a description of the scenarios. The fourth section contains an analysis of the energy transformation scenarios in Poland. A summary of the results of the analysis, as well as recommendations and possible policy implications, are presented in the fifth section.

The study provides strategic insights on the consequences of Poland's choice of a specific energy transformation scenario. The results may serve as a starting point for understanding Poland's restraint towards achieving zero emissions, as well as contribute to the discussion of the direction of development of the Polish energy sector.

## 2. Literature Review

Each country creates its own scenarios for the development of the energy sector, which aim to identify different directions of development, which are feasible, and moreover, which support the formulated policy objectives [5,6]. Unfortunately, the future is becoming more uncertain and forecasts are more difficult to prepare [7]. Therefore, the creation of several scenarios, having the same conditions but different enough to capture a realistic range of possibilities for future development paths, including the speed of transformation, should be used to construct a vision for energy policy in a given country [8]. Several factors need to be considered in these projections: economic in nature (economic growth and income growth) and social in nature (population growth rate and life expectancy), as they play a significant role in transforming the energy system [9]. It is worth emphasizing that the transformation towards sustainable development is the result of both technological changes and comprehensive changes in the behavior of society at various levels of activity, which is a stimulus for the implementation of the energy transformation. Social innovations refer to fundamental changes in attitudes, strategies, and policies. Social innovation plays an important role in transforming society into a community where people look for ways to meet their own needs and thus reduce dependence on standardized offers for market economy products and energy sector organizations [10]. In the transition to sustainable development, technical and social innovation co-evolve and interact positively [11]. Transforming Social Innovation (TIS) views the emergence and development of technology as a global process that transcends sectoral and geographic boundaries [12].

Scenarios illustrate the long-term consequences of policy decisions and provide perspectives for policy debate. It is worth mentioning that sustainable scenarios, in contrast to the stringent ones, which include stringent climate targets and high energy demand, are characterized by a lower rate of development of green technologies, as they have to meet overall energy needs, building on existing generation technologies, without the tension of rapid expansion of renewable energy sources (RES) and the issue of their financing [13]. This is because states tend to achieve some stability and resist any fundamental change. Very often, states have institutionalized power and incumbent organizational structures that prevent them from seeing new development alternatives open up and keep supporting the old system. Moreover, infrastructure, production technologies, and domestic raw material resources also influence the state's restraint towards systemic change [11]. As a result, unblocking the energy system requires sufficient time to implement policy measures to stimulate the development of sustainable technologies. Political intervention is most effective in the early stages of transformation. When old technology is fully developed and there are several niche markets, state actions may turn out to be negligible, but their effect may increase by increasing niche markets and slowing the development of the existing energy system [14].

Experience shows that energy transitions take time, typically half a century from initial entry to the majority market share. Previous energy transitions have been driven by technological change, economic factors, access to resources, or the offer of higher levels of energy services to consumers. Therefore, business opportunities, the economic benefits of the transition, or state self-determination have been at the heart of the change [15]. Energy transition relies on an energy policy framework designed by the government that can accelerate the process and determine its direction. A well-designed transition policy takes into account the characteristics of the energy system and includes energy demand and supply. It is therefore necessary to use policy instruments that evolve over time to meet the needs that exist on both the demand and supply side [16].

When creating energy scenarios, it is important to consider new technologies that will help create an Intelligent Energy Management System (IEMS). One of the solutions that will help to meet the Paris requirements is the concept of a virtual power plant (VPP), which will facilitate cooperation between individual market participants, ensuring monitoring and energy efficiency through a two-way energy flow. This concept helps consumers to trade excess electricity on the market at the desired price without third-party interference [17,18].

The energy transition process is characterized by the interplay of old and new technologies as well as a structural link with other sectors such as information and communication technology (ICT) [19]. Blockchain-based technologies can play an important role in the energy transformation, offering profitable local energy trading, accelerating renewable energy production, and providing grids with new demand-response resources to increase grid stability [20].

The energy system is indifferent as a result of the deep-rooted dependence of energy infrastructure on development pathways. According to the shock theory applied to Poland in the 1990s by the then Minister of Finance L. Balcerowicz to switch the Polish economy, struggling with numerous economic problems, to a free-market economy, it is unlikely that the gradual introduction of any policy—in this case, climate policy based on renewable energy sources—has transformed the system on the necessary scale [21,22]. What is needed is a systemic shock that throws the system out of balance, creating incentives for new business models and technologies [23,24]. In other words, new technologies enabling a cost-effective share of 100% renewable energy will be developed only if the right premises are created. The rapid development of green energy sources, in particular in the electricity sector, in several countries around the world has resulted in a surplus of energy coming onto the market that has accelerated a shift in thinking about new models and coalitions of market participants [25,26]. In this way, critical points can move the energy system towards new technological offers. In a simple, gradual change, the current fossil fuel-based energy system is more likely to adapt and return to the old equilibrium [27]. The system shock is also intended to signal to market participants that the transition goes beyond gradual change. Actors must therefore quickly familiarize themselves with the coming changes in order to generate new ideas and business models as quickly as possible [28,29].

As can be seen, energy transitions contribute not only to changes in the energy system itself but also touch the social sphere, hence viewing the process of creating a low-carbon or zero-carbon economy only through the prism of fuel and technology is hardly diagnostic for energy transition. A change in the social-energy order can occur when large numbers of consumers become producers [30].

So, scenarios are tools used to create space for thinking about what is possible. They make it possible to create a simulation in relation to a specific decision or strategy that cannot be easily tested in real conditions, e.g., due to costs and/or social problems [31]. Comparing the similarities and differences that have emerged in scenarios allows a better understanding of the factors that influence the pace of change [32].

Summing up, creating scenarios allows selecting an action plan, without which it is difficult to maintain energy security, develop domestic business, create new jobs, or improve the innovativeness of the economy.

## 3. Methodology

The methodological approach in this research is mainly based on a review of the literature, descriptions of the most realistic scenarios of the Polish energy transformation, quantification of the scenarios, and their comparison. The main step of the research is the description of the scenario where each scenario has been defined on the basis of verified information. The time frame of the study was set for the period from 2030 to 2040, as the current energy policy of Poland (PEP 2040), which was adopted by the government in January 2021, is envisaged until then. It shows that the energy transition in Poland will be carried out based on three pillars:

- I equitable transition (providing new development opportunities for regions and communities most negatively affected by the energy transition);
- II zero-emission energy system (achieving zero-emission in the energy sector will be possible through the construction of a nuclear power plant, implementation of offshore energy, development of prosumer energy while increasing the share of gas in the electricity generation sector);
- III good air quality (moving away from fossil fuels not only in the energy sector but also in transport and construction) [33].

After a long wait of more than ten years for this document, the ruling elite did not find it necessary to extend the time horizon of this document to 2050. The PEP would then be in line with the timeframe set by the European Union in the European Green Deal Strategy. The PEP 2040 is another attempt to find a consensus between the EU requirements contained in the European Green Deal and the expectations of mining communities. Extending the period of coal mining in Poland seems unjustified, especially in the context of rising coal prices and increasingly difficult access to deposits. Referring to PEP 2040, there is only one scenario—diversified with nuclear energy. It is based on diversified energy sources with nuclear energy, which allows replacing coal-based production with nuclear energy. In order to prevent the loss of continuity of energy supply, some existing coal power plants are being modernized to significantly extend their lifetime. Other important energy sources in this scenario are natural gas and energy from renewable sources.

Despite the absence of the second scenario in PEP 2040, many researchers and market observers consider it appropriate to distinguish a diversified scenario with natural gas. This scenario is similar to the first one, except that it is based on energy carriers that currently exist in Poland, without the nuclear energy subsector. In this variant there is increased energy production from natural gas and RES. In both scenarios, apart from the leading source, green energy plays an important role. The development of energy production from renewable sources, supported by cogeneration units, is therefore assumed. It is worth mentioning that the coal-based scenario, which relied on coal-burning generating units to produce electricity, has been strongly promoted until recently [34], but Poland's adoption of the Paris Agreement and the European Green Deal completely precludes the implementation of this very scenario, hence the transformation plans contained in the Polish energy strategy do not envisage the use of coal in a perspective longer than 2049.

Many countries are considering one more energy transformation scenario—the RES scenario, which is entirely based on renewable energy and assumes a gradual withdrawal from coal, without modernizing coal blocks to extend their lifetime. This scenario has not been analyzed because the Polish government did not even take it into account when preparing Poland's energy strategy until 2040, hence its entry into force is not realistic.

The study consisted in a separate analysis of two variants of the Polish energy transition, during which four diagnostic features were identified and used: electricity production, electricity price, share of RES in final energy consumption, and reduction of $CO_2$ emissions. Both scenarios are based on a separate key energy carrier to drive change in the Polish energy sector. The study indicates the consequences of the pace of transformation, the shape of the resulting energy landscape, and the effects of climate change mitigation during the implementation of each scenario. Various research methods were used in the study. The analysis and criticism of the literature allowed for deepening the knowledge in the area of the assumed research issues. The formulation of research problems was possible thanks to synthesis. The institutional and legal method analysis was used to present the applicable legal provisions related to the analyzed phenomenon. The forecasting method was used to determine the changes in the Polish economy that will occur as a result of selecting each of the presented scenarios of energy transformation. The inductive inference has been used to refine general conclusions.

## 4. Polish Energy Transformation Scenarios

### *4.1. Diversified Scenario with Nuclear Energy*

The scenario included in the PEP 2040 allows for the replacement, initially in a small and then in a larger part of the electricity production generated from coal, by energy from the atom. This scenario plays a leading role in countries with nuclear power plants and a high proportion of their electricity generation from coal. Hence, it can be seen in the energy strategies of the Czech Republic, Romania, Slovakia, and France, among others [35]. Other important energy sources in this scenario are natural gas and energy from renewable sources. Such a scenario is also forecast for Poland, but there is one major barrier that makes it difficult to implement—there is no nuclear power plant in Poland. For over a decade, the ruling elites have been discussing a return to the idea of building such a unit but apparently without success. Poland's first experience with a nuclear power plant was still under communist rule, with the construction of the Żarnowiec Nuclear Power Plant commencing in 1982 [36]. However, in 1990 the government of T. Mazowiecki suspended the construction of this investment due to financial difficulties and lack of public acceptance [37]. The first attempt to reactivate the nuclear program in the Polish energy sector took place in 2009–2012. However, at that time, the nuclear energy landscape looked very different. In Europe alone, two nuclear power plants were being built, one in France and one in Finland. The situation changed after the disaster at Japan's Fukushima Dai Ichi power plant, after which Germany announced the decommissioning of its nuclear units by 2022. This led to a global freeze of nuclear projects, including in Poland [38]. Recently, the discourse of nuclear revival is visible in official documents issued by the Polish government [39]. According to the assumptions of the Polish Nuclear Power Program of 2020, two power plants with three nuclear reactors III and III + generation each with a total capacity of 6 to 9 GWe are to be built in Poland. In 2022 a final decision will be taken on the location of the nuclear power plant, and four years later construction of the first power plant will begin, with commissioning scheduled for 2034. Ten years later, the second nuclear power plant is to be commissioned [40]. Poland's ruling elite believes that if Poland is to remain competitive in the global market for goods and services it must introduce the atom into its energy sector, especially in view of the withdrawal of coal from the energy mix. The emphasis on the competitiveness of the economy is signaled by reasoning based on market rationality [41].

There are number of factors that could affect the described scenario. The first of these is capital expenditures which, as history shows, are usually higher than estimated and are caused by delays in the timing of investments [42]. The second risk factor is the already mentioned delay in the implementation of the investment, even a delay of several months is particularly undesirable in this scenario, as it will significantly hinder the process of reducing greenhouse gas emissions. The times when a nuclear power plant could be commissioned within a decade are gone forever. For example, Finland has been building its power plant for 17 years, the Slovaks, after 12 years of construction, have just commissioned the 3rd unit at the Mochovce power plant [43], and the only known example of an investment only slightly delayed is the Barakah power plant in the United Arab Emirates (2012–2020), obviously thanks to the UAE's huge financial resources [44]. It is worth adding that replacing a 1000 MW coal power plant with a nuclear power plant allows for the reduction of annual $CO_2$ emissions three times in comparison with replacing a gas power plant [45].

The recovering Polish economy after the COVID-19 pandemic will need increased amounts of energy; this will be associated with a shift in demand for final energy from fossil fuels towards electricity, resulting from the increasing mechanization of industry and services, the spread of electric vehicles (plug-in hybrids), and the electrification of the process of heating water and producing heat in many households so far using coal or gas for this purpose. It is forecasted that the increase in demand for power at its peak in 2020–2040 will be about 27.8%, which means that after 2040 it will reach a value of 31 GW [46].

In the diversified scenario with nuclear energy, the share of coal in domestic energy production by 2030 will still be high and will reach 56%, gas power plants and gas heating plants will be another source of energy generation (10.5%), while renewable sources will constitute 32%. The nuclear power plant, to be commissioned only in 2034, will initially provide 8% of the electricity, and the energy shortage will be made up by imports. The inclusion of a nuclear power plant in the system will reduce the amount of pollution from the energy sector by phasing out generating units with low efficiency. Increased demand for energy necessitates the expansion of transmission infrastructure, which will improve power supply reliability and increase cross-border exchange opportunities. To improve efficiency, smart electricity grids will be implemented, which will facilitate the integration of the activities of connected grid users. By 2040, a virtually new electricity system will be built in Poland. Based on the analysis of effects and impact on GDP and savings potential, Poland declares a national target of 23% energy efficiency improvement by 2030. At the same time, according to the Energy Efficiency Directive, in each year of the 2021–2030 period, Poland will achieve new savings of at least 0.8% of annual final energy consumption. In 2040, in the scenario with nuclear energy, the share of RES will increase to 40%, the share of nuclear energy will increase to ca. 14% and of gas to 17%, while the share of coal will decrease to 28% (Figure 1) [33].

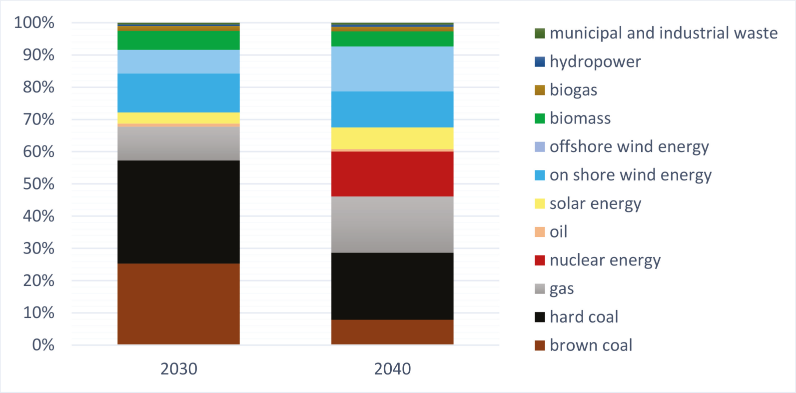

**Figure 1.** Gross electricity generation forecast by fuel, in %. Source: Own elaboration based on: [46].

An important element of the transition that directly affects society is the price of energy. For several years, one can observe an increase in wholesale electricity prices in Poland, which at the same time are among the highest in the EU [47]. It is worth adding here that the wholesale price is a derivative of fuel prices and $CO_2$ costs, hence the wholesale price of energy in Poland is coupled to the price of hard coal, which accounts for 50% of energy produced in the country. The increase in prices results firstly from the growing value of coal extracted from domestic deposits, which has become more expensive than imported coal [48] and secondly from increased actions of the Union in favor of climate, resulting in increased prices of greenhouse gas emission allowances. The Union plans to deepen the reduction of $CO_2$ emissions by 2030 in relation to 1990 by 55%, instead of the previously approved 40% [49]. Lower electricity prices in other EU member states are due to, among other things, switching the electricity generation subsector from coal to gas or having nuclear power plants. Electricity prices in Poland are only expected to stabilize between 2030 and 2035, mainly as a result of coal units being switched off and the price of greenhouse gas emission allowances falling as demand for them decreases (Figure 2).

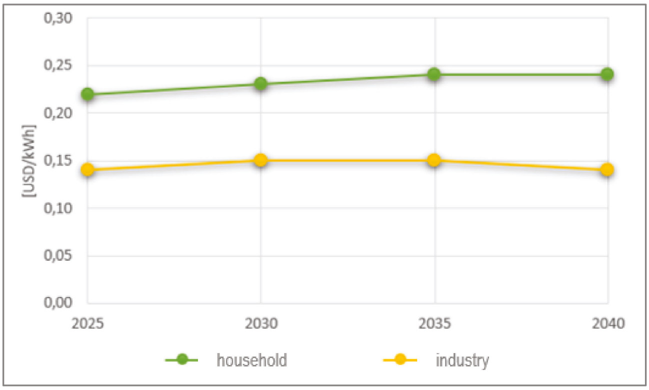

**Figure 2.** Electricity prices in Poland by customer. In USD/kWh. Source: Own elaboration based on: [46].

The growing prices of energy in Poland and energy raw materials in the world will increase the operating costs of individual sectors and industries generating gross value added, which in turn will increase energy poverty in this country.

Another important element of the diversified nuclear-based scenario is to ensure energy security. For many years, the most important domestic energy source in Poland was coal; it gave Poland a comparative advantage, placing it in the forefront of Community countries not dependent on electricity imports. However, as a result of the already known decarbonization prospects, coal production will be phased out in Poland by 2049. Coal mining will not maintain its competitive advantage in the domestic market, even assuming an increase in its productivity. In the case of the discussed scenario, there will be a balancing of domestic coal supply with power sector demand, due to the diversification of the generation mix and the growing share of nuclear and RES. By utilizing the domestic renewable energy potential, 65.6 TWh of electricity will be produced in 2030, i.e., about 23% in final energy consumption, while ten years later it will already be 92 TWh, which is only 28.5% (Figure 3).

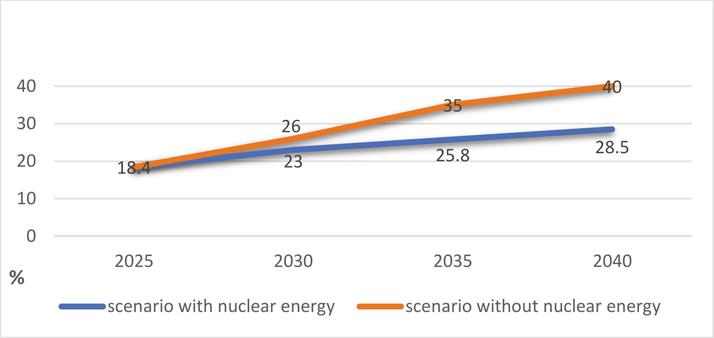

**Figure 3.** Projection of RES share in gross final energy consumption, by scenario. Source: Own elaboration based on: [46,50].

As the energy transition is aimed at reversing unfavorable global climate change, a very important element of the energy transition scenarios is the reduction of the energy sector's impact on climate and the environment. In the analyzed scenario, the situation with the reduction of $CO_2$ emissions will start to improve after the nuclear power plant becomes operational, i.e., after 2034. The $CO_2$ emission intensity for electricity and heat production in 2030 will be 268 million tonnes, hence the reduction will be 29% in relation to 1990, while ten years later it will be 209 million tonnes, i.e., there will be a decrease of 45% in relation to 1990 [46].

To sum up, the lack of profitability of investing in new coal-based generation capacity will result in a dynamic process of reducing the number of coal power plants after 2030, which at the same time will force a faster development of non-coal energy sources and will affect the reduction of $CO_2$ emissions.

### 4.2. Diversified Scenario with Natural Gas

The transition towards climate neutrality will be based on a wide share of natural gas, which in this scenario is treated simultaneously as the main and transition fuel before RES reach higher technological viability. It is worth noting that transitional fuel in this scenario means a low-carbon fuel that is intended to be an alternative to fossil fuels in order to reduce greenhouse gasses emissions [51]. The role of natural gas in the energy transition is time-limited. The European Commission has decided to change the rules for providing financial support to projects belonging to the Trans-European Energy Networks (TEN-E), in order to mobilize member states to redirect their investment efforts towards the energy infrastructure of the future. The end of funding for the construction of oil and gas infrastructure has thus been announced. The aftermath of this decision is the withdrawal of financing for new gas projects by a number of banks, including the European Investment Bank, which will not be granting loans for gas investments from 2022 [52].

For several years, the demand for gas in Poland has been constantly growing. It is used not only in the energy sector but also in the industry: for the production of fertilizers, in metallurgy (steel and glass) and for heating in households [53].

Over the last decade, Poland has developed its gas infrastructure to such an extent that it is able to cut itself off from supplies from the East and thus diversify its sources of gas supply. Of strategic importance for the energy security of the country is the LNG terminal in Świnoujście, thanks to which Poland has the possibility to import gas from any direction. This will be complemented by the Baltic Pipe pipeline which will enable the transmission of gas from Norway to Poland and Denmark, as well as to final customers in neighboring countries. Thanks to the reverse flow it will also be possible to transport gas from Poland to Denmark. Deliveries will start in October 2022. Another important investment that will affect the expansion of the Polish gas portfolio will be the construction of a floating regasification terminal (FSRU) in the port of Gdansk. The unit is to commence operation in 2024 or 2025. [24,54]. In addition, the expanding technical infrastructural capabilities increase the chances of achieving energy self-sufficiency in the supply of gaseous fuel [55].

In the diversified scenario with natural gas, as in the scenario with nuclear energy, a high share of coal in domestic energy production equal to 56% will persist for the next decade, but there is no structural coal supply gap. Although significant amounts of the raw material will be imported, in the long run, convergent dynamics of demand and supply of domestic coal will be established [50].

The emerging production gap after the closure of coal power plants will be filled in large part by gas sources. Poland is planning the largest increase in gas consumption in electricity generation in the entire EU from 14.5 TWh achieved in 2019 to 53 TWh in the next 10 years [46]. This will place it third among the Community countries in the ranking of electricity production from gas. It is worth mentioning that over the next three years, the gasification level in the country will increase to approximately 76%, which will contribute to the elimination of places without access to the raw material [33]. By 2030, new gas units will be built in as many as eight locations [56].

Activities undertaken within the framework of the scenario outlined in PEP 2040, which takes into account the development of the nuclear subsector, do not differ too much from those contained in the alternative scenario, assumed by most researchers and observers of the energy market in Poland. This is a result of the time horizon included in the Polish energy strategy, with 2040 as the cut-off year and the date of nuclear power plant commissioning (2034). In view of the above, in both scenarios until the mid-2030s the forecast of the energy mix, electricity prices, and greenhouse gas emissions will look similar. The situation will become much more complicated when the political elite delays or withdraws from the nuclear power plant construction. Then, there will be a need for further development of the import infrastructure guaranteeing diversification of sources of supply, such as: Baltic Pipe 2, further LNG import capacities, or in the worst-case scenario, gas supplies from Germany, namely Nord Stream and Nord Stream 2 (if the Russians manage to complete the investment). Furthermore, an additional 6.4 GW of new CCGT capacity and 2.8 GW of new gas-fired reserve capacity will have to be built to make up for the production from the missing nuclear units. Investment activities in RES units will also be intensified (e.g., offshore installations, hydrogen, photovoltaics, which can reduce the demand for energy in the summer season and improve the economic efficiency of the system) (Figure 3) [50].

As far as the EU strives for climate neutrality, the development of energy hybrid systems based on intersectoral cooperation between gas systems and electricity systems could prove very beneficial. This cooperation should include allowing the TSO to own and provide services in the power to gas facility for the conversion of electricity into hydrogen or the use of underground gas storage facilities as energy storage facilities injected, inter alia, with hydrogen, which can secure the needs of both the gas system and the electricity system [57].

Gas consumption is highest in the diversified scenario with gas, in which this fuel is used not only for the purposes of reserving variable RES but also for producing electricity, which will translate into an increase in wholesale energy prices and an increase in its import, which will be much higher (ca. 70 TWh) than in the case of the scenario with nuclear energy and will amount to 449 TWh [46,50]. The problem of greenhouse gas emissions, which according to the European Green Deal should be decreasing, is inextricably linked with the increase in gas consumption. Thanks to the transition of the system from coal to gas, its emissivity will start to decrease and in 2030 it will amount to 268 million tonnes, hence the reduction will be 29% in relation to 1990 [46]. Due to the increase in gas capacity in 2040, the emissivity will be higher than in the PEP 2040 scenario and will be around 220 million tonnes [50].

To sum up, in the coming decades low-emission gas generation technologies may play a significant role in the Polish energy transformation process. Thus, gas as a transition fuel will play a regulating and balancing role in generation or cogeneration [56]. The gas scenario forces the growth of RES, because only in this way Poland will be able to effectively reduce $CO_2$ emissions and thus reduce the risk resulting from climate policy and potential costs at the European and pan-European levels.

## 5. Conclusions

The Polish Energy Strategy PEP 2040 announced in 2021 is a strategic document whose implementation will determine the shape of the Polish economy for the coming decades. Unfortunately, it only covers the period until 2040 and thus is not correlated with the EU climate neutrality goal planned until 2050. In many aspects it is based on surreal assumptions, for example, with regard to the most important issue, such as the forecast price of $CO_2$ emissions. To make matters worse, the Polish energy strategy does not provide for another variant of the energy transition in the event that the proposed solutions are delayed. Thus, this scenario is characterized by high investment uncertainty, which will discourage investors from taking action [58]. In both scenarios, the role of RES in the transformation process has been diminished, thus more emphasis has been put on the security of supply than on solving the problem of balancing the electricity system. The greatest hopes are placed in the development of offshore wind energy. It is also incomprehensible that the development of this form of onshore energy generation, which has been blocked since 2016 since the entry into force of the so-called Distance Law, has been blocked. It prevents windmills from being built within a radius of less than 10 times the total height of the windmill from residential buildings and forms of nature protection [59]. The nuclear scenario pushed by the Polish government does not take into account the potential of photovoltaics in electricity generation—it does not foresee any increase in installed capacity between 2025 and 2035.

Gas capacity in many countries is intended to serve as a supplement in a system of unstable RES. In the case of both analyzed scenarios, gas capacity will operate not only in the situation of a decline in green energy production but, what is unusual in the basis of the system, analogously to coal capacity which is currently in operation. Based on PEP 2040 assumptions, the wholesale price of electricity will exceed 72 Euro/MWh, i.e., there will be a 40% increase compared to 2020. In practice, this means that neighboring countries intensively developing RES will have much lower energy prices than Poland [60].

Decision-makers in Poland should be aware that in 15 years, the gas boom of today will be replaced by a recession in the gas market. Therefore, investment decisions taken today should take into account the risk of decarbonization of the gas sector by 2050. The Polish economy has no other choice but to develop the gas market, even under the assumption that it is a transitional fuel and will replace coal. For in this way, the energy security of the country will be maintained at an optimum level. On the other hand, the energy transition without introducing the atom into the Polish energy system will increase Poland’s dependence on natural gas, thereby increasing the country’s dependence on imports of this fuel. In the mid-2030s, there may be further increases in gas prices due to the move away from less carbon-intensive fossil fuels in the world. However, critics of the rationale for using natural gas in the energy transformation process fail to see the important role it will play in the process of controlling energy systems, ensuring the stability of system operation [61].

Emissions in Poland arise mainly in five sectors of the economy: industry, energy, transport, construction, and agriculture. The analysis shows that the reduction of $CO_2$ emissions will be slightly higher (about 3.5%) in the diversified scenario with a nuclear power plant and will amount to 45% in 2040 compared to 1990. Therefore, in the next decade, Poland must reduce further 55% in order to achieve emission neutrality assumed by the EU in 2050. Actions are necessary for all emission areas, mainly consisting of resignation from fossil fuels in favor of emission-free energy sources (RES, hydrogen, ammonia, fuel cells, electrification of the heat generation process and technologies of capturing, using, and storing $CO_2$).

An important element of the transformation having a direct impact on society is the price of energy carriers. Both scenarios assume an increase in energy prices, and in addition, in the diversified scenario with natural gas, one should take into account a large increase in natural gas prices, which has recently started to grow rapidly due to the high demand for this raw material and investments of producers limiting new production capacities for climatic reasons. There is no doubt that the cost of energy carriers has an impact on the prices of products purchased by consumers. On the other hand, at the level of enterprises or local governments, energy is an important component of the costs incurred, and an increase in its price may reduce the competitiveness of some industries. Ultimately, this can lead to instability in livelihoods and affect social and political stability. Another important social effect resulting from the transformation of the energy system is the depopulation of Silesia—the largest mining region in Poland. Both scenarios assume a move away from coal, hence the situation of the population living in this region, who are massively employed in the mining and extractive industries, will depend on the methods of transforming the region and the number of funds allocated for this purpose.

The diversified scenario with nuclear energy proposed in PEP 2040, as well as the unwritten one based on gas, is in fact only an announcement of a reduction in greenhouse gas emissions and not a turn towards low and zero emission energy systems. Both options for the development of Poland's energy mix are a continuation of the current policy based on a centralized energy management system. Projects promoting the development of local and regional electro power are treated as competitive to the projects of energy concerns. The concept of distribution of financial resources obtained from the Just Transition Fund basically assumes their transfer to the investments of state energy companies. This will allow them to maintain their monopolistic position in the market and will hinder the development of electro power for the next decade [62]. Furthermore, most importantly, despite a significant decline in share, coal power plants will remain a significant producer of electricity until 2049.

Poland has chosen the path of energy transformation through the balanced scenario, which is characterized by a lower rate of RES development. It allows Poland to meet its overall energy needs based on its existing generation technologies, without the tension associated with the rapid expansion of green technologies and the issue of their financing.

Polish decision-makers should take into account the alternative diversified scenario with natural gas analyzed in the study, in case the implementation of nuclear energy cannot be implemented on time, as the history of nuclear projects in Poland does not encourage optimism, especially with the current poor level of advancement of works. The most effective measure leading to independence from imports is the construction of renewable energy sources, thanks to which the Polish energy mix will also catch up with the European one and the wholesale energy prices will be equalized.

Slowing down the energy transformation by Poland will certainly have a negative impact on its development. The energy transition has become an economic development plan, an engine of innovation, and a tool to create jobs. Poland's lack of climate neutrality in 2050 will mean that it will not fully participate in the global technological revolution, and its membership in the EU, which is shaken in the context of other political events in recent years, may be called into question. In addition, the economic backlogs that have made up for the last decade will increase again.

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# Factors of Renewable Energy Consumption in the European Countries—The Bayesian Averaging Classical Estimates Approach

**Atif Maqbool Khan [1,2], Jacek Kwiatkowski [3,*], Magdalena Osińska [1] and Marcin Błażejowski [4]**

[1] Department of Economics, Faculty of Economic Sciences and Management, Nicolaus Copernicus University in Torun, Gagarina 13 A, 87-100 Torun, Poland; khan@umk.pl (A.M.K.); emo@umk.pl (M.O.)
[2] University Centre of Excellence IMSErt-Interacting Minds, Societies, Environments, Nicolaus Copernicus University in Torun, Gagarina 11, 87-100 Torun, Poland
[3] Department of Econometrics and Statistics, Faculty of Economic Sciences and Management, Nicolaus Copernicus University in Torun, Gagarina 13 A, 87-100 Torun, Poland
[4] Faculty of Finance and Management, WSB University in Torun, Młodzieżowa 31a, 87-100 Torun, Poland; marcin.blazejowski@wsb.torun.pl
* Correspondence: jkwiat@umk.pl

**Abstract:** The paper aims to identify the most likely factors that determine the demand for energy consumption from renewable sources (renewable energy consumption—REC) in European countries. Although in Europe, a high environmental awareness is omnipresent, countries differ in scope and share of REC due to historical energetic policies and dependencies, investments into renewable and traditional energetic sectors, R&D development, structural changes required by energetic policy change, and many other factors. The study refers to a set of macroeconomic, institutional, and social factors affecting energetic renewable policy and REC in selected European countries in two points of time: i.e., before and after the Paris Agreement. The Bayesian Average Classical Estimates (BACE) is applied to indicate the most likely factors affecting REC in 2015 and 2018. The comparison of the results reveals that the Gross Domestic Product (GDP) level, nuclear and hydro energy consumption were the determinants significant in both analyzed years. Furthermore, it became clear that in 2015, the REC depended strongly on the energy consumption structure, while in 2018, the foreign direct investment and trade openness played their role in increasing renewable energy consumption. The direction of changes is gradual and positive. It complies with the Sustainable Development Goals (SDGs).

**Keywords:** energy from renewable sources; economic; institutional and social factors; Bayesian Average Classical Estimates (BACE); Paris Agreement

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## 1. Introduction

Since the last decade of the 20th century, energy from renewable sources (RE) has received attention across the globe among the different parts of society. The main reason for this popularity is environmental damage, biodiversity change, land loss, global warming, rapid increase in population, higher fuel prices, geopolitical and military conflicts, ultimately affecting all other sectors of the economy. Consumption of energy from renewable sources (renewable energy consumption—REC, hereafter) has climbed by 16.1% in Europe and Euro-Asia, 19.9% in Middle Eastern countries, 26.8% in Africa, 27.7% in North America, 35.1% in Asia-Pacific, and 50.5% in South and Central America in the last two decades. On the other hand, global use of energy from non-renewable sources climbed by only 1.25%. It indicated small rises in regions such as Africa (2.9%) and the Middle East (3.6%), as well as negative growth in the European Union (EU), Europe, and Euro-Asian countries (−1.7%, −0.9%, and −0.6%, respectively) [1].

Identifying the REC determinants and understanding which factors drive new energy sources are critical for policymakers and government authorities. The appropriate selection of determinants for the REC plays a crucial role in mechanizing suitable policies to find an efficient alternative solution to tackle the increasing energy demand. Moreover, it helps to control carbon emissions and further achieve the climate change targets. It also assists them in shifting their energy demand from fossil fuel to renewable energy to achieve Sustainable Development Goals in the long run.

The current study examines economic, social, and institutional determinants of renewable energy consumption in selected European countries. The energy consumption structure according to its sources is included in the analysis. All European countries were taken into account initially, but the data availability limited the selection. Finally, 28 countries were considered, including 25 EU members, Norway, Switzerland, and the United Kingdom. It is worth mentioning that countries in Europe are fairly diversified concerning the exploitation of renewable energy sources. Particularly, Central and Eastern European countries are under-invested in that area. Therefore, the outcomes of this study are crucial in defining and implementing appropriate energy policies to increase the share of renewable energy sources in total energy consumption. As a result, this research can significantly impact policy recommendations and practice in Europe. Finally, this study contributes to the existing empirical literature by identifying the factors driving renewable and non-renewable energy demand in European countries.

The methodology is based on the BACE method. The main advantage of the BACE is to rank the factors according to the probability when the number of potential variables is fairly large. Furthermore, it ensures comparativeness results and suggests the most likely model specifications among a vast range of competing ones [2,3]. The current study is based on an encompassing approach by incorporating the different sets of determinants of REC.

In this research, we concentrated on the newest data, which seems to be the most reliable. This is due to the huge increase in the use of energy from renewable sources in recent years. From the energetic policy perspective, the Paris Agreement prepared in 2015 and signed in 2016 was the milestone to prevent climate change and limit global warming. What is essential is that 194 countries and the EU ratified the document, which means a strong interest of different parties in climate resilience. The goals of the Paris Agreement are strongly related to the low greenhouse gas emissions development, which can be done by changing the structure of energy production and consumption. Consequently, our analysis was prepared in two separate years, i.e., 2015 and 2018, conducted separately for cross-sectional data. The approach considered in the current study is strongly supported by The Intergovernmental Panel on Climate Change (IPCC) report issued on 9 August 2021 (https://www.ipcc.ch/assessment-report/ar6 accessed on 20 September 2021), which confirmed the role of humans in climate change affecting many kinds of weather and climate extremes.

The research questions were whether implementing more restricted policies for environment protection and against climate change could help to increase the impact of renewable energy sources on total energy consumption, which covers electricity, heating/cooling, and transportation. The answer to such a question is provided using descriptive statistical analysis with the coefficient of variation and a more advanced BACE approach.

The novelty of the current research lies in a direct comparison of the renewable energy consumption factors in two years and finding the incentives for the REC in the European countries. Furthermore, a few causal models useful for implementing appropriate energy policy in terms of energy usage patterns are suggested. As a result, this research can significantly impact policy recommendations and practice in the European countries, taking into account their current development and the scale of REC. Finally, this study adds to the existing empirical literature by identifying the factors driving renewable energy demand in Europe. To the best of our knowledge, no empirical research incorporates and investigates a large set of REC determinants using the BACE approach at the regional level.

The rest of the paper is organized as follows. Section 2 reports the relevant literature review. Section 3 provides materials and methods. Section 4 presents the empirical results and checks their robustness. Section 5 provides a discussion of the results, conclusions, and future research plans.

## 2. Literature Review

In the literature, several studies analyzed the relationship between economic growth and deployment of renewables [4–7], and there is some agreement on how they interact. It seems evident that the factors such as GDP or GDP per capita reflect the country's wealth and play a considerable effect in deciding the use of renewables. Moreover, a surplus revenue implies a greater possibility for RE growth or more resources to support it. Increased income allows countries to cover developing RE technologies while also supporting the costs of government policies promoting and regulating RE. Several studies have focused on the determinants of REC in the economic literature [8–10].

According to a study [11], RE technologies are relatively expensive and cannot compete with traditional energy technologies without government support. Several studies [12–14] emphasized how public policies are one of the primary motivators of RE growth in this context. Subsidies, quota rules, direct investment, research and development (R&D), feed-in tariffs, and green certificates are some of the most frequent public policy initiatives to boost renewables. Ref. [15] investigated the relationship between RE, terrorism, fossil fuels, commerce, and economic growth for France. Their findings suggested that trade openness and REC are linked in both directions (bidirectional causality).

Some authors (e.g., [11,12,16,17]) explicitly consider the effects of political factors on REC. On the other hand, other studies focus exclusively on the factors that influence RE use without separating the impact of various policy instruments [5,18–21]. Political, socioeconomic, and country-specific issues are all included in the models of these studies [11,16]. Most studies have revealed that real income is one of the key drivers of REC [5,18,21,22]. Furthermore, because high-income countries can readily fund costly RE investments and give incentives due to abundant sources, countries may use more renewables as their GDP rises [11,16,17].

Some studies found that carbon emissions increase REC [5,11,18–22]; others found that carbon emissions negatively impact [11,12,17]. Concerns about the environment, particularly global warming, are highlighted as key factors in reducing fossil fuel consumption and increasing REC [5,11,21,22]. As the main cause of global warming and climate change is the release of large amounts of greenhouse gases into the atmosphere [16], emissions are used in models to account for environmental concerns. Increases in emissions may be associated with increased use of renewables to meet emissions targets set by international agreements [17,19,20]. Other important factors influencing REC include energy prices, which have been found to have statistically significant effects in some studies [5,17,18,20–22]. Other energy sources, particularly fossil fuels, might be considered alternatives for renewables. As fossil fuel prices rise, it will increase the consumption of RE [5,16–18,20–23].

Furthermore, because there is a close relationship between energy prices and inflation, and inflation and economic growth, the use of RE can reduce the cost-push inflationary pressures caused by price increases in fossil fuels and the risk of stagflation, according to [20]. Furthermore, other studies [12,17] stressed the importance of policy consistency and clarity for RE investments. The relevance of institutions, such as EU membership, is highlighted by [16]. Common targets and EU energy policy may boost renewable deployment in the case of EU membership.

According to Ref. [11], if a country has serious energy security issues, it may be compelled to rely extensively on fossil fuels, lowering its RE share. Changes in energy consumption, especially electricity consumption, may negatively or positively impact REC [11,12,16]. Previous research has found that trade openness [21], international trade [22], and economic growth [24] have statistically significant and positive effects on REC.

In recent debates around the world, the importance of RE in economic development and its environmental benefits in climate risk management has piqued interest. Increasing RE production and consumption investment could be more cost-effective and practical than using non-renewable energy [25,26]. According to Ref. [27], RE can be a crucial tool in climate change adaptation and mitigation. It is commonly known that $CO_2$ emissions from RE sources are lower than those from traditional energy sources.

In Ref. [5], there was discovered that in the G7 countries, higher real GDP per capita leads to higher REC per capita. While $CO_2$ emissions have a positive effect, increasing oil prices has a smaller but negative impact. In another study, authors discovered a similar beneficial influence of real GDP per capita on REC per capita for 18 emerging economies [24]. Ref. [21] found the same effect of real GDP per capita on REC per capita for a panel of 64 countries. The study also discovered that trade openness influences REC per capita.

From 1995 to 2011, Ref. [28] utilized a panel data model to investigate the determinants of RE investment in the EU-27 in solar and wind scenarios. Their findings imply that a robust regulatory perception negatively impacts solar energy investment, with decreased sunshine hours catalyzing increased investment in wind energy in the EU-27. Between 1990 and 2014, Ref. [29] investigated the impact of macroeconomic and social variables on RE usage in the G7 countries. The study shows that research spending (as a percentage of GDP), the human development index, and energy imports positively impact RE use.

Between 2003 and 2014, Ref. [30] investigated if RE stimulates economic growth in (EU-28) countries. The findings show that RE (biomass, hydropower, geothermal, wind, and solar) contributes favorably to energy growth in EU-28 countries, with biomass having the most significant impact. There is also a unidirectional causal relationship between sustainable energy growth and primary RE output in the medium and long run. It was claimed that a 1% increase in primary RE output results in a 0.05 to 0.06 percent rise in GDP per capita.

The study [31] analyzed the determinants for 53 countries by using the WDI data set from 1990–2017. The study used the variables (e.g., REC (hydroelectricity terawatt-hour) and non-renewable energy consumption (daily consumption of barrels of oil) as dependent variables and human capital (average years of schooling population), and non-renewable energy price (barrel price of oil constant 2016 USD) as independent variables. The selection of this study is consistent with the previous studies (e.g., [32–35]). The study found a positive and statistically significant relationship between the non-renewable energy price and the two types of energy consumption.

Similarly, Ref. [36] examined variables relating to RE production and the financial sector using panel data for 119 non- Organisation for Economic Co-operation and Development (OECD) countries. The study discovered that the Kyoto Protocol and commercial banking have a positive effect on RE. On the other hand, Ref. [37] examined the RE capacity, global knowledge stock, GDP per capita, electricity consumption growth rate, Kyoto Protocol, and alternative energy source production in 26 OECD countries. The study discovered that while ratification of the Kyoto Protocol and the deployment of nuclear and hydroelectric energy technologies improves RE, energy security, fossil fuel production, future electricity demand, and national RE policies have no effect. In conclusion, the relationship between different variables (e.g., economic growth, carbon emissions, and RE generation) is not consistent across nations or estimating methods, as evidenced by the above review. Table 1 includes a summary of previous studies on determinants of renewable energy consumption.

**Table 1.** Summary of previous studies on determinants of renewable energy consumption.

| S. No. | Reference No. | Sample | Country(s) | Target Variable(s) | Methodology | Empirical Findings |
|---|---|---|---|---|---|---|
| 1 | [4] | 1985–2005 | 22 OECD countries | Y, REC, GCF, LF | Granger causality | $REC \longleftrightarrow Y$ |
| 2 | [5] | 1980–2005 | G7 countries | REC, Y, P, $CO_2$, OP | Panel Cointegration | Increases in real GDPpc and $CO_2$pc are proven to be important drivers of RECpc usage in the LR. These findings hold true when using two alternative Panel Cointegration estimators. OP has a smaller, but nevertheless negative impact on the REC. |
| 3 | [11] | 1990–2010 | 38 countries | REC, $CO_2$, GDPpc, Pg, Enuse, OP, CP, NGP, Deregulations, Kyoto, EI, EPOS, EPCS, EPNGS, EPNS, ERI | FEVD,<br>PCSE Estimator | [+,S] effect of $CO_2$, [−] effect of Fiscal, Financial, and Voluntary policy measures, Enuse, [NS] effect of EI, energy prices, GDPpc, Pg, and deregulation on REC. |
| 4 | [12] | 1990–2007 | 23 EU countries | REC, $CO_2$pc, CRES, ECpc, IDE, IGEG, ICEG, INEG | PCSE Estimator | Policies promoting renewables, ECpc affect [+,S] to renewable energy share. [−,NS] effects of EI, lobby, and $CO_2$pc. |
| 5 | [15] | 1980–2015 | France | REC, T, fossil EC, EG, TO, GDPpc | ARDL, GC | All variables and REC have LR bidirectional causalities and SR unidirectional causalities. |
| 6 | [16] | 1990–2006 | 24 European countries | CRES, $CO_2$pc, ECpc, IDE, IGEG, ICEG, INEG, SURF, CP, NGP, OP, EU's member in 2001, Y | OLS, RE, FE, FEVD | [−,NS] lobby effect, [−] effect of $CO_2$pc, and [+] effect of Enuse per capita.<br>The effects of income, fossil fuel prices, and EI were found to be [NS]. |
| 7 | [17] | 1990–2006 | 24 European countries | CRES, $CO_2$pc, ECpc, IDE, ICEG, IOEG, IGEG, INEG, Y, OP, NGP, CP | FE, (difference and system GMM), Least Squares Dummy Variable Corrected (LSDVC) | (Coal, oil, gas, and nuclear) the energy source is [S] and consistent effect.<br>Per capita energy effect on RE use is [+,S]. |
| 8 | [18] | 1980–2011 | 25 OECD countries | RECpc, GDPpc, $CO_2$pc, OP | PECM | In LR and SR [+,S] effects of GDPpc, $CO_2$pc, and OP on RECpc. All variables have bidirectional causalities in LR and SR. |
| 9 | [20] | 1997–2006 | OECD countries | contribution of RE to energy supply, GDP, CPI for energy | Panel Threshold Regression model | Energy prices have [+,S] effect in a high growth regime, whereas in a low growth regime, [−,NS] effects are found. |
| 10 | [21] | 1990–2011 | 64 countries | REC, $CO_2$, OP, GDPpc, TO | Pooled OLS, FE, R, Dynamic (difference and system GMM) | $CO_2$pc growth and GDPpc growth had [S] effects on RECpc growth for all subsamples (HIC, MIC, LIC, and all countries). Except in HIC, TO also raises REC. For the entire sample of countries, OP growth has a [+,S] effect. |

**Table 1.** *Cont.*

| S. No. | Reference No. | Sample | Country(s) | Target Variable(s) | Methodology | Empirical Findings |
|---|---|---|---|---|---|---|
| 11 | [22] | 1990–2011 | 64 countries | REC, $CO_2$pc, OP, GDPpc, TO | Dynamic system-GMM panel model | $CO_2$pc growth was observed to cause an increase in REC growth. For MIC and LIC, and the entire sample, the results revealed a [+,S] effect of TO. HIC and MIC were found to have a positive impact on GDPpc growth. The OP growth had a negative impact in MIC and the entire sample. |
| 12 | [24] | 1994–2003 | 18 Emerging economics | REC, NREC, HC, OP | PECM | $Real\ GDPpc \rightarrow RECpc$ |
| 13 | [31] | 1990–2017 | 53 countries | REC, NREC, HC, OP | Generalized Least Squares (GLS), FMOLS | HC has an [S] effect on REC at the global level, in MIC, HIC, and LMIC. On NREC and REC, OP has a [+,NS] impact. |
| 14 | [38] | 1990–2012 | 58 countries | AE, GDP, GDPpc, FDI, Enuse, EI, EPNS, EPCS, EPNGS, EPOS, EPRS, CPI, trade, REC, UP, GHGs, LF, CR, OR, NGR, GCF, TP, REO, ASED | Linear model (FE), nonlinear model (Panel Threshold Regression) | The coefficients on AE, CPI, UP, Enuse, and EI are [S] effects for both regimes with the same signs. GDPpc, EPNS, trade, OR, and ASED. [S] effects on the REC in both regimes with varied signs and sizes. |
| 15 | [39] | 1980–2014 | 72 countries (24 developed and 48 developing) | REP, REPpc, REC, RECpc, SREP, SREC, REPpc, SRECpc, EG (as GDP, GDPpc), $CO_2$, $CO_2$pc, OP | Panel unit root tests, OLS | 1% increase in GDP or GDPpc leads to an increase in RE between 0.05% and 1.01%, and a 1% increase in energy price causes an increase in RE between 0.07% and 0.99% concerning various proxies. |
| 16 | [40] | Quarterly data from 1984–2004 | 20 Latin American and 30 European countries | RE capacity, CPR, GPR, $CO_2$pc, GDPpc, energy dependence, auctions, portfolio standard, feed-in tariffs, fiscal incentives | FE, RE, PCSE models | [+,S] effects of feed-in tariffs, portfolio standard, auctions, CPR per capita, GDP per capita, [+,NS] effects of fiscal incentive, [−,S] effects of electricity demand growth, $CO_2$pc. |
| 17 | [41] | 1990–2007 | 80 countries | REC, NREC, LF, GCF, Y | PECM | $\text{LR}: REC \longleftrightarrow Y$<br>$\text{SR}: REC \longleftrightarrow Y$ |
| 18 | [42] | 1980–2009 | G7 countries | REC, LF, GCF, Y, NREC | Hatemi-J causality tests | $\text{France, Italy, Canada, and U.S.A.}: REC \neq Y$<br>$\text{England and Japan}: REC \longleftrightarrow Y$<br>$\text{Germany}: Y \longleftrightarrow REC$ |

**Table 1.** *Cont.*

| S. No. | Reference No. | Sample | Country(s) | Target Variable(s) | Methodology | Empirical Findings |
|---|---|---|---|---|---|---|
| 19 | [43] | 1980–2009 | 108 countries | GDP, ELC used as a proxy of REC | FMOLS | 79% of the countries : $REC \longleftrightarrow Y$<br>19% of the countries : $REC \neq Y$<br>2% of the countries : $Y \rightarrow REC$ |
| 20 | [44] | 1985–2005 | 108 developing countries | GDP, FEDI, Kyoto, CPR, GPR, TO, hydro share, RE policy, FD | Two-step selection models | [−,S] effects of TO, FDI, policy support programs, growth of ELC, and production from fossil fuels. FD and Kyoto Protocol was [NS] effects. |

**Abbreviations of Variables**: Access to electricity (% of population) (AE); Adjusted savings: energy depletion (current USD) (ASED); Carbon dioxide emissions ($CO_2$); Carbon dioxide emission per capita ($CO_2$pc); Consumer price index (2010 = 100) (CPI); Coal rents (CR); Coal production (CPR); Coal price (CP); Contribution of Renewables to total Energy Supply (CRES); Energy consumption (EC); Economic growth (EG); Energy imports (EI); Energy use (Enuse); Electricity consumption (ELC); Electricity production from coal sources (% of total) (EPCS); Electricity production from natural gas sources (% of total) (EPNGS); Electricity production from oil sources (% of total) (EPOS); Electricity rates for industry (ERI); Electricity production from renewable sources, excluding hydroelectric (% of total) (EPRS); Electricity production from nuclear sources (% of the total) (EPNS); Financial development (FD); Foreign direct investment (FDI); Gross Domestic Product (GDP); GDP per capita (GDPpc); Gas production (GPR); Greenhouse gases (GHGs); Gross capital formation (GCF); Human capital (HC); Income production (IP); Import dependency of energy (%) (IDE); Importance of gas to electricity generation (%) (IGEG); Importance of oil to electricity generation (%) (IOEG); Importance of coal to electricity generation (%) (ICEG); Importance of nuclear to electricity generation (%) (INEG); Labor force (LF); Natural gas rents (NGR); Non-renewable energy consumption (NREC); Natural gas price (NGP); Oil price (OP); Oil rents (OR); Population growth (Pg); Per capita energy consumption (ECpc); Per capita renewable energy consumption (RECpc); Per capita renewable energy production (REPpc); Real GDP (Y); Renewable electricity output (% of total electricity output) (REO); Renewable energy (RE); Renewable energy production (REP); Renewable energy consumption (REC); Share of RE production in total energy production (SREP); Share of RE consumption in total energy consumption (SREC); Share of per capita RE production in per capita total energy production (SREPpc); Share of per capita RE consumption in per capita total energy consumption (SRECpc); Surface area (SURF); Terrorism (T); Total population (P); Trade openness (TO); Urban population (UP). **Abbreviations of Methods:** Fixed Effects Vector Decomposition (FEVD); Fixed Effect (FE); Fully Modified Ordinary Least Squares (FMOLS); Ordinary Least Squares (OLS); Panel Corrected Standards Error (PCSE); Panel Error Correction Model (PECM); Random Effect (RE). **Abbreviations of Results:** Positive and significant results: [+,S]; Negative and significant results: [−,S]; Negative and insignificant results: [−,NS]; [Positive and insignificant results: [+,NS]); REC↔Y indicates a bidirectional causality between REC and EG; Y→REC indicates a unidirectional causality from EG to REC; REC→Y indicates a unidirectional causality from REC to EG; Neutral indicates no causal relationship; Long-run (LR); Short-run (SR); Low-income countries (LIC); Low-middle-income countries (LMIC); Middle-income countries (MIC); High-income countries (HIC).

## 3. Materials and Methods

### *3.1. Data Sources and Descriptive Statistics*

The current study uses cross-sectional data on the REC and its determinants in selected European countries in 2015 and 2018. The years 2015 and 2018 were selected for two reasons. Firstly, analysis for the years earlier than 2014 (such as 2007) gave no economically reasonable results. The explanation comes from the fact that in Europe, some countries are very advanced in consuming energy from renewable sources. Still, there exists a number of countries that are rather underdeveloped in that area. A significant group of countries entered the European Union only in 2004 (ten countries), 2007 (Bulgaria and Romania), and 2013 (Croatia). These years can be treated as structural breaks in the countries' economic and energetic policies, particularly from the post-Soviet Bloc. Furthermore, the financial crisis and post coming recession harmed these countries by limiting investment in the newest energetic technologies. It seems that after the Paris Agreement and stronger policy on $CO_2$ emissions, the state of the art has begun to change. Secondly, the data for 2018 was complete for almost all European countries. Newer data were incomplete, and starting from 2020 may be affected by the COVID-19 pandemic and other structural breaks such as the US presidential election. In this study, we tried to avoid the impact of new structural breaks, which creates new areas of analysis.

The further explanation comes directly from the Eurostat data. It shows that the target for the overall share of energy consumption from renewable sources for the EU in 2020 is 20%. In 2018, this share equaled 18.01%. The overall energy consumption comprises electricity, heating and cooling, and transport. Figure 1 compares the actual shares of overall energy consumption in 2015, 2018, and 2020 target values in EU27 and individual countries. Similar to Iceland and Norway, leading countries exceeded as much as three times the European target value for overall energy consumption from renewable sources. In contrast, Finland, Sweden, and Latvia exceeded twice as much. However, there are substantial differences between 2015 and 2018. In general, the share achieved in 2018 is higher than in 2015. There are also some cases that indicate the opposite direction, although it can result from local policies and investments. The increase in the share of energy consumption from renewable sources can be perceived as gradual, caused by growing awareness of adverse global warming effects, but the determinants that influence that rise change over time and should be identified.

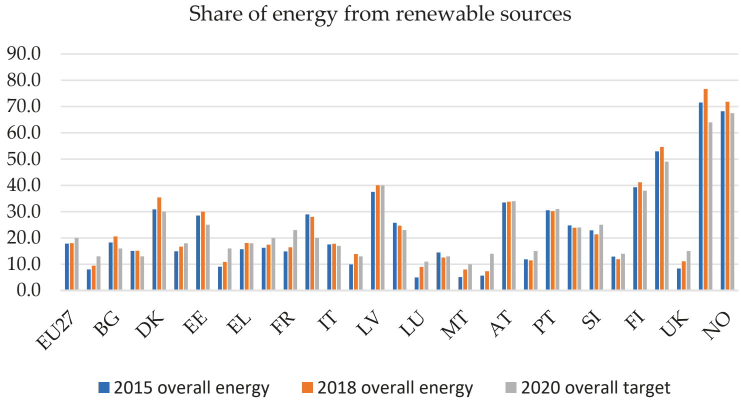

**Figure 1.** Overall energy consumption from renewable sources in Europe in 2015, 2018, and 2020 (target value). Source: Based on https://ec.europa.eu/eurostat/web/energy/data/shares (accessed on 25 October 2021).

As the situation is dynamically developing, the study answers the question of if there is any difference in the number and strength of factors determining REC in selected European countries in 2015 and 2018.

The study is based on secondary data sources, including World Development Indicators (WDI-2019); Statistical Review of World Energy (BP-2019); International Monetary Fund (IMF); Energy Information Administration (EIA); Worldwide Governance Indicators (WGI); International Renewable Energy Agency (IRENA), and the International Energy Agency (IEA) consisting of annual observations on selected European countries. The list of countries used in the study, due to the data accessibility, is given in Table 2.

**Table 2.** The list of selected countries.

| Countries | Codes | Countries | Codes | Countries | Codes | Countries | Codes |
|---|---|---|---|---|---|---|---|
| Austria | AUT | Finland | FIN | Latvia | LVA | Romania | ROU |
| Belgium | BEL | France | FRA | Lithuania | LTU | Slovak Republic | SVK |
| Croatia | HRV | Germany | DEU | Luxembourg | LUX | Slovenia | SVN |
| Cyprus | CYP | Greece | GRC | Netherlands | NLD | Spain | ESP |
| Czech Republic | CZE | Hungary | HUN | Norway | NOR | Sweden | SWE |
| Denmark | DNK | Ireland | IRL | Poland | POL | Switzerland | CHE |
| Estonia | EST | Italy | ITA | Portugal | PRT | United Kingdom | GBR |

Taking into account the literature review, many economic, institutional, and energy variables were specified as potential determinants of REC. They can be divided into the following subgroups, while symbols used in the study are given in parentheses:

(1) Economic: Gross Domestic Product (GDP), FDI net inflow (FDI_BOP), unemployment (UNEMP), trade openness (TO).
(2) Disaggregate energy consumption from the following sources: oil (OC), coal (CC), gas (GC), nuclear (NC), and hydro (HC).
(3) Social: Education index (EI), Life expectancy index (LEI), School enrollment, tertiary (% gross) (SET).
(4) Institutional: political stability absence and absence of violation (PSA), control of corruption (CCUR), the rule of law (RL).
(5) Demographic: Surface area (SURF).
(6) Dummies: Top developed countries' group of world's advanced economies and wealthiest liberal democracies, and G7 countries (TDC), and former members of the Eastern Bloc countries (FEBC).

A remarkable disparity between highly developed European and developing economies justifies a dummy variable corresponding to the division in (6). The selection of variables is based on both the environmental economics fundamentals [45] and empirical literature review. The selected variables, GDP, oil price, and oil consumption, were used by [22]; Foreign direct investment, net inflows (% of GDP) by [34]; Rule of law, Control of corruption, Political stability and Absence of violence/terrorism by [46]; Education index by [47]. The description of all variables and their units is given in Table A1 in Appendix A.

Table A2 presents descriptive statistics for the population of selected European countries in the years 1995, 2000, 2005, 2010, 2015, and 2018. It confirms the general change in the structure of the energy consumption from different sources. On average, the consumption of oil, gas, nuclear, and, particularly coal, in Europe decreases gradually while hydro and renewable energy use increases substantially. The most substantial reduction is observed in coal energy consumption, which amounts to almost 39% between 1995 and 2018. On the other hand, the increase in renewable energy consumption was over 2200% from the average 0.2409 in 1995 to 5.7405 in 2018. Values of standard deviation (SD) show that dispersion is quite huge, and coefficients of variation exceed 100 percent. In Figure A1, the coefficients of variation for energy consumption from different sources are shown. They inform about the general tendency towards convergence among the countries in energy consumption [48]. The convergence is observed for oil and gas energy consumption. The remaining energy sources reveal rather a divergence, which confirms huge variability among the countries. The empirical distributions are positively skewed and leptokurtic.

### 3.2. Methodology

One potential problem in the linear model selection procedure is finding a significant set of explanatory variables among all potential determinants. The problem is not trivial if we imagine that, for the sake of this analysis, we have 18 potential variables with 262,144 linear combinations; some of them are equally likely with similar explanatory power. To overcome this problem, we decided to use BACE—Bayesian Averaging of Classical Estimates introduced in [2], which is essential for the credibility and conclusiveness of presented results. Briefly speaking, BACE parameter estimates are obtained by applying Ordinary Least Squares (OLS) and then averaged across all possible combinations of models, given their explanatory power. Therefore, we do not only make inferences on the "best" single model, but we take into account the uncertainty of all models. Consequently, we can easily identify significant determinants of a dependent variable based on a whole model space without specific knowledge [3]. The latest review of model averaging techniques and their implementation is presented in [49].

The construction of the BACE model methodology is explained by Equations (1)–(6). Let us consider the following linear regression model for a cross-sectional dataset:

$$M_j : y = \alpha\iota_N + X_j\beta_j + \epsilon, j = 1, \ldots, 2^K \tag{1}$$

where $K$ denotes the total number of potential explanatory variables, $2^k$ is a total number of possible linear combinations, $\iota_N$ is a $(N \times 1)$ vector of ones, $y$ is a vector of observations (in our case, renewable consumption index), $X_j$ is $\left(N \times k_j\right)$ matrix containing the set of regressors included in the model $M_j$, $k_j$ is number of regressors included in the model $M_j$, $\beta_j$ is $\left(k_j \times 1\right)$ vector of unknown parameters, and $\epsilon$ is $(N \times 1)$ vector of errors, normally distributed, $\epsilon \sim N\left(0_N, \sigma^2 I_N\right)$. Notation $N(\mu, \Sigma)$ denotes a normal distribution with location $\mu$ and covariance $\Sigma$.

Based on Ref. [2], we can use OLS estimates to calculate the approximation of the posterior probability of every model $M_jS$ using the following formula:

$$\Pr(M_j \mid y) \approx \frac{\Pr(M_j)N^{-\frac{k_j}{2}}SSE_j^{-\frac{N}{2}}}{\Sigma_{i=1}^{2K}\Pr(M_i)N^{-\frac{k_i}{2}}SSE_i^{-\frac{N}{2}}} \tag{2}$$

where $SSS_j$ and $SSS_j$ are the OLS sum of squared errors, $k_j$ and $k_{is}$ are the number of regression parameters $\beta_j$ and $\beta_i$, $P_r\left(M_j\right)$, and $P_r(M_i)$ are prior probabilities of models $M_j$ and $M_i$.

In our case, we use the popular binomial model prior [50]:

$$\Pr\left(M_j\right) = \theta^{k_i}(1-\theta)^{K-k_i}, \theta \in [0,1] \tag{3}$$

We know that we only need to specify a prior expected model size $E(\Xi) = K\theta$ to set the prior probability for all competitive models from binomial distribution properties. For example, if $\theta = 0.5$, then the prior expected model size equals the average number of potential regressors, and all models have an equal prior probability.

In the BACE approach, we can also obtain the averages of parameter estimates $\beta$ based on the whole model space [2,51]:

$$E(\beta \mid y) \approx \sum_{i=1}^{2^K}\Pr(M_i \mid y)\hat{\beta}_i \tag{4}$$

$$\mathrm{Var}(\beta \mid y) \approx \sum_{i=1}^{2^K}\Pr(M_i \mid y)\mathrm{Var}(\beta_i) + \sum_{i=1}^{2^K}\Pr(M_i|y)\left(\hat{\beta}_i - E(\beta|y)\right)^2 \tag{5}$$

where $\hat{\beta}_i$ and $Var(\beta_i)$ are the OLS estimates of $\beta_i$ from model $M_i$.

Another useful and popular characteristic in model averaging is so-called posterior inclusion probability (PIP), which is defined as the posterior probability that the independent variable $x_i$ is relevant in explaining the dependent variable [38,52]. In our case, the PIP is calculated as the sum of the posterior model probabilities for all of the models that include a specific variable:

$$\Pr(\beta_i \neq 0 \mid y) = \sum_{i=1}^{2^K} \Pr(M_r \mid \beta_i \neq 0, y) \tag{6}$$

Thus, PIP can be understood as the importance of each variable for explaining the dependent variable.

## 4. Results

### 4.1. Empirical Results

The study takes into account a group of independent variables that represent potential factors responsible for renewable energy consumption (REC) in 28 European economies. The variables and their symbols are presented in Section 3.1 and Table A1. Referring to the environmental policy adopted in Europe after the Paris Agreement in 2015, we considered two points of time:

(a) the year 2015, just before the Paris Agreement ratification;
(b) the year 2018, after the Paris Agreement ratification.

It should be mentioned that the EU and all its members individually ratified the Paris Agreement in 2016.

The research question was whether implementing a more restricted policy for environment protection and against climate change could cause a substantial change in the determinants of REC in European countries.

In order to identify determinants of REC, we used the BACE selection procedure, which enables searching all possible combinations of potential variables and selecting the most probable candidates. The BACE also enables calculations of the averages of the coefficient means and standard deviations of parameters, and the explanatory power of competitive models. We used the BACE 1.1 package (the BACE 1.1 package is available at http://ricardo.ecn.wfu.edu/gretl/cgi-bin/gretldata.cgi?opt=SHOW_FUNCS (accessed on 1 August 2021) and was developed by [53]), which is available in the gretl program as open-source software. Gretl is free program and it may be redistributed and/or modified under the terms of the GNU General Public License (GPL) as published by the Free Software Foundation, originally developed in North Carolina, USA and and Ancona, Italy.

The whole model space in the regression model (excluding intercept) was equal to $2^{18} = 262,144$. The total number of Monte Carlo iterations was 1,000,000 (including 10% burn-in draws). The correlation coefficient between the analytical and numerical probabilities of the top models was above 0.99, which means that convergence of simulation was confirmed. Model prior was set to uniform, which means that all possible specifications were equally likely.

The posterior results are given in Table 3. It shows posterior inclusion probabilities, the average value of the coefficient (parameter estimate overall considered models), and the corresponding average standard error. The posterior inclusion probability (PIP) equalled at least 0.7, and shows a high probability of being included in the model. Although there is no formal requirement for high posterior probability, it is reasonable to assume that it is at least higher than 0.5 and treats the results higher than 0.7 as reliable.

**Table 3.** Posterior estimates of renewable consumption determinants in 2015 and 2018.

| Variable | 2015 | | | 2018 | | |
|---|---|---|---|---|---|---|
| | **PIP** | **Avg. Coefficient** | **Avg. Std. Error** | **PIP** | **Avg. Coefficient** | **Avg. Std. Error** |
| Const | **1.0000** | 10.9202 | 15.5713 | **1.0000** | 6.3989 | 14.5596 |
| NC | **1.0000** | −0.3141 | 0.0634 | **0.9992** | −0.2503 | 0.0767 |
| GDP | **0.8834** | 0.0099 | 0.0056 | **0.9808** | 0.0119 | 0.0042 |
| FDI_BOP | 0.3705 | −0.0028 | 0.0055 | **0.9186** | 0.0184 | 0.0088 |
| TO | 0.4940 | −0.0077 | 0.0110 | **0.8550** | −0.0203 | 0.0126 |
| HC | **0.7368** | −0.1845 | 0.1607 | **0.7770** | −0.1481 | 0.1294 |
| GC | **0.9933** | −0.5105 | 0.1646 | 0.4701 | −0.1247 | 0.2003 |
| OC | **0.9196** | 0.2859 | 0.1728 | 0.4443 | 0.0673 | 0.1206 |
| CC | 0.2480 | 0.0058 | 0.0305 | 0.4036 | 0.0258 | 0.0452 |
| TDC | 0.5894 | 7.1765 | 9.1039 | 0.3741 | −0.5901 | 6.9248 |
| SURF | 0.6361 | 0.000006 | 0.000006 | 0.3274 | 0.000001 | 0.000004 |
| SET | 0.3528 | −0.0108 | 0.0224 | 0.3048 | 0.0082 | 0.0208 |
| PSA | 0.1980 | 0.0586 | 0.8835 | 0.2994 | 0.6116 | 1.5392 |
| LEI | 0.4445 | −10.1697 | 16.4292 | 0.2966 | −5.8818 | 15.5512 |
| FEBC | 0.3009 | −0.0741 | 1.4099 | 0.2430 | −0.2563 | 1.0624 |
| UNEMP | 0.3690 | −0.0628 | 0.1405 | 0.2291 | 0.0091 | 0.1133 |
| CCUR | 0.4248 | −0.9699 | 1.8046 | 0.2136 | −0.1381 | 0.8091 |
| RL | 0.2933 | 0.4730 | 1.7139 | 0.2083 | 0.1680 | 1.0496 |
| EI | 0.2326 | 0.4600 | 7.8276 | 0.1901 | 0.0202 | 5.8023 |

Note: Bold font indicates PIP values greater than 0.7. Abbreviations of Variables: (NC) Nuclear consumption; (GDP) Gross Domestic Product; (FDI_BOP) FDI net inflow; (TO) Trade openness; (HC) Hydro consumption; (GC) Gas consumption; (OC) Oil consumption; (CC) Coal consumption; (TDC) Top developed countries; (SURF) Surface area; (SET) School enrollment, tertiary; (PSA) Political stability absence; (LEI) Life expectancy index; (FEBC) Former members of the Eastern Bloc countries; (UNEMP) Unemployment; (CCUR) Control of corruption; (RL) The Rule of law; (EI) Education index.

The results in Table 3 exhibited a substantial difference between factors of REC in European countries in 2015 and 2018. The results for 2015 indicated nuclear and hydro energy consumption, oil and gas energy consumption, and the value of GDP. The signs of parameters for NC, HC, and GS were negative, which means that there was a competition between specified energy sources in Europe depending on hitherto resources, infrastructure, and long-term contracts. The GDP denotes the country's economic position and readiness for renewable infrastructure investments. The average coefficient of 0.0099 shows that increasing GDP by USD 1000 will increase renewable energy consumption by 11.9 Mtoe, keeping all other factors unchanged.

The results for the year 2018 revealed that the following factors are the most likely: nuclear and hydro energy consumption, GDP, FDI net inflow, and trade openness. What is more interesting is that the signs of the mean parameters are in line with the knowledge and intuition. GDP and FDI_BOP have positive parameter estimate signs, while nuclear and hydro energy consumption have negative signs. Additionally, the parameter estimate for the GDP is higher than in 2015 and is supported by the positive value of FDI_BOP. The trade openness has a negative parameter estimate. Such variables focus on the economic and energy factors that mostly influence renewable energy consumption in European countries. The GDP and FDI support investments in the renewable energy sector; thus, their positive impact aligns with economic logic.

On the other hand, nuclear and hydro energy consumption compete with the renewable energy sector (https://energypost.eu/renewable-energy-versus-nuclear-dispelling-myths/ (accessed on 24 July 2021)). However, the recent findings support renewable energy as much faster in building the infrastructure as compared with the nuclear one (2019 World Nuclear Industry Status Report, available at https://www.worldnuclearreport.org/-World-Nuclear-Industry-Status-Report-2019-.html (accessed on 24 July 2021)). The trade openness, measured as the sum of a country's exports and imports as a share of that country's GDP (in %), shows a negative sign, which is in line with the findings presented in the literature [31,54].

Three important issues need to be clarified. Firstly, European countries gradually introduced renewable energy sources, and after ratifying the Paris Agreement, they were ready to fight against climate change. Secondly, countries in Europe are diversified concerning the infrastructure in the energy sector. Thirdly, the European countries are quite homogenous as concerning social and institutional environments; therefore, the variables included in social and institutional groups did not impact renewable energy consumption.

Tables A3 and A4 include the top three models according to their posterior probabilities for 2015 and 2018, respectively. The total probability of the presented models is 0.0270 (2015) and 0.0258 (2018), so it is easy to see that the best models have a very low posterior probability. This means that there is no one dominant specification, and inferences based on only one model can be very misleading because each of them has very low explanatory power. The top three models consist of 7–12 variables, and some of them are significant in a single regression. Still, due to the small explanatory power of the model, they have low PIP values and thus do not significantly impact the dependent variable. This means our results justify the necessity of using the model averaging (BACE) approach instead of a single model selection procedure. There is one more important remark on the example models. In 2015, the division into top developed countries and the former Eastern Bloc was significant across all models, while in 2018, the dummies are less likely or insignificant.

### *4.2. Robustness Check*

In order to confirm the empirical findings for variable and model selection obtained by BACE, we performed robustness analysis using different prior model assumptions. We applied the idea proposed in [55] and set different variants of the prior average model size to check the sensitivity of variable selection results. In Section 4.1, the prior average model size is set to $E(\Xi) = K/2$ (where $K$ represents the number of all available independent variables considered in the model). It means that the prior model distribution is uniform, i.e., each model has an equal prior probability, and we do not prefer any specification. To explore the robustness in more detail, we use two additional prior model sizes, namely: $E(\Xi) = K/3$ and $E(\Xi = K/4$ (the most restrictive case). Table 4 presents the BACE estimates for renewable consumption determinants in 2015 with different average prior model sizes, while Table 5 shows the results for the 2018 year. The results contain values of PIP, average coefficients, and average standard errors.

The comparison of the results revealed that there are no substantial differences in the output between $E(\Xi) = K/2$, $E(\Xi) = K/3$, and $E(\Xi) = K/4$. Any observed differences are negligible; therefore, the empirical results are robust.

The results for posterior estimates of the top 3 models for renewable consumption determinants in 2015 and 2018 are presented in Tables A3 and A4, respectively.

**Table 4.** Posterior estimates of renewable consumption determinants in 2015 for different average prior model sizes.

| | *E*(Ξ) = *K*/2 | | | *E*(Ξ) = *K*/3 | | | *E*(Ξ) = *K*/4 | | |
|---|---|---|---|---|---|---|---|---|---|
| **Variable** | **PIP** | **Avg. Coefficient** | **Avg. Std. Error** | **PIP** | **Avg. Coefficient** | **Avg. Std. Error** | **PIP** | **Avg. Coefficient** | **Avg. Std. Error** |
| const | **1.0000** | 10.9202 | 15.5713 | 1.0000 | 10.7550 | 15.4740 | 1.0000 | 10.8044 | 15.4340 |
| NC | **1.0000** | −0.3141 | 0.0634 | 0.9999 | −0.3150 | 0.0635 | 1.0000 | −0.3144 | 0.0627 |
| GDP | **0.8834** | 0.0099 | 0.0056 | 0.8829 | 0.0099 | 0.0056 | 0.8820 | 0.0099 | 0.0056 |
| FDI_BOP | 0.3705 | −0.0028 | 0.0055 | 0.3645 | −0.0028 | 0.0055 | 0.3656 | −0.0028 | 0.0055 |
| TO | 0.4940 | −0.0077 | 0.0110 | 0.5033 | −0.0078 | 0.0110 | 0.4945 | −0.0077 | 0.0110 |
| HC | **0.7368** | −0.1845 | 0.1607 | 0.7398 | −0.1866 | 0.1607 | 0.7384 | −0.1855 | 0.1606 |
| GC | **0.9933** | −0.5105 | 0.1646 | 0.9930 | −0.5118 | 0.1648 | 0.9957 | −0.5109 | 0.1622 |
| OC | **0.9196** | 0.2859 | 0.1728 | 0.9181 | 0.2870 | 0.1732 | 0.9198 | 0.2859 | 0.1725 |
| CC | 0.2480 | 0.0058 | 0.0305 | 0.2375 | 0.0055 | 0.0300 | 0.2392 | 0.0055 | 0.0297 |
| TDC | 0.5894 | 7.1765 | 9.1039 | 0.5960 | 7.3017 | 9.1289 | 0.5867 | 7.2000 | 9.0915 |
| SURF | 0.6361 | 0.000006 | 0.000006 | 0.6437 | 0.000006 | 0.000006 | 0.6352 | 0.000006 | 0.000006 |
| SET | 0.3528 | −0.0108 | 0.0224 | 0.3500 | −0.0107 | 0.0223 | 0.3453 | −0.0105 | 0.0220 |
| PSA | 0.1980 | 0.0586 | 0.8835 | 0.2025 | 0.0616 | 0.8837 | 0.1995 | 0.0606 | 0.8749 |
| LEI | 0.4445 | −10.1697 | 16.4292 | 0.4384 | −9.9560 | 16.3019 | 0.4369 | −10.0044 | 16.3088 |
| FEBC | 0.3009 | −0.0741 | 1.4099 | 0.2978 | −0.0769 | 1.4074 | 0.3002 | −0.0570 | 1.3982 |
| UNEMP | 0.3690 | −0.0628 | 0.1405 | 0.3741 | −0.0643 | 0.1406 | 0.3639 | −0.0629 | 0.1389 |
| CCUR | 0.4248 | −0.9699 | 1.8046 | 0.4266 | −0.9818 | 1.8108 | 0.4193 | −0.9519 | 1.7880 |
| RL | 0.2933 | 0.4730 | 1.7139 | 0.2933 | 0.4749 | 1.7128 | 0.2872 | 0.4576 | 1.6893 |
| EI 0.2326 | 0.4600 7.8276 | 0.2335 | | 0.4740 | | | 7.8625 | | 0.2289 0.3891 7.6372 |

**Table 5.** Posterior estimates of renewable consumption determinants in 2018 for different average prior model sizes.

| **Variable** | *E*(Ξ) = *K*/2 | | | *E*(Ξ) = *K*/3 | | | *E*(Ξ) = *K*/4 | | |
|---|---|---|---|---|---|---|---|---|---|
| | **PIP** | **Avg. Coefficient** | **Avg. Std. Error** | **PIP** | **Avg. Coefficient** | **Avg. Std. Error** | **PIP** | **Avg.Coefficient** | **Avg. Std. Error** |
| const | **1.0000** | 6.3989 | 14.5596 | 1.0000 | 6.3212 | 14.3276 | 1.0000 | 6.2041 | 14.1475 |
| NC | **0.9992** | −0.2503 | 0.0767 | 0.9992 | −0.2504 | 0.0764 | 0.9996 | −0.2499 | 0.0755 |
| GDP | **0.9808** | 0.0119 | 0.0042 | 0.9842 | 0.0119 | 0.0041 | 0.9868 | 0.0119 | 0.0041 |
| FDI_BOP | **0.9186** | 0.0184 | 0.0088 | 0.9187 | 0.0184 | 0.0088 | 0.9217 | 0.0185 | 0.0087 |
| TO | **0.8550** | −0.0203 | 0.0126 | 0.8548 | −0.0201 | 0.0125 | 0.8570 | −0.0202 | 0.0125 |
| HC | **0.7770** | −0.1481 | 0.1294 | 0.7804 | −0.1477 | 0.1281 | 0.7856 | −0.1486 | 0.1276 |
| GC | 0.4701 | −0.1247 | 0.2003 | 0.4695 | −0.1249 | 0.1994 | 0.4641 | −0.1233 | 0.1971 |
| OC | 0.4443 | 0.0673 | 0.1206 | 0.4381 | 0.0661 | 0.1191 | 0.4361 | 0.0650 | 0.1168 |
| CC | 0.4036 | 0.0258 | 0.0452 | 0.4008 | 0.0257 | 0.0449 | 0.4022 | 0.0256 | 0.0447 |
| TDC | 0.3741 | −0.5901 | 6.9248 | 0.3769 | −0.6803 | 6.8824 | 0.3741 | −0.7285 | 6.7650 |
| SURF | 0.3274 | 0.000001 | 0.000004 | 0.3160 | 0.000001 | 0.000004 | 0.3183 | 0.000001 | 0.000004 |
| SET | 0.3048 | 0.0082 | 0.0208 | 0.2985 | 0.0079 | 0.0203 | 0.3047 | 0.0082 | 0.0204 |
| PSA | 0.2994 | 0.6116 | 1.5392 | 0.2873 | 0.5748 | 1.4895 | 0.2935 | 0.5881 | 1.4970 |
| LEI | 0.2966 | −5.8818 | 15.5512 | 0.2934 | −5.7424 | 15.3203 | 0.2903 | −5.6288 | 15.1293 |
| FEBC | 0.2430 | −0.2563 | 1.0624 | 0.2412 | −0.2475 | 1.0388 | 0.2328 | −0.2437 | 1.0167 |
| UNEMP | 0.2291 | 0.0091 | 0.1133 | 0.2237 | 0.0089 | 0.1111 | 0.2217 | 0.0088 | 0.1095 |
| CCUR | 0.2136 | −0.1381 | 0.8091 | 0.2109 | −0.1309 | 0.7841 | 0.2086 | −0.1315 | 0.7773 |
| RL | 0.2083 | | 0.1680 | | | 1.0496 | | 0.2038 0.1635 | 1.0231 0.2049 0.1612 1.0141 |
| EI | 0.1901 | | 0.0202 | | | 5.8023 | | 0.1839 0.0009 | 5.5651 0.1789 −0.0050 5.4166 |

## 5. Discussion and Conclusions

Application of the BACE procedure provides a reliable result since it allows to search the entire model space to find the most likely determinants of renewable energy consumption. Furthermore, it gives robust results against more restrictive models. The most important advantages of the model averaging were indicated in [2,56]. The first one is including the model uncertainty into the model selection procedure, which reduces overconfidence in a single model. Furthermore, it avoids the all-or-nothing mentality that is associated with classical hypothesis testing, where a model is either accepted or rejected wholesale. BACE gracefully updates its estimates as the data accumulate and the resulting model weights are continually adjusted. Finally, BACE is relatively robust to model misspecification. The successful application of BACE is possible for different databases as cross-sectional data, time-series data, and panel data [57–59].

The study focuses on European countries because Europe, although quite keen on promoting renewable energy sources, is still diversified in using energy from different sources. Mainly, Central and Eastern European countries are mostly underdeveloped in investments in the renewable energy sector. European countries tend to realize sustainable energy plans. Although, between 2015 and 2018, the total primary energy consumption in Europe has increased by 2.7% from 1996.8 to 2050.7 (Mtoe) but the production of fossil fuels was reduced. The total oil production was reduced by 2.16%, and gas production decreased by 4.22% from 2015 to 2018. The most significant reduction was observed in coal production (reduction by 9.19%) and consumption (reduced by 9.46%). Europe is in one of the top positions in renewable energy consumption, fluctuating from 141.5 to 172.2 Mtoe from 2015 to 2018, which indicates a 21.70% change [60].

In the current study, we put the research question on determinants of renewable energy consumption in European countries. Using the BACE approach, substantial differences between factors observed in 2015 and 2018 were found. In 2015, GDP was the only economic variable that supported energy consumption from renewable sources. The other factors comprised the alternative energy sources competing with REC. In 2018, GDP supported by the FDI and Trade Openness are responsible for the country's investments in the renewable energy sector. The alternative energy sources such as nuclear energy and hydro energy remained reasonably likely. Considering the technological and environmental viewpoints, it is clear that nuclear energy, due to its enormous efficiency, must support "purely" renewable energy sources. There is a discussion of whether nuclear energy can be thought of as a renewable one (https://world-nuclear.org/information-library/energy-and-the-environment/renewable-energy-and-electricity.aspx, accessed 25 October 2021).

When comparing the results with the findings presented in the literature, Ref. [61] indicated that income is significant as a factor of renewable energy consumption. She focused on financial variables that can be omitted in developed economies but cannot be excluded in developing ones because RE technologies require a high upfront investment.

The question arises whether a qualitative change resulting from the study comes directly from the Paris Agreement ratified in 2016. On one side, the strong warnings on the effects of climate change resulted in the energy policy change in European countries, particularly, the energy based on fossil fuels was remarkably reduced. The difference can be visible in both household and industry sectors. On the other side, there is no evidence in the literature that over five years after the Paris Agreement, a rapid limitation in gas emissions could be observed. Ref. [62] indicated signs of progress, such as several nations that strengthen their initial pledges by promising to cut their net climate emissions to zero by 2050. These are the European Union, Canada, South Korea, Japan, South Africa, the United Kingdom, and recently, the USA. Furthermore, China declared cutting climate pollution faster than initially promised, aiming for carbon neutrality by 2060. There are also signs that the temperature spikes predicted for later this century are easing slightly. The changes are relatively slow, and the COVID-19 pandemic changes its direction. There are some adverse examples such as USA climate policy under the Trump presidency and deforestation in the Amazon (Brazil), which enabled global emissions of warming gases to continue climbing to a record high in 2019. The pandemic year 2020 has stopped the emissions in the short run.

What is worth noting, is that the Paris Agreement increased global awareness of climate change and its consequences. It is in line with the results obtained by [11]. They suggested that environmental concern is an essential factor in explaining participation of renewables in different countries.

As comes from the results of this study, there is a divergence concerning REC in Europe. Although renewable energy requires both new investments in infrastructure and social acceptance, the increase of the REC in Europe is visible. As it was mentioned, the renewable energy plans require new investment as well as changing the structure of the energy sector by replacing old energy infrastructure with a new one. It is related to closing traditional industries, local environment changes, and construction of new energetic complexes. Increasing GDP and FDI inflow can help activate the changes, particularly in less advanced countries such as Croatia, Cyprus, Latvia, Lithuania, Poland, Romania, Slovakia, and Slovenia. The presence of trade openness in 2018 as the factor influencing renewable energy consumption aligns with the results presented in [15].

However, there remains a social context of the aforementioned changes. Ref. [63] prepared a literature review on the social acceptance of renewable energy projects (REP) in European countries. They found that social acceptance is a significant barrier in the implementation of REP. They argued that governments must consider the general trends in local acceptance and create a framework that will increase the probability of local acceptance, and reduce the chances of an opposition network that will hinder the development of an REP Trust in principal actors which remains a significant driver in local acceptance. It has been demonstrated that to foster acceptance of renewable energy projects, the public must gain trust in local authorities and developers. To achieve the goal, full transparency of the project is recommended.

The study confirmed that the global awareness of climate change increased after the Paris Agreement creating room for changing the energy policy in both developed and developing countries in Europe. Although the change is gradual and divergence tendencies are quite strong, the investments in the RE sector and GDP redistribution allow achieving climate neutrality goals.

The limitation of the study is that it covers cross-sectional data from two years: 2015 and 2018. It seems too short of catching the changes that resulted from the Paris Agreement, with soundness being fairly high. Based on the experience of the current study, further research plans are fostered. The next attempt is to consider determinants of the REC from a worldwide perspective. Both developed and developing countries should be taken into account. The panel data approach is also planned. The final step of the research is to combine renewable energy consumption and production with the green economic growth indicator. It will also be interesting to measure the impact of the COVID-19 pandemic on the REC in different countries.

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## Appendix A

**Table A1.** Descriptions of variables.

| No. | Abbreviation of Variable | Variable Name | Proxy/Scale of Measurement | Data Source |
|---|---|---|---|---|
| | | | **Energy-based Variables** | |
| 1 | REC | Renewable consumption | million tons of oil equivalent to exajoules (Mtoe) | BP-2019 |
| 2 | OC | Oil consumption | million tons of oil equivalent to exajoules (Mtoe) | BP-2019 |
| 3 | GC | Gas consumption | million tons of oil equivalent to exajoules (Mtoe) | BP-2019 |
| 4 | CC | Coal consumption | million tons of oil equivalent to exajoules (Mtoe) | BP-2019 |
| 5 | HC | Hydro consumption | million tons of oil equivalent to exajoules (Mtoe) | BP-2019 |
| 6 | NC | Nuclear consumption | million tons of oil equivalent to exajoules (Mtoe) | BP-2019 |
| | | | **Economic Variables** | |
| 7 | GDP | Gross Domestic Product | Data are in constant 2010 US dollars. | WDI-2019 |
| 8 | TO | Trade openness | Trade openness = Exports of goods and services (% of GDP) + Imports of goods and services (% of GDP). | WDI-2019 |
| 9 | FDI_BOP | Foreign direct investment, net inflows (BOP) | Foreign direct investment refers to direct investment equity flows in the reporting economy. It is the sum of equity capital, reinvestment of earnings, and other capital. Data are in current US dollars. | WDI-2019 |
| 10 | UNEMP | Unemployment, total | Unemployment refers to the share of the labor force that is without work but available for and seeking employment. Measured in % of the total labor force. | WDI-2019 |
| | | | **Social Variables** | |
| 11 | PSA. | Political stability and absence of violence | Political stability and Absence of violence/terrorism measures perceptions of the likelihood of political instability and/or politically-motivated violence, including terrorism. | WGI-2020 |
| 12 | RL | Rule of law | Reflects perceptions of the extent to which agents have confidence in and abide by the rules of society, and, in particular, the quality of contract enforcement, property rights, the police, and the courts, as well as the likelihood of crime and violence. | WGI-2020 |
| 13 | CCUR | Control of corruption | Reflects perceptions of the extent to which public power is exercised for private gain, including both petty and grand forms of corruption, as well as "capture" of the state by elites and private interests. | WGI-2020 |
| 14 | EI | Education index | Education index is an average of mean years of schooling (of adults) and expected years of schooling (of children), both expressed as an index obtained by scaling with the corresponding maxima. | http://hdr.undp.org/en/indicators/103706 (accessed on 25 June 2021) |
| 15 | LEI | Life expectancy index | Life expectancy at birth expressed as an index using a minimum value of 20 years and a maximum value of 85 years. | http://hdr.undp.org/en/indicators/103206103706 (accessed on 25 June 2021) |
| 16 | SET | School enrollment, tertiary | The gross enrollment ratio is the ratio of total enrollment, regardless of age, to the population of the age group that officially corresponds to the level of education shown. measured in (% gross). | WDI-2019 |
| | | | **Other Variables** | |
| 17 | SURF | Surface area | Surface area is a country's total area, including areas under inland bodies of water and some coastal waterways. measured in (sq. km). | WDI-2019 |
| | | | **Dummy Variables** | |
| 18 | TDC | Top developed countries | Dummy variable if a country is a member of the G-7, group of world's advanced economies and wealthiest liberal democracies. | Authors elaboration |
| 19 | FEBC | Former Eastern Bloc | Dummy variable if a country was a member of the Eastern Bloc. | Authors elaboration |

**Table A2.** Descriptive statistics for energy consumption according to different sources in European countries.

| **Source** | **Oil Consumption** | | | | | | **Gas Consumption** | | | | | | **Coal Consumption** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Years** | **1995** | **2000** | **2005** | **2010** | **2015** | **2018** | **1995** | **2000** | **2005** | **2010** | **2015** | **2018** | **1995** | **2000** | **2005** | **2010** | **2015** | **2018** |
| **Mean** | 25.5868 | 26.4246 | 27.2254 | 25.1221 | 22.8585 | 23.5671 | 11.9391 | 14.2396 | 16.0359 | 16.1486 | 12.9957 | 14.2033 | 12.7343 | 11.2384 | 11.0827 | 9.7995 | 9.1320 | 7.7798 |
| **S.E.** | 6.7471 | 6.7588 | 6.6116 | 6.0195 | 5.4955 | 5.5243 | 3.5395 | 4.2928 | 4.6006 | 4.5435 | 3.6295 | 4.0108 | 4.0922 | 3.6148 | 3.4981 | 3.3070 | 3.1943 | 2.8294 |
| **Med** | 11.2194 | 10.8897 | 11.0132 | 10.7220 | 10.0999 | 10.5758 | 3.0019 | 4.0149 | 4.1146 | 4.5813 | 3.8785 | 4.2757 | 4.8950 | 3.9199 | 3.8506 | 3.7908 | 3.2514 | 3.0665 |
| **S.D.** | 35.7025 | 35.7644 | 34.9852 | 31.8520 | 29.0794 | 29.2317 | 18.7294 | 22.7155 | 24.3439 | 24.0421 | 19.2053 | 21.2232 | 21.6539 | 19.1275 | 18.5103 | 17.4990 | 16.9028 | 14.9718 |
| **Kurt** | 3.3606 | 2.5040 | 1.6758 | 1.8892 | 2.6849 | 2.2979 | 3.3539 | 4.1808 | 2.9618 | 2.6442 | 2.5919 | 2.9565 | 7.0533 | 8.6580 | 7.9418 | 8.9482 | 11.3421 | 10.6100 |
| **Skew** | 2.0038 | 1.8380 | 1.6656 | 1.6737 | 1.8107 | 1.7290 | 2.0433 | 2.2053 | 1.9877 | 1.9135 | 1.9006 | 1.9648 | 2.6952 | 2.8583 | 2.7512 | 2.9604 | 3.2493 | 3.2712 |
| **Range** | 138.9582 | 134.1266 | 126.1889 | 118.0561 | 112.6862 | 111.6916 | 66.8421 | 87.1382 | 85.4571 | 84.6886 | 66.1682 | 75.9176 | 90.5155 | 85.2689 | 81.2447 | 77.0423 | 78.6773 | 66.3859 |
| **Min** | 1.3299 | 1.1655 | 1.4394 | 1.4336 | 1.4848 | 1.5026 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1070 | 0.0360 | 0.0440 | 0.0147 | 0.0033 | 0.0133 |
| **Max** | 140.2881 | 135.2921 | 127.6283 | 119.4897 | 114.1710 | 113.1941 | 66.8421 | 87.1382 | 85.4571 | 84.6886 | 66.1682 | 75.9176 | 90.6225 | 85.3049 | 81.2887 | 77.0569 | 78.6806 | 66.3992 |
| **Obs** | 28 | 28 | 28 | 28 | 28 | 28 | 28 | 28 | 28 | 28 | 28 | 28 | 28 | 28 | 28 | 28 | 28 | 28 |
| **Source** | **Hydro Consumption** | | | | | | **Renewable Consumption** | | | | | | **Nuclear Consumption** | | | | | |
| **Years** | **1995** | **2000** | **2005** | **2010** | **2015** | **2018** | **1995** | **2000** | **2005** | **2010** | **2015** | **2018** | **1995** | **2000** | **2005** | **2010** | **2015** | **2018** |
| **Mean** | 3.9275 | 4.3418 | 3.8380 | 4.2364 | 4.1194 | 4.1456 | 0.2409 | 0.5116 | 1.2068 | 2.4582 | 4.8355 | 5.7405 | 7.1857 | 7.7039 | 8.1038 | 7.4965 | 6.9924 | 6.7636 |
| **S.E.** | 1.2203 | 1.3679 | 1.2593 | 1.1868 | 1.2995 | 1.2958 | 0.0667 | 0.1470 | 0.3936 | 0.7882 | 1.5340 | 1.8756 | 3.2612 | 3.5624 | 3.8111 | 3.5740 | 3.5644 | 3.3637 |
| **Med** | 0.9256 | 0.9559 | 1.0466 | 1.0880 | 1.1500 | 1.1514 | 0.0700 | 0.1095 | 0.3433 | 0.7046 | 2.0728 | 2.2679 | 0.4546 | 0.9821 | 1.0807 | 0.4491 | 0.4614 | 0.3953 |
| **S.D.** | 6.4572 | 7.2384 | 6.6636 | 6.2802 | 6.8763 | 6.8567 | 0.3528 | 0.7778 | 2.0829 | 4.1707 | 8.1170 | 9.9248 | 17.2567 | 18.8502 | 20.1666 | 18.9117 | 18.8611 | 17.7989 |
| **Kurt** | 6.0942 | 7.5019 | 9.6198 | 4.7663 | 8.3324 | 8.6433 | 4.9283 | 4.5466 | 10.2783 | 9.7951 | 10.7530 | 11.5624 | 16.4649 | 17.2537 | 18.7523 | 19.9556 | 22.8416 | 22.7416 |
| **Skew** | 2.3838 | 2.5596 | 2.8797 | 2.0801 | 2.6703 | 2.6869 | 2.0445 | 2.0316 | 2.9772 | 2.9885 | 3.0497 | 3.1839 | 3.8487 | 3.9592 | 4.1321 | 4.2727 | 4.6172 | 4.5977 |
| **Range** | 27.4992 | 32.0899 | 30.7028 | 26.4176 | 31.0680 | 31.3382 | 1.4979 | 3.2366 | 9.6991 | 19.0421 | 38.3485 | 47.2298 | 85.3580 | 93.9408 | 102.1698 | 96.9636 | 98.9790 | 93.4905 |
| **Min** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.0002 | 0.0165 | 0.0750 | 0.1049 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Max** | 27.4992 | 32.0899 | 30.7028 | 26.4176 | 31.0680 | 31.3382 | 1.4979 | 3.2366 | 9.6993 | 19.0586 | 38.4235 | 47.3347 | 85.3580 | 93.9408 | 102.1698 | 96.9636 | 98.9790 | 93.4905 |
| **Obs** | 28 | 28 | 28 | 28 | 28 | 28 | 28 | 28 | 28 | 28 | 28 | 28 | 28 | 28 | 28 | 28 | 28 | 28 |

**Note:** Med: Median; S.E. = Standard error; S.D. = Standard deviation; Kurt = Kurtosis; Skew = Skewness; Min = Minimum; Max = Maximum; Obs = Observations.

**Table A3.** Posterior estimates of top 3 models for renewable consumption determinants in 2015.

| **Variables** | **Coefficient** | **Std. Error** | ***t*-Stat** | ***p*-Value** |
|---|---|---|---|---|
| **Model 1.** Posterior probability: 0.010350 | | | | |
| Const | 9.2429 | 3.5399 | 2.6110 | 0.0090 |
| NC | −0.3798 | 0.0381 | −9.9660 | <0.0001 |
| TO | −0.0205 | 0.0077 | −2.6490 | 0.0081 |
| HC | −0.3540 | 0.0979 | −3.6170 | 0.0003 |
| GC | −0.6612 | 0.1026 | −6.4430 | <0.0001 |
| OC | 0.3574 | 0.1019 | 3.5090 | 0.0005 |
| TDC | 14.5325 | 5.0625 | 2.8710 | 0.0041 |
| SURF | 0.00001 | 0.000004 | 3.1190 | 0.0018 |
| FEBC | −2.3601 | 1.6237 | −1.4540 | 0.1461 |
| UNEMP | −0.3520 | 0.1299 | −2.7090 | 0.0067 |
| CCUR | −2.6847 | 1.0634 | −2.5250 | 0.0116 |
| GDP | 0.0083 | 0.0034 | 2.4630 | 0.0138 |
| **Model 2.** Posterior probability: 0.009376 | | | | |
| Const | 4.5462 | 1.4922 | 3.0470 | 0.0023 |
| NC | −0.3643 | 0.0378 | −9.6470 | <0.0001 |
| TO | −0.0147 | 0.0069 | −2.1480 | 0.0317 |
| HC | −0.2807 | 0.0866 | −3.2420 | 0.0012 |
| GC | −0.6316 | 0.1038 | −6.0830 | 0.0000 |
| OC | 0.3625 | 0.1051 | 3.4500 | 0.0006 |
| TDC | 13.2797 | 5.1492 | 2.5790 | 0.0099 |
| SURF | 0.00001 | 0.000004 | 2.6740 | 0.0075 |
| UNEMP | −0.2083 | 0.0870 | −2.3940 | 0.0167 |
| CCUR | −1.3370 | 0.5374 | −2.4880 | 0.0129 |
| GDP | 0.0082 | 0.0035 | 2.3740 | 0.0176 |

**Table A3.** *Cont.*

| **Variables** | **Coefficient** | **Std. Error** | ***t*-Stat** | ***p*-Value** |
|---|---|---|---|---|
| | | **Model 3.** Posterior probability: 0.007232 | | |
| Const | 8.2507 | 3.5768 | 2.3070 | 0.0211 |
| NC | −0.3950 | 0.0395 | −10.0000 | <0.0001 |
| TO | −0.0238 | 0.0081 | −2.9460 | 0.0032 |
| HC | −0.3467 | 0.0965 | −3.5920 | 0.0003 |
| GC | −0.6747 | 0.1016 | −6.6390 | <0.0001 |
| OC | 0.3862 | 0.1030 | 3.7510 | 0.0002 |
| TDC | 17.3483 | 5.4843 | 3.1630 | 0.0016 |
| SURF | 0.00001 | 0.000004 | 3.2710 | 0.0011 |
| FEBC | −2.2588 | 1.6005 | −1.4110 | 0.1581 |
| UNEMP | −0.3235 | 0.1300 | −2.4890 | 0.0128 |
| CCUR | −4.5852 | 1.8667 | −2.4560 | 0.0140 |
| RL | 2.6548 | 2.1589 | 1.2300 | 0.2188 |
| GDP | 0.0069 | 0.0035 | 1.9710 | 0.0487 |

**Table A4.** Posterior estimates of top 3 models for renewable consumption determinants in 2018.

| Variables | Coefficient | Std. Error | *t*-Stat | *p*-Value |
|---|---|---|---|---|
| | | **Model 1.** Posterior probability: 0.011631 | | |
| Const | 2.1936 | 1.0344 | 2.1210 | 0.0340 |
| GC | −0.2202 | 0.0944 | −2.3320 | 0.0197 |
| NC | −0.2864 | 0.0370 | −7.7330 | <0.0001 |
| HC | −0.1698 | 0.0637 | −2.6670 | 0.0077 |
| TO | −0.0207 | 0.0072 | −2.8640 | 0.0042 |
| OC | 0.1226 | 0.0572 | 2.1440 | 0.0320 |
| GDP | 0.0126 | 0.0025 | 5.0630 | <0.0001 |
| FDI_BOP | 0.0188 | 0.0050 | 3.7280 | 0.0002 |
| | | **Model 2.** Posterior probability: 0.009196 | | |
| Const | 1.7875 | 1.2368 | 1.4450 | 0.1484 |
| NC | −0.2087 | 0.0323 | −6.4680 | <0.0001 |
| HC | −0.1499 | 0.0603 | −2.4850 | 0.0130 |
| TO | −0.0184 | 0.0080 | −2.3060 | 0.0211 |
| TDC | −7.7559 | 3.4780 | −2.2300 | 0.0257 |
| GDP | 0.0131 | 0.0010 | 12.5300 | <0.0001 |
| FDI_BOP | 0.0239 | 0.0050 | 4.8050 | <0.0001 |
| | | **Model 3.** Posterior probability: 0.004942 | | |
| Const | 1.8534 | 1.1568 | 1.6020 | 0.1091 |
| GC | −0.2145 | 0.0977 | −2.1960 | 0.0281 |
| NC | −0.2960 | 0.0392 | −7.5540 | <0.0001 |
| HC | −0.3334 | 0.1055 | −3.1590 | 0.0016 |
| TO | −0.0187 | 0.0077 | −2.4360 | 0.0148 |
| SURF | 0.00001 | 0.000004 | 1.7460 | 0.0809 |
| GDP | 0.0156 | 0.0023 | 6.9230 | <0.0001 |
| FDI_BOP | 0.0137 | 0.0056 | 2.4380 | 0.0148 |

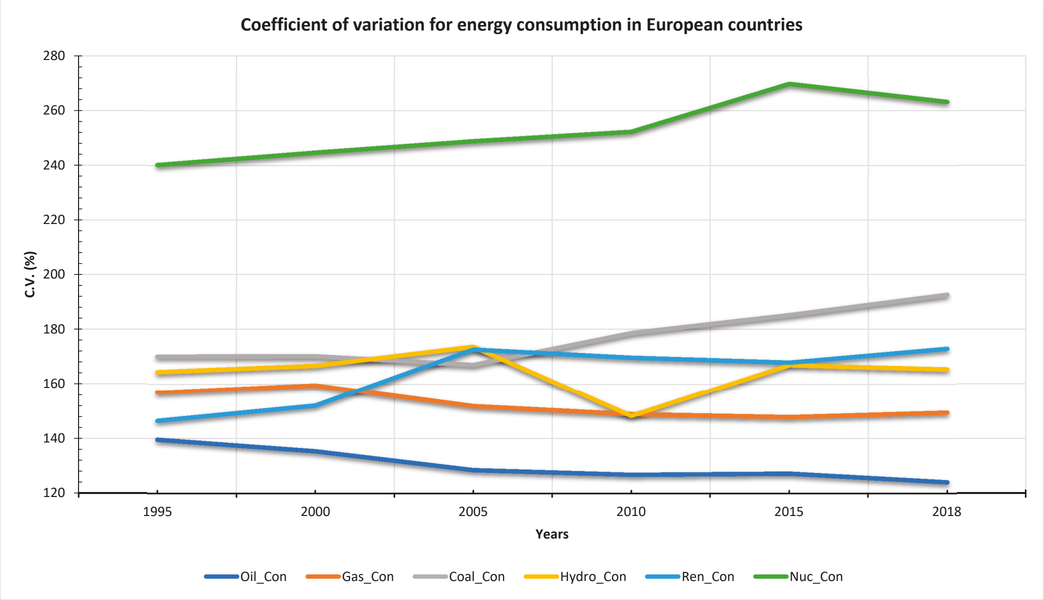

**Figure A1.** Energy consumption coefficient of variation 1995–2018.

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# Determinants of Electrical and Thermal Energy Consumption in Hospitals According to Climate Zones in Poland

**Małgorzata Cygańska [1,*] and Magdalena Kludacz-Alessandri [2,*]**

[1] Faculty of Economics, University of Warmia and Mazury in Olsztyn, 10-917 Olsztyn, Poland
[2] College of Economics and Social Sciences, Warsaw University of Technology, 09-400 Plock, Poland
* Correspondence: m.cyganska@uwm.edu.pl (M.C.); magdalena.kludacz@pw.edu.pl (M.K.-A.)

**Abstract:** Energy use in hospitals is higher than in other public buildings, so improving energy efficiency in healthcare buildings is a significant challenge in this sector of engineering. For this, it is necessary to know the various determinants of energy consumption. Until now, the main factor affecting energy consumption in healthcare facilities studied in the literature was hospital capacity. However, the commonly used variables connected with hospital size and the number of beds do not take into account the medical activities carried out in these buildings. Assuming that energy consumption in hospitals is multiple and shaped by many factors that overlap, not only on an individual level but also on a higher scale level, this study devises a more integrated approach to its determinants. This study aims to investigate the determinants of electrical energy costs (EEC) and thermal energy costs (TEC) in Polish hospitals with regard to factors related to their size, work intensity and climate zones. The analysis was carried out using financial and resource data from all Polish hospitals for the years 2010–2019. The study used a multivariate backward stepwise regression analysis. In order to use climate as a moderating variable, a sample of Polish hospitals from 16 Polish NUTS 2 was divided into four climate zones. This article provides new empirical evidence on the determinants of electricity consumption in Polish hospitals related to their size and medical activity, taking into account climate zone as a moderating variable. The results of the analysis show that both electricity and heat consumption in hospitals are positively related to the number of doctors, beds and the number of medical operations performed. As expected, larger hospitals seem to use more energy. Moreover, there is regional heterogeneity in energy consumption in hospitals related to the climatic zone in which they operate. The conducted analysis shows that Polish hospitals located in the warmest climatic zone are characterized by higher energy consumption than hospitals in the coldest zone. It especially regards EEC in surgery hospitals. The warmer the climate zones, the higher intensity in terms of the number of surgeries, the higher EEC. In terms of nonsurgical hospitals, the influence of climate zone on EEC was not observed. Knowing the factors influencing energy consumption in hospitals can facilitate the correct adoption of an energy-saving strategy in the health sector, which is a reasonable response to climate change and supports a healthy and sustainable future.

**Keywords:** energy costs; hospitals; climate zone; energy consumption; Poland

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## 1. Introduction

The issue of energy consumption, in general, attracts a lot of attention, especially with regard to energy efficiency and its benefits for climate change [1]. Currently increases in energy consumption generate a continuous increase in the cost of electricity and heat and have a significant negative impact on the environment, resulting from the emission of greenhouse gases into the atmosphere [2]. In recent decades, researchers have paid much attention to energy analysis and consumption optimization in various industries and buildings. Some of them proposed new methods that are very helpful in assessing different options for thermal insulation investments [3]. In this context, healthcare facilities (especially for hospitals due to their large size) are of particular interest. Due to rising energy prices, the lack of natural resources for energy production and standards based on sustainable development to reduce $CO_2$ emissions, it is necessary to analyze the factors influencing energy consumption by these systems. As more than half of the energy consumption in healthcare systems is in hospitals [4,5], this study mainly focuses on data on energy consumption in hospitals. The implementation of sustainable energy systems is one of the main goals of the European Union (EU) energy policy, and experience in the hospital sector can be very useful in achieving this [6].

Among healthcare facilities, hospitals are among the most energy-intensive buildings due to their constant energy consumption patterns and different activities. They must operate 24 h a day, 365 days a year, so in the construction sector, hospitals are the buildings with the highest energy use [7]. On average, a hospital complex consumes 2.5 times more energy than a public building, e.g., an office. This is mainly due to the operation of a complex building, utility systems to accommodate energy-intensive medical equipment and the unique requirements for air quality and disease control. In addition, the fact that they are more energy-consuming than other buildings in the service sector is due to the constant need for powering medical devices and special requirements for air quality and patient health monitoring [8].

The highest costs of energy consumption are incurred by specialist hospitals, which use energy-intensive tomographs, x-rays, or the best-equipped operating theaters. Most expensive is the operation of the operating theater and the performance of specialist examinations. Currently, the expenditure of public hospitals on electricity in Poland accounts for an average of almost 2% of their total operating costs, which, given tight budgets, is a significant burden. Energy expenditure is a small percentage of hospital budgets, but almost all of them want to increase energy efficiency and invest in renewable energy sources to improve their financial situation in connection with rising energy prices [9]. The use of renewable energy sources in Polish hospitals is very important in the context of the energy transformation of the national economy because it affects the creation of modern technologies and increases the competitiveness and innovation of the country. The research carried out so far shows that solar, wind and biomass have the greatest development opportunities in Poland [10].

Energy demand in Polish hospitals is. Therefore, high, so understanding the factors influencing energy consumption in hospitals could be important not only for scientists and practitioners, but also for policymakers aiming to encourage and promote wise, efficient, and sustainable energy use through a variety of policies, schemes, and measures.

Despite great interest in determinants of energy consumption in the healthcare sector, the results of previous studies are inconclusive and need further investigation. This can be explained by the fact that energy consumption in hospitals is shaped by many different factors, not only at the individual level but also at a higher scale level, e.g., the region. So far, empirical research on energy consumption in the health sector has put a lot of effort into examining the relationship mainly between energy consumption and hospital capacity rather than hospital activity, and little research to date has been conducted in the healthcare sector in countries of central and eastern Europe. Climate zone as moderating variable has not been investigated so far in this region. It is difficult to determine climate zone impacts on demand for energy consumption, and which determinants of energy consumptions connected with medical size and hospital activity are significant in various climate zones. This means that the area is full of ambiguities, and our goal is therefore to reduce this research gap.

This study aims to investigate the determinants of electrical energy costs (EEC) and thermal energy costs (TEC) in Polish hospitals, taking into account not only their size but also medical activity and with climate zone as a moderating variable. The analysis was carried out using data from hospital reports regarding financial data and medical activity for the years 2010 to 2019. The study used a multivariate backward stepwise regression analysis on a sample of all Polish hospitals from 16 Polish NUTS 2, which were divided into four climate zones. The constructed models test new determinants of the considered endogenous variables according to the climatic zones, which develops a more integrated approach to studying the drivers of energy consumption in hospitals at the regional level. This shows that there are common, universal determinants of energy consumption, regardless of the climatic zone and those that depend on these zones. This article is the first study that collects and analyzes data on energy costs in all hospitals in Poland. As far as we know, no previous research on this topic has focused on such a large sample of hospitals.

The study assumes that energy consumption in hospitals is determined by the size of the hospital and its medical activity and differs among climatic zones. Therefore, our research hypotheses are as follows:

**Hypothesis 1 (H1)**. The size of the hospital has a positive impact on electrical energy costs.

**Hypothesis 2 (H2)**. The size of the hospital has a positive impact on thermal energy costs.

**Hypothesis 3 (H3)**. The activity of the hospital has a positive impact on electrical energy costs.

**Hypothesis 4 (H4)**. The activity of the hospital has a positive impact on thermal energy costs.

**Hypothesis 5 (H5)**. The electrical energy costs in hospitals differ among climate zones.

**Hypothesis 6 (H6)**. The thermal energy costs in hospitals differ among climate zones.

The rest of the article is structured as follows. Section 2 presents a literature review. Section 3 presents the econometric methodology, variables, and data used. Section 3 discusses the empirical results and discussion. Finally, the last three sections present the concluding remarks, limitations and further research.

## 2. Literature Review

The literature lists three groups of features that affect energy consumption in hospitals. The first group concerns the capacity of the hospital, which is primarily determined by the total area of hospital rooms and the number of beds. Additional measures of capacity include the number and size of operating theaters and intensive care units, as well as the amount of high-energy medical equipment. The second group concerns the medical activities of the hospital. Energy consumption in hospitals should increase with the provision of more medical services. A medical product can be tracked by a variety of metrics, including days of hospitalization, admission or discharge, and the number of patients. The third group includes the location in a specific climatic zone, which determines the limits for thermal and lighting conditions [8]. These factors influence overall energy consumption regardless of performance and should, therefore, be taken into account in this research.

The majority of earlier studies analyzed energy consumption at a microeconomic level, combining energy demand with room characteristics in buildings [11,12]. The literature emphasizes that the most significant predictor of energy consumption by these facilities is the size of the facility (area), types of services, number of employees and number of beds [4,13]. The capacity of the hospital can also be measured by the surface of the hospital rooms ($m^2$), bed days in inpatient-departments and in out-patient-departments, and the number of staff members [14]. A regression analysis of energy consumption was carried out in the Spanish banking sector, and among independent variables, in addition to the number of employees, the area and number of energy-consuming devices (in this case, ATMs) were taken into account [15]. Another study conducted on the basis of data from 20 Spanish hospitals determined average final energy consumption by calculating energy efficiency indicators as a function of several functional indicators, i.e., building area, number of beds and number of employees [16].

Studies in Brazilian hospitals found that variability in energy consumption was due not only to the size of facilities, the number of beds and covered area, but also to the complexity of the services offered, energy standards, and the efficiency of the medical equipment used [17]. Other studies also took into account the impact of hospital activity indicators, which can be represented by the number of annual discharges, rescue operations, hospitalizations, operations, laboratory tests, births, and endoscopy [18]. However, studies regarding the impact of hospital activity on energy consumption are rare. The number of surgical operations can be an especially important factor influencing energy consumption due to the fact that surgery is a resource-hungry medical activity that requires expensive equipment, sterilization procedures, advanced operational technologies, and compulsory life-support systems. These activities consume significant amounts of energy [19]. In addition, there has been a discussion for several years about ventilation systems in operating rooms that can be the main factor affecting the electric energy consumptions in the hospitals [20].

An important factor influencing energy consumption may also be the degree of use of medical devices, especially in areas directly related to diagnostics and treatment. The demand for electricity is growing in hospitals due to more sophisticated medical devices. An interesting observation can be made in terms of the relationship between the energy consumed during use and the hours of inactivity. Linear accelerators, CT scanners and MRI scanners require 36, 64 and 47% of weekly energy requirements, respectively, when not in use [20].

In the literature, there are studies of energy consumption that combine energy demand with climatic and environmental indicators [21–23], as well as with geographic location [13]. Some authors also highlighted weather conditions as essential determinants of energy consumption [24,25]. The empirical literature in this field is oriented to the national research level, using, in most cases, a dataset at the micro-level. It is worth adding that several studies carried out at the subnational level in the EU showed that regional climatic differences do have an impact on energy consumption, although these studies were related to households (e.g., in the case of Germany [26]; and Austria [27]). Other studies looked at the impact of climate change on energy consumption in hospital buildings, e.g. looking at six different cities located in six countries in the Indian Ocean region [28].

There is agreement that the climate has a significant impact on the energy consumption of buildings [29]. Climate is usually treated as an independent parameter in energy efficiency regressions [30]. Climate can influence energy consumption in several ways because of a non-linear pattern of energy use in response to climate change. In a warmer climate zone, a greater demand for cooling could be expected, which would lead to increased consumption of electricity. On the other hand, fewer frosty winter days would result in a lower heating demand, which would lower the demand for natural gas, oil and electricity [31–33]. Research conducted in the US found that consumers in warmer locations rely relatively more on electricity than on natural gas, oil and other fuels. In winter, they use less heating fuel, and in summer they install more cooling power and buy much more electricity. The model estimated in these studies suggests that fuel selection component may be an important aspect of climate change adaptation. In warmer climates, electricity is selected for heating and cooling. Electricity is, therefore, more attractive than combining electricity with other heating fuels in areas where heating is less important [34]. Some USA studies have quantified heat-attributable healthcare expenditure based on counts of hospital admissions [35,36]. The use of the climate zone as a moderating variable in the study allowed research to be carried out at the regional level, which is the most crucial level for the design and implementation of EU policy. Climatic zones make it possible to determine the basic calculation parameters of the outside air. Therefore, the calculation parameters of the outside atmosphere have a direct impact on the parameters of the power of cooling, ventilation and air-conditioning devices of buildings and for determining the heat load design of buildings [37]. Each climate zone has a different outside temperature, wind strength and direction, and sunlight. Designers adjust building materials to this and define the parameters of heating the building under maximum conditions. Property managers and administrators take this into account when ordering power to heat the building. Currently, Poland is divided into climatic zones according to the PN-EN 12831 standard [38,39].

In winter, there are five general climatic zones in Poland, of which Vth zone is characterized by the lowest temperatures, and the firstone the highest. The temperature of the outside air in the zones ranges from −16 degrees Celsius (coastal areas) to −24 degrees Celsius (mountain areas, Suwalki region). The outside designed temperature in five climatic zones for winter in Poland is presented in Table 1.

**Table 1.** The outside designed temperature in five climatic zones for winter in Poland.

| Climate Zone | Temperature |
|---|---|
| I | −16 |
| II | −18 |
| III | −20 |
| IV | −22 |
| V | −24 |

For the purposes of the study, the climatic zones of Poland were adapted to the NUTS classification, which refers to the hierarchical division of the EU economic area into three main NUTS levels: NUTS 1, NUTS 2 and NUTS 3. The first level applies to the entire country, while the second and third levels in Poland are voivodeships and counties [40]. Taking into account the NUTS 2 level required merging of the fourth and fifth zones and assignment of Polish voivodships to the four climatic zones shown in Figure 1.

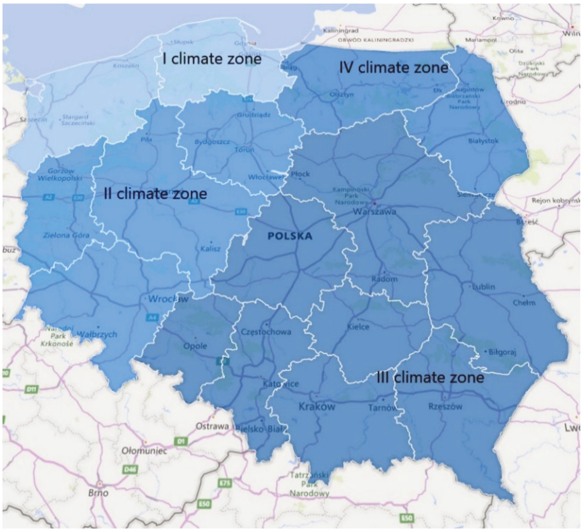

**Figure 1.** Map of climate zones in Poland.

The climate of Poland is characterized by great variability of weather and significant fluctuations in the course of the seasons. Poland is crossed by the border between a warm and rainy (oceanic) climate and a boreal, snow-forest (continental) climate. There is a significant difference in air temperature between the north-eastern (fourth zone) and north-western (first zone) regions of Poland. In the east, in zone IV, winters are colder than in the rest of Poland, which is the result of the influence of continental climate. In zone I, in the west of the country, winters are warmer than in the rest of Poland because of the influence of air masses from the Atlantic Ocean and the mitigating effect of the Baltic Sea. Therefore, the lowest average annual air temperatures occur in north-eastern Poland (6.5 °C). The average number of frosty days is lower in zone I (less than 25 days a year) than in zone IV (up to 65 days in the Suwałki Lake District).

The main type of energy consumed by hospitals is electricity. Therefore, the results of the study regarding the relationship between climatic zone and energy consumption can be applied to power design requirements in the energy sector, fuel consumption for electricity generation, end-use space heating and cooling [41].

## 3. Materials and Methods

The methodology of the study involves a two-stage approach: (i) estimation of a linear regression model to examine the impact of identified independent variables on electrical and thermal energy costs in hospitals according to the climate zones in Poland, (ii) estimation to what extent the electrical and thermal energy unit costs differ according to the climate zones in Poland.

Quantitative data ae shown as mean (standard deviation, SD) and median (interquartile range, IQR). Categorical data are expressed as percentages. Independent predictors of EEC and TEC were analyzed using stepwise backward regression analyses. A $p$-value of $<0.05$ was considered statistically significant.

To measure the hospital electrical and thermal energy costs, we used the variables electric energy cost (EEC), electric energy cost per patient (EECP), electric energy cost per hospitalization day (EECD), electric energy cost per surgery (EECS), thermal energy cost (TEC), thermal energy cost per patient (TECP), thermal energy cost per hospitalization day (TECD), and thermal energy cost per surgery (TECS). To measure the hospital size, we used the number of beds (BEDS), nurses (NURS) and doctors (DOC) as variables. Based on bed numbers, we classified the hospitals into four categories as follows: small hospitals (number of beds lower than 100); medium (number of beds lower than 300 and above 101), big (number of beds lower than 600 and above 301) and large (number of beds above 601). To measure the hospital activity, we used: the number of surgeries (SURG), the number of hospitalization days (DAYS), and the number of patients (PAT). To analyze the influence of hospital profile (in terms of surgery intensity), we classified the hospitals based on the surgery index (SI). We calculated SI as the relationship between numbers of surgeries to admitted patients and based on this we classified the hospitals into four categories as follows: non-surgical hospitals (with $SI = 0$—non-surgeries in hospital); low-intensity surgery hospital ($0 < SI < 0.3$); medium-intensity surgery hospital ($0.31 < SI < 0.6$) and high-intensity surgery hospital ($0.61 < SI$).

### *3.1. Data and Sample*

Electrical and thermal energy costs were thoroughly analyzed in order to perform a comparison of energy consumptions in hospitals in terms of hospitals activity in different climate zones. Financial data were obtained from the E-Health Center, which is a state budget unit established by the Minister of Health. Data on energy consumption costs came from the MZ-03 reports on the finances of independent public healthcare institutions. On the other hand, data on the activities of each hospital (the number of patients, the number of operations, the number of beds, the number of medical personnel) were obtained from the annual reports of the MZ-29-report on the activities of the general hospital. The analysis considered hospital data from 2010 to 2019 for 376 hospitals. Finally, our research covered 3289 hospital years.

### *3.2. Key Variables*

The characteristics of analyzed hospitals according to the climate zone in Poland are presented in Table 2, and Figures 2 and 3.

**Table 2.** The characteristics of analyzed hospitals according to the climate zone in Poland.

| Variables | Climate Zone | | | | Total |
|---|---|---|---|---|---|
| | I | II | III | IV | |
| | *n* (%) | | | | |
| Hospital years * | 249 (7.57) | 679 (20.64) | 2047 (62.24) | 314 (9.55) | 3289 |
| DAYS | 20,160,208 (8.17) | 55,261,425 (22.40) | 153,752,238 (62.33) | 17,504,144 (7.10) | 246,678,015 |
| BEDS | 73,282 (8.29) | 199,434 (22.55) | 546253 (61.77) | 65388 (7.39) | 884,357 |
| PAT | 3,596,544 (8.63) | 9,697,673 (23.26) | 25,266,118 (60.60) | 3,134,437 (7.52) | 41,694,772 |
| SURG | 1,672,340 (10.38) | 3,647,777 (22.65) | 9,614,112 (59.70) | 117,0610 (7.27) | 16,104,839 |
| NURS | 71,208 (8.42) | 184,516 (21.83) | 528,267 (62.50) | 61,286 (7.25) | 845,277 |
| DOC | 41,056 (9.14) | 98,309 (21.88) | 278,273 (61.95) | 31,577 (7.03) | 449,215 |

* A sample of 3289 hospital-years contains data of the 376 hospitals for the period 2010–2019.

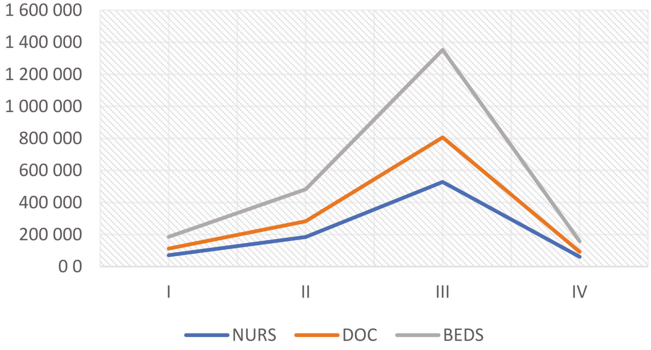

**Figure 2.** Hospital size measures according to climate zones.

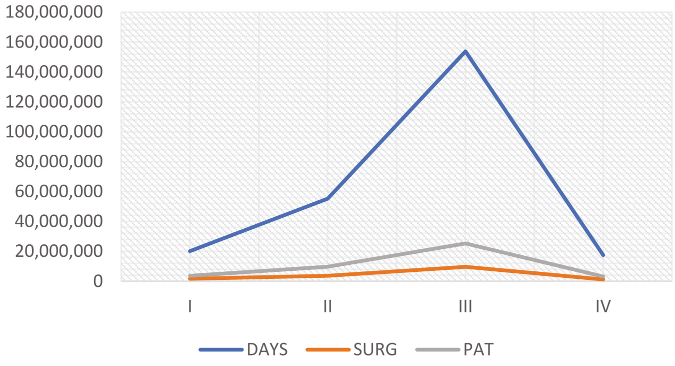

**Figure 3.** Hospital activity measured according to climate zones.

Most of the hospitals are located in the third climate zone, which covers the most extensive area of Poland. More than 60% of hospital beds are located in this climate zone, which accompanies the highest percentage of treated patients (60.60%) and performed surgeries (59.70%). Accordingly, more than 61% of nurses and doctors take care of patients in hospitals located in the third climate zone.

### *3.3. Research Model*

In the first stage of our research, we specified and estimated linear models in order to examine the impact of hospital size and its activity on electrical and thermal energy costs. The models are specified as follows:

$$EEC = \beta0 + \beta1(DAYS) + \beta2(BEDS) + \beta3(PAT) + \beta4(SURG) + \beta5(NURS) + \beta6(DOC) + e \quad (1)$$

$$TEC = \beta0 + \beta1(DAYS) + \beta2(BEDS) + \beta3(PAT) + \beta4(SURG) + \beta5(NURS) + \beta6(DOC) + e \quad (2)$$

To analyze whether the influence of the identified variables is the same in all the climate zones, we built the EEC and TEC models separately for each Polish climate zone as follows:

$$EEC_i = \beta0 + \beta1(DAYS_i) + \beta2(BEDS_i) + \beta3(PAT_i) + \beta4(SURG_i) + \beta5(NURS_i) + \beta6(DOC_i) + e \quad (3)$$

$$TEC_i = \beta0 + \beta1(DAYS_i) + \beta2(BEDS_i) + \beta3(PAT_i) + \beta4(SURG_i) + \beta5(NURS_i) + \beta6(DOC_i) + e \quad (4)$$

where $_i$ is the climate zone in Poland

### *3.4. Kruskal–Wallis One-Way Analysis of Variance*

We used a nonparametric method for testing whether samples originated from the same distribution. We used the Kruskal–Wallis one-way analysis of variance to analyze to what extent the climate zone had a statistically significant influence on the electrical and thermal energy unit cost. A *p*-value of less than 0.05 was considered statistically significant.

For the statistical analysis, we used STATISTICA, TIBCO Software INC., Poland, Statsoft Polska, version 13.3.

## 4. Results and Discussion

### *4.1. Descriptive Statistics*

In order to evaluate the influence of climate on hospital energy costs, we identified models of determinants of energy consumption in Polish hospitals, taking into account the climate zones determined at the NUTS 2 level. In addition, we checked whether the climate zones moderate other factors of energy consumption in hospitals connected with their size and type. Table 3 and Figures 4–6 provide a view of descriptive statistics (means, standard deviations, medians and interquartile ranges) for all independent variables separately for each climate zone.

The highest average electrical and thermal energy costs are in hospitals located in the first climate zone and the lowest in the fourth one. On average, in hospitals located in the first climate zone, thermal energy costs are higher by nearly 40% and electrical energy costs are 1.5 times higher than in hospitals located in the fourth climate zone.

Based on the analysis, in the first climate zone, the hospitals are the biggest, and in the fourth one, the smallest. In terms of the number of beds, the number of doctors and nurses, hospitals located in the first climate zone is respectively more than 44, 58, and 42% bigger than in the fourth climate zone. According to the level of hospital activity, measured by the number of patients, hospitalization days, and the number of surgeries, hospitals in the first climate zone are respectively 1.40, 1.49, and 1.80 times higher than in the fourth one.

**Table 3.** Characteristics of analyzed hospitals according to the climate zones in Poland.

| **Variables** | **Climate Zone** | | | | **Total** |
|---|---|---|---|---|---|
| | **I** | **II** | **III** | **IV** | |
| | **Mean (SD) Median (Q1–Q3)** | | | | |
| EEC (PLN) | 1,034,553 (122,6397)<br>659,786 (306,546–1,201,155) | 1,025,393 (980,078)<br>717,520 (318,689–1,407,173) | 910,042 (1,177,533)<br>598,957 (338,093–1,028,006) | 665,117 (779,879)<br>389,828 (244,459–828,121) | 919,899 (1,114,355)<br>597,540 (315,505–1,114,377) |
| TEC (PLN) | 975,732 (1,302,336)<br>491,888 (244,066–1,063,739) | 922,536 (1,018,291)<br>545,981 (252,885–1,255,279) | 821,019 (1,023,326)<br>515,932 (240,081–1,032,906) | 701,529 (726,990)<br>435,569 (314,578–862,438) | 842,282 (1,023,982)<br>505,367 (253,492–1,055,089) |
| DAYS | 93,334 (83,881)<br>64,880 (28,156–140,736) | 91,341 (69,644)<br>68,910 (34,060–134,650) | 84,946 (64,884)<br>69,227 (36,910–111,610) | 62,738 (52,114)<br>47,767 (29,282–77,934) | 84,769 (66,825)<br>66,627 (34,276–115,936) |
| BEDS | 339 (292)<br>260 (110–434) | 330 (266)<br>243 (136–488) | 301 (240)<br>256 (121–408) | 234 (200)<br>176 (105–311) | 303 (248)<br>243 (123–419) |
| PAT | 15,705 (13,958)<br>11,021 (5612–25,441) | 15,976 (11,547)<br>12,313 (6457–24,156) | 13,806 (11,333)<br>11,382 (5987–17,635) | 11,234 (97,707)<br>7968 (5044–16,585) | 14,157 (11,537)<br>11,021 (5932–19,004) |
| SURG | 6716 (9392)<br>2866 (694–8756) | 5372 (6274)<br>2787 (1114–8986) | 4696 (6142)<br>2718 (631–6356) | 3728 (4771)<br>2035 (366–4471) | 4896 (6392)<br>2667 (705–6858) |
| NURS | 311 (316)<br>187 (101–423) | 304 (253)<br>220 (116–454) | 288 (267)<br>218 (102–379) | 219 (204)<br>154 (89–286) | 287 (264)<br>206 (106–395) |
| DOC | 179 (211)<br>102 (50–234) | 162 (155)<br>113 (51–238) | 152 (157)<br>107 (53–195) | 113 (131)<br>64 (39–153) | 152 (160)<br>101 (50–202) |

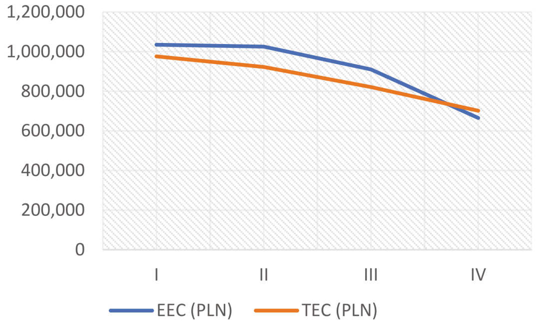

**Figure 4.** Mean EEC and TEC according to climate zones.

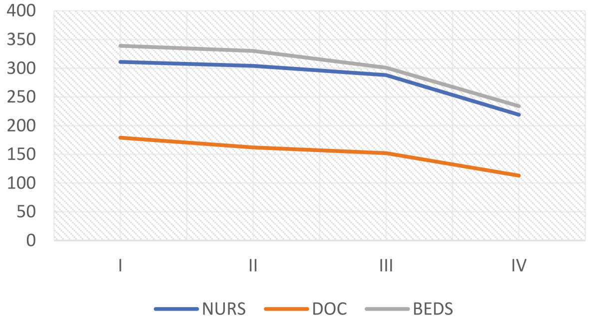

**Figure 5.** Mean hospital size measurements according to climate zones.

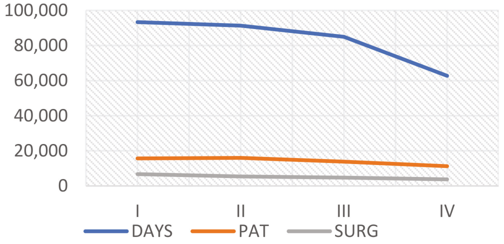

**Figure 6.** Mean hospital activity measurements according to climate zones.

### *4.2. Linear Regression Models*

First, the multivariate regression analysis took into account various factors relating to the hospital's capacity and its medical activities. To analyze the indicators affecting EEC and TEC, we used linear regression models. The regression statistics of Equations (1) and (2) are given in Table 4.

**Table 4.** Backward stepwise regression analysis with EEC and TEC as the dependent variable.

| **Variables** | **EEC** | | | | **TEC** | | | |
|---|---|---|---|---|---|---|---|---|
| | **B** | **SE** | **t** | ***p*-Value** | **B** | **SE** | **t** | ***p*-Value** |
| (Constant) | −89,543.40 | 20,655.90 | −4.335 | $p < 0.001$ | −99,791.80 | 21,668.51 | −4.605 | $p < 0.001$ |
| BEDS | 660.10 | 115.63 | 5.708 | $p < 0.001$ | 1793.30 | 131.46 | 13.641 | $p < 0.001$ |
| PAT | | | | | −13.70 | 3.16 | −4.321 | $p < 0.001$ |
| SURG | 23.00 | 3.24 | 7.096 | $p < 0.001$ | 18.00 | 3.56 | 5.067 | $p < 0.001$ |
| NURS | 437.90 | 99.14 | 4.416 | $p < 0.001$ | | | | |
| DOC | 3389.20 | 169.77 | 19.964 | $p < 0.001$ | 2797.40 | 171.69 | 16.293 | $p < 0.001$ |
| $R^2$ | 0.710 | | | | 0.630 | | | |

The best subsets and the resulting backward stepwise regression models are:

$$\text{EEC} = -89{,}543.40 + 660.10(\text{BEDS}) + 23.00(\text{SURG}) + 437.90(\text{NURS}) + 3389.20(\text{DOC}) \quad (5)$$

$$\text{TEC} = -99{,}791.80 + 1793.30(\text{BEDS}) - 13.70(\text{PAT}) + 18.00(\text{SURG}) + 2797.40\,(\text{DOC}) \quad (6)$$

The dependent variables were EEC and TEC. In terms of EEC, the regression model demonstrated that a number of beds, surgeries, nurses, and doctors were found to be statistically significant. In terms of TEC, the number of beds, patients, surgeries and doctors. were found to be statistically significant.

The standard error (SE) for each regression coefficient was less than the value of the B coefficient. Otherwise, there would have been a large confidence interval, indicating a low significance of including the corresponding variable in the regression model. The most significant variable in both models was DOC, with a $p$-value <0.001. More doctors employed results in higher consumption of electricity and heat, which is related to the total energy consumption. The annual energy consumption is also influenced to a great extent by the number of beds occupying a particular area that is to be heated in winter. If the number of beds increases, so does energy consumption. In other studies, regarding factors connected with the medical activity, there was also a clear correlation between the number of hospitalizations and the annual energy consumption. Hospitals with less than 20,000 hospital admissions per year use less energy per bed than hospitals with more than 20,000 hospital stays. Hospitals with less than 20,000 annual stays have also been found to use less energy per discharge [18].

The next stage of the analysis consisted of grouping these factors according to the moderating variables represented by four climatic zones. We analyzed the influence of the identified variables describing hospital size and activity according to the climate zones by building the EEC and TEC models separately for each Polish climate zone (Tables 5 and 6). We found that the number of hospitalization days (DAYS) and the number of doctors (DOC) were factors influencing the level of EEC independently from the climate zone. In terms of TEC, only the number of doctors (DOC) was the factor affecting analyzed costs independently from the climate zone. Observing the equations for models assigned to four climate zones, it can be concluded that the DOC variable had a significant impact on the annual energy consumption in all zones.

**Table 5.** Backward stepwise regression analysis with EEC as dependent variable according to the climate zones in Poland.

| **Climate Zone** | **I** | | | | **II** | | | | **III** | | | | **IV** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Variables** | **B** | **SE** | **t** | ***p*-Value** | **B** | **SE** | **t** | ***p*-Value** | **B** | **SE** | **t** | ***p*-Value** | **B** | **SE** | **t** | ***p*-Value** |
| (Constant) | 54,723.96 | 45,449.20 | 1.204 | NS | 56,628.14 | 40,665.19 | 1.392 | NS | −173,399 | 29,507.34 | −5.876 | $p<0.001$ | −78,941.9 | 32,153.37 | −2.455 | $p < 0.01$ |
| DAYS | 5.85 | 1.17 | 5.013 | $p < 0.001$ | 5.03 | 0.73 | 6.875 | $p < 0.001$ | −5 | 1.26 | −4.283 | $p < 0.001$ | 4.8 | 0.87 | 5.484 | $p < 0.001$ |
| BEDS | | | | | | | | | 2057 | 352.99 | 5.827 | $p < 0.001$ | | | | |
| PAT | −39.86 | 7.18 | −5.553 | $p < 0.001$ | | | | | | | | | | | | |
| SURG | 28.65 | 7.03 | 4.076 | $p < 0.001$ | 28.49 | 7.18 | 3.967 | $p < 0.001$ | 19 | 4.47 | 4.242 | $p < 0.001$ | | | | |
| NURS | | | | | | | | | 471 | 134.65 | 3.495 | $p < 0.001$ | | | | |
| DOC | 4714.66 | 433.29 | 10.881 | $p < 0.001$ | 2117.82 | 330.45 | 6.408 | $p < 0.001$ | 3854 | 237.13 | 16.254 | $p < 0.001$ | 4045.2 | 337.29 | 11.993 | $p < 0.001$ |
| $R^2$ | 0.903 | | | | 0.677 | | | | 0.688 | | | | 0.868 | | | |

**Table 6.** Backward stepwise regression analysis with TEC as dependent variable according to the climate zones in Poland.

| **Climate Zone** | **I** | | | | **II** | | | | **III** | | | | **IV** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Variables** | **B** | **SE** | **t** | ***p*-Value** | **B** | **SE** | **t** | ***p*-Value** | **B** | **SE** | **t** | ***p*-Value** | **B** | **SE** | **t** | ***p*-Value** |
| (Constant) | −29,521.6 | 88,032.76 | −0.335 | NS | −143,060 | 45,072.70 | −3.173 | $p < 0.01$ | −151,998 | 28,734.94 | −5.289 | $p < 0.001$ | 10,781.47 | 35,420.74 | 0.304 | NS |
| DAYS | | | | | | | | | −6 | 1.23 | −5.097 | $p < 0.001$ | 5.70 | 0.96 | 5.941 | $p < 0.001$ |
| BEDS | 4241.0 | 657.95 | 6.445 | $p < 0.001$ | 1710 | 186.60 | 9.165 | $p < 0.001$ | 3015 | 329.19 | 9.160 | $p < 0.001$ | | | | |
| PAT | −93.5 | 13.43 | −6.960 | $p < 0.001$ | | | | | | | | | | | | |
| SURG | 42.4 | 12.16 | 3.487 | $p < 0.001$ | 38 | 7.34 | 5.155 | $p < 0.001$ | | | | | | | | |
| NURS | −1290.5 | 406.47 | −3.174 | $p < 0.01$ | | | | | | | | | | | | |
| DOC | 5616.9 | 772.39 | 7.272 | $p < 0.001$ | 1234 | 348.20 | 3.543 | $p < 0.001$ | 3200 | 183.67 | 17.420 | $p < 0.001$ | 3086.73 | 371.56 | 8.307 | $p < 0.001$ |
| $R^2$ | 0.740 | | | | 0.657 | | | | 0.608 | | | | 0.813 | | | |

The uncertainty of these models is acceptable considering that other factors influence energy consumption, which were not controlled in the study [42]. It is important to emphasize that regression models are only valid within the range of values that determine the independent variables under consideration, and there is no assurance that successful results will be obtained when this range of values is exceeded [15].

The results obtained with multiple regression models confirm that energy consumption is determined by various factors related to the size and medical activity of hospitals. Among them, both for electricity and thermal energy, the most important factors connected with hospital size were the number of beds and the number of doctors. Our results are consistent with other studies. For example, in studies conducted in a German hospital on the factors influencing the average annual energy consumption, three indicators were analyzed (built-up area, number of employees and number of beds). The number of beds was shown to be the most appropriate as a reference indicator for quantifying the average energy consumption in a hospital [13]. In our study, the number of physicians turned out to be the most significant factor influencing the consumption of both electricity and heat. Knowledge of the importance of this factor makes us aware that subsequent analyses of the planned demand for electricity in the healthcare sector should refer to employment forecasts in the medical profession [43–46].

Other previous studies on the effect of hospital size on energy consumption showed a low correlation between the number of beds and the average annual heat energy and electricity consumption. These studies, carried out in private Spanish hospitals, also found a weak correlation between the number of employees and the average yearly heat energy consumption, as well as a high correlation with total and electric energy consumption. However, according to the study, hospitals with less than 275 employees used less energy per bed than hospitals with more than 275 employees, and hospitals with less than 100 beds used less energy per surgery [18]. In studies conducted in 45 hospitals in Thailand, no relationship was established between energy consumption and hospital capacity. This capacity was measured with the surface of air-conditioning area ($m^2$), the surface of the non-air-conditioning area ($m^2$), bed days in in-patient-departments, bed-days in out-patient-departments and number of staff members [14].

From the point of view of energy conservation, it would be appropriate to indicate the most effective size of the hospital. According to previous studies, this size varies from 200 to 300 beds, as this size allows the centralization of energy-producing equipment and the use of economies of scale, using more advanced facilities with higher capacity. On the other hand, it should be borne in mind that larger hospitals have higher energy consumption, and the great number of patients and medical workers hamper the implementation of appropriate policies to optimize energy consumption [18].

### *4.3. The Influence of Climate Zone on Energy Unit Costs by Hospital Activities*

The results presented in Table 7 illustrate the average annual energy consumption per individual unit, expressing the size or effects of medical activity. The unit costs were calculated according to the individual hospital measures. These results show that energy consumption is more significant in areas with milder winter climates, which is mainly in the first climate zone. In this climatic area, the annual consumption of electricity and heat per patient and treatment per night is higher than in climatic zones with harsher winters.

According to our research, in the first climate zone EECD is nearly 19% higher than in the fourth zone, and TECS are more than three times higher in comparison to the third climate zone. TECP in the first zone is nearly 16% higher in relation to the fourth climate zone. The difference in EECP and EECS was not found statistically different according to the climate zones in Poland. In terms of the TECD, the differences between the climate zones were statistically significant, but the size of these differences was not meaningful.

**Table 7.** Electrical and thermal energy unit costs according to climate zones in Poland.

| **Variables** | **Climate Zone** | | | | ***p*** |
|---|---|---|---|---|---|
| | **I** | **II** | **III** | **IV** | |
| | **Mean (SD)**<br>**Median (Q1–Q3)** | | | | |
| EECP | 85.68 (169.29) | 73.40 (82.77) | 84.15 (174.46) | 60.57 (30.35) | NS |
| (PLN/pateint) | 56.29 (43.89–75.53) | 54.79 (40.89–74. 70) | 54.57 (42.05–77.11) | 52.51 (39.31–69.02) | |
| EECD | 12.13 (9.76) | 11.34 (7.12) | 13.10(39.46) | 10.21 (5.47) | $p < 0.001$ |
| (PLN/day) | 10.21 (7.65–13.90) | 9.68 (7.63–12.20) | 9.01 (6.58–12.54) | 8.84 (6.84–11.64) | |
| EECS | 1338.04 (16,068.53) | 1299.32 (13,898.40) | 264.44 (887.92) | 2249.96 (30,949.91) | NS |
| (PLN/surgery) | 158.07 (103.77–253.68) | 170.78 (122.16–251.48) | 168.30 (113.38–263.94) | 153.37 (109.23–232.67) | |
| TECP | 80.59 (143.44) | 76.04 (197.24) | 80.25 (153.91) | 69.53 (38.70) | $p < 0.001$ |
| (PLN/pateint) | 60.48 (35.05–89.08) | 53.12 (34.11–77.01) | 54.76 (34.22–80.84) | 59.55 (48.53–77.14) | |
| TECD | 11.81 (8.17) | 10.21 (9.38) | 11.61 (29.80) | 11.97 (7.10) | $p < 0.001$ |
| (PLN/day) | 10.85 (5.91–16.15) | 9.381 (5.95–13.00) | 8.74 (5.46–12.57) | 10.25 (8.01–13.77) | |
| TECS | 1 632.21 (19902.77) | 543.39 (4355.41) | 252.72 (987.43) 153.68 | 1496.19 (18,335.59) | $p < 0.001$ |
| (PLN/surgery) | 161.75 (43.89 –278.65) | 151.78 (92.01–257.51) | (83.20–265.71) | 177.87 (120.75–278.32) | |

In the first climatic zone, both the size of the hospital (number of doctors) and its medical activity (number of operations) has a positive effect on electricity consumption. The number of beds also has a significant influence on the consumption of thermal energy in this zone. In colder regions, no significant impact of medical activity (number of operations) on electricity and thermal energy consumption was noticed. In these regions, there is much less hospital activity and a much higher cost of electricity per operation.

According to our results, Polish hospitals operating in the fourth (coldest) climatic zone use less electricity and thermal energy than hospitals in the first climatic zone (the warmest). We presume that this is caused by the higher demand for cooling systems in the warmer zone [47]. It can, therefore, be concluded that the hospitals in the fourth climate zone, which perform the least operations per year and where the average annual hospital stay is shorter, manage energy better than the hospitals with more significant health care activity in the first zone. Other researchers from China evaluated that annual electricity consumption for hospitals in a frozen zone is 67.9% lower than for hospitals located in hot summer and warm winter zones. They concluded that annual electricity consumption is higher in the southern area in China than in the northern area because of use of air conditioning systems in summer. This is in line with our research, where the electrical energy costs in the hospitals located in the coolest zone (IV) are more than 64% lower than in the warmest climate zone (I). The influence of the climate on energy consumption was confirmed by other studies where the influence of temperatures on energy consumption was analyzed throughout the whole year [48,49]. These studies showed that higher needs for cooling systems between May and November result in a greater need for energy use at higher temperatures.

The better energy efficiency in hospitals from colder regions can also be associated with the health status of the patients in the regions and higher risks of some diseases in higher temperature regions [33]. Other researchers reported, for instance, that a one-degree Celsius increase in maximum monthly average temperature was associated with a 0.34 increase in heat-stress illness hospitalization rate per 100,000 population in thinly populated counties compared with 0.02 per 100,000 in highly urbanized counties [35]. Another study calculated that the annual excess days of hospitalizations and costs in 14 geographic regions of New York State for temperatures above a certain threshold, and estimated that respiratory diseases attributable to extreme heat at baseline in NYS resulted in 100 hospital admissions, US$644,069 in direct hospitalization costs, and 616 days of hospitalization per year [50]. Our analysis showed that the hospitals located in the fourth climate zone have fewer patients and perform fewer surgical operations. As a result, less intensive medical activity is carried out in these regions.

Another reason why the hospitals from colder regions use less energy is the fact that lower energy consumption in the hospitals from the IV zone is due to the poorer economic situation of these regions. The results of other studies show that the economic situation in a region may be a factor influencing energy consumption. For example, using the example of eastern Europe post-communist economies, it was shown that GDP growth is a key factor in increasing both energy efficiency and energy consumption [51–53]. In subsequent studies, it would be worth checking the relationship between energy consumption in hospitals and the economic situation of the region in which these hospitals operate.

We also analyzed the energy cost consumption in terms of the size of the hospitals measured by the number of beds.

According to Figure 7, the highest average EEC was among large hospitals located in the I climate zone and the lowest in the IV one. Among the big hospitals, the highest EEC was observed in the II climate zone. We didn't observe a significant difference in average EEC in terms of medium and small hospitals. The highest variation in terms of EEC can be observed among large hospitals, especially in the IV climate zone.

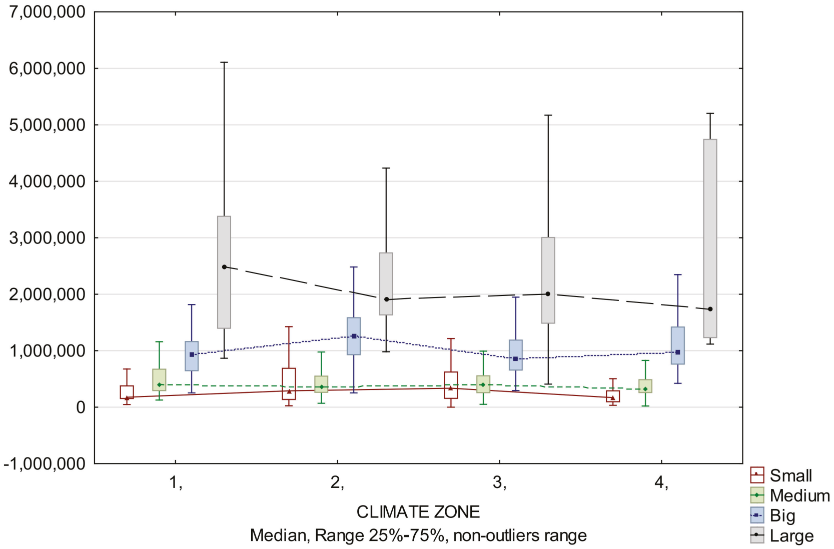

**Figure 7.** EEC by the size of the hospitals relative to the climate zones in Poland.

In terms of TEC (Figure 8), the differences between large hospitals according to the climate zones were not significant. The most significant difference in TEC was seen among big hospitals, where the lowest TEC was in the first climate zone and the highest in the IV one. The influence of climate zone on TEC was not observed among small and medium-sized hospitals.

When comparing the energy efficiency of a group of hospitals, it was appropriate to calculate this consumption in relation to variables regarding healthcare activities, as different hospitals have different workloads and healthcare needs. Including activity variables prevents the most efficient hospitals from being penalized and promotes more efficient management. Taking into account hospital activity, we also analyzed to what extent the influence of climate zone on energy costs can depend on surgical or non-surgical hospital profile. The results are presented in Figures 9 and 10.

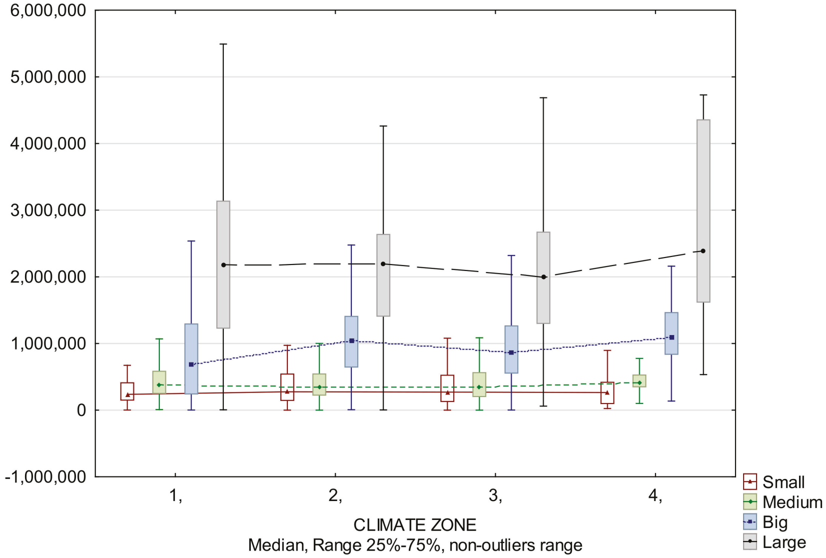

**Figure 8.** TEC by the size of the hospitals related to climate zones in Poland.

We found that the warmer climate zones, the higher intensity in terms of surgeries, and the higher EEC. In terms of non-surgical hospitals, the influence of climate zone on EEC was not observed. In terms of TEC, the observations were similar. The difference in the level of TEC was observed for high and medium-intensity hospitals. However, the most noticeable difference was observed for high-intensity hospitals between the I-II climate zone and III-IV zone. There was no significant difference for non-surgical and low-intensity surgery hospitals.

In our study, we found that the number of surgery operations is an important variable related to the activity of hospitals that affects energy costs. This was observed especially for medium and high-intensity surgery hospitals in terms of TEC in the first and second climate zone. A high correlation between the average annual energy consumption and hospital activity indicators was also observed in studies carried out in Spain. Health indicators were represented by the number of annual discharges, the number of rescue operations and the number of hospitalizations. A direct link to the annual energy consumption per employee was also shown by the number of annual operations, laboratory tests, births, and endoscopies [18].

The number of surgical operations is an important factor influencing energy consumption due to the fact that operating theaters are characterized by an exceptionally high energy demand in hospitals. The operating theaters were found to be three to six times more energy-intensive than the hospital as a whole, mainly due to heating, ventilation and air conditioning requirements [19]. Hospitals with less than 3000 operations per year had lower energy consumption per bed than hospitals with more than 3000 operations. In addition, it was observed that hospitals with fewer than 2500 operations per year used less energy per hospital discharge [18]. It turns out that operating theaters use far more energy per area than other types of hospital areas. As lighting uses between one-third and almost half of the energy demand, this should encourage the use of more efficient types of lamps in hospitals, lower brightness levels, and encourage staff to switch lights off more consistently. In addition, there has been a discussion for several years about the time of using ventilation in operating rooms when no surgical operations are performed [20]. There is no certainty among medical personnel whether disabling this involves high risk.

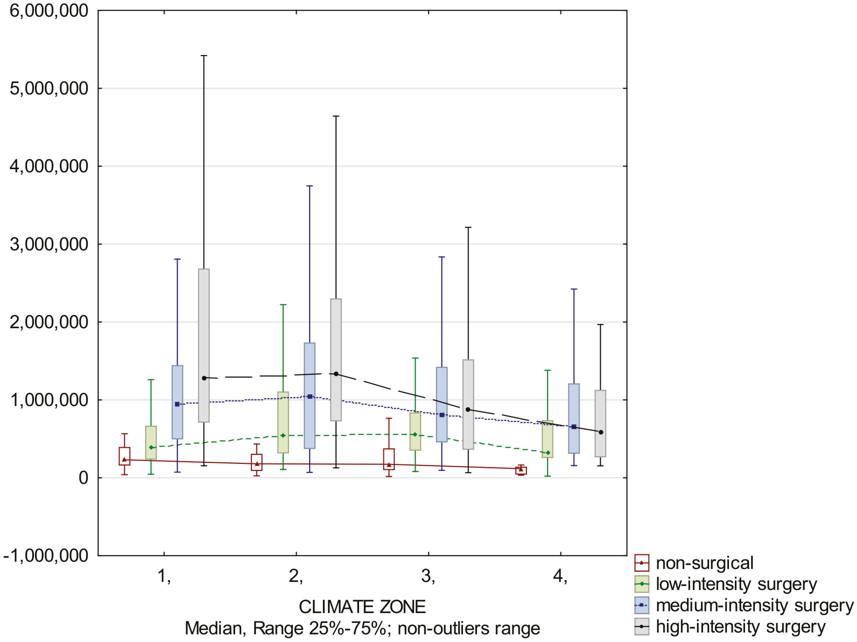

**Figure 9.** EEC by hospital surgery intensity related to climate zones in Poland.

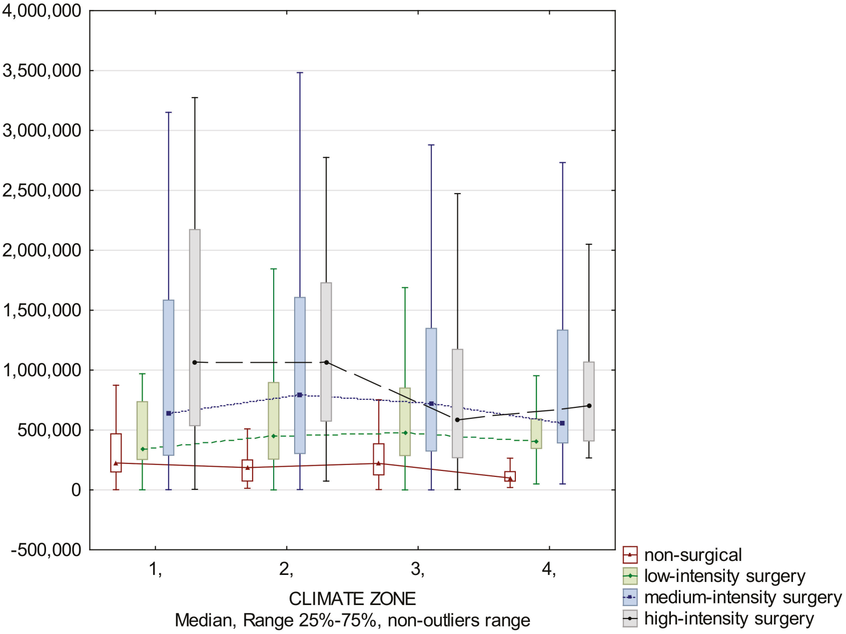

**Figure 10.** TEC by hospital surgery intensity related to climate zones in Poland.

The number of surgical operations also turned out to be a significant variable in a model used to forecast electricity from hospital air conditioners using an artificial neural network. Other variables included in this model were temperature, relative humidity, and electricity from the previous hour, time of day. This model was used not only to control the operation of the air-conditioning system but also to forecast hot water production using the hospital's reheating system [54].

Our research does not confirm other studies, according to which energy consumption is higher in facilities operating in colder climatic zones. For example, in studies of fifty-one high-performance buildings around the world, it was found that the energy consumption in the hot zone was lower than in the rest of the zones. It was considered that the reason for this was the probable lack of space heating and the widespread use of natural ventilation in this climatic zone. However, the differences in energy consumption were influenced not only by the climate but also by the size of the building, efficient technologies, human behavior, and operations and maintenance practices (O&M) [55].

As the exact factors that influence a building's energy consumption remain unclear, energy-saving strategies should take into account all the elements that can affect the actual energy consumption of a specific hospital. For example, climate can only affect cooling and heating loads, and the use of daylight and natural ventilation. In turn, the number of medical doctors employed affects a building's operational schedule, and thus energy consumption in hospitals is influenced by other factors connected with human behavior regarding energy-saving habits [55].

To reduce energy consumption in the building sector, where most of the energy is used for heating and cooling applications, as it is in climate zone I hospitals, different strategies to reduce energy consumption should be implemented. One of them can be the Passive House (PH) concept [42,56]. The PH concept employs continuous insulation throughout the entire building envelope without any thermal bridging. The building envelope is extremely airtight, preventing infiltration of outside air and loss of conditioned air. In some countries, PH standards have been used to design hospital buildings [57,58]. Air conditioning energy consumption can account for 20–40% of a building's energy consumption. Replacing energy-intensive mechanical ventilation with natural ventilation can therefore reduce energy consumption in hospitals in warmer climates [59]. Other studies analyzed utilizing thermal insulation as a passive strategy for reducing cooling and heating energy consumption in hospitals. Results showed that the use of an envelope of thermal insulation in hospitals allowed a reduction in energy consumption for cooling and heating while increasing the thermal comfort within the hospital [28] used to assess the performance of the HVAC system. The thermal comfort perceived by the staff inside is related to the indoor air quality of the operating theatres and the risk of nosocomial infection [60]. For this purpose, the "predicted average vote" and the "predicted percentage of dissatisfied" derived from Fanger's comfort equation are usually calculated [61]. It is worth remembering, however, that in operating theaters, medical and surgical criteria must prevail over the criteria of thermal comfort. Another criterion for assessing the performance of an HVAC system is the rate of surgical site infections (SSI) for the total number of surgical operations performed in a given room [62].

Passive strategies to improve the energy performance of buildings were also assessed at three locations in the Baltic region (Kaunas, St. Petersburg and Warsaw). Results showed that total energy consumption varied by 27.4% between the most energy-intensive (coldest) and the least energy-consuming (warmest) region in the same climatic zone, strongly dominated by heating. The properties of the walls are able to reduce (or increase) energy consumption significantly. Overall, insulation has been essential in all three locations in the Baltic region [63].

We presume that the different influences of the climate zone on energy costs in Poland can also be associated with different levels of renewable energy production. Basically, all of Poland is suitable for air-to-water heat pumps and solar-powered energy sources. However, according to previous studies, depending on the climate zone, the profitability of those investments is different [64]. Because of intense solar radiation and lower outside air temperatures over the year in the south of Poland, the performance of renewable energy sources is best in the coldest regions. The exception is in the northeast part of Poland, where the temperature and solar radiation are both low [65]. It would be worth analyzing to what extent the hospital energy costs depend on the level of renewable energy production. It is worth noting that due to the high growth of the renewable energy sector, new financing channels are now available. A review of investment trends revealed that investors see great potential in renewable energy [66–68].

Other studies that considered European climatic zones showed that cities with cooler climates have energy consumption partially mitigated by the good thermophysical properties of the building envelope. On the other hand, for cities with warmer climates, an air treatment center can bring significant energy benefits. This is mainly due to the efficiency of the air conditioning unit's heat exchanger, which processes warmer outside air in cities with milder climates [69]. Another study on the weather characteristics of European regions aimed to outline energy-saving climate strategies based on human thermal comfort. Strategies have been aligned with conceptual technologies such as glazing, shading and insulation. It turned out that in the northern climatic zone in which Poland belongs, the most influential strategies were ventilation with heat recovery (about 20% reduction from the initial base), improvement of glazing (reduction by 10–12% from the initial base) and improvement of insulation (10–5% reduction from the initial base). The effects of ventilation with heat recovery were more evident in the Nordic colder countries due to the savings in the pre-heating necessary for introducing outside air at very low temperatures. Locations with a warmer climate closer to the southern climate zone benefit from the use of efficient shading devices [70]. According to studies carried out in Spain, the energy demand of buildings located in similar climatic zones but in different countries is the same [71]. It is, therefore, necessary to gradually coordinate various national laws enacted to implement the Energy Performance of Buildings Directive (EPBD). This can contribute to reducing energy consumption in European buildings by sharing knowledge and best practices on energy efficiency and energy savings between all EU member states and Norway [72].

## 5. Conclusions and Implications

Energy consumption in the Polish healthcare sector, and particularly in hospitals, is very high compared to other commercial industries in the country. In order to take appropriate measures to optimize the energy consumption of these units, it is first necessary to understand the factors that influence this consumption. In this study, we assumed that energy consumption in Polish hospitals is manifold, shaped by many interrelated factors that overlap not only on an individual level but also at a higher level. The aim of the article was to investigate the determinants of electricity and heat consumption in Polish hospitals related to their size and medical activity, taking into account climate zone as a moderating variable. Our intention was, therefore, to investigate whether there are differences in the determinants of energy consumption between hospitals from different climatic zones. We used data from M-03 financial statements and M-29 activity reports from all Polish hospitals for 2010 to 2019 and applied backward stepwise regression analysis to their analysis.

The results confirmed that variables related to hospital size (number of doctors, number of beds) and variables related to their medical activity (number of surgical operations) are important determinants of energy consumption, regardless of the type of energy. Additionally, in the EEC model, the number of nurses turned out to be a statistically significant variable, and in the TEC model, the number of patients. The most essential variable in both models was the number of physicians. More doctors employed resulted in higher consumption of electricity and heat energy, which is related to the total energy consumption. In subsequent studies, it would be worth considering their behavior in the context of energy-saving activities.

In order to investigate the determinants of energy consumption in Polish hospitals operating in various climatic conditions, four models covering four climatic zones divided according to NUTS 2 regions were additionally examined. The result showed that the climate zone influences energy consumption in hospitals. The only variable that had a significant impact on the annual energy consumption in all climate zones was the number of doctors. Additionally, irrespective of the climatic zone, the level of electricity consumption was influenced by the number of days of hospitalization, and the level of thermal energy by the number of beds. In addition, energy consumption was more significant in areas with milder winters than in areas with harsher winters. This was especially true for surgical hospitals; he warmer the climatic zones, the greater the intensity of surgical procedures, the higher the EEC. In the case of non-surgical hospitals, no influence of the climatic zone on the EEC was observed.

The results of this study contribute in several ways to the literature on energy consumption in hospitals. First, the study develops a more integrated approach to studying the drivers of energy consumption in hospitals at the regional level, examining not only variables connected with hospital capacity but also medical activity variables that have proven to be important determinants. These variables have not been taken into account in previous studies on this topic. This study shows which factors can be considered universally relevant determinants of energy consumption, regardless of the location of hospitals.

Secondly, this study demonstrates the advantages of including the climatic zone as a moderating variable in analyzing the impact of hospital size and activity on electricity and heat consumption. The analysis showed that the context presented by the regional level, and especially the climate, can play an important role in making decisions about energy consumption.

Third, while the energy sector has a significant environmental and social impact, no empirical cross-sectional study specific to the healthcare sector has been carried out so far with such a large hospital base from one country. This article is the first study to collect and analyze data on energy costs in all hospitals in Poland. As far as we know, no previous research on this topic has focused on such a large sample of hospitals.

The present study, therefore, adds new evidence to the existing literature on the factors influencing energy consumption in the health sector. The impact of such related variables on energy consumption in the health sector has not yet been investigated.

Empirical findings can be useful in designing energy-saving policies at the national as well as regional levels. They can also be useful in other countries with a similar level of development as Poland. Researching the factors influencing energy use in healthcare facilities allows us to look for effective ways to implement improvements in energy management. Optimizing these factors may allow for a reduction in energy consumption, which will not only reduce greenhouse gas emissions but also reduce plant operating costs.

The results of our research describing the influence of climate zone on energy costs can also be used when designing the construction of new hospital buildings or modernization of existing ones.

Moreover, when designing heating systems for hospitals in the first climate zone, particular attention should be paid to the integrated heating and cooling system. Additional research still requires checking what other factors cause differences in energy consumption between individual regions of Poland, and especially to what extent the greater energy consumption in the western regions than in the eastern regions results from the influence of a humid, warmer climate on greater morbidity in these regions, or from a better economic situation in these regions.

## 6. Limitation and Future Research

The study has several limitations, which should be considered when evaluating the results. The study did not take into account the source of energy used by hospitals and their energy efficiency for all major fuels: (e.g., electricity, natural gas, fuel oil, and district heat.). However, other studies conducted in Polish hospitals show that electricity costs account for almost half (46%) of the energy costs used by hospitals. In second place is natural gas (35%), which hospitals use to generate heat. Hospitals spend significantly less on thermal energy from external sources (17%). The low oil expenditure (2%) with 24% of the plants that indicated it as one of their energy sources may be due to the fact that the units used fuel for company cars. As hospitals do not use energy from biomass/biogas/biofuels, they do not spend money on these types of fuel [73]. Other studies show that the main types of energy used in hospitals are natural gas and electricity. Natural gas is mainly used for space and water heating and cooking. Electricity is mainly used for cooling purposes [4]. In Poland, energy is mainly produced in utility power plants. In 2020, the production volume in these facilities amounted to 82.8% of the total production. For Poland, which has an economy based on coal, the most important fuel used to generate electricity was hard coal, with a share of 47.0%, and lignite with a share of 24.9%. The share of coal is systematically decreasing in favor of green sources, which, in 2020, accounted for 10.75% [74].

Another limitation of the study is the lack of an analysis of the cost of energy consumption, taking into account renewable energy sources. It is unclear how quickly Polish hospitals are switching to alternative renewable energy sources. The importance of the problem is increasing because, in accordance with the assumptions of the Europe 2010 strategy [75], it is necessary to take measures to reduce $CO_2$ emissions by 20% by 2020, increase energy efficiency by 20% compared to 1990 and increase the share of renewable energy sources (RES) up to 20% in the entire European Union. Renewable energy is wind energy, solar radiation, aerothermal, geothermal and hydrothermal energy, ocean energy and hydropower, the energy obtained from biomass, gas from excavations, sewage treatment plants and biological sources. It is worth noting, however, that the sector of renewable energy sources (other than wind) in Poland recorded the highest growth in the last year. In September 2021, this sector recorded an increase of 88.73 percent compared to the previous year. In wind farms, production has increased by 15.67 percent on an annual basis. Since 2000, 36% of hospitals have installed solar panels, and 2% of hospitals invested in geothermal energy and photovoltaic installations. Solar installations are the most frequently indicated among the planned investments (44%). No hospital has used heat pumps so far, but their installation is declared by 16% of hospitals [73].

The article also does not take into account where hospitals consume energy. Hospitals have a high energy demand due to continuous operation, mainly heating, ventilation and air conditioning [76]. Unfortunately, this survey does not show the breakdown of energy consumption by these activities. The most energy-intensive activities in hospitals are typically ventilation, cooling and lighting, while the main uses of natural gas are space heating [4]. About 61% to 79% of a hospital's energy consumption is generated by the production of lighting, heating, cooling and hot water [77]. Similar results can be found in literature studies that found that HVAC systems are the main consumers of electricity consumption in hospitals [78,79]. For example, air and room heating in UK hospitals used 44% of total energy [80]. In India, HVAC systems are also the main consumers of electricity, followed by lighting and water pumps [81]. In Thailand, HVAC systems accounted for more than half of the total energy consumption [14]. Therefore, energy-saving efforts in hospitals should focus on managing the HVAC system.

Consideration of these aspects should be taken into account in subsequent studies regarding Polish hospitals, as these buildings have many energy-intensive activities such as laundries, use of medical and laboratory equipment, sterilization, use of computers and servers, catering and refrigeration.

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energies

*Article*

# Key Growth Factors and Limitations of Photovoltaic Companies in Poland and the Phenomenon of Technology Entrepreneurship under Conditions of Information Asymmetry

**Bartosz Wachnik * and Zbigniew Chyba ***

Faculty of Mechanical and Industrial Engineering, Warsaw University of Technology, 00-661 Warsaw, Poland
* Correspondence: bartosz.wachnik@pw.edu.pl (B.W.); zbigniew.chyba@pw.edu.pl (Z.C.)

**Abstract:** Nowadays photovoltaic trade in Poland is growing rapidly due to contemporary challenges in sustainable energy. The first Polish photovoltaic firms were established in the second decade of XXI century. It was the answer of looking for new innovative energy sources including solar energy. It was necessary to change the structure of energy sources in Poland mainly based on carbon and oil & gas. The aim of this article was the identification and assessment the key opportunities and barriers to photovoltaic industry enterprises in Poland in the context of technology entrepreneurship under conditions of information asymmetry. The paper was prepared based on the results of qualitative research using the case study method. A comparative analysis was performed based on results of a study of four purposefully selected enterprises. All of them are SMEs. The research was done in 2021. The case study method allowed for comparing the analysed enterprises in pairs, which is discussed more extensively further on in the text. The research performed will lead to conclusions and recommendations for the photovoltaic sector enterprises in Poland which will allow them to act more effectively and efficiently in conditions of competing on the global market. This paper contains the characteristics of photovoltaic trade in Poland, its macro and micro environment, the opportunities and threats of this trade and key strengths and weaknesses of characterized photovoltaic enterprises in Poland. Finally, the conclusion and recommendations of discussed Polish photovoltaic trade firms in future are evaluated.

**Keywords:** solar energy; solar photovoltaic; photovoltaic firms; barriers; photovoltaic trade in Poland; technology entrepreneurship; information asymmetry

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## 1. Introduction

### 1.1. Theoretical Background and the Aim of Article

Demand for renewable energy sources is growing rapidly in today's world [1,2]. This is a global phenomenon pertaining to most countries, including those that belong to the European Union. It is also true in Poland, whose structure of energy sources is especially unfavorable in the context of the sustainable development concept being followed currently as well as the ever-widening use of so-called "green energy" [3]. One of responses to these challenges has been the development of the photovoltaic sector in Poland, characterized by a high rate of growth compared to other European Union countries' [4]. The establishment and growth of photovoltaics sector enterprises is the effect of the technology entrepreneurship undertaken by their founders and the entire organizations which skillfully utilize the key element of technology opportunity that appears in their surroundings to create and implement new technology solutions. The barriers to the development of photovoltaic enterprises are also due to the asymmetry of information between energy source producers and consumers, hereinafter collectively referred to as prosumers. The sector's development in Poland is largely determined by external factors, both positive (opportunities) and negative (threats, including development barriers).

Based on a BP (British Petroleum) report in 2020 [5], Poland produced 74.4% of electricity from coal in 2019, which represents a decrease of about 4% in comparison to 2018. However, the percentage of coal in the energy mix in Poland is four times more than the average in European countries (17.5%). The CO2 emission reached 309 million tonnes overall and 151 million tonnes in heat and electricity sectors [6]. Poland's environmental targets to 2030 are a 40% decrease of greenhouse gases (GHG) from the 1990 year level. Also Poland should increase the level of renewable energy sources (RES) in total Energy consumption to 32%, and ought to increase simultaneously the energy efficiency to 32.5% [7]. In 2018, the two last objectives were adjusted to 27% [8]. Nevertheless, environmental targets are demanding challenges for Poland. In the European Parliament, they are much more ambitious. According to [9], Europe intends to achieve carbon neutrality by 2050.

The Ministry of Energy of Poland presented an updated 2040 forecast for the Polish energy mix in November 2019—the EPP (Energy Policy of Poland) 2040 [10]. The document includes eight scenarios with a holistic prognosis of the energy system, including electricity, heat and transport. Those scenarios include a whole supply chain (from sources capture to the end consumer). This prognosis was constructed based on five main assumptions:

- A 56–60% coal share in electricity production in 2030;
- 23% of RES in the final gross energy consumption in 2030;
- Implementation of nuclear energy in 2033;
- A 30% $CO_2$ emission reduction by 2030 (in comparison to 1990);
- An increase in energy efficiency of 23% by 2030 (concerning the primary energy consumption from 2007).

The aim of this paper is to identify and evaluate key development prospects and barriers for photovoltaic sector enterprises in Poland in the context of technology entrepreneurship under conditions of information asymmetry. The paper was prepared based on the results of qualitative research using the case study method. It attempts to answer the following research question: "What are the key opportunities and limitations of photovoltaics development in Poland from the point of view of your company?".

A comparative analysis was performed based on results of a study of four purpose-selected enterprises. The case study method allowed for comparing the analysed enterprises in pairs, which is discussed more extensively further on in the text. The research performed will lead to conclusions and recommendations for the photovoltaic sector enterprises in Poland, which will allow them to act more effectively and efficiently in conditions of competing on the global market.

Generally the case study method allows the exploration and understanding of complex issues [11]. It can be considered a robust research method particularly when a holistic, in-depth investigation is required. There are a lot of applications of mentioned method in many social science studies, especially in education [12], sociology [13] and community-based problems [14]. Case study helps to explain both the process and outcome of a phenomenon [15].

Past literature explains the application of the case study method e.g. in Sociology [13], Law [16], and Medicine [17]. So the mentioned method is very universal one and useful for scientific research.

### *1.2. The Essence of "Photovoltaic"*

In the last 20 years, the penetration of renewable energy sources (RESs) in energy systems around the world has progressively increased due to the rise of environmental concerns and governmental policies. Of the different RESs, the worldwide growth of photovoltaic (PV) technologies has been close to exponential [1,2]. The most important and challenging problem arising from the great penetration of PV in electrical systems is the high level of variability in the power supplied. In fact, this strictly depends on local weather conditions. The resulting uncertainty and variability in the PV power profile create various problems for the management of the electricity grid. First, large frequency oscillations can be induced by abrupt changes in power. Secondly, in the case of the high penetration of renewables, reverse active power flows may occur in the medium-voltage distribution power supply, or even in the high-voltage transmission line. Finally, the high penetration of PV increases the costs of the allocation of the spinning reserve, ancillary services and the energy planning of the dispatchable generators [18]. For all these reasons, highly accurate photovoltaic power prediction systems are required to optimize the management of the electricity grid from both a technical and economic point of view, without reducing energy reliability and quality.

The word "photovoltaics" consists of two elements: photo, i.e., light, and voltaics, from volt, the unit of electric potential [19]. This reflects the essence of the term, since photovoltaics concerns transforming sunlight into electrical energy. For that to happen, however, requires the photovoltaic effect (phenomenon). The photovoltaic effect signifies a process that occurs in photovoltaic cells under the influence of solar radiation. In the simplest terms, it involves the freeing of valence electrons from atomic bonds in silicon crystals (of which the cells are made). The freeing of electrons leads to a difference of potentials, which causes the formation of a direct current. An inverter then converts it to an alternating current that powers devices.

The photovoltaic effect is not the only concept related to photovoltaics, which as a field of science and technology covers a number of terms. One of them is the photovoltaic cell mentioned in the definition of the photovoltaic effect. The cell is the smallest element of a solar panel. Cells are made using polycrystalline or monocrystalline silicon. Interconnected cells make up a photovoltaic module. Photovoltaic modules are connected with each other, fastened with a special frame and covered with a protective coating, thanks to which they are properly protected against mechanical damage and UV radiation, hail, snow and other adverse weather conditions. That is a short description of the production of a solar panel, the principal element of a photovoltaic installation. A photovoltaic installation is a system of devices that makes it possible to convert sunlight into electricity. As mentioned above, its basic and at the same time most characteristic element are photovoltaic cells. However, in order to function correctly, the installation also requires other elements. One of them is an inverter, a device that converts direct current into alternating current and therefore makes it possible to power devices with electrical energy produced by the sun.

Another concept term inseparably linked with photovoltaics is the consumer. According the Renewable Energy Sources, any owner of a photovoltaic micro-installation with a capacity of up to 50 kW may become a prosumer, provided that the energy produced is not used for sale but for their own needs. Poland's RES Act is a law on renewable energy sources. It contains definitions of the principles and conditions of power generation—not only from the sun but also so-called green energy sources (wind, water, nuclear energy or biomass). The amendment of 11 August 2021 is aimed at facilitating investment processes in renewable power generation and to extend the support mechanisms available to investors applying for public guarantees of energy sales.

Photovoltaics is an area covering many concepts, which would be impossible to cover in a single article. The above text helps in understanding those that are the most important and most common in industry articles. In order to select the correct installation, it is necessary first to consider what type of interaction with the power grid will best satisfy the investor's needs. Taking this factor into consideration, the following options are available:

- On-grid photovoltaic installations, which can operate only after being connected to the power grid. They are less expensive that other PV systems since they do not require the purchase of batteries. What is more, not only do they enable generating current for own use but also for selling surplus energy to the network. These are the most frequently chosen options. Depending on the type of inverter used, on-grid photovoltaic installations can be divided into three categories: systems with a central inverter, systems with string inverters and systems with microinverters.
- Off-grid photovoltaic installations (autonomous, independent) are not connected to the power grid. The generated energy is stored in batteries, which allows it to be used

later. They work well wherever access to the grid is difficult or uneconomical, e.g., in summer houses.
- Hybrid installations (mixed, combination); in their case, PV panels are supplemented by another source of electrical energy, e.g., wind turbines or combustion generators. The produced current can be used at once or stored for later. It is also possible to connect a mixed installation to the power grid.

Photovoltaic installations can also be classified according to their location. PV systems are usually installed on roofs or on the ground, but can also be installed on balconies. Regardless of where they are located, they should not be shaded. Photovoltaic installations, whether on roofs, on the ground or on balconies, are mounted on special structures adapted to their specific location. The entire installation should be not only durable and resistant to external factors, but also visually attractive.

Photovoltaic installations can also be classified based on the destination of the energy produced. They can then be divided into:

- Small PV systems—generating current for a single road sign or streetlamp.
- Consumer systems—in the case where all of the energy produced is used by the investor.
- Prosumer systems—a portion of the generated energy is used for own needs and a portion is transferred to the power grid.
- PV farms (power plants)—which transfer all of the energy generated to the power grid.

The Energy Law Act introduced the criterium of power, classifying photovoltaic installations as micro PV installations, small PV installations and large PV installations. These installations achieve a power higher than 200 kW. They are PV farms. Photovoltaic installations can be classified based on various criteria. The type of PV system an investor chooses depends on individual needs as well as the amount of the available budget.

### *1.3. Characteristics of the Photovoltaic Market in Poland*

The Polish PV market is experiencing a development boom stimulated by EP legislation. During the five years through the end of 2020, Poland reached first place in the EU, taking into account the growth rate of photovoltaic power. Successive ever-better forecasts confirm the Polish photovoltaic market's strength, potential, and growing position [20].

In 2020 Poland was 4th in the European Union with respect to the increase in PV capacity installed, behind only Germany, the Netherlands and Spain. The Institute for Renewable Energy (IEO) predicts that in 2021 Poland will maintain the high growth rate and its 4th place in the EU [21].

According to the IEO, the full complement of installed capacity in PV sources includes:

- Micro-installations—installations with a total installed capacity not exceeding 50 kW; their total capacity was 3022 MW at the end of 2020, and as of Q1 2021 it is 3500 MW.
- Small installations—installations with a capacity of 50 kW–500 kW; their installed capacity in Poland at the end of 2020 reached 65 MW, and currently exceeds 71 MW.
- Photovoltaic installations with a capacity above 500 kW, built under the system of certificates of origin or outside the auction support scheme; their total installed capacity was estimated at 75 MW.
- Photovoltaic installations built under the RES auction; their total installed capacity at the end of 2020 is 750 MW, and currently their capacity may be 820 MW. Most often, these are photovoltaic farms and solar power plants with a capacity of approx. 1 MW.

In Poland micro-installations possess the biggest share of the PV market. In 2020 they accounted for 77% of the installed photovoltaic capacity. This is due to several factors, including the technology's increasing popularity among prosumers, subsidies granted under Regional Operational Programs and the government program of subsidies for photovoltaics—the "My Electricity" program. The program was carried out between September 2019 and December 2020 and had its highest impact on the growth of the PV market in 2020. The program's next iteration is currently being planned. In 2020, PV installations constructed under the RES auction accounted for 19 percent of the installed capacity. The total capacity of these installations doubled compared with 2019. Further increases are expected in the coming years due to the expiring deadlines for returning the energy into the grid for the first time for projects contracted under the 2018 and 2019 RES auctions. Small PV installations account for less than 2% of the entire installed photovoltaic capacity; this small share is due to the lack of support for installations in the 50 kW–500 kW range.

The share of installed photovoltaic capacity in relation to the installed capacity in renewable energy will reach 30% at the end of 2020, being twice as high as in 2019. Thus, PV installations were ahead of biomass (11%), hydroelectric plants (8%) and bi-ogas (2%). Onshore wind power continues first to be the leading renewable energy source, accounting for 49% of installed capacity. The above data clearly indicate that for 3 years photovoltaics has been the fastest growing RES in Poland and has achieved the highest annual increases, and within 1-2 years it may have similar installed capac-ity as wind energy [20].

### 1.4. Global and EU-Specific Development Challenges of Photovoltaics

The photovoltaic market in the EU-28 continues to grow very rapidly. Year by year, photovoltaics continues to record high increases in installed capacity. At the end of 2020, the installed capacity in the European Union in photovoltaics amounted to approximately 153 GW, which was an increase of 18.8 GW compared to 2019. According to estimates based on IRENA data, EU countries achieved a 14% increase in the total installed PV capacity compared to 2019. The increase recorded in 2020 was 1.13 times greater than that obtained in 2019 [20].

The largest increase in photovoltaic capacity—4.74 GW—was recorded by Germany. In second place was the Netherlands, with an installed capacity of 3 GW. Spain (2.8 GW of new capacities) is in third place; it also recorded the largest increase in 2019. Poland's increase in the order of 2.4 GW puts it in fourth place, ahead of France (0.9 GW), whose share in the increase in the number of new PV installations fell. In 2020, Poland found itself in the top four in the European Union in terms of the increase in new photovoltaic capacity, after being in the top five in 2019. The growth rate of the Polish market continues to be high, keeping the country among the European leaders.

Poland leads Europe with respect to the growth rate of its photovoltaic market. Poland was followed by Sweden, Hungary, Ukraine, the Netherlands and Spain, re-spectively. Solar Power Europe predicts that by 2024 Poland will achieve an increase of installed capacity by 8.3 GW to 13 GW and will retain its fourth place in terms of in-creasing new photovoltaic capacity. The latest IEO forecasts indicate that at the end of 2024 total installed capacity will amount to 12.5 GW (an increase by 8.5 GW during 2021-2024).

### 1.5. Technology Entrepreneurship

The rapid growth in photovoltaic sector enterprises in Poland is made possible by the entrepreneurial behaviour of numerous managers who are able to perceive in their surroundings opportunities for technology change that can translate into market success.

Under conditions of a technology race and the shortening of product and technology lifecycles, technology entrepreneurship is gaining particular importance as one of the key manifestations of entrepreneurship. Technology entrepreneurship is interdisciplinary and multifaceted in character and can be considered both at the level of individual initiatives and innovative undertakings at the level of the whole organisation. This entrepreneurship combines the issues of academic entrepreneurship, technology management (including technology transfer) and intellectual entrepreneurship [22].

Technology entrepreneurship has been attracting significant interest in recent years, both from management theoreticians and practitioners. Even though the term has been known in the world literature for several decades, the number of publications on it did not increase markedly until the 2010s. The theoretical foundations of the concept in its modern understanding appeared in a special edition of the *Strategic Management Journal* in 2012, by scientific editor Ch. Beckman and co-editors K. Eisenhardt, S. Kotha, A.

Meyer and N. Rajagopolan, entitled “Technology Entrepreneurship” [23]. Other papers presenting an attempt to explain the concept include T. Bailetti [24]. The topic of technology entrepreneurship was undertaken by numerous authors, including S. Muegge and T. Bailetti et al. [25,26].

In recent years, many Polish-language publications on technology entrepreneurship have also appeared. Different Polish authors define the term “technology entrepreneurship” differently. According to Lachiewicz et al. [27], technological entrepreneurship can be understood “as a process that combines the elements of academic and intellectual entrepreneurship with the entrepreneurship of commercial organizations—owners, managers and employees implementing new technologies and innovative business solutions in the market environment”. In the opinion of Kordel [28] “the phenomenon of technology entrepreneurship occurs when scientific or engineering development creates a key element of an opportunity, which is then transformed into a new investment. The technology project, based on the latest engineering knowledge, is a direct result of technological entrepreneurship”.

Technology entrepreneurship should be considered in the broader context of an enterprise’s organisational and, especially, development strategy. For that reason, the appropriate measures of the efficiency and effectiveness of technological entrepreneurship are those that relate to competitive advantage (e.g., market share, profitability ratios, etc.) [29].

The concept of technological entrepreneurship should be placed in the area of strategic management, including innovation theory and entrepreneurship theory. Technological entrepreneurship primarily concerns advanced technology sectors, although it can also be applied with respect to traditional industries. It is a process consisting of the entrepreneurial activities of an innovation leader, the team members and the members of the entire organisation. It is a special process that is primarily characterized by creative, collaborative activities or processes, innovation, a propensity toward risk and a positive focus on actions and their results, and primarily serving to the benefit of society.

Technological entrepreneurship is an innovative process that can be considered on two levels. The first of these is the stage of creating the idea for an innovation and the probability of its practical use. The second is the actual implementation and commercialisation of the innovation idea. This means that technological entrepreneurship is also a special, complex, multi-stage undertaking, requiring non-routine actions, often unique decisions, as well as specific project management competences. It must be emphasized that technological entrepreneurship should be considered in a broader context of corporate strategy and be the determinant of its formulation.

### *1.6. Information Asymmetry in the Conditions of Information Uncertainty in the Photovoltaic Industry*

Economists have often marginalized the importance of access to complete and reliable information. Their assumption of the rationality of actions prevented many of them from pursuing further considerations. However, there were also those who, when analysing the problems of cartels, tenders, negotiations, cooperation, consumer choices, etc., noticed that potential solutions to the problem depend on access to information [30].

One of the first to do so was Adam Smith who in the 18th century described the impact of information on establishing the equilibrium in the model in which an increase in interest rates causes the best borrowers to withdraw from the market [31]. Another important researcher on access to information was A. Marshall, who lived in the 19th century, who pointed out that wages do not always correspond to the tasks that employees actually perform. The main reason is that employers do not have full information on how employees perform the tasks entrusted to them, due to imperfect procedures for controlling and verifying the effects of the work. The precursor of considering the role of information in the economy was F. von Hayek, who investigated the concept of Walrasian equilibrium, subordinating economic entities only to the market mechanism, assuming that consumers have excellent information on prices [32].

Theories that take into account the influence of information or the lack of it were developed mainly in the 1960s. They frequently concerned the idea of conflict, as was the case with the research performed by T.C. Scheling [33], leading up to the publication of *A Strategy of Conflict* in 1960. The phenomenon of incomplete access to information gained importance with the development of decision-making theory and the spread of research on conflict resolution. An interesting contribution to the development of knowledge on incomplete information was made by W. Vickrey [34], who proposed a principle of conducting an auction making use of game theory and incomplete information, known as the second-price method. The principle assumes that participants in an auction submit sealed bids. The winner is the bidder who submits the highest price but the price he has to pay is the second-highest of those proposed. This research won W. Vickrey the 1996 Nobel Prize. In the 1970s, G.A. Akerlof together with J.E. Stiglitz and M. Spence developed the foundations of the theory of markets characterised by information asymmetry. The authors concluded that entities operating in markets where there is insufficient information behave differently than those operating under the conditions of complete information. The importance of information problems in the 20th century is emphasized by the fact that the Nobel laureates in the field of economics were often economists dealing with issues directly or indirectly related to access to information. The developing research on difficulties in access to information has distinguished the types of conditions under which the market model can be considered [35]. The analyses showed that the following situations are possible:

- Imperfect information, meaning a situation in which at least one of the parties does not know the decisions made by the other parties and, as a result, is unable to precisely define its market situation.
- Uncertain information, meaning a situation in which random factors occur and the decision-maker is unable to determine the probabilities of possible solutions.
- Incomplete information, meaning a situation in which participants of the market game do not have all the information needed to make decisions, for example, they do not know about all the available resources, do not fully know the rules of the game, the set of possible solutions, the amount of pay-outs or the decisions of other market players.
- Information asymmetry, meaning a situation where one of the entities has more information than the others and can use it to gain an advantage.

Information asymmetry is defined as a situation in which one of the parties to a transaction possesses more information than the other party on the market exchange in which they are participating, which many economists perceive as a negative phenomenon [32].

According to J. Oleński [36] there are two types of asymmetry: full asymmetry, when the recipient of information buys something of which they have no knowledge and has no means of confirming the information prior to the transaction; and incomplete asymmetry, which occurs when somebody buying a product or service does not possess full information on them but can demand such information before the transaction. The existence of full and incomplete asymmetry is indispensable in some areas, for example, in the medical, pharmaceutical, legal or advisory services sectors, or in film production.

According to Y. Lichtenstein [37], the reconciliation of high-tech projects, including photovoltaic installation—i.e., reconciling the commercial terms of the transaction—can be described using agency theory. Agency theory presents the enterprise as a network of contracts referred to as agency relations, entered into by individual participants who generally consist of shareholders, managers and lenders. The theory takes into account the sharing of risk together with the so-called agency problem, occurring when the cooperating parties have different objectives and a different division of work. According to agency theory, the company's owner agency is referred to as the principal and the recipient of the photovoltaic system as the agent [38].

We can distinguish the following players on the photovoltaic market: Producer—the principal manufacturer of equipment and software for photovoltaics; Designer—the creator and architect of hardware and software technology solutions; Supplier—the provider of materials, raw materials and resources for the manufacture of photovoltaic solutions. The area of distribution has been divided into two categories: regional distribution companies (Distributors) and companies that design and install photovoltaic equipment (Resellers).

Another group of players are the Customers who decide to invest in a photovoltaic system, which constitutes an investment asset. Customers expect a return on their invested capital within specific legal, technological, ecological and economic conditions. The last category of players are local Regulators who enact Polish law and those from the EU who enact European law. The phenomenon of information asymmetry occurs between players in the photovoltaic market. The relations within which the asymmetry phenomenon occurs are presented below, together with examples of the causes of this phenomenon:

- Producer and Supplier (examples: availability of components for the production of photovoltaic devices, production requirements).
- Producer and Designer (examples: access to intellectual properties, patents, knowledge allowing for R & D).
- Producer and Distributor (examples: increase in technology advancement, mega-technological and commercial trends, limitations to the constant supply of the supplier's equipment).
- Producer and Reseller (examples: increase in technology advancement, mega-technological and commercial trends, limitations to the constant supply of the supplier's equipment).
- Reseller and Customer (examples: lack of transparency in long-term legal changes, frequent legislative changes, reduction of the profitability of installations during the investment cycle, technological conditions of devices, total cost of ownership of the installation, opportunistic behaviour).
- Reseller and Regulator (examples: lack of transparency in long-term legal changes, frequent legislative changes, reduction in the profitability of installations during the investment cycle).
- Regulator and Customer (examples: lack of transparency in long-term legal changes, frequent legislative changes, reduction in the profitability of installations during the investment cycle).

Summing up, the phenomenon of information asymmetry occurs in the relationship between each player on the market, and in addition, regulators, through the frequent and dynamic process of establishing legal standards in the field of photovoltaic installations, are a source of imperfect and uncertain, incomplete information, which may increase the asymmetry of information between the market players.

## 2. Materials and Methods

### *2.1. Research Goals/Questions. Definition of Case Study Method*

The aim of this article was the identification and assessment the key opportunities and barriers to photovoltaic industry enterprises in Poland in the context of technology entrepreneurship under conditions of information asymmetry. The paper was prepared based on the results of qualitative research using the case study method.

The research questions are as follows:

Q1: What key development opportunities and barriers do enterprises involved in the sale and installation of photovoltaic devices in Poland face?

Q2: What is the impact of information asymmetry on the growth of enterprises involved in the sale and installation of photovoltaic devices in Poland face?

The explanation of case study method we can find in many literature sources [39]. Yin [40] defines the case study research method "as an empirical inquiry that investigates a contemporary phenomenon within its real-life context; when the boundaries between phenomenon and context are not clearly evident; and in which multiple sources of evidence are used." [11].

### 2.2. Research Method

A comparative analysis was performed based on results of a study of four purposefully selected enterprises. The case study method allowed for comparing the analysed enterprises in pairs, which is discussed more extensively further on in the text. The research performed will lead to conclusions and recommendations for the photovoltaic sector enterprises in Poland, which will allow them to act more effectively and efficiently in conditions of competing on the global market. The case study procedure is presented in Table 1.

**Table 1.** Case study stages.

| | |
|---|---|
| Stage 1 | Formulating the research question |
| Stage 2 | Selection of cases |
| Stage 3 | Development of data-collection tools |
| Stage 4 | Fieldwork |
| Stage 5 | Data analysis |
| Stage 6 | Formulating generalisations |
| Stage 7 | Confrontation with the literature |
| Stage 8 | Study conclusion–generalisation |

Source: [22,41,42].

The selection of cases was deliberate and made on the basis of five basic criteria: data availability, vividness of the case, ensuring diversity in multiple case studies, a critical phenomenon and a metaphor that directs the researcher to a specific direction of the studied phenomenon [38]. The first is the purely pragmatic question of the availability of data, which allows for the most incisive description of the cases of those enterprises that are especially pertinent to the research question. The second criterium is the vividness of the case, which illustrates the properties being studied in an extreme form, which, however, allow for an unambiguous interpretation of the properties being studied. The third criterium is diversity. This requires that many cases be investigated in such a way as to present at least different circumstances or contradictory situations.

The number of cases studied should range from four to ten cases, which are usually compared in pairs. This gives from two to five pairs of comparisons of phenomena with a different course or taking place in different industries, enabling the formulation of generalizations largely free from the factors of circumstances or industry. The selection then consists of creating appropriate pairs of cases, e.g., high technology–low technology, mature market–emerging market, simple product–complex product and local enterprise–global enterprise.

The fourth criterium is the critical phenomenon, whose course, either extreme or running counter to the generally accepted opinion, allows for formulating generalisations. The fifth criterium concerns a metaphor that directs the researcher's attention to a specific course of the phenomenon under study or allows them to assume a specific research position. For instance, the lifecycle metaphor requires the selection of cases that will allow for observation of the emergence, development phases, maturity, decline and disappearance of a given phenomenon [22].

## 3. Results

### 3.1. Characteristics of Analysed Enterprises

Company X specialises in the construction of photovoltaic installations and provides photovoltaic services. It combines innovation, the latest technology and visionary professionals—specialists, experienced engineers and architects with extensive portfolios, as well as fitters and electricians thoroughly trained in the assembly of photovoltaic installations and thermo-modernisation. It possesses its own logistical hub and extensive structures composed of experienced professionals. It also uses the most modern technology to coordinate its operations (information based on data from the studied enterprises' web pages).

Company Y also provides photovoltaic services and specialises in the construction of installations. It provides customers with modern photovoltaics solutions. They specialize in rooftops and free-standing installations. It has designed and delivered thousands of installations in Poland. In September, it joined the Partner Programme organised by the Pomeranian Special Economic Zone. Its task is to support the business development of Kujawy and Pomorze. This cooperation is the next step toward energy transformation of the region.

Company Z is considering investing in the construction of a photovoltaic plant as a business activity. They would like to sell and install rooftops and free-standing installations. It currently specialises in refrigeration installations on semi-trailers. The company has been operating in Poland and is a leading supplier of cooling equipment. It employs ca. 70 people and its annual turnover stands at ca. EUR 25 million. Currently, it also provides services in the field of sales, installation and service of refrigeration equipment in semi-trailers.

Company Q has been operating in the energy industry uninterruptedly since 2013. It specialises in the sale and assembly of photovoltaic installations. It provides services in the area of the design, sale, installation and service of photovoltaics throughout Poland. It currently employs 50 persons and has an annual turnover of 5.4 million euros. It offers comprehensive service over all the stages of an investment project—free calculation and consulting, individualised offer, assistance in obtaining favourable funding, assembly of the installation, notification of the power plant and comprehensive assistance.

### *3.2. Environment and Its Factors—Threats and Opportunities*

Table 2 presents the key growth factors and barriers for the most important determinants of the macroenvironment.

**Table 2.** Barriers and growth factors in the development of companies in the photovoltaic industry in Poland.

| Barriers and Growth Factors | Company X | Company Y | Company Z | Company Q |
|---|---|---|---|---|
| Legal–growth factors | The need to develop renewable energy sources, also in Poland.<br>Declarations of support for technology entrepreneurship. | Favourable legal situation, tax breaks for thermo-modernization.<br>In general, "an embarrassment of riches". | Tax breaks. | Tax breaks and promotion of renewables. |
| Legal–barriers | The main barrier is the political environment.<br>Risk caused by politicians' decisions.<br>Changeable regulations. | Changes in regulations starting in Jan. 2022 may be a threat. | Highly changeable regulations. | New regulations starting in 2022. |
| Economic growth factors | Other companies aren't perceived as competitors. This is due to the niche strategy being pursued. | The increased prevalence of photovoltaics.<br>Electricity is relatively expensive, which is an opportunity.<br>People possess knowledge on new technologies. | Increasing customer awareness.<br>Strong correlation between location and energy efficiency. | Fake news on solar energy farms.<br>Rising price of electricity |

**Table 2.** *Cont.*

| Barriers and Growth Factors | Company X | Company Y | Company Z | Company Q |
|---|---|---|---|---|
| Economic barriers | Access to funding for large investments.<br>A certain slowdown in the industry probably due to the pandemic. | Photovoltaic seller wants to get the balance on an annual basis. | The high demand for installations is a bottleneck.<br>There is a price war<br>Increased prices of photovoltaic panels due to the rise in polysilicon, the raw material from which panels are made.<br>Increased prices of freight.<br>Problems with post-installation servicing processes. | Increased prices of freight. Many photovoltaic components come from China.<br>Problem with determining the total cost of possessing an installation over a period of 25 years. |
| Societal growth factors | Large number of unqualified workers. | No barriers in acquiring new workers. | Well-educated specialists.<br>Very high competences of sales personnel. | Specialists' high level of professionalism. |
| Societal barriers | Specialists'/designers' high income expectations. | | Problems with finding specialist fitters.<br>High income expectations.<br>Problem with finding persons able to establish contacts with customers.<br>Problem with employee turnover. | Problem with employee turnover. |
| Technological barriers | Relatively small changes in the sector.<br>Frequent technical errors in the installation | The requirement to replace meters is a small bottleneck.<br>Imbalance as a type of barrier | The introduction of new technologies causes the competitiveness more difficult. | Low quality of the installations as a source of problems. |
| Technological growth factors | Development of IT tools.<br>New technology tools. | Use of modern technology has become widespread.<br>New hydrogen technology combined with photovoltaics. | Development in panel technology.<br>Artificial intelligence supporting automation. | New types of solar panels increase efficiency. |

Source: based on interviews.

The use of the case study method allowed to compare the organizations in pairs. The representatives of individual companies presented very divergent opinions on the issues of the political and legal environment. The president of Company X presented a particularly harsh criticism regarding the regulator's actions. He believed that the policy pursued by the regulator was, above all, a threat. The consequence of this is the instability of the law and the high unpredictability of the regulator's decisions. He stated that the declared development opportunities are in fact illusory because the dynamic changes introduced by the regulator significantly hinder the investment process both among resellers and clients.

The opinion of the representative of Company Y was diametrically opposed. He focused mainly on the good economic situation. In his opinion, the political and economic climate are very favourable for photovoltaics. He also showed an appreciation for the numerous subsidies and aid measures for the sector. Society is also showing increased interest in novel solutions in this area. This also results from consumers' growing knowledge of about modern technologies and their common use in households.

The representatives of Company Z and Company Q pointed mainly to the high qualifications of knowledge professionals and their particular technology competences. They also perceived the opportunities and threats resulting from market competition and the high social demand for modern solutions in the photovoltaic industry. Modern technology solutions, intelligent technologies and the development of artificial intelligence, combined with a high demand for those solutions, create a particularly favourable market situation and success opportunities for new entities in the photovoltaic industry. New types of solar panels are increasing the energy efficiency of photovoltaic enterprises' products, allowing them to achieve potential and an actual competitive advantage.

The main barriers mentioned by the representatives of the enterprises were the instability of regulations and the announcement of new legislative solutions for 2022. Another obstacle are problems related to employee turnover. There are problems with finding people able to effectively establish relations with customers and convince potential buyers to purchase photovoltaic enterprises' products. This is somewhat paradoxical in view of the large demand for renewable energy sources and customers' growing knowledge about new technology solutions.

### *3.3. Information Asymmetry in Photovoltaic Enterprise Operations in Poland*

All research participants representing resellers indicated that there is a phenomenon of information asymmetry in which the risk of a failed photovoltaic installation is transferred to the end customer. Research participants indicated the following defects in the information provided within the value chain:

1. Producer–Reseller. The manufacturer does not provide information on how the photovoltaic installation will function in 10–15 years from the perspective of the technology used, so it is not possible to determine the total cost of ownership of the installation over the investment cycle horizon.

2. Regulator–Reseller. The regulator, through quick and non-determinable decisions, creates an atmosphere of uncertainty for resellers who want to sell and service devices. Resellers focus on customer service at the moment, not caring about what will happen with a given installation in a few years.

3. Regulator–Customer. Due to the changes in the principle of purchasing electricity from prosumers, it is possible to predict revenues in a limited way in the investment cycle, which lasts 10–15 years.

Research shows that between the supplier of the photovoltaic infrastructure and installation services and the end customer there exists a type of incomplete information asymmetry, when the customer buying a photovoltaic installation, including assembly, does not have full information about the configuration of devices, TCO and economic benefits. The purchase of photovoltaic installations is characterised by the following: between the supplier of the photovoltaic infrastructure and installation services and the end customer there is a type of incomplete information asymmetry, when the customer buying a photovoltaic installation, including assembly, does not have full information about the configuration of devices, TCO and economic benefits. The purchase of photovoltaic installations is characterised by the following:

- The buyers do not know what they are buying, finding out what configuration of service and equipment they decided to buy only sometime after the transaction.
- The object of the transaction is a piece of equipment and configuration service described using metainformation. What is significant, both the transaction and the

long-term utilisation are carried out in conditions of uncertainty, due mainly to the activity of the regulator.
- Due to the lack of full information on the photovoltaic installation over its entire lifecycle, the buyer is unable to make an ex-ante evaluation of its precise utility, worth, quality and, hence, its relevance and pertinence.
- Potential customers frequently have imprecisely defined information needs and consequently are unable to specify what value the information they intend to purchase has for them.

In the market game, the winner is the one who has information that is complete and certain, or perfect, and is able to use it, while the other conditions are unchanged. There are, however, two issues which need to be considered:

- Access or lack of access to information.
- The costs of acquiring, processing and internalising information.

In the case of a purchase transaction of a photovoltaic installation, access to information between the supplier and the recipient is characterized by:

- Incomplete information on information on the long-term operation of equipment throughout its life cycle, i.e., 10–15 years.
- Imperfect information due to the activity of the regulator.

In addition, the costs of acquiring, processing and internalising information may exceed the possible benefits in the long run. Respondents indicated that customers obtain information on the installations based on the knowledge of Resellers, who obtain it from the manufacturers. This information is incomplete, which is due to the early stage of the technology's development that at the same time is very rapid.

The authors' research results show that for customers investing in a photovoltaic installation, the level of information asymmetry between the supplier and customer constitutes a key factor that determines economic success over the entire lifecycle of the photovoltaic equipment. The asymmetry pertains to information on:

- Economic benefits resulting from the technological specificity of photovoltaic devices.
- Non-economic benefits resulting from the technological specificity of photovoltaic devices.
- Economic benefits resulting from the long-term (10–15 year) operation of photovoltaic devices.
- Reliability of photovoltaic devices in the long-term horizon, i.e., 10–15 years of device operation.

In the research on the phenomenon of information asymmetry carried out by the author, the suppliers admitted after completing the installation (ex post) that before the project customers did not have adequate knowledge regarding the implementation of IT systems. It was only after the implementation of the project did customers realize how little knowledge they had had about the devices and services they had acquired, and how they were exposed to abuse of trust by the supplier. The group of suppliers studied indicated the following main reasons for the information asymmetry:

- The customers' insufficient preparation in terms of defining their needs regarding the demand for electricity.
- The lack of precisely defined technological and organizational conditions for the installation of photovoltaic devices.
- The lack of sufficient knowledge on the part of the customer about the total cost of maintaining photovoltaic devices in a 10–15-year operating perspective.
- The lack of sufficiently precise knowledge on the part of the customer-prosumer of the economic benefits that can be obtained from the use of a photovoltaic installation in a 10–15-year operating perspective.

Lichtenstein [38] explains the reason of information asymmetry high level. This situation often pertains to the relationships between the supplier and the recipient of the project specified in the contract. Especially during projects carried out based on a fixed budget, the supplier-agent may be strongly motivated to bring costs down below the budgeted amount, which may impact the quality of the services provided. The authors' research shows that the supplier, when selling the photovoltaic installation project, provided mainly meta-information with a high level of generality, which was often difficult to verify. The suppliers attempted to emphasise their competences, experience and skills, pointing to:

- The employees possessing certificates relating to installation of photovoltaic devices.
- The product possessing certificates.
- References to projects performed.
- Access to information on ways of carrying out photovoltaic projects.

Summing up the above considerations, it should be stated that the information characteristics considered in the transaction between the supplier and the customer, i.e., the partial and incomplete character of the information, imperfect information and information asymmetry are an important factor determining the economic efficiency of a photovoltaic installation during its operation period, i.e., 10–15 years, which affects the stability of the development of the photovoltaic sector in Poland. A significant challenge confronting suppliers is reducing the incompleteness and imperfection of information and the asymmetry of information in their customer relations. In this case, the characteristics of the relationship in terms of information are influenced by other stakeholders of the global market, such as the regulator, device and software manufacturers, and suppliers of raw materials for the production of photovoltaic devices.

## 4. Conclusions

The photovoltaics sector in Poland is developing very dynamically. It is among the fastest-growing photovoltaics sectors in the entire European Union. The growing demand for renewable energy sources combined with customers' ever-increasing knowledge on new technology and its applications are creating development opportunities for new entities in the photovoltaic industry. At the same time, there is no shortage of challenges under conditions of particular uncertainty in the surroundings. Unstable law and frequently changing legislative solutions are a disincentive and weaken the optimism of the economic demand for the products of photovoltaic companies.

The qualitative research performed using the case study method allowed for analysing the key development opportunities and barriers of photovoltaic sector enterprises in Poland. The selection of four enterprises that represented differing opinions on many issues, were at different stages of the organisation lifecycle and had different market positions allowed for making certain generalisations and drawing conclusions.

The research points to the following conclusions:

- Strong demand for renewable energy sources presents a historic opportunity for photovoltaic enterprises in Poland.
- Actions resulting from the government's economic policy in the form of incentives and/or incentives to initiate business activity are a favourable.
- Declarations of support for technology entrepreneurship, seen as an effective means of using market opportunity for technological change, frequently translate into specific support initiatives for the development of new technologies and technologically advanced products.
- The worldwide trend of abandoning conventional energy sources in favour of renewable sources are one of the key development opportunities for the photovoltaic sector enterprises in Poland.
- The growing level of social awareness is encouraging potential customers to seek the latest photovoltaic product solutions.
- The frequent changes to regulations and political and legislative instability prevent photovoltaic enterprises from fully utilising growth opportunities.
- The high level of uncertainty partially nullifies the opportunity of technology change.
- One barrier from the point of view of enterprises is the high rotation of employees, especially those with special technological competences. This is the effect of rising salary expectations.

- Great opportunities to recruit unskilled workers are associated with the need to conduct additional training, which increases the costs of business activity. Salary expectations are also rising in this group.

In addition, the present research has identified the phenomenon of information asymmetry between the supplier and the recipient, which is a source of uncertainty regarding the customer's investment and uncertainty in running a business from a long-term perspective. The main source of information asymmetry is the operation of the regulator, the technological conditions related to the early stage of technology development and the customer's lack of sufficiently precise information regarding the investment. However, despite significant factors of uncertainty and risk, the development of this sector in Poland has been extremely dynamic in recent years.

Summing up, it should be emphasized that the analysed entities have differing perceptions, especially when it comes to the political, legal and economic environment. Some see official declarations of support for new technologies in the development of renewable energy sources as opportunities. Others emphasize the threats resulting from the instability of legal regulations, numerous legal loopholes and the uncertain political and economic situation.

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# Do COVID-19 Lock-Downs Affect Business Cycle? Analysis Using Energy Consumption Cycle Clock for Selected European Countries

**Tadeusz Kufel [1], Paweł Kufel [2,*] and Marcin Błażejowski [2]**

[1] Department of Econometrics and Statistics, Nicolaus Copernicus University, ul. Gagarina 13a, 87-100 Torun, Poland; tadeusz.kufel@umk.pl
[2] Faculty of Finance and Management, WSB University in Torun, ul. Młodzieżowa 31a, 87-100 Torun, Poland; marcin.blazejowski@wsb.torun.pl
* Correspondence: pawel.kufel@wsb.torun.pl; Tel.: +48-566609245

**Abstract:** On 11 March 2020, the WHO declared the COVID-19 epidemic to be a global pandemic. This was a consequence of the rapid increase in the number of people with positive test results, the increase in deaths due to COVID-19, and the lack of pharmaceutical drugs. Governments introduced national lockdowns, which have impacted both energy consumption and economies. The purpose of this paper is to answer the following question: do COVID-19 lockdowns affect the business cycle? We used the cycle clock approach to assess the magnitude of decrease in electricity consumption in the three waves of the epidemic, namely, April 2020, November 2021, and April 2021. Additionally, we checked the relation between energy consumption and GDP by means of spectral analysis. Results for selected 28 European countries confirm an impact of the introduced non-pharmaceutical interventions on both energy consumption and business cycle. The reduction of restrictions in subsequent pandemic waves increased electricity consumption, which suggests movement out of the economic recession.

**Keywords:** consumption of electricity; COVID-19; lockdown; non-pharmaceutical interventions (NPIs); business cycle clock

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## 1. Introduction

In the early period of the COVID-19 pandemic's spread, the first lockdown was introduced on 23 January 2020, in Hubei Province, China [1]. In Europe, the first non-pharmaceutical interventions (NPIs), like advice to self-isolate if experiencing a cough or fever, were introduced in Switzerland on 2 March 2020. In Italy, there were nationwide school closures (5 March 2020), and the ordered lockdown—the government closes all public places, people have to stay at home except for essential travel—started on 11 March 2020 [2]. In the next days and weeks, many countries conducted NPIs. The range of interventions was very vast. The classification and ranking of NPIs are presented in the paper [2].

The work of [3] indicates that the COVID-19 pandemic is the stimulus for a research focused on the politics of crisis, which stems from defining crisis as a threat, uncertainty, and time pressure on economic and political processes. Many governments introduced non-pharmaceutical interventions in order to fight against the virus. Imposing restrictions on borders, transportation (movements); closure of airports; restrictions on trade, tourism, catering; closure of schools and universities; and many other things have made up the national lockdowns. The introduced restrictions range was classified in [4] into the following three classes: soft lockdown, moderate lockdown, hard lockdown. The above-mentioned restrictions imposed in several countries had an impact on regulations in all economic sectors. As a result, those restrictions slowed down the economic activity and a question therefore arises: can the magnitude of this slow down be assessed by the decrease in electricity consumption?

### *Energy Consumption, Business Cycle and Economic Growth*

In the classical approach to economic growth theory, energy consumption is assumed to be an input factor of production (complement to capital and labor). On the other hand, in the so-called conservation hypothesis, it is assumed that ”green” policy has little or no impact on GDP since energy consumption does not influence the dynamics of GDP. On the contrary, the so-called feedback hypothesis assumes that there is a bi-directional causal relationship between energy consumption and GDP. In the neutrality hypothesis, it is assumed that there is no relationship between economic growth and energy consumption. All this means that there is no consensus on the causal linkages between energy consumption and economic growth. Furthermore, results of empirical analysis in this field are ambiguous as well, though we can find some common patterns across geographical regions, which are discussed in Section 2.

Another question is the relation between energy consumption and the business cycle. Although we can extract the business cycle directly from GDP for quarterly time-series, it may be useful to treat energy consumption as a leading business cycle indicator. This is because energy consumption is highly correlated with industrial production and sales (supply side) and consumers expenditures (demand side). There are also some empirical results [5,6] supporting this approach.

Figure 1 shows the average daily number of positive COVID-19 tests for a given month. We are focusing on three moments during the pandemic: April 2020, November 2020, and April 2021 for selected European countries. During those waves, the lockdowns were introduced (as non-pharmaceutical interventions) and impacted energy consumption. NPIs were loosened in January 2021 because the COVID-19 vaccination campaign began.

Taking all this into account, we formulate the following research hypotheses:

**Hypothesis 1 (H1).** *Energy consumption can be used as an leading indicator of the business cycle.*

**Hypothesis 2 (H2).** *The energy consumption cycle clock can assess the impact of pandemic lockdowns on the business cycle.*

In order to verify these hypotheses, we used tools for time-series filtering in both frequency and time domains. In the former, we used the spectral analysis approach, especially the phase angle measure. In the latter, we used the cycle clock approach, which gives us the possibility to trace changes in business cycle phases. We used quarterly time-series covering the period from the first quarter of 2008 up to the second quarter of 2021 for the following 28 European countries: Austria, Belgium, Bulgaria, Cyprus, Czechia, Germany, Denmark, Estonia, Greece, Spain, Finland, France, Croatia, Hungary, Ireland, Italy, Lithuania, Luxembourg, Latvia, Netherlands, Norway, Poland, Portugal, Romania, Sweden, Slovenia, Slovakia, Turkey. Details of our methodology are described in Section 3.

The remainder of this paper is as follows. In Section 2 we conduct the literature review concerning the impact of the Covid pandemic on energy consumption. We also concentrate on energy consumption as an economic growth barometer studying the results across countries. The next section relates to the methods and data used in our research. The results are described in Section 4. The discussion is provided in the last Section 5. Additionally, we include a broad set of plots for graphical presentation of the results, which can be found in the Appendix A.

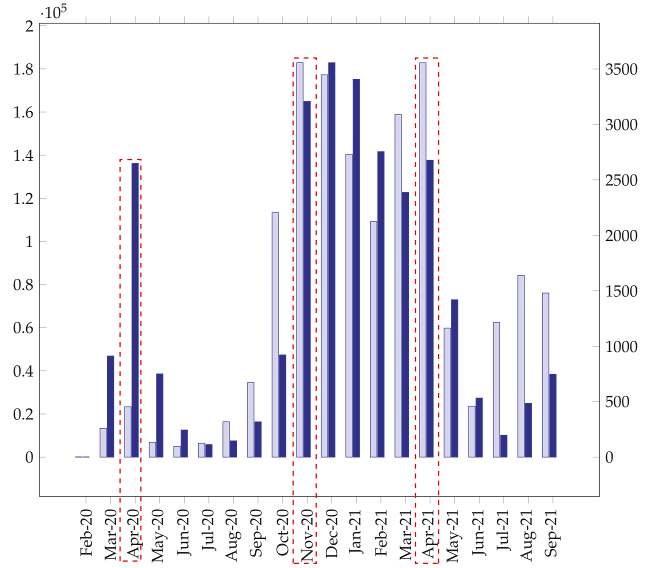


**Figure 1.** Daily average number of confirmed COVID-19 cases (left axis, light blue bars) and deaths (right axis, dark blue bars) in 28 European countries.

## 2. Literature Review

### *2.1. Impact of COVID-19 Lockdows on Energy Consumption*

In [7], authors using econometric models for the UK, France, and Germany, evaluate the impact of lockdown on human behavior, which led to changes in demand for energy. A broad description of the three components, pandemic, economic downturn, and climate change, are presented in the paper [8]. Another paper [9] presents ten scenarios of energy consumption changes for 20 European countries, indicating an inevitable decrease in consumption from $-1.81\%$ to $-10.46\%$. The paper [10] compares long-term trends in energy consumption using ARIMA models and determines the impact of lockdown on the decline in consumption. The paper [11] indicates the effects on six sectors of the economy, including the energy sector, using the example of India. In [12] the impact of the COVID-19 on the economy, energy, and environment is analyzed, indicating catastrophic implications on the entire economy. Similar analyses for the tourism industry are presented in the paper [13].

The impact of lockdown on energy consumption in five regions of India is described in [14], but the effect is different for different sub-periods due to various lockdown measures.

In [15–20] the effect of lockdowns on the electricity consumption of domestic users is evaluated showing activity changes in energy consumption levels. The flattening of energy consumption peaks over the daily cycle is presented in the paper [21]. Managing energy consumption to mitigate the effects of lockdown is presented in [22]. Daytime and nighttime energy consumption during the pandemic period is shown as a barometer of economic activity in the work [23].

### *2.2. Relation between Energy Consumption and Economic Growth*

#### 2.2.1. World Wide Analysis

In the paper [24] authors verified different hypotheses of economic growth focusing on the intellectual links between economics and engineering. In the case of oil-exporting counties, there is some evidence for a strong unidirectional causality from economic growth to energy consumption [25]. In the paper [26] authors analyzed 93 countries, and they found that, at the individual country level, there are significant variations in results on the impact of energy consumption on real GDP. In most countries, energy does not have a long-run Granger causal effect on real GDP. In countries where a causality relationship exists, the sign of the effect is negative, meaning that energy consumption has a negative effect on real GDP. The results for panel data were similar: energy consumption caused real GDP for Western Europe, Asia, Latin America, Africa, G6, and the globe. However, the sign of the effect was positive for Asia, Africa, and the world, but the point estimates were all either zero or close to zero. On the other hand, for a two-times smaller panel of economies [27], authors found evidence for energy-led growth hypothesis in 46 selected economies. They also showed that the energy-led growth hypothesis was more prevalent in the high- and middle-income countries compared with their low-income counterparts.

### 2.2.2. Results for OECD Countries

In [28] authors found that there is a strong cointegrating relationship between energy consumption and economic growth. They propose factor decomposition to distinguish between common and specific factors of energy consumption in OECD countries. In the paper [29] authors found some evidence that a very short-run bidirectional causality exists, and strong unidirectional causality running from capital formation and GDP to energy usage for 30 OECD countries. Results in [30] show that, for OECD countries, it is not only economic complexity that is positively associated with a higher rate of economic growth, but also both non-renewable and renewable energy consumption.

### 2.2.3. Results for European Union

In the paper [31] authors found that the level of compliance with energy policy targets influences linkages between energy consumption and economic growth. The results indicate causal relations in the group of countries with the greatest reduction of greenhouse gas emissions, the highest reduction of energy intensity, and the highest share of renewable energy consumption in total energy consumption. In the remaining groups, the results mostly confirm the neutrality hypothesis. In further research [32] they show that the relationships between economic growth and electricity consumption depend on the level of renewable energy sector development. In countries with relatively well-developed renewable energy sectors, renewable electricity consumption boosts the economy and vice versa. In the remaining countries, economic growth and electricity consumption are independent.

### 2.2.4. Results for North and Central America

For the US, in [33] the author did not find evidence that there is a long-term causal relationship between gross energy use and GDP. On the other hand, in [34] the author found evidence for unidirectional long-run Granger causality in the commercial sector from growth to energy, as well as evidence for bi-directional long-run Granger causality in the transport sector. Finally, in [35] authors found that the conservation hypothesis is valid for the US. For Canada in [36] authors found a bidirectional relation between output growth and energy use in the short-run. For Central America, authors in [37] found evidence for both short-run and long-run causality from energy consumption to economic growth, which supports the growth hypothesis.

### 2.2.5. Results for Africa

For African counties, the author in [38] found that causality runs from GDP to energy consumption in the short-run, and from energy consumption to GDP in the long-run. In addition, they found unidirectional causality running from electricity consumption to GDP in the long-run.

### 2.2.6. Results for Asia

For Asian countries, ref. [39] found that although economic growth and energy consumption lack short-run causality, there is a long-run unidirectional causality running from energy consumption to economic growth. In the paper [40], authors analyzed energy consumption and GDP in Korea in the period 1970–1999 and for an annual date; they found a long-run bidirectional causal relationship between energy and GDP, and short run unidirectional causality running from energy to GDP. They also analyzed energy consumption and economic growth in Korea based on quarterly data in the period of January 1981–April 2000 [41] and they found no evidence for causality between energy and GDP in the short run and a unidirectional causal relationship running from GDP to energy in the long run. For China in [42] authors found evidence that, from 1999 to 2009, there was unidirectional causation from economic growth to energy consumption in the long-run.

### 2.2.7. Results for Emerging Economies

For selected emerging economies authors in [43] found that the neutrality hypothesis is valid for Bangladesh, Egypt, Indonesia, Iran, Korea, Mexico, Pakistan, and Philippines, while for Turkey the growth hypothesis is valid. On the other hand, similar analysis conducted in [35] revealed that for Bolivia, Brazil, Canada, El Salvador, Honduras, Nicaragua, Panama, and Paraguay, the growth hypothesis is valid, while the conservation hypothesis is valid for Colombia and Mexico. For the Commonwealth of Independent States, authors in [44] found unidirectional causality from energy consumption to economic growth in the short-run and bidirectional causality in the long-run, which supports the feedback hypothesis. For Greece, authors in [45] found a bi-directional causal relationship between electricity consumption and economic growth. At the same time, results in [46] revealed significant unidirectional linear and non-linear causal linkages running from total useful energy to economic growth.

## 3. Methods and Data

The comparison analysis of energy consumption dynamics with GDP dynamics was performed based on quarterly data from the period 2008 Q1–2021 Q1. All statistical data were taken from Eurostat databases. We employ the spectral analysis framework, and to verify the first hypothesis, we use the phase angle. The spectral analysis investigates the time series in the frequency domain instead of the time domain. The relation between frequency domain and time domain is obtained directly from the Fourier transform. Taking the frequency bands into account instead of the time moments allows finding the relations between cycles in particular frequencies (low and high).

Let's consider two time series $x_t$ and $y_t$. Taking into account the covariance of those processes and applying the Fourier transform, we receive the cross-spectral density $f_{xy}(\omega)$ represented in complex numbers as follows:

$$f_{xy}(\omega) = c_{xy}(\omega) + iq_{xy}(\omega),$$

where $\omega \in (0;\pi)$ is a certain frequency, $c_{xy}(\omega)$ is the real part of a complex number and is called the co-spectrum, while the $q_{xy}(\omega)$ is the imaginary part and is called the quadratic spectrum. The low frequencies relate to long-time lags, while the high frequencies refer to short-time periods. The spectral analysis gives the following instruments for analysis: the coherence coefficient, which indicates the strength of relation between two series $x_t$ and $y_t$, and the phase angle to obtain the differences in frequencies and the magnitude of frequency amplitudes. In this research, we use the phase angle to evaluate the leading of examined processes:

$$\phi_{xy}(\omega) = \arctan \frac{-q_{xy}(\omega)}{c_{xy}(\omega)}. \qquad (1)$$

This measure presents the phase difference and can be used as a time lag within the frequencies domain. If one phase is leading the second one in the time domain, then the ratio $\phi_{xy}(\omega)/\omega$ is the lag indicator in the frequency domain. When the phase angle has a constant slope, then the time lag is equal for frequencies for both processes [47]. In our case, a positive value of the phase angle indicates that energy consumption is ahead of business cycle (is a leading indicator). A negative value of the phase angle indicates that business cycle is ahead of energy consumption.

The last tool we use in our research is the business cycle clock, which is the coordinate system where the vertical axis presents the deviation (measured in standard deviations) of differences from the trend. The horizontal axis is the trend component's year-to-year change (expressed as a percentage). The position (quarter) in the coordinate system indicates the phase of the business cycle. The first quarter is the expansion phase (above the trend with an upward tendency). The second quarter represents the slowdown phase (above the trend with a downward tendency). The third quarter is the recession phase (below the trend with a downward tendency), and the fourth quarter corresponds to the recovery phase (below the trend with an upward tendency).

### *Research Scenario*

In order to check whether energy consumption is a leading indicator of the business cycle, we calculated the phase spectrum between energy consumption (GWh) and GDP. For this purpose, the quarterly data series have been cleared of seasonality and calendar effects using the X-13-ARIMA procedure. A more extensive description of the X-13-ARIMA procedure is presented in [48]. Next, the series were detrended using the Hodrick-Prescott filter with parameter $\lambda = 1600$, which means filtering out the 9-year intermediate-term trend. The application of the HP filter gives the business cycle component of zero average, an irregular sinusoid shape, and different duration of growth and decline phases. The HP filter is presented in the work [49], with modification in [50] and its usage for business cycles in [51]. The estimated phase angles (calculated according to formula (1)) are shown in Figures A1–A28 (graphs (b)).

In the second step, we build the business cycle clocks for energy consumption for 28 European countries. To do this, we need two components: the long-term trend and the business cycle component, which were found through the the X-13-ARIMA procedure and marked as SCA at Figures A1–A28 (graphs (c)). Next, we used the HP filter with the smoothing parameter $\lambda = 14400$, which corresponds to cutting off 90.57 months (7.55 years). This gives us the trend component marked at Figures A1–A28 as a trend with a green line on graphs (c).

All the calculations have been computed using `gretl` program [52] and detailed results are available as a supplementary material attached to the article.

## 4. Results

Figures A1–A28 present energy consumption and GDP cycles (graphs (a)) and the phase angle between those time series (graphs (b)). We obtained positive values of phase angle for 24 of 28 countries (support for H1) with the following remarks:

- In the case of 8 countries, i.e., Austria, Bulgaria, Cyprus, Czech Republic, Finland, Hungary, Sweden, and Slovenia, values of phase angle are always positive (for all frequencies).
- In the case of 11 countries, i.e., Belgium, Estonia, Greece, Spain, Italy, Croatia, Poland, Portugal, Romania, Slovakia and Turkey, values of phase angle are positive only for low frequencies (which corresponds to a period longer than eight quarters).
- In the case of 4 countries, i.e., Lithuania, Luxembourg, Netherlands, Norway, and France, values of phase angle are positive only for high frequencies (up to 5 quarters).
- In the case of 4 countries, i.e., Germany, Denmark, Ireland, and Latvia, we got either negative values of phase angle or results were inconclusive (which means lack of support for H1).

The above results are crucial for our research and allow us to use energy consumption as a leading indicator of the business cycle.

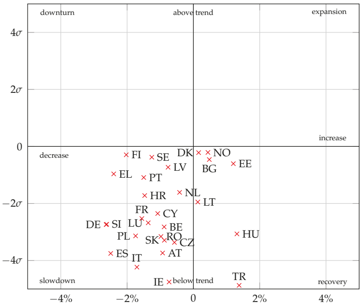
The second hypothesis is verified using the cycle clock approach for energy consumption. Figure 2 presents cycle clocks for energy consumption for all analyzed countries drawn at three crucial moments of COVID-19 pandemic, i.e., April 2020 (Figure 2a), November 2020 (Figure 2b), and April 2021 (Figure 2c). Table 1 summarizes situation of those countries in terms of energy consumption cycle phase.

**Table 1.** Changes in the trend, cycle, and phase of energy consumption in the analyzed countries after 3 waves of the COVID-19 pandemic.

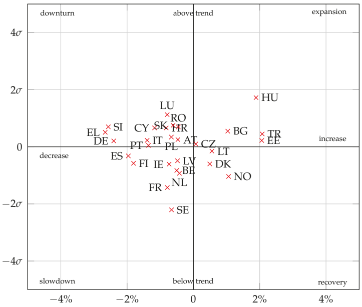
| | **Trend Direction** | | | **Position in Cycle in Relation to Trend** | | | **Cycle Phase** | |
|---|---|---|---|---|---|---|---|---|
| | **April 2020** | **November 2020** | **April 2021** | **April 2020** | **November 2020** | **April 2021** | **November 2020** | **April 2021** |
| Austria | decrease | decrease | decrease | below | above | above | changed | unchanged |
| Belgium | decrease | increase | increase | below | below | above | changed | changed |
| Bulgaria | increase | decrease | decrease | below | above | above | changed | unchanged |
| Cyprus | decrease | increase | increase | below | above | above | changed | unchanged |
| Czech Republic | decrease | increase | increase | below | above | above | changed | unchanged |
| Germany | decrease | decrease | decrease | below | above | above | changed | unchanged |
| Denmark | increase | increase | increase | below | below | above | unchanged | changed |
| Estonia | increase | decrease | decrease | below | above | above | changed | unchanged |
| Greece | decrease | decrease | decrease | below | above | above | changed | unchanged |
| Spain | decrease | decrease | decrease | below | below | above | unchanged | changed |
| Finland | decrease | decrease | decrease | below | below | above | unchanged | changed |
| France | decrease | decrease | decrease | below | below | above | unchanged | changed |
| Croatia | decrease | increase | increase | below | above | above | changed | unchanged |
| Hungary | increase | decrease | decrease | below | above | above | changed | unchanged |
| Ireland | decrease | decrease | decrease | below | below | above | unchanged | changed |
| Italy | decrease | increase | increase | below | above | above | changed | unchanged |
| Lithuania | increase | decrease | decrease | below | below | above | changed | changed |
| Luxembourg | decrease | decrease | decrease | below | above | above | changed | unchanged |
| Latvia | decrease | decrease | decrease | below | below | above | unchanged | changed |
| Netherlands | decrease | increase | increase | below | below | above | changed | changed |
| Norway | increase | decrease | increase | below | below | above | changed | changed |
| Poland | decrease | decrease | decrease | below | above | above | changed | unchanged |
| Portugal | decrease | decrease | decrease | below | above | above | changed | unchanged |
| Romania | decrease | decrease | decrease | below | above | above | changed | unchanged |
| Sweden | decrease | decrease | decrease | below | below | above | unchanged | changed |
| Slovenia | decrease | decrease | decrease | below | above | above | changed | unchanged |
| Slovakia | decrease | increase | increase | below | above | above | changed | unchanged |
| Turkey | increase | increase | increase | below | above | above | changed | unchanged |

According to results presented in Figure 2 and in Table 1 we can draw the following conclusions:

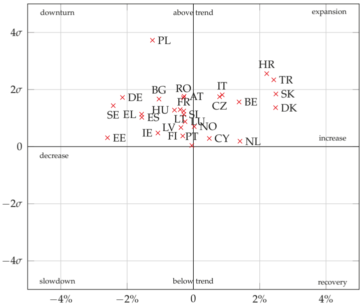
1. In April 2020, at the time of the outbreak of the first wave of the COVID-19 pandemic, energy consumption in all countries was below the trend (all points are below the zero line on Figure 2a).
2. A year later, i.e., in April 2021, the position of energy consumption in the cycle moved above the trend in all countries (all points are above the zero line on Figure 2c).
3. Successive waves of the COVID-19 pandemic changed the phase of the cycle in all countries at least once. This means that there has been no country whose energy cycle is immune to changes in the economic environment, such as the occurrence of pandemic waves. In other words, when we compare Figure 2a–c, each country moved to another quarter (changed its position) at least once.
4. The energy consumption cycle phase was changed twice in 4 countries: Belgium, Lithuania, Netherlands, and Norway.
5. In 7 countries, i.e., Denmark, Spain, Finland, France, Ireland, Latvia, and Sweden, the energy consumption didn't change its cycle phase after the impact of the first wave of the COVID-19 pandemic.
6. In the remaining 11 of the 28 countries analyzed, energy consumption changed its cycle phase only after the first wave of COVID-19 and after successive waves their cycle phases remained stable.



(**a**) April 2020



(**b**) November 2020



(**c**) April 2021

**Figure 2.** Cycle clocks for energy consumption at April 2020, November 2020 and April 2021 in 28 European countries: Austria (AT), Belgium (BE), Bulgaria (BG), Cyprus (CY), Czechia (CZ), Germany (DE), Denmark (DK), Estonia (EE), Greece (EL), Spain (ES), Finland (FI), France (FR), Croatia (HR), Hungary (HU), Ireland (IE), Italy (IT), Lithuania (LT), Luxembourg (LU), Latvia (LV), Netherlands (NL), Norway (NO), Poland (PL), Portugal (PT), Romania (RO), Sweden (SE), Slovenia (SI), Slovakia (SK), Turkey (TR).

Detailed results of energy consumption cycle clocks are presented in Figures A1–A28 (graphs (d)). An essential decrease in energy consumption occurred for Turkey and Ireland. Also, a noticeable change appeared in Estonia, Italy, and Austria. The magnitude of the change in energy consumption levels in April 2020 was so substantial that all analyzed economies went to the slowdown or recovery phase of their business cycle, which was below their long-term trend (see Figure 2a). In April 2021, the introduced NPIs were less rigorous. The lockdowns were not as crucial for the economy or industry as previous lockdowns. All studied countries increased their energy consumption above the trend and turned to a downturn or expansion phase. The highest increase was for Poland. Hungary and Turkey also consumed extensively more energy compared to the long-term trend (see Figure 2c).

Analysis of Figures A1–A28 (graphs (c)) reveals that the trend in energy consumption, estimated for a period from January 2008 to May 2021, did not change its direction in 2020–2021 for many countries and remained constant in 12 countries (Austria, Belgium, Germany, Greece, Spain, Finland, France, Ireland, Italy, Portugal, Sweden, Slovenia). The long-term stability remained unchanged in 10 countries (Bulgaria, Cyprus, Lithuania, Luxembourg, Latvia, Netherlands, Norway, Poland, Romania, Slovakia). Despite a temporary decline, the upward trend remained unchanged in 6 countries (Czech Republic, Denmark, Estonia, Croatia, Hungary, and Turkey). However, the decrease in April 2020 (due to lockdowns imposed in March 2020) and its persistence in the next few periods strongly impacted the energy consumption in many countries, reducing the usage and changing the long-term trend.

## 5. Discussion and Conclusions

If we look at Figures A1–A28 we can observe that in analyzed countries the largest decline in energy consumption occurred during the first pandemic wave (the first several weeks starting from March 2020). This was related to deep lockdowns introduced by governments. For subsequent waves of increased morbidity, lockdowns were no longer as broad as during the first wave.

After the first wave (March–April 2020), many European governments lifted the restrictions by May–June 2020. People became more reckless during the summer of 2020, and the pandemic returned, starting the so-called second wave in September–November. In all European countries that did well during the first wave, i.e., where infection rates were low, during the second wave infection rates increased in September and October 2020. In many countries, governments reintroduced countermeasures to limit the spread of the pandemic, including identification and isolation of infected people, together with tracking and quarantining people with whom they have had close contact. Governments closed borders and imposed strict pandemic rules again, but only for some selected sectors of the economy (e.g., tourism, hospitality, food service, and trade). Many companies switched to remote working, including primary and higher education. Local lockdowns were also introduced. The range of initiated economic restrictions was smaller and did not cause such a substantial impact on the economy as during the first wave. Still, it did not protect societies from a solid increase in the level of illnesses and deaths. The change in the level of electricity consumption can be seen in Figure 2b.

Looking at the results of business cycle clocks, the business cycle phase changed from a deep recession to the middle level (trend) or to the recovery phase in most countries. Only in 2 of the 28 analyzed economies, i.e., Sweden and Norway, the cycle phase changed a little and remained around its long-term trend (zero level horizontal axis). This is probably because these countries did not introduce taught economic restrictions, but only those of a social nature (social distance, masks, closure of mass events).

The third pandemic wave occurred in March and April 2021, and governments also introduced restrictions to control its spread. These restrictions were mainly of a "soft" type, i.e., limited to social restrictions (distance, masks) with minor economic countermeasures. These limited lockdowns resulted from the start of the vaccination campaign in December 2020 and its widening in the subsequent months. The ongoing broad vaccination campaign discouraged the governments from the introduction of subsequent non-pharmaceutical economic restrictions. Figure 2c indicates that the influence of lockdown constraints on economic sectors were negligible, and the cycle clock indicated positions above the long-term trend level for all 28 analyzed economies.

By May 2021, we had three waves of the COVID-19 pandemic. In the summer of 2021 (July–September), a fourth wave appeared in some countries. In Europe, a substantial increase in new COVID-19 cases has been observed since October or November. Central and Eastern European countries are the most affected (Slovenia, Slovakia, Romania, Latvia, Hungary, Russia, Ukraine), where the rate of increase in new COVID-19 cases may be related to the vaccination rate. At the beginning of November 2021, the best situation was in Portugal and Spain, where over 80% of the population was vaccinated. At the same time, an average for all European countries was 60% [53]. The above-mentioned CEE countries have vaccination rates far below the European mean. It seems that two factors can assess the current pandemic status in different countries: vaccination rate, and a related set of imposed non-pharmaceutical restrictions (which is well described by the Stringency Index). Those two factors can directly influence economic activity measured by many economic factors, including electricity consumption.

A literature review confirms that the range of non-pharmaceutical interventions introduced by national governments were so broad that in many countries it was referred to as a so-called hard lockdown [4,54–56]. The non-pharmaceutical countermeasures introduced in March and April 2020 aimed to gain control over the spread of the virus and prevent the health system's collapse. This objective was achieved, however, these preventatives had a strong negative impact on the economy, including the level of energy consumption. Similar results have been obtained in [9], where authors point out that the strongest decline has occurred in the hotel, restaurant, and retail sectors. The results of our research are in line with [57] who state that the COVID-19 pandemic affected the energy markets, increasing an overall uncertainty. We agree with [58] that COVID-19 restrictions imposed in order to slowdown the morbidity of coronavirus cases changed people's habits and work practices, which impacted both energy demand and its consumption. The COVID-19 pandemic also changed the structure of energy consumption, which is presented in [17] in the case of Canada.

We found in our research that energy consumption can be used as a leading indicator of the business cycle. The limitation of this study concerns the following issues. We have focused on the European countries, mainly from European Union, where the differences in introducing the NPIs are not so substantial. Most of these countries have proceeded similarly with the fight with the virus. We do not take into account the adoption in people habits during the pandemic period, i.e., work habits or more intensive home residence. The effect of this change influenced energy consumption by reducing the usage of electricity [58].

Future research on the relation between COVID-19 restrictions and energy consumption or GDP growth can be directed to the MIDAS approach, where we may use time-series at different frequencies. Examples of such analysis are in [59,60]. In [61], authors use energy consumption as a GDP factor in Denmark. Similar conclusions for Sweden are presented in [62]. In [63], authors pointed out that energy consumption datasets are available at relatively high frequencies and are always accessible, what makes them very useful.

The COVID-19 pandemic can have long-term consequences not only for human health but also for economic conditions. In our opinion, the fact that the position of energy consumption in the cycle moved above the trend in all countries (Figure 2c) may be the biggest threat for reducing energy use and implementing green policy in Europe.

**Supplementary Materials:** The following are available online at https://www.mdpi.com/article/10.3390/en15010340/s1.

**Author Contributions:** All authors contributed equally to this work. All authors have read and agreed to the published version of the manuscript.

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**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Publicly available datasets were analyzed in this study. This data can be found at https://ec.europa.eu/eurostat/data/database.

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

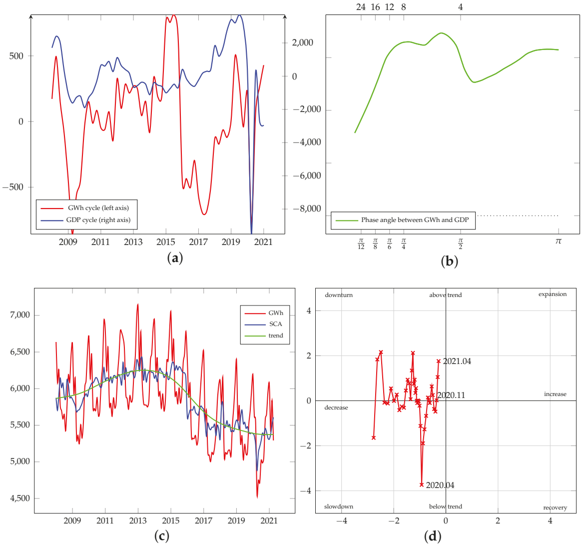
## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| NPI | Non-pharmaceutical interventions |
| SCA | Seasonally and Calendar Adjusted |
| GDP | Gross Domestic Product |
| MIDAS | Mixed-data sampling |
| CEE | Central and Eastern Europe |

## Appendix A

The energy consumption (GWh) and GDP cycles (graphs (a)), phase angle between GWh and GDP (graphs (b)), original values (red lines), the seasonally and calendar adjusted data (blue lines), and the trend (green lines) of energy consumption (graphs (c)), and energy consumption cycle clocks (graphs (d)) for selected European countries.



(a) (b)

(c) (d)

**Figure A1.** Detailed results of cross-spectral analysis for Austria.

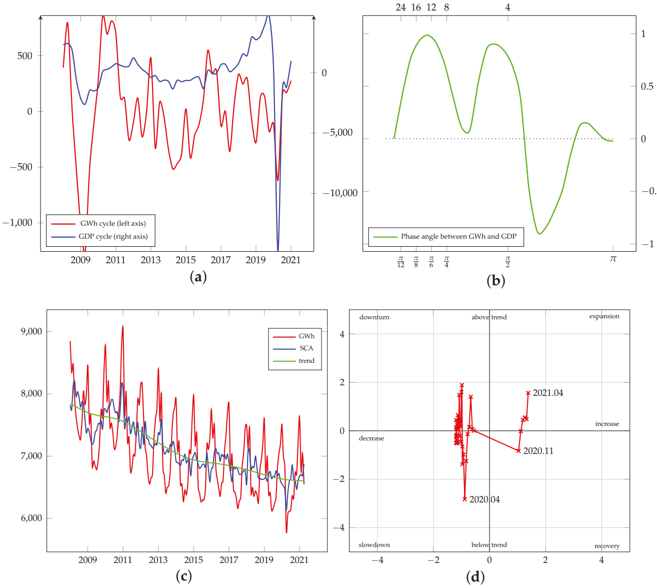


**Figure A2.** Detailed results of cross-spectral analysis for Belgium.

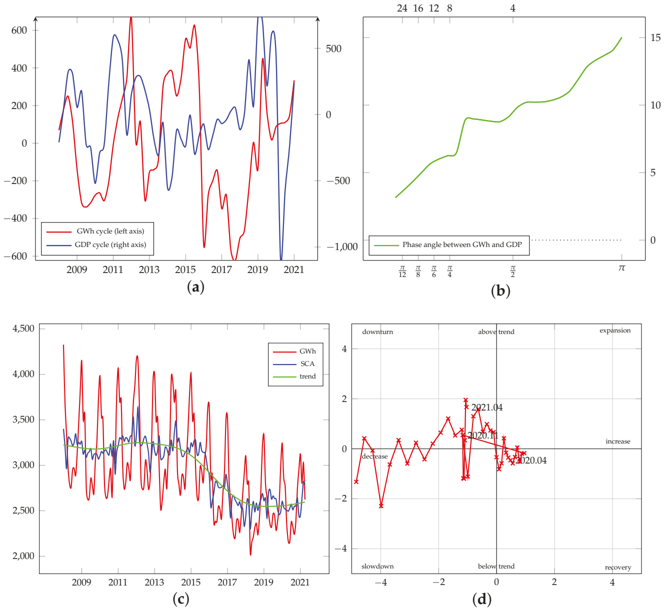
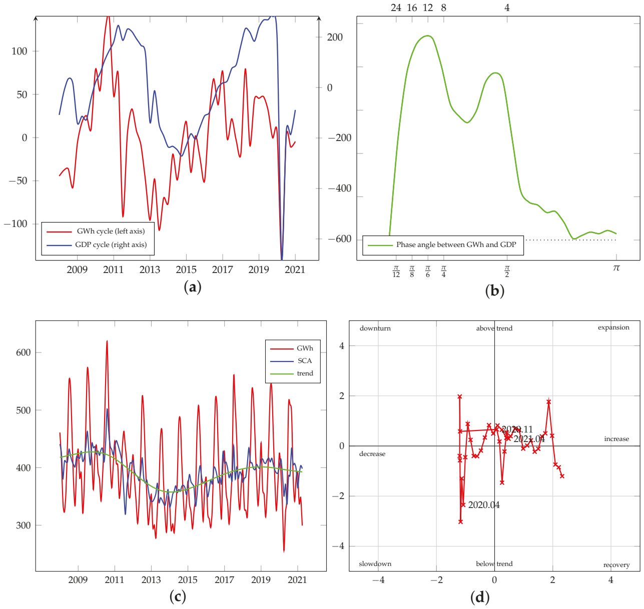
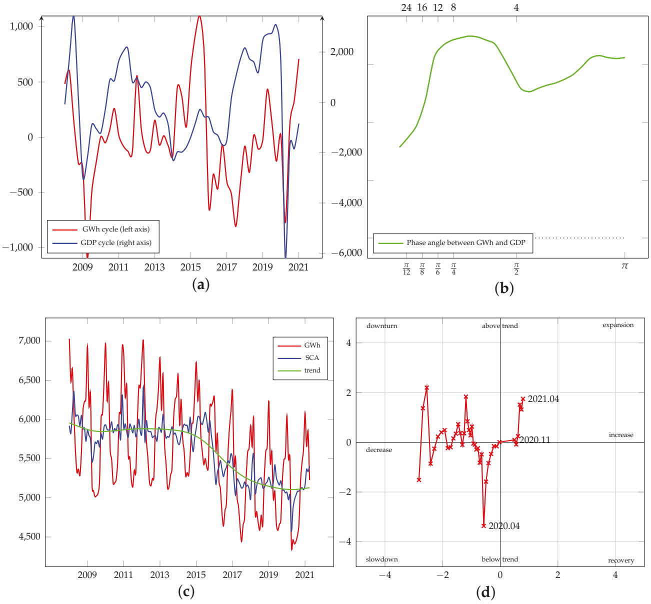


**Figure A3.** Detailed results of cross-spectral analysis for Bulgaria.



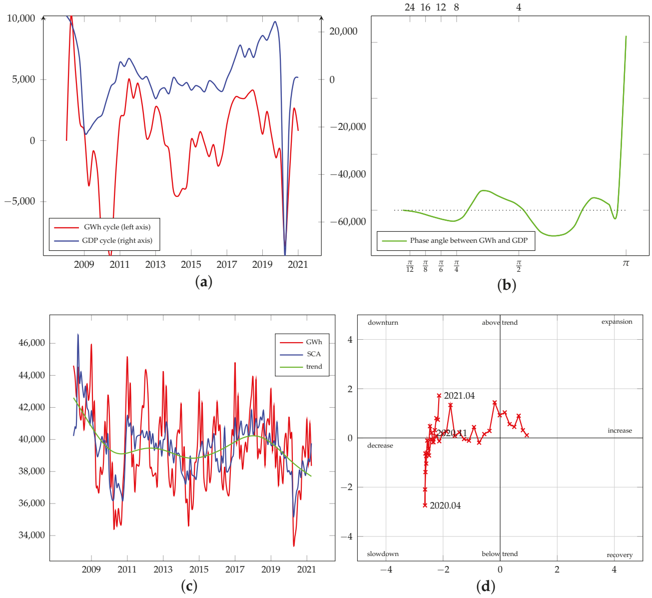
(**a**) (**b**) (**c**) (**d**)

**Figure A4.** Detailed results of cross-spectral analysis for Cyprus.



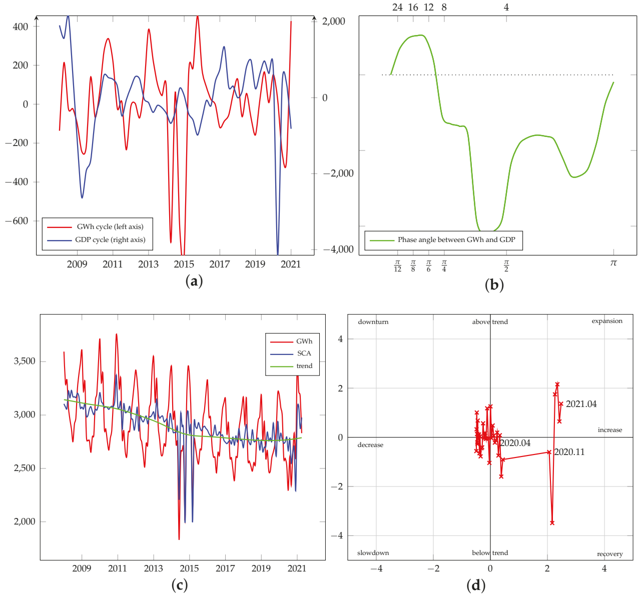
(**a**) (**b**) (**c**) (**d**)

**Figure A5.** Detailed results of cross-spectral analysis for Czech Republic.



(**a**) (**b**) (**c**) (**d**)

**Figure A6.** Detailed results of cross-spectral analysis for Germany.



(**a**) (**b**) (**c**) (**d**)

**Figure A7.** Detailed results of cross-spectral analysis for Denmark.

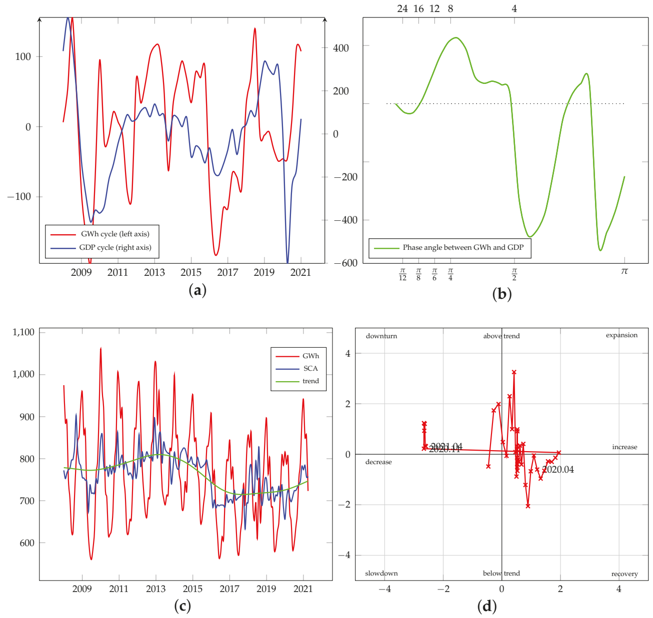


**Figure A8.** Detailed results of cross-spectral analysis for Estonia.

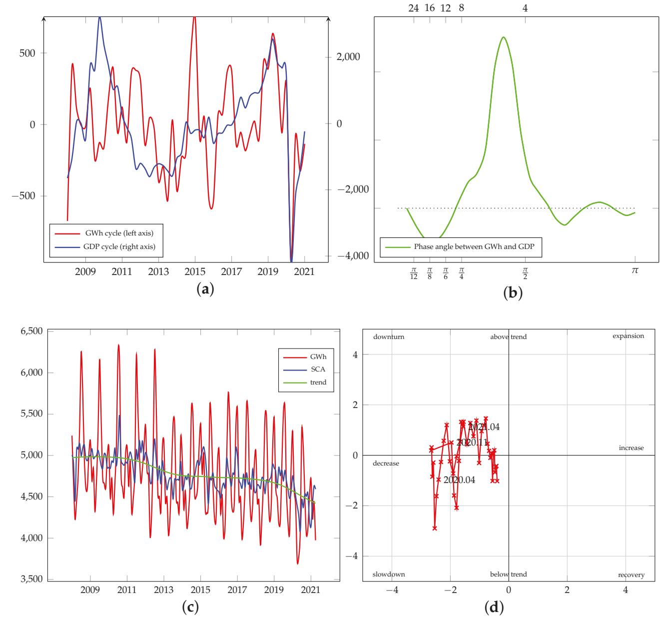


**Figure A9.** Detailed results of cross-spectral analysis for Greece.

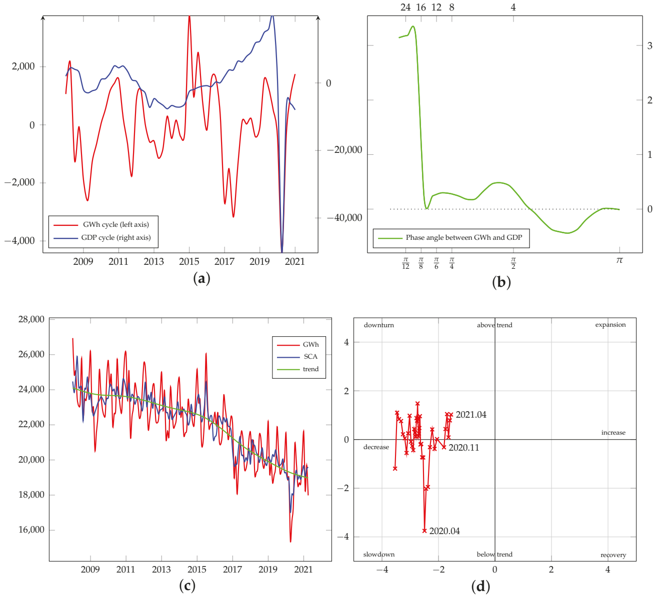


**Figure A10.** Detailed results of cross-spectral analysis for Spain.

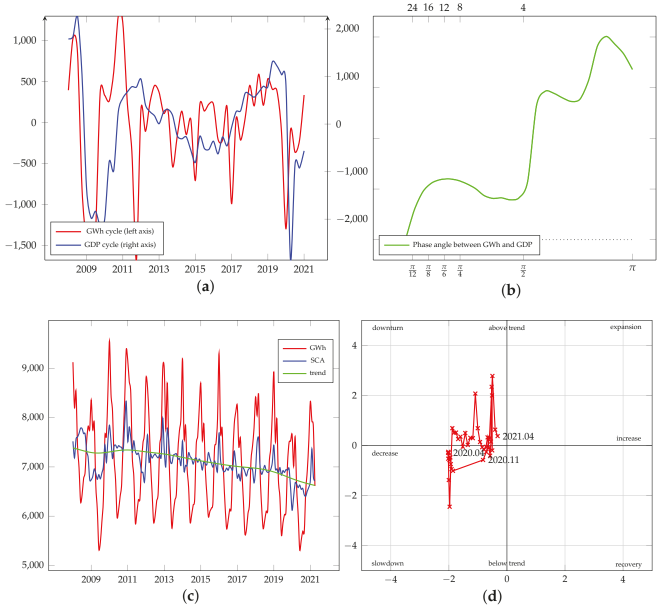


**Figure A11.** Detailed results of cross-spectral analysis for Finland.

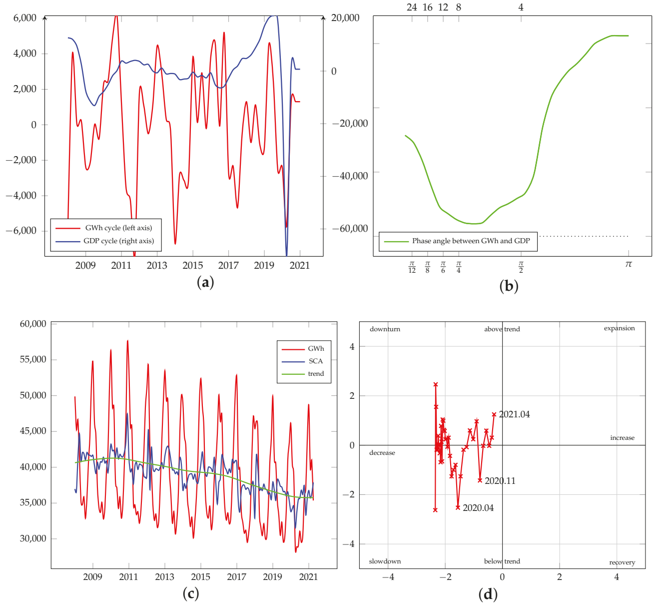


**Figure A12.** Detailed results of cross-spectral analysis for France.

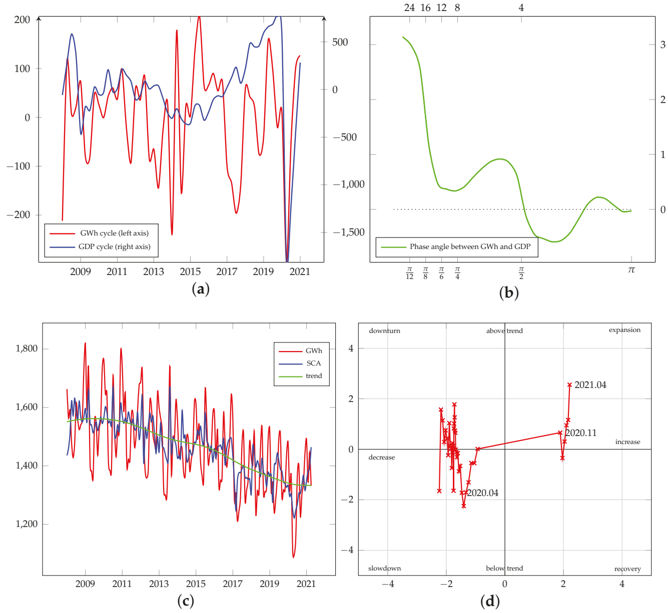
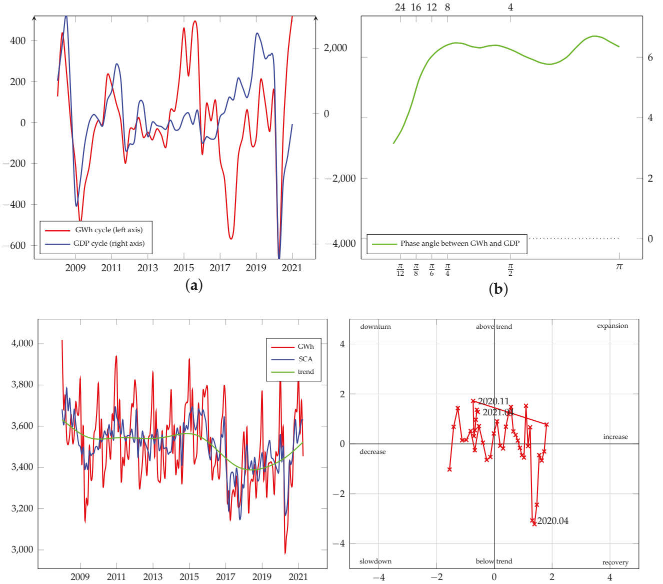


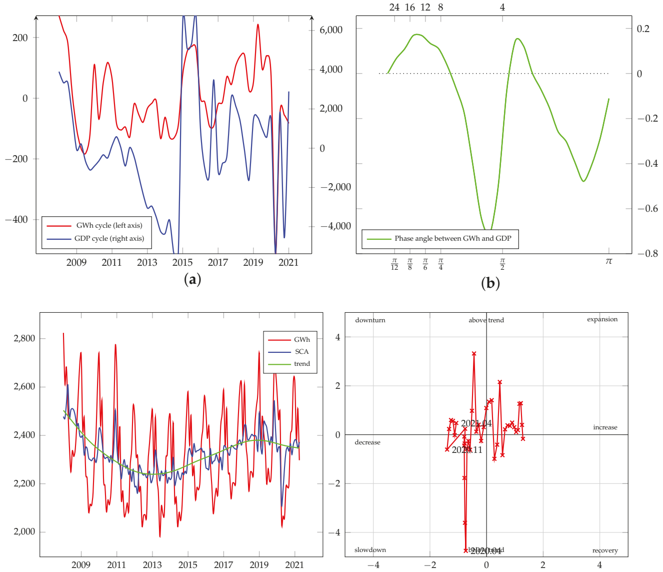
**Figure A13.** Detailed results of cross-spectral analysis for Croatia.



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

(**c**) (**d**)

**Figure A14.** Detailed results of cross-spectral analysis for Hungary.



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

(**c**) (**d**)

**Figure A15.** Detailed results of cross-spectral analysis for Ireland.

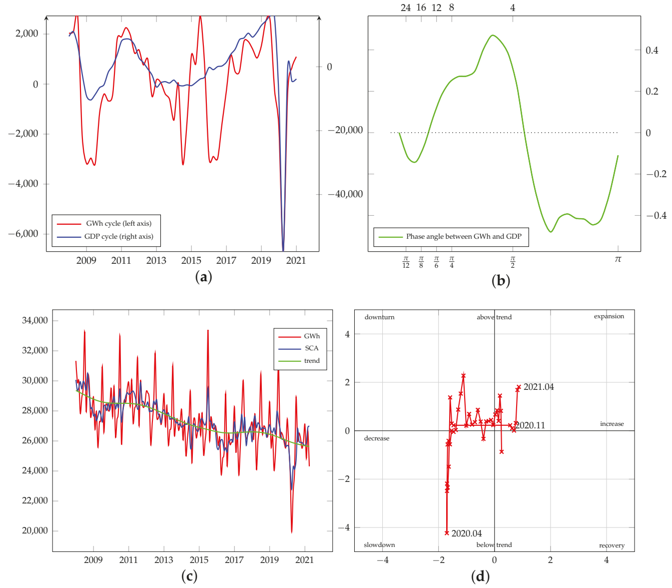


**Figure A16.** Detailed results of cross-spectral analysis for Italy.

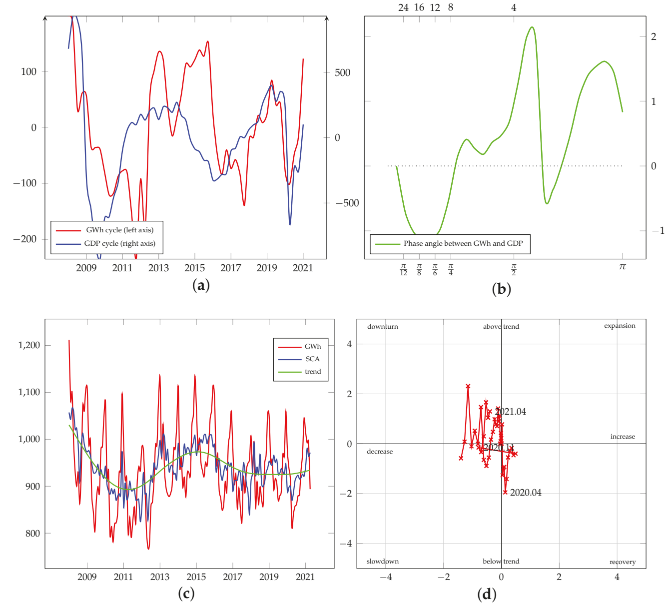


**Figure A17.** Detailed results of cross-spectral analysis for Lithuania.

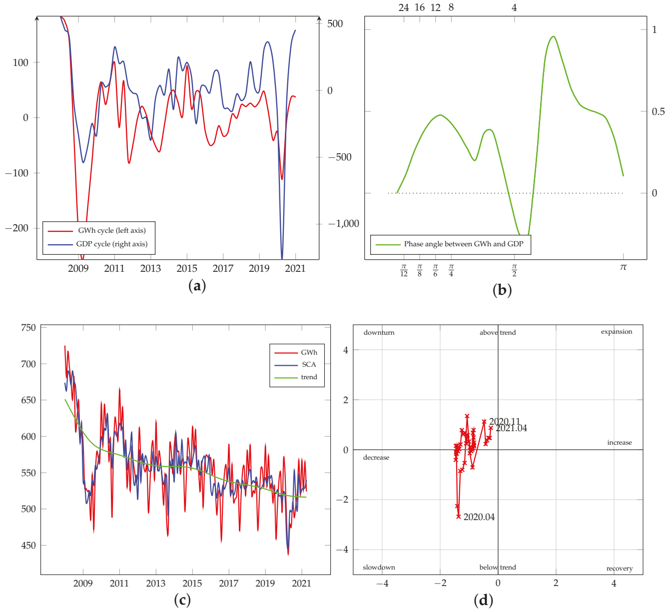


**Figure A18.** Detailed results of cross-spectral analysis for Luxembourg.

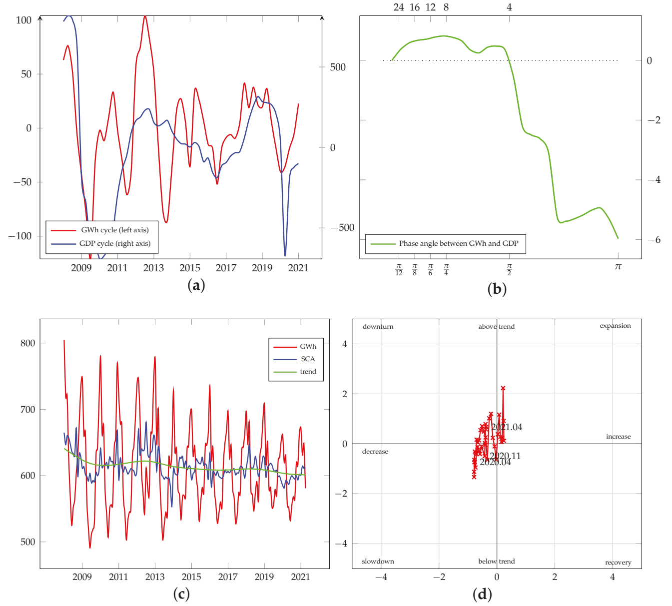


**Figure A19.** Detailed results of cross-spectral analysis for Latvia.

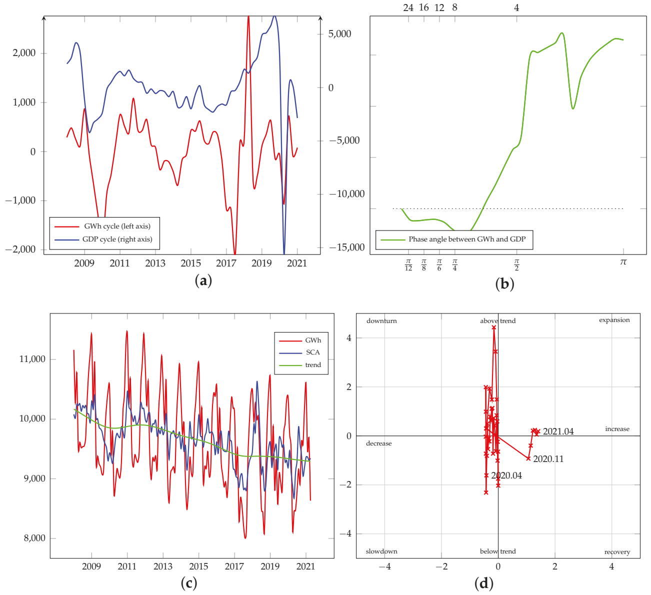


**Figure A20.** Detailed results of cross-spectral analysis for Netherlands.

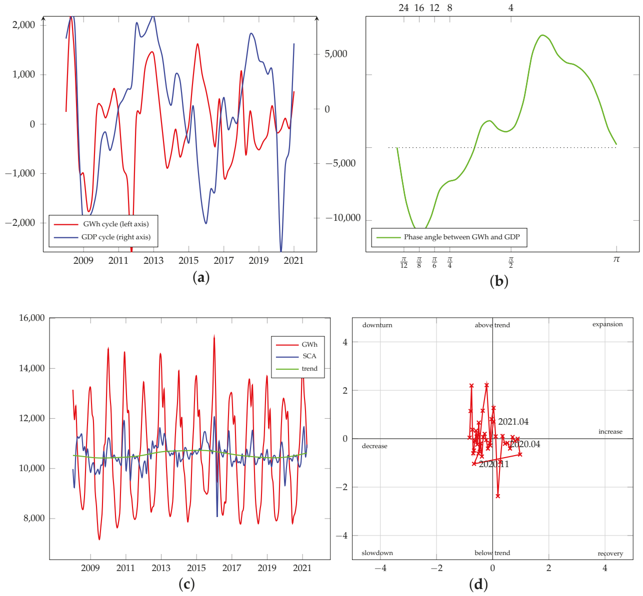
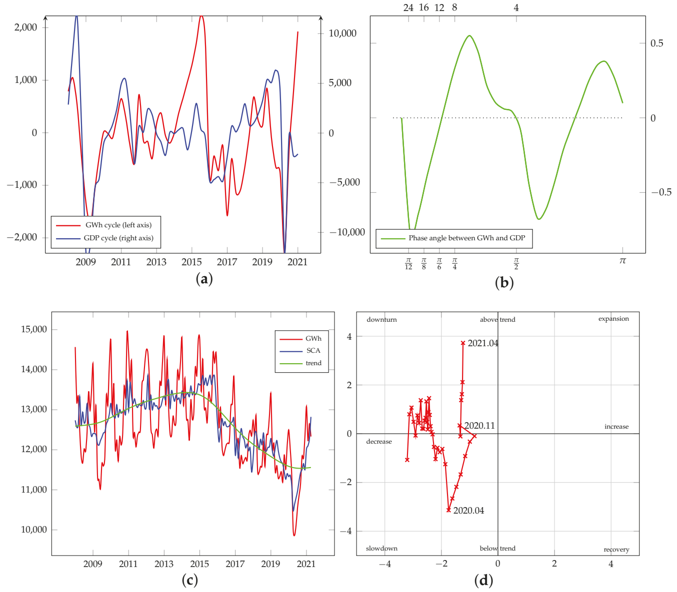


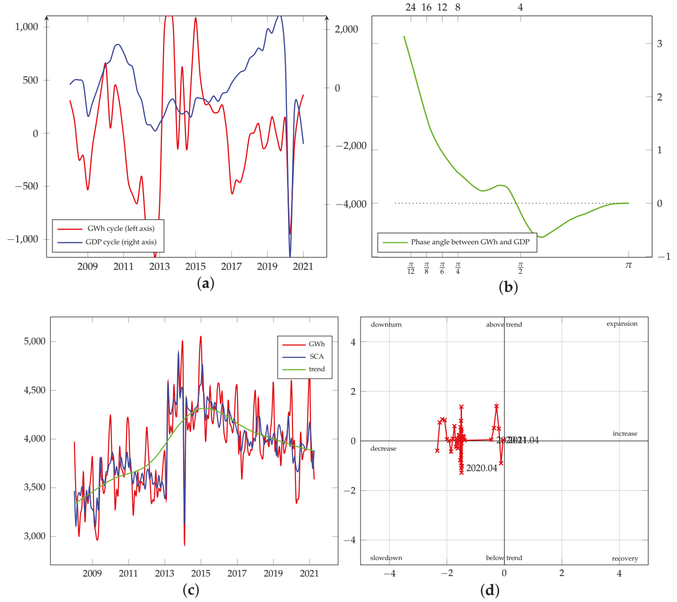
**Figure A21.** Detailed results of cross-spectral analysis for Norway.



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

(**c**) (**d**)

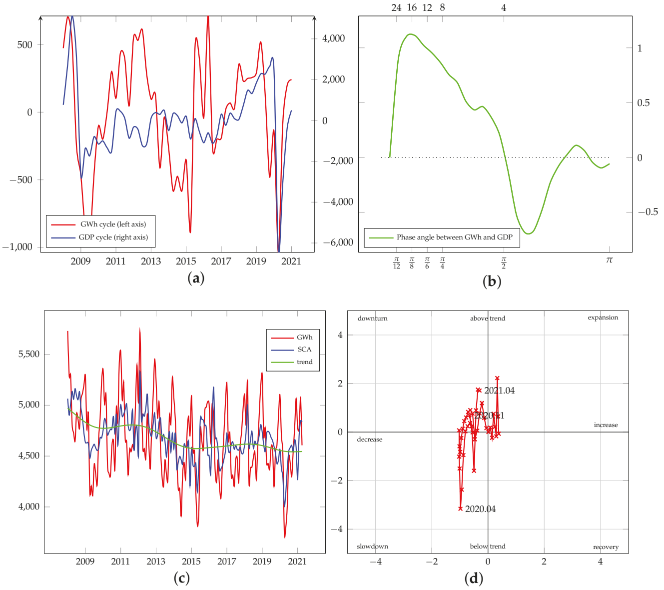
**Figure A22.** Detailed results of cross-spectral analysis for Poland.



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

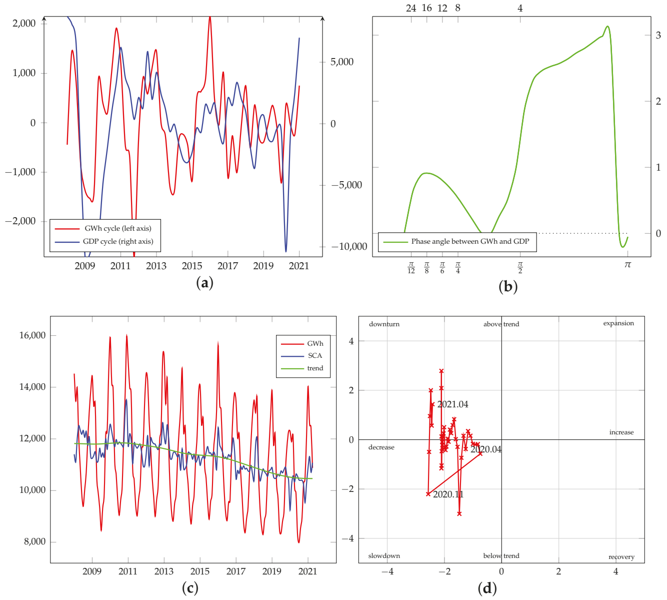
(**c**) (**d**)

**Figure A23.** Detailed results of cross-spectral analysis for Portugal.



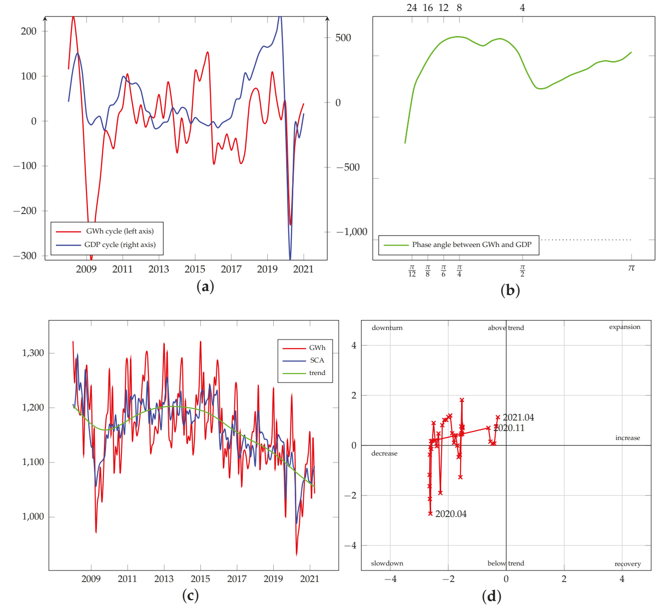
(**a**) (**b**) (**c**) (**d**)

**Figure A24.** Detailed results of cross-spectral analysis for Romania.



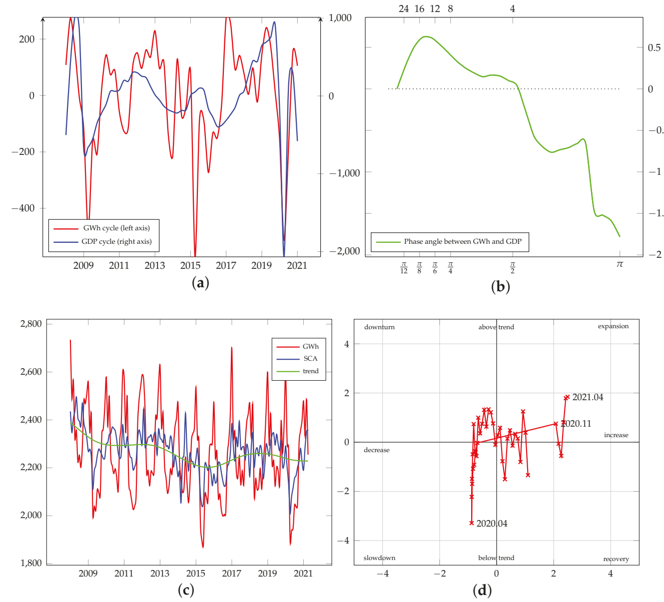
(**a**) (**b**) (**c**) (**d**)

**Figure A25.** Detailed results of cross-spectral analysis for Sweden.



(**a**) (**b**) (**c**) (**d**)

**Figure A26.** Detailed results of cross-spectral analysis for Slovenia.



(**a**) (**b**) (**c**) (**d**)

**Figure A27.** Detailed results of cross-spectral analysis for Slovakia.

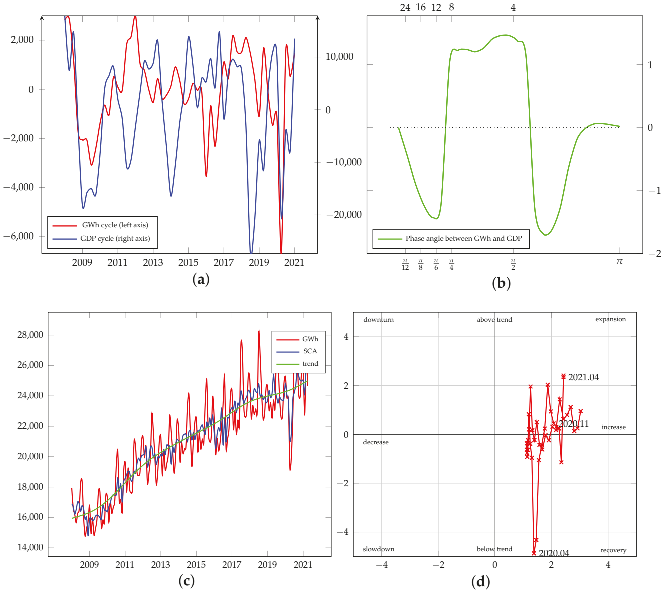


**Figure A28.** Detailed results of cross-spectral analysis for Turkey.

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# Assessment of the Feasibility of Energy Transformation Processes in European Union Member States

**Michał Bernard Pietrzak [1,*], Magdalena Olczyk [2] and Marta Ewa Kuc-Czarnecka [1]**

[1] Department of Statistics and Econometrics, Faculty of Management and Economics, Gdańsk University of Technology, Gabriela Narutowicza 11/12, 80-233 Gdańsk, Poland; mkuc@zie.pg.gda.pl
[2] Department of Economics, Faculty of Management and Economics, Gdańsk University of Technology, Gabriela Narutowicza 11/12, 80-233 Gdańsk, Poland; mw@zie.pg.gda.pl
* Correspondence: michal.pietrzak@zie.pg.gda.pl

**Abstract:** The energy transition is now treated in most countries as a necessary condition for their long-term development. The process of energy transformation assumes the simultaneous implementation of the Sustainable Development Goals, which are a major challenge for modern economies and introduce significant restrictions in their functioning. Our study aims to group EU member states according to their ability to achieve energy transition over time. The novelty of our approach is the assessment of energy transformation in the European Union through two aspects. The first one, "smart and efficient energy systems", assess the current, widely understood energy consumption in economy, and the second one, "macroeconomic heterogeneity", refers to the economic potential of a country. In our analysis, we included indicators from the 7th, 8th, 10th, 11th, and 12th Sustainable Development Goals. Using taxonomic methods, we created clusters of countries according to the emissivity of their economies and the socio-economic potential for the energy transition. The analysis results revealed that countries vary more due to their emissivity than economic potential.

**Keywords:** energy transition; sustainable development; Sustainable Development Goals; economic growth; renewable energy

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## 1. Introduction

The paper focuses on the process of energy transition in the European Union and the new approach to its assessment. By energy transition, we mean the shift from a fossil–nuclear energy system to one based on renewable energy sources, including the associated technological, political, and economic structures [1–4]. In the literature, energy transition is described as one of the most urgent challenges for the global economy and one of the most desirable processes in almost any country, i.e., a panacea to solve certain pressing socio-economic problems [5–7]. Undoubtedly, all world economies are currently undergoing energy transformation. This process is the result of intensive globalization processes already in the early 1990s, which translated into a significant increase in interdependence between economies [8,9]. In subsequent stages of the development of economies, there has been a significant increase in investment, innovation, economic development of countries, an increase in the level of wealth of the society, and changes in consumption patterns in the world and on the labor market [10–20]. All this contributed to the fact that the goals of sustainable development found ground for implementation. In addition, a significant reduction in the costs of technologies for producing energy from renewable sources and the commercialization of green energy for individuals and business entities made the step towards energy transformation consistent with the goals of sustainable growth possible. Energy transition is crucial for three main reasons. Firstly, energy transition can help slow down global warming, which has devastating effects on both nature and people, especially in terms of food security and potential migration [21,22]. Secondly, a successful energy transition may facilitate closing the gap between energy supply and demand [23,24]. As the average annual growth rate of the global economy was around 3.5% in the last decade (not taking into account the pandemic period), increasing demand for energy has been observed, regardless of the energy source [25]. Furthermore, the world population is expected to grow by about two billion people over the next two decades, while living standards are significantly rising, especially in India and China [26]. All of the above indicates that energy production will increase by 49% by 2040 under conditions of shrinking natural resources; therefore, energy transition provides the global economy with the possibility of closing the gap between supply and demand [27]. The third reason is that the effective energy transformation process has become an essential element, referred to as "green competitiveness" [28]. Changes in the consumption patterns related to new groups of customers on the markets, namely Gen Z, Millennials, and Gen X, and alterations in innovations cause energy transition to be necessary in implementing new "green" business models and smart green innovations in the economy. That is why the fundamental question is how to effectively carry out this desirable energy transformation process and how to measure it.

In our paper, we focus on the institutional framework of the energy transition process and its measurement in the European Union (EU) using the approach based on the Sustainable Development Goals. This topic was first undertaken in 2010, when the United Nations (UN) stated that the year 2012 was to be the International Year of Sustainable Energy for All "( . . . ) to ensure access to affordable, reliable, sustainable and modern energy for all". In 2015, the United Nations General Assembly adopted a new post-2015 agenda of universal Sustainable Development Goals (SDGs) containing 17 goals and 169 targets concerning sustainable development [29]. As discussed earlier, the development of globalization processes, the economic growth of most of the economy combined with an increase in investment and the level of innovation, as well as a significant change in consumption patterns contributed to the fact that the goals of sustainable development found ground for implementation. It should be noted that energy transition constitutes the center of sustainable development. It is particularly visible in the seventh (to ensure access to affordable, reliable, sustainable, and modern energy) and twelfth (responsible consumption and production) Sustainable Development Goals, which include signposts related to "greening" the economy for all countries. As a political and economic association of 27 members, the European Union adopted the SDG declaration known as "the 2030 Agenda for Sustainable Development" to achieve 17 universal sustainable goals [30]. To reach SDGs in the field of energy transformation, the EU, as an institution, has also ratified and implemented several legal acts. The most important initiatives include the Paris Agreement, in which the EU has agreed to put the European Union on track to become the first climate-neutral economy and society by 2050. Additionally, the EU introduced a set of policies referred to as the European Green Deal, i.e., an ambitious package of measures ranging from ambitious cuts in greenhouse gas emissions to investment in cutting-edge research and innovation to preserve Europe's natural environment [31].

What distinguishes European Union countries from others implementing the universal sustainable development agenda is solid institutional cooperation and the need to introduce uniform legal acts by all EU members [32]. This also applies to the fulfilment of SDGs in the context of energy transition. This is why our idea was to assess this shift through the lens of SGDs. Previous analyses evaluating the energy transition referred to composite indices that combine a wide range of energy indicators. They often refer to a specific aspect of this phenomenon, e.g., the Energy Security Index [33] and the Multidimensional Energy Poverty Index [34] to accessibility, the World Energy Council Energy Trilemma Index [35] to energy security, and the Energy Transition Index (ETI) to four aspects: accessibility, security, sustainability, and readiness [36]. However, one should be aware that composite indexes, despite their intuitiveness and simplicity, are often constructed with methodological errors. These errors can take the form of omitted or subjective weighting stage; questionable selection of diagnostic variables not supported by the literature; or a non-transparent construction process [37–41]. The authors of this study also showed methodological flaws in the construction of the Energy Transition Index: ETI turns out to be unbalanced and includes many variables of marginal importance for the shape of the final ranking (most of which are “soft variables” such as transparency, credit rating, or the rule of law) [36].

The aim of our article is to propose a new method of assessing the feasibility of energy transition in European Union countries by applying selected indicators of the Agenda for Sustainable Development Goals. Our original approach consisted of selecting individual SDGs and some diagnostic variables that describe two main aspects related to the energy transition. The first one, named “smart and efficient energy systems”, refers to the assessment of the current state of the economy in terms of energy consumption, energy production, and circular economy. The second aspect, called “macroeconomic heterogeneity”, refers to factors associated with or regulated by macroeconomic policy, such as investments, GDP, research and development (R&D) expenditures, education level and income of citizens, and air pollution.

The remaining part of the paper is structured as follows: Section 2 describes the selection of SDGs and indicators related to the energy transition. Section 3 contains the analytical framework, while Section 4 includes the empirical results of our analysis. Section 5 provides conclusions and policy recommendations.

## 2. Implementation of Sustainable Development Goals Relating to the Energy Transition in the EU Countries

There are some studies in the literature that relate the concept of sustainable development to the energy transition in European countries. Mostly, they refer to the concept of sustainable energy transition [42] or effective energy transition [43]. These studies strongly focus on a selected aspect of sustainable development such as energy security [44], financing [45], citizen activity [46], COVID pandemics [47,48], income distribution [49], or negative externalities [50]. They often focus on a selected SDG, e.g., [51] for SDG 7 or analyses refer to only one economy [52] for Germany; [53] for Greece. In our research, we assume that a multi-criteria perspective is required to evaluate energy transition through the prism of implementing the Sustainable Development Goals. This is due to the nature of SGDs, which affect almost all areas of human activity. In the literature, we find several attempts to construct an index that combines the concepts of sustainability and development, named a sustainable energy development indicator (SEDI) [54–57]. Based on the review of the SEDI methodology by [58] and some improvements suggested by [59,60], we use it to assess the sustainable energy development of the EU-28 countries. The analysis shows that Denmark, the Netherlands, and Austria are leading in sustainable energy development in Europe.

In turn, there are very few proposals in the literature for an index linking sustainability to energy transition. Neofytou et al. (2020) propose assessing the EU’s readiness for a sustainable energy transition and introduce an index based on a multi-criteria scoring system inspired by the AHP and PROMETHEE II methodologies. They rank countries based on societal, political, economic, and technological indicators that are considered drivers of the energy transition. Taking all factors into account, Sweden, Spain, and Austria seem to be leading the EU in terms of conditions for the transition to a more sustainable energy system. Our approach is new in the context of the above research. It has a clear focus on energy transition and uses a number of different but coherent criteria to emphasize the potential, rather than progress, and readiness for energy transition. Our approach foregrounds the energy transition in the context of selected Sustainable Development Goals, which is not as broad as the diversity of all the SDGs.

### 2.1. "Smart and Efficient Energy Systems" in the SDG Agenda in the Context of the Energy Transformation in EU Countries

According to Eurostat [61], energy efficiency is vital on the path towards an affordable, reliable, sustainable, and modern energy system, as indicated in the SDGs. Efficient energy systems are connected to reduce consumption and costs, limit energy dependency, and mitigate the environmental and climate impacts associated with the use and supply of energy [62]. Acceleration of the transition into a sustainable energy system in the EU involves taking into account developments in energy consumption, energy supply, and access to affordable energy [63].

In previous decades, economies were developed in line with an increase in energy consumption, as higher resource and energy use contribute to economic growth. Energy consumption must decrease to address the climate crisis, which implicates a "decoupling" of economic growth from energy consumption [64]. Many empirical analyses indicate a strong decoupling of economic growth and energy consumption in EU countries, which can be perceived as a positive trend [65,66]. This is the reason why we used three indicators related to energy consumption in our analysis; its changes may determine the country's potential for a successful energy transition. The first indicator, energy losses, shows the energy sector's energy consumption and losses occurring during the transformation and distribution of energy. The second one, energy productivity, measures the amount of economic output produced per unit of gross available energy. The last one is greenhouse gas emissions' intensity of energy consumption, evaluated as the ratio between energy-related GHG emissions and gross inland consumption of energy (see Table 1).

An efficient energy system cannot exist without a functional supply system. Almost every industry, home, and transport system, as well as the Internet, depends on energy. Additionally, the global energy supply chain is stretched almost to its breaking point, and each new disruption creates problems, partially due to the already conducted decarbonization [67]. A successful shift towards climate neutrality requires a massively increased use of renewable energies to allow for industrial transformation [68]. Technological advancements and cost reductions in wind and solar power and their storage mean that the use of renewable sources now constitutes the most competitive form of electricity generation [69]. According to Krepl et al. [70], the increasing share of renewable energy in gross final energy consumption not only ensure the stability of the energy system but also help promote sustainable development in the post-pandemic era (by reducing greenhouse gas emissions, protecting the environment, increasing energy efficiency, creating jobs, etc.). Considering that the European Commission [71] set a target of −55% greenhouse emissions by 2030, a long-term goal of net zero GHG emissions by 2050, as well as an increase in the minimum share of renewable energy in final energy consumption to 40% by 2030 [71], we decided to include the indicator "share of renewable energy in gross final energy consumption" in our analysis (see Table 1). We also incorporated the second indicator related to energy supply, i.e., the energy import dependency. Between 2004 and 2019, in the European Union, the fuel import from non-EU countries did not change significantly and remains very high—56.9% of gross energy available in the EU was imported in 2004, while in 2019, it was 60.7% [16]. According to Eurostat [16], in 2019, all member states were net importers of energy, with 17 countries importing more than half of their total energy consumption from others (EU countries and non-EU countries). It shows that EU countries need to enhance domestic energy production, and energy import dependency can be regarded as a good measure of the energy transition process.

Apart from three energy consumption measures and two energy supply indicators, we took into account one indicator, which presents access to affordable energy. According to IEA [27], in 2019, 759 million people still had no access to electricity, and at the same time, 2.6 billion people remained without the ability to use clean cooking facilities. Although the lack of access to affordable energy is closely related to low-income levels combined with high energy expenditure and poor building efficiency standards [72], Eurostat [61] confirmed that, in 2019, 6.9% of the EU population were still unable to keep their homes adequately warm, since expanding access to electricity and other forms of energy is fundamental not only to improve the lives of people and their communities but also to increase the level of social acceptance. Flachsbarth [73] used a German example to present how social acceptance is becoming a factor limiting the implementation of the energy transition. Segreto et al. [74] analyzed 25 case studies of the most significant social drivers and barriers that include all European countries and confirmed that a low level of local acceptance has hindered the development of renewable energy projects (while general acceptance of renewable energy systems is high). That is why our study includes "the share of the population who are unable to keep home adequately warm" as a proxy indicator of public acceptance of the energy transition.

**Table 1.** Indicators related to the "smart and efficient energy systems" aspect of energy transition.

| Variable | Description | Type * | Symbol |
|---|---|---|---|
| | **Energy Consumption** | | |
| Energy losses | Energy consumption of the energy sector itself and losses occurring during transformation and distribution of energy (tonnes of oil equivalent (TOE) per capita). | D | $X_1$ |
| Energy productivity | The indicator measures the amount of economic output that is produced per unit of gross available energy. The gross available energy represents the quantity of energy products necessary to satisfy all demand of entities in the geographical area under consideration (PPS per kilogram of oil equivalent (KGOE)). | S | $X_2$ |
| Greenhouse gas emissions intensity of energy consumption | The indicator is calculated as the ratio between energy-related GHG emissions and gross inland consumption of energy. It expresses how many tonnes $CO_2$ equivalents of energy-related GHGs are being emitted in a particular economy per unit of energy that is being consumed. | D | $X_3$ |
| | **Energy Supply** | | |
| Share of renewable energy in gross final energy consumption | The indicator measures the share of renewable energy consumption in gross final energy consumption according to the Renewable Energy Directive. The gross final energy consumption is the energy used by end-consumers plus grid losses and self-consumption of power plants. | S | $X_4$ |
| Energy import dependency | The indicator shows the share of total energy needs of a country met by imports from other countries.<br>Energy dependence = (imports − exports) / gross available energy. | D | $X_5$ |
| | **Access to Affordable Energy** | | |
| Population unable to keep home adequately warm | The indicator measures the share of the population who are unable to keep home adequately warm. | D | $X_6$ |
| | **The Circular Economy** | | |
| Circular material use rate | The circular material use rate (CMR) measures the share of material recovered and fed back into the economy in overall material use. | S | $X_7$ |
| Generation of waste excluding major mineral wastes | The indicator measures all waste generated in a country (kg per 1000 inhabitants). Due to the strong fluctuations in waste generation in the mining and construction sectors and their limited data quality and comparability, major mineral wastes, dredging spoils and soils are excluded. | D | $X_8$ |
| Gross value added in environmental goods and services | The gross value added in EGSS represents the contribution of the environmental goods and services sector to GDP and is defined as the difference between the value of the sector's output and intermediate consumption (% of GDP). | S | $X_9$ |

Source: Authors' study based on [75]; * S—stimulant, D—destimulant.

Furthermore, our analysis includes certain indicators of circular economy (CE). CE aims to "design out" waste through reducing, reusing, recycling, and recovering of materials, all to achieve resource sustainability [76]. According to Chen and Kim [77], energy transition needs to be broadened to cover the conversion of non-energy use and the achievement of a closed-loop non-energy use that constitutes part of the circular economy. The coordinated approach of the CE and energy transition may lead to synergy effects, i.e., promoting circular economy activities in the industry, reducing energy demand, and acquiring the additional potential to reduce greenhouse gas emission [78]. That is why the analysis cover three indicators of circular economy: the circularity rate (the share of material recovered and fed back into the economy in the overall material use), the generation of waste excluding major mineral wastes (which measures all waste generated in a country), and gross value added in environmental goods and services, (which shows the contribution of the environmental goods and services sector to gross domestic product).

### *2.2. "Macroeconomic Heterogeneity" of the SDG Agenda in the Context of Energy Transformations in EU Countries*

Many countries are making numerous efforts to switch from fossil fuels to cleaner fuels and increase energy efficiency to become carbon-free economies. Still, the transition process is not easy, mainly due to its complexity [79]. It affects different regions of the world to different degrees, depending on their local energy consumption basket, geographic location, and economic ties to fossil fuels [80]. An essential question in the economic literature is how macroeconomic variables can accelerate the energy transition in different regions, leading to similarities in energy transition patterns between these regions. Sovacool [81] discussed the speed of this process in various countries and found that the potential for energy transition is not identical in all countries and depends on various factors, policies, geographical location, and energy flows. For this reason, we have chosen certain macroeconomic indicators described in the SDG agenda to assess a country's potential for the energy transition.

Many previous analyses suggested the occurrence of a positive relationship between economic growth (measured by means of GDP) and energy transition (see [82] for CEE countries; [80] for Asian economies). A unique role is played by investment as a part of GDP. Apergis and Payne [83] found a positive relationship between renewable energy consumption and gross fixed capital formation in a panel of 16 emerging economies between 1990 and 2011. Similarly, Sineviciene [84] indicated that fixed capital constitutes an essential driver of energy efficiency in analyzed countries. Therefore, our analysis includes the investment share of GDP, defined as gross fixed capital formation expressed as a percentage of GDP for the government, business, and household sectors (see Table 2).

**Table 2.** Indicators related to the "macroeconomic heterogeneity" aspect of energy transition.

| Variable | Description | Type * | Symbol |
|---|---|---|---|
| **Investment** | | | |
| Investment share of GDP (total investment) | Defined as gross fixed capital formation (GFCF) expressed as a percentage of GDP for the government, business, and household sectors. | S | $X_{10}$ |
| **Innovation** | | | |
| Gross domestic expenditure on R&D | The indicator measures gross domestic expenditure on R&D (GERD) as a percentage of the gross domestic product (GDP). | S | $X_{11}$ |
| R&D personnel | The indicator measures the share of R&D personnel. Data are presented in full-time equivalents as a share of the economically active population. | S | $X_{12}$ |
| **Education and Income Household** | | | |
| Tertiary educational attainment | The indicator measures the share of the population aged 25–34 who have successfully completed tertiary studies. | S | $X_{13}$ |
| Adjusted gross disposable income of households per capita | The indicator reflects households' purchasing power and ability to invest in goods and services or save for the future by accounting for taxes and social contributions and monetary in-kind social benefits. | S | $X_{14}$ |
| **Dirtiness of Economy** | | | |
| Air emission intensity from industry | This indicator measures the emissions intensity of fine particulate matter (PM2.5). | D | $X_{15}$ |
| Average $CO_2$ emissions per km from new passenger cars | The indicator is defined as the average carbon dioxide ($CO_2$) emissions per km by new passenger cars in a given year. | D | $X_{16}$ |

**Source**: Authors' study based on [75]; * S—stimulant, D—destimulant.

We also took into account the R&D expenditures as a potential driver of the energy transition. The International Renewable Energy Agency (IRENA) [85] indicates technological breakthroughs are necessary to reduce carbon emissions in the energy sector. Even if economically viable and scalable renewable energy-based solutions are available for about two-thirds of the world's energy supply, population growth and rising energy demand could outpace energy decarbonization without urgent investment in research and development (R&D). In our research, we focused on R&D expenditures, which helps increase energy efficiency through innovation in technology [86], promotes a reduction in $CO_2$ emissions [87], and positively contributes to the carbon neutrality targets [88]. Therefore, our macroeconomic variables covered gross domestic expenditure on R&D (% of GDP) and R&D personnel (% of the labor force).

In addition, in our study, we applied variables characterizing two features of household members, namely their education and income. The literature shows that households' energy literacy is crucial in shaping a successful energy transition and building its resilience [89]. Energy literacy does not mean only the device energy literacy but also the awareness of, attitude, and behavior towards the energy process [90]. A positive attitude to the energy transformation with its costs and benefits strongly depends on the education of citizens [91]; that is why we adopted tertiary educational attainment as a determinant of this process. It is worth emphasizing that universities are the most important institutions for the dissemination of knowledge through teaching and for the creation of new knowledge through research. These aspects make universities important players in achieving the Sustainable Development Goals [92].

Moreover, we assumed that a household's income could determine the energy transition. As indicated by Nguyen et al. [93], the occurrence of such a shift varies between wealthy and poor groups of citizens. Poor households still heavily rely on traditional energy sources, including coal and biomass to meet their energy needs. In their analysis of the German energy transition, Schlesewsky and Winter [94] also pointed to a larger share of consumers from high-income households than poor households in this process.

At last, we added two variables that constrain the energy transition process. They include the pollution of the economy, i.e., the intensity of air emissions from the industry and the average $CO_2$ emissions (per km from new passenger cars). In this study, we assumed that social aspects are essential for the success of this transformation. The energy transition is costly to almost every household as a result of higher electricity prices, partly due to the renewable energy levy, but also entails many positive environmental impacts (the mitigation of pollution) and public health benefits [95]. The costs and benefits should be shared equitably and transparently across society, particularly in the context of rising inequality in the majority of countries [96]. The health benefits are particularly important and expected by each household, as air pollution emissions are recognized as a major contributor to the global burden of disease, especially cardiovascular and respiratory mortality [97]. That is why we included air pollution indicators in our study as the most crucial aspect of the economy's pollution.

To sum up, we selected (out of 17 Sustainable Development Goals) 16 individual SDG diagnostic variables describing two main aspects related to the energy transition, i.e., smart and efficient energy systems and macroeconomic factors of the energy transition.

## 3. Research Methods and Data

In this paper, the Ward's method, which constitutes one of the hierarchical cluster analysis approaches, was used to identify groups of countries similar to each other in terms of energy consumption and potential for the energy transition. We decided to use clustering methods rather than a composite indicator, as the former seems to have fewer design pitfalls. It has been tentatively mentioned that composite indicators often suffer from an inadequate weighting system [98]. Therefore, we have opted for a more robust method that focuses on the taxonomic similarity of objects and does not require artificial and subjective weights [99]. Ward's method represents agglomeration clustering methods, i.e., it is based on the assumption that, initially, every object creates a separate class, and pairs of clusters are merged as one moves up in the hierarchy—the so-called "bottom-up" approach [100].

The Ward's approach can be described in the following steps:

Every object $Q_i = (i = 1, 2, \ldots, m)$ creates a separate class; thus, the initial number of single-element classes equals m.

1. Based on the lowest value in the distance matrix, a pair of the most similar objects p and q is established,
2. Objects p and q are formed into one cluster, reducing the number of groups to $m - 1$,
3. The distance between the newly formed cluster and other items is calculated,
4. Steps 2–4 are repeated until sample units are combined into a single large cluster of size m.

The distance between the objects is a positive, definite, and symmetric [101] vector onto the positive reals, fulfilling the triangular inequality. Therefore, for the object p, q, v, the following relation occurs:

$$d(p,q) > 0; d(p,q) = 0 \Leftrightarrow p = q;\ d(p,q) = d(g,p); d(p,q) \leq d(p,v) + d(v,q) \quad (1)$$

where: d—distance; p, q, v—observations.

The distance is calculated as the error sum of squares:

$$ESS = \sum_{i=1}^{k} x_i^2 - \frac{1}{k}\left(\sum_{i=1}^{k} x_i\right)^2 \quad (2)$$

where: $x_i$—criterion of segmentation for ith unit; k—number of objects in a given cluster. At each stage of cluster analysis, the total ESS is minimized.

The number of clusters was determined based on the dendrogram analysis and supported by the value of the silhouette index [102] calculated for the analogous analysis carried out using the k-means method. Since, in this case, the results obtained with Ward's approach and the k-means method were similar, we decided to present only the former. In a subsequent analysis step, we also verified the mean values of diagnostic variables in the selected group of countries. Using the Kruskal–Wallis test [103], we studied whether differences between these groups were statistically significant. Finally, the chi-square test of independence [104] indicated whether the obtained clustering based on different variables was independent.

Table 3 presents the basic descriptive statistics for the variables used in the analysis. An analysis of the data in Table 3 shows that most of the variables are characterized by significant differentiation (the coefficient of variation above 0.3), thus indicating their high ability to differentiate the discussed European Union member states. These countries are particularly enormously diversified in terms of generation of waste ($X_8$), air emission intensity ($X_{15}$), and proportion of population unable to keep home adequately warm ($X_6$). In most cases, the analyzed variables were characterized by positive asymmetry, which means that, in most countries, the values of the discussed variables were below the average. The opposite situation was observed only in the case of four diagnostic variables, i.e., values above the average were observed in the majority of countries. This concerned the following variables: energy import dependency ($X_5$), average $CO_2$ emission per km from new passenger cars ($X_{16}$), tertiary education attainment ($X_{13}$), and R&D personnel ($X_{12}$).

**Table 3.** Descriptive statistics of the variables used in the study.

| Variable | Min | Max | Mean | Median | S.D. | C.V. | As |
|---|---|---|---|---|---|---|---|
| $X_1$ | 0.25 | 1.39 | 0.78 | 0.74 | 0.38 | 0.49 | 0.37 |
| $X_2$ | 5.53 | 19.63 | 9.20 | 8.45 | 2.93 | 0.32 | 2.09 |
| $X_3$ | 63.10 | 102.60 | 81.82 | 80.95 | 8.87 | 0.11 | 0.19 |
| $X_4$ | 8.77 | 56.39 | 23.96 | 20.62 | 11.86 | 0.50 | 1.06 |
| $X_5$ | 4.83 | 77.48 | 55.68 | 60.47 | 19.27 | 0.35 | −0.81 |
| $X_6$ | 1.80 | 30.10 | 7.91 | 5.15 | 7.82 | 0.99 | 1.81 |
| $X_7$ | 1.30 | 30.00 | 9.66 | 7.20 | 7.46 | 0.77 | 1.28 |
| $X_8$ | 0.02 | 7.36 | 0.53 | 0.21 | 1.47 | 2.79 | 4.78 |
| $X_9$ | 0.88 | 5.68 | 2.42 | 2.21 | 1.16 | 0.48 | 1.42 |
| $X_{10}$ | 10.14 | 45.60 | 22.64 | 21.59 | 6.09 | 0.27 | 2.10 |
| $X_{11}$ | 0.48 | 3.40 | 1.76 | 1.47 | 0.90 | 0.51 | 0.49 |
| $X_{12}$ | 0.36 | 2.12 | 1.32 | 1.32 | 0.48 | 0.36 | −0.18 |
| $X_{13}$ | 25.50 | 55.40 | 41.33 | 42.60 | 8.04 | 0.19 | −0.24 |
| $X_{14}$ | 10,875.00 | 30,142.00 | 20,872.79 | 19,952.00 | 5094.83 | 0.24 | 0.09 |
| $X_{15}$ | 0.02 | 0.88 | 0.18 | 0.08 | 0.24 | 1.31 | 2.24 |
| $X_{16}$ | 98.40 | 137.60 | 122.41 | 122.60 | 9.26 | 0.08 | −0.61 |

S.D.—standard deviation; C.V—coefficient of variation, As—skewness. Source: Authors' study based on [75].

## 4. Results

### 4.1. "Smart and Efficient Energy Systems" Analysis

The subject of the analysis consisted of 24 European Union countries in 2019 (Cyprus, Malta, and Luxembourg were excluded due to the missing data). The empirical research began with the energy-intensity aspect, which includes energy consumption, energy supply, access to affordable energy, and circular economy aspects. It is created by the variables $X_1$–$X_9$ (a detailed description of these variables is provided in Table 1 in the second section of the article). In this case, four groups of countries were distinguished (Figures 1 and 2).

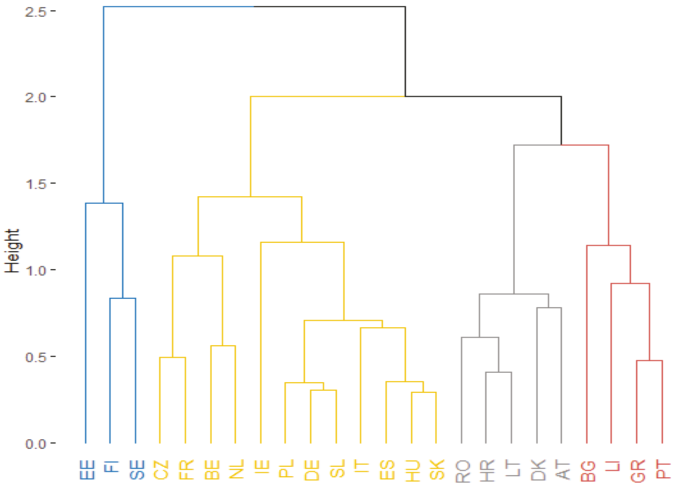

**Figure 1.** Cluster dendrogram for "smart and efficient energy systems". Source: Authors' study based on [75].

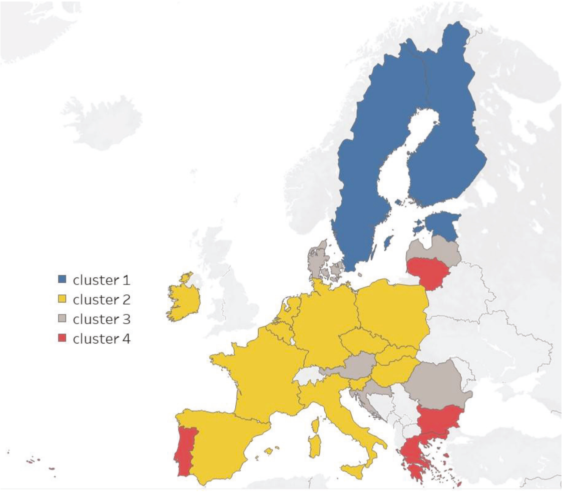

**Figure 2.** Choropleth map for "smart and efficient energy systems". Source: Authors' study based on [75].

An analysis of Figures 1 and 2 allows establishing cluster 1 (blue), which consists of the most prominent users of renewable energy sources that are simultaneously the least dependent on external energy sources. This cluster is made up of the following countries: Estonia, Finland, and Sweden. Compared to other groups, countries assigned to cluster 1 also stand out in terms of the lowest values of the variables $X_5$ and $X_6$ (population unable to keep home adequately warm, and greenhouse gas emissions intensity of energy consumption) and the highest values of variables $X_1$, $X_8$, and $X_9$ (energy losses, generation of waste excluding major mineral wastes, and gross value added in environmental goods and services) (Table 4). The actual values of the diagnostic variables for the "smart and efficient energy systems" aspect for the first cluster are included in Table 4. The analysis of the data in this table shows that these three countries are indeed similar in terms of the levels of diagnostic variables. Estonia slightly differs from the others (variables $X_5$, $X_7$, and $X_8$). Despite these differences, the inclusion of Estonia in cluster 1 is still justified, as in the case of other groups, the differences would be even more visible.

**Table 4.** "Smart and efficient energy systems"—values of diagnostic variables for countries constituting cluster 1.

| ISO | $X_1$ | $X_2$ | $X_3$ | $X_4$ | $X_5$ |
|---|---|---|---|---|---|
| SE | 1.38 | 7.39 | 68.30 | 56.39 | 30.24 |
| EE | 1.36 | 6.91 | 79.70 | 31.89 | 4.83 |
| FI | 1.22 | 5.53 | 69.60 | 43.08 | 42.09 |
| **MEAN** | 1.32 | 6.61 | 72.53 | 43.78 | 25.72 |
| **ISO** | $X_6$ | $X_7$ | $X_8$ | $X_9$ | - |
| SE | 1.90 | 6.50 | 0.21 | 2.08 | - |
| EE | 2.50 | 15.60 | 7.36 | 4.45 | - |
| FI | 1.80 | 6.30 | 0.47 | 5.68 | - |
| **MEAN** | 2.00 | 9.46 | 2.68 | 4.07 | - |

Source: Authors' study based on [75].

An opposite to cluster 1 is cluster 2, which is the largest and contains 12 elements(yellow). Cluster 2 is formed by countries of Central and Eastern Europe, which includes: Belgium, Czechia, France, Germany, Hungary, Ireland, Italy, Netherlands, Poland, Slovakia, Slovenia, and Spain. They are characterized by the highest circular material use rate ($X_7$) and a relatively high energy import dependency (X4). At the same time, they have the lowest share of renewable energy in gross final energy consumption ($X_4$), the lowest level of waste generation excluding major mineral waste ($X_8$), and the lowest gross value added in environmental goods and services ($X_9$) (Table 5). Therefore, these economies are largely dependent on energy imports and are based on non-ecological energy sources (mostly coal or gas). The actual values of the diagnostic variables for the "smart and efficient energy systems" aspect for the second cluster are included in Table 5. In this case, there are no significant differences between the values of the variables observed in individual countries and the average level of a given variable in the cluster. The exceptions are Ireland for the variable $X_2$, Italy for $X_6$, and Belgium for $X_7$).

**Table 5.** "Smart and efficient energy systems"—values of diagnostic variables for countries constituting cluster 2.

| ISO | $X_1$ | $X_2$ | $X_3$ | $X_4$ | $X_5$ | $X_6$ | $X_7$ | $X_8$ | $X_9$ |
|---|---|---|---|---|---|---|---|---|---|
| IE | 0.47 | 19.63 | 79.6 | 11.98 | 68.4 | 4.90 | 1.60 | 0.33 | 0.88 |
| BE | 1.16 | 6.50 | 84.6 | 9.92 | 76.68 | 3.90 | 24.20 | 0.31 | 0.94 |
| HU | 0.61 | 8.34 | 77.3 | 12.61 | 69.70 | 5.40 | 6.80 | 0.11 | 1.11 |
| SK | 0.88 | 7.01 | 77.7 | 16.89 | 69.76 | 7.80 | 6.40 | 0.29 | 1.47 |
| SL | 0.80 | 8.36 | 89.8 | 21.97 | 52.14 | 2.30 | 11.40 | 0.72 | 1.6 |
| FR | 1.34 | 8.81 | 79.5 | 17.22 | 47.60 | 6.20 | 20.00 | 0.02 | 1.62 |
| IT | 0.51 | 11.38 | 82.2 | 18.18 | 77.48 | 11.10 | 19.50 | 0.03 | 1.87 |
| DE | 0.82 | 10.16 | 87.2 | 17.35 | 67.61 | 2.50 | 12.30 | 0.02 | 1.96 |
| PL | 0.71 | 8.37 | 85.9 | 12.16 | 46.82 | 4.20 | 10.30 | 0.06 | 2.21 |
| ES | 0.73 | 9.95 | 79.7 | 18.36 | 74.96 | 7.50 | 10.00 | 0.03 | 2.22 |
| NL | 0.78 | 7.88 | 92.6 | 8.77 | 64.72 | 3.00 | 30.00 | 0.15 | 2.25 |
| CZ | 1.39 | 7.17 | 73.6 | 16.24 | 40.89 | 2.80 | 8.30 | 0.15 | 2.30 |
| **MEAN** | 0.85 | 9.46 | 82.48 | 15.13 | 63.06 | 5.13 | 13.4 | 0.19 | 1.70 |

Source: Authors' study based on [75].

The third group (cluster 3) consists of countries such as Austria, Croatia, Denmark, Latvia, and Romania (grey in Figure 2). They are characterized by the lowest energy losses and relatively low generation of waste (Table 6 includes actual values of the diagnostic variables for countries included in third cluster). The last group, including Bulgaria, Greece, Lithuania, and Portugal, form cluster 4 (red in Figure 2) and consists of countries with the highest energy dependence ($X_5$), and greenhouse gas emissions intensity of energy consumption ($X_3$) as well as the highest proportion of the population struggling to maintain an appropriate temperature in their apartments ($X_6$) (Table 7). As in the previous cases, the actual values of the diagnostic variables for the countries included in the fourth cluster are included in Table 7. The analysis of Table 7 shows that it is the most homogeneous cluster.

**Table 6.** "Smart and efficient energy systems"—values of diagnostic variables for countries constituting cluster 3.

| ISO | $X_1$ | $X_2$ | $X_3$ | $X_4$ | $X_5$ | $X_6$ | $X_7$ | $X_8$ | $X_9$ |
|---|---|---|---|---|---|---|---|---|---|
| HR | 0.32 | 9.37 | 86.60 | 28.47 | 56.22 | 6.60 | 5.20 | 0.22 | 1.45 |
| LV | 0.25 | 8.32 | 83.80 | 40.98 | 43.96 | 8.00 | 4.30 | 0.36 | 2.53 |
| RO | 0.42 | 12.68 | 85.70 | 24.29 | 30.37 | 9.30 | 1.30 | 0.06 | 3.00 |
| DK | 0.43 | 13.05 | 63.10 | 37.20 | 38.78 | 2.80 | 7.60 | 0.31 | 3.19 |
| AT | 0.45 | 10.08 | 83.90 | 33.63 | 71.73 | 1.80 | 11.50 | 0.21 | 4.30 |
| **MEAN** | 0.37 | 10.7 | 80.62 | 32.91 | 48.21 | 5.70 | 5.98 | 0.23 | 2.89 |

Source: Authors' study based on [75].

**Table 7.** "Smart and efficient energy systems"—values of diagnostic variables for countries constituting cluster 4.

| **ISO** | $X_1$ | $X_2$ | $X_3$ | $X_4$ | $X_5$ | $X_6$ | $X_7$ | $X_8$ | $X_9$ |
|---|---|---|---|---|---|---|---|---|---|
| GR | 0.75 | 8.53 | 74.90 | 19.68 | 74.11 | 17.90 | 4.20 | 0.14 | 0.84 |
| BG | 1.20 | 6.09 | 97.10 | 21.56 | 38.10 | 30.10 | 2.30 | 0.44 | 1.90 |
| LI | 0.26 | 9.10 | 102.60 | 25.46 | 75.22 | 26.70 | 3.90 | 0.50 | 2.20 |
| PT | 0.48 | 10.24 | 78.60 | 30.62 | 73.85 | 18.90 | 2.30 | 0.13 | 2.28 |
| **MEAN** | 0.67 | 8.49 | 88.30 | 24.33 | 65.32 | 23.40 | 3.17 | 0.30 | 1.81 |

Source: Authors' study based on [75].

The results of the Kruskal–Wallis test (Table 8) indicate that the variables selected as forming the aspect of "smart and efficient energy systems" are discriminatory with regard to the analyzed countries. The null hypothesis should be rejected in the case of seven out of nine variables, which indicates a statistically significant difference in the median values of variables under study. The null hypothesis should not be rejected in the case of variable $X_3$ (greenhouse gas emission intensity) and variable $X_8$ (waste generation). However, it is worth emphasizing that the variables mentioned above distinguish cluster 1 from the others. It takes place because in cluster 1, variable $X_3$ takes much lower values than in the other three groups, while variable $X_8$ takes much higher values. Taking into account this observation, it is justified to leave variables $X_3$ and $X_8$ in the set of diagnostic variables.

**Table 8.** "Smart and efficient energy systems" aspect—Kruskal–Wallis test results.

| **Test Chi-Squared** | $X_1$ | $X_2$ | $X_3$ | $X_4$ | $X_5$ | $X_6$ | $X_7$ | $X_8$ | $X_9$ |
|---|---|---|---|---|---|---|---|---|---|
| Statistics | 13.891 | 6936 | 3584 | 18.212 | 8657 | 13.270 | 9502 | 5112 | 8169 |
| *p*-Value | 0.003 | 0.074 | 0.310 | 0.0004 | 0.034 | 0.004 | 0.023 | 0.163 | 0.042 |

Source: Authors' study based on [75].

### *4.2. "Macroeconomic Heterogeneity" Analysis*

In the previous part, countries were grouped according to the emissivity of economies and the degree of dependence on energy imports. These variables, associated with the 7th and 12th SDG, determined the actual demand of economies and indicated the primary energy sources. This section focuses on the potential for the energy transition, understood as the strength of the economy entering the transition process. Variables used in this section of the analysis focus on aspects such as investments, innovation, education, and dirtiness of the economy. They are therefore connected with 8th, 9th, and 10th SDG.

Figure 3 presents a dendrogram created for variables $X_{10}$–$X_{16}$. When analyzing Figures 3 and 4, it is possible to notice a clear distinction of two groups, nearly identical to the "old" and "new" Europe. Countries marked as blue (Figure 4), i.e., Austria, Belgium, Denmark, Finland, France, Germany, Netherlands, and Sweden form cluster 1. They are economically stronger, and therefore, the energy transformation in these countries is likely to run more efficiently, for example, due to increased investments and the functioning of the R&D sector ($X_{10}$ and $X_{11}$). In addition, these countries are characterized by a larger percentage of people with higher education and wealthier households (Table 9). As already mentioned in the theoretical part of this work, the education and wealth of the inhabitants translate into environmental awareness as well as absorption of novelties and trends in the field of less or zero waste movements. The real values of the diagnostic variables for the first cluster of countries created based on the "macroeconomic heterogeneity" aspect are included in Table 9. The analysis of data from this table shows that the values observed in individual countries do not differ significantly from the average value, which proves the high homogeneity of the cluster.

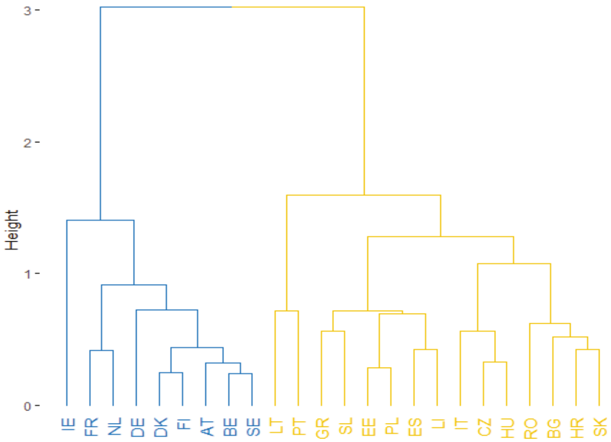

**Figure 3.** Cluster dendrogram for the "macroeconomic heterogeneity" aspect. Source: Authors' study based on [75].

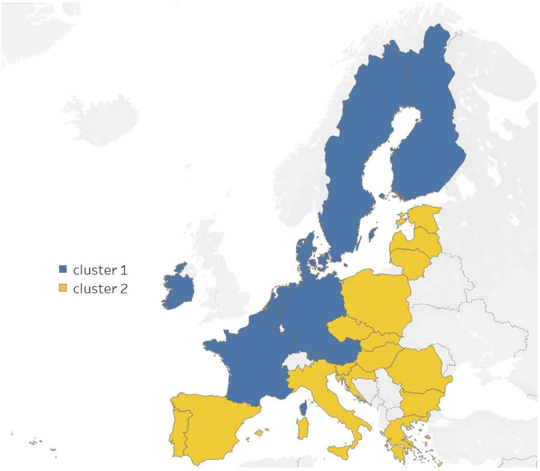

**Figure 4.** Choropleth map for the "macroeconomic heterogeneity". Source: Authors' study based on [75].

**Table 9.** "Macroeconomic heterogeneity"—values of diagnostic variables for the countries constituting cluster 1.

| ISO | $X_{10}$ | $X_{11}$ | $X_{12}$ | $X_{13}$ | $X_{14}$ | $X_{15}$ | $X_{16}$ |
|---|---|---|---|---|---|---|---|
| BE | 24.16 | 2.89 | 1.91 | 47.30 | 27,082 | 0.07 | 121.5 |
| DK | 21.30 | 2.91 | 2.12 | 47.10 | 25,754 | 0.02 | 111.9 |
| DE | 21.69 | 3.18 | 1.73 | 33.30 | 30,142 | 0.02 | 131.2 |
| IE | 45.60 | 0.78 | 1.58 | 55.40 | 22,541 | 0.02 | 114.00 |
| FR | 23.63 | 2.19 | 1.59 | 48.20 | 26,158 | 0.06 | 113.7 |
| NL | 21.25 | 2.16 | 1.78 | 49.10 | 26,842 | 0.05 | 98.40 |
| AT | 24.68 | 3.19 | 1.87 | 41.60 | 28,177 | 0.02 | 125.5 |
| FI | 23.74 | 2.79 | 1.93 | 42.00 | 25,912 | 0.09 | 115.30 |
| SE | 24.41 | 3.40 | 1.72 | 48.40 | 25,004 | 0.06 | 119.70 |
| **MEAN** | 25.61 | 2.61 | 1.80 | 45.82 | 26,401.30 | 0.04 | 116.8 |

Source: Authors' study based on [75].

The countries of Central and Eastern Europe including Bulgaria, Croatia, Czechia, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia, Slovenia as well as Greece, Italy, Portugal and Spain, constitute cluster 2 (yellow in Figure 4). They are characterized by high air emission intensity from the industry and high average $CO_2$ emissions per km from new passenger cars ($X_{15}$ and $X_{16}$). This indicates that their economies are based mainly on coal and that old passenger cars, imported from Western Europe, dominate on the roads. The lower material status of inhabitants translates into smaller absorption of pro-ecological solutions, which are often more expensive, at least in the short term (Table 10). Table 10 contains the values of diagnostic variables observed among the members of the second cluster. Additionally, in this case, there were no significant deviations from the average value in the cluster, and therefore, the group was well separated.

**Table 10.** "Macroeconomic heterogeneity"—values of diagnostic variables for countries constituting cluster 2.

| ISO | $X_{10}$ | $X_{11}$ | $X_{12}$ | $X_{13}$ | $X_{14}$ | $X_{15}$ | $X_{16}$ |
|---|---|---|---|---|---|---|---|
| BG | 18.52 | 0.84 | 0.81 | 32.70 | 10,875 | 0.27 | 137.60 |
| CZ | 27.07 | 1.94 | 1.51 | 32.60 | 20,106 | 0.04 | 128.70 |
| EE | 26.21 | 1.61 | 0.97 | 42.80 | 17,786 | 0.44 | 130.10 |
| GR | 10.14 | 1.27 | 1.18 | 42.40 | 15,904 | 0.25 | 115.60 |
| ES | 19.87 | 1.25 | 1.01 | 46.50 | 20,346 | 0.10 | 121.30 |
| HR | 21.02 | 1.11 | 0.82 | 35.50 | 14,969 | 0.19 | 119.40 |
| IT | 17.96 | 1.45 | 1.41 | 27.70 | 23,003 | 0.06 | 119.40 |
| LV | 22.19 | 0.64 | 0.64 | 43.80 | 15,519 | 0.88 | 127.90 |
| LI | 21.37 | 1.00 | 0.92 | 55.20 | 19,798 | 0.04 | 132.00 |
| HU | 27.12 | 1.48 | 1.24 | 30.60 | 15,896 | 0.09 | 131.80 |
| PL | 18.52 | 1.32 | 0.99 | 43.50 | 17,306 | 0.32 | 132.00 |
| PT | 18.15 | 1.40 | 1.23 | 37.40 | 19,628 | 0.87 | 109.40 |
| RO | 23.63 | 0.48 | 0.36 | 25.50 | 16,608 | 0.22 | 124.30 |
| SL | 19.64 | 2.04 | 1.67 | 44.10 | 19,548 | 0.14 | 123.70 |
| SK | 21.49 | 0.83 | 0.78 | 39.20 | 16,043 | 0.06 | 133.40 |
| **MEAN** | 20.86 | 1.244 | 1.04 | 38.63 | 17,555.70 | 0.26 | 125.77 |

Source: Authors' study based on [75].

Furthermore, in this case, the hypothesis concerning the equality of medians was verified using the Kruskal–Wallis test. The results of the procedure are presented in Table 11. For each of the analyzed variables $X_{10}$–$X_{16}$, the null hypothesis should be rejected since statistically significant differences occur in the median levels between the two groups, and thus, the indicated set of diagnostic variables has discriminatory properties.

**Table 11.** "Macroeconomic heterogeneity"—Kruskal–Wallis test results.

| Test Chi-Squared | $X_{10}$ | $X_{11}$ | $X_{12}$ | $X_{13}$ | $X_{14}$ | $X_{15}$ | $X_{16}$ |
|---|---|---|---|---|---|---|---|
| Statistics | 3875 | 10.561 | 15.254 | 5270 | 15.724 | 9337 | 5004 |
| *p*-Value | 0.049 | 0.001 | 0.0001 | 0.021 | 0.001 | 0.002 | 0.025 |

Source: Authors' study based on [75].

### *4.3. Analysis of Potential to Follow up Energy Transition Processes*

In the third part of the empirical analysis, we juxtaposed variables of the two aspects discussed above. We believe that the emissivity of the economy and its economic strength determines the potential to conduct the energy transition; thus, constituting an indicator that allows establishing the economies in which this process will be the most difficult, and those that should relatively quickly achieve the set of energy, environmental, or broadly understood Sustainable Development Goals.

In this case, we also divided the countries according to their taxonomic similarity. The analysis of the dendrogram (Figure 5) and the indication of the silhouette index divided the European Union Member States into four clusters (Figures 5 and 6). The first one, which includes Bulgaria, Croatia, Greece, Latvia, Lithuania, Portugal, and Romania (blue on Figure 6) appears to comprise of countries that are likely to find it very challenging to achieve the EU's energy targets within the set time frame. This interpretation is supported by the fact that countries within this cluster are characterized by the highest values of variables concerning greenhouse gas emissions ($X_3$), air emissions intensity from the industry ($X_{15}$), and the percentage of people who struggle to maintain an adequate temperature in their houses ($X_6$) (Table 12). Moreover, these countries have the lowest circular material use ($X_7$) and values of five out of eight economic and development variables ($X_{10}$–$X_{14}$), describing investments, innovations, and the wealth and education of the inhabitants. Taking into account the high emissivity of economies, an unremarkable renewable energy fraction, as well as the poor economic condition, it can be assumed that achievement of the EU's energy targets, both at the national level and the level of individual households, may be challenging in these countries. It appears that, without adequate financial support, the desired greening of the economy will not be possible, even after taking into account the overall downturn caused by the global COVID pandemic. Nevertheless, as a positive phenomenon, it can be indicated that they are the countries with the lowest energy losses.

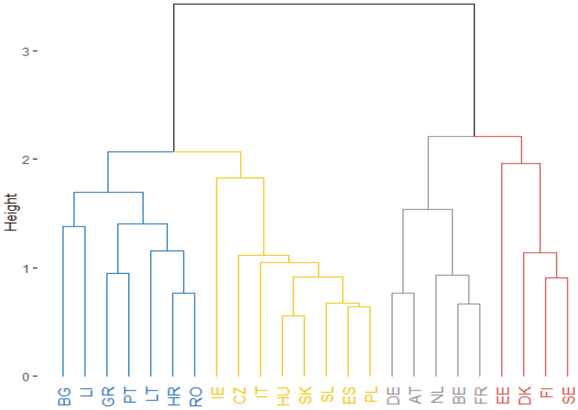

**Figure 5.** Cluster dendrogram for a holistic approach. Source: Authors' study based on [75].

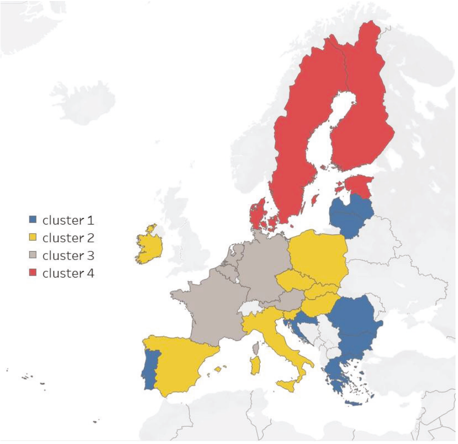

**Figure 6.** Choropleth map for a holistic approach. Source: Authors' study based on [75].

**Table 12.** Mean values of diagnostic variables in each cluster.

| Variable | Cluster 1 | Cluster 2 | Cluster 3 | Cluster 4 | Variable | Cluster 1 | Cluster 2 | Cluster 3 | Cluster 4 |
|---|---|---|---|---|---|---|---|---|---|
| $X_1$ | 0.53 | 0.76 | 0.91 | 1.10 | $X_9$ | 2.03 | 1.71 | 2.21 | 3.85 |
| $X_2$ | 9.19 | 10.03 | 8.69 | 8.22 | $X_{10}$ | 19.29 | 24.66 | 23.08 | 23.92 |
| $X_3$ | 87.04 | 80.73 | 85.56 | 70.18 | $X_{11}$ | 0.96 | 1.39 | 2.72 | 2.68 |
| $X_4$ | 27.29 | 16.05 | 17.38 | 42.14 | $X_{12}$ | 0.85 | 1.27 | 1.78 | 1.69 |
| $X_5$ | 55.98 | 62.52 | 65.67 | 28.99 | $X_{13}$ | 38.93 | 39.95 | 43.90 | 45.08 |
| $X_6$ | 16.79 | 5.75 | 3.48 | 2.25 | $X_{14}$ | 16,185.86 | 19,348.63 | 27,680.20 | 23,614.00 |
| $X_7$ | 3.36 | 9.29 | 19.60 | 9.00 | $X_{15}$ | 0.39 | 0.10 | 0.04 | 0.15 |
| $X_8$ | 0.26 | 0.22 | 0.14 | 2.09 | $X_{16}$ | 123.74 | 125.54 | 118.06 | 119.25 |

Source: Authors' study based on [75].

The second cluster (yellow in Figures 5 and 6), including eight countries: Czechia, Hungary, Ireland, Italy, Slovakia, Slovenia, Spain, and Poland, is the cluster with the highest values of energy productivity ($X_2$), investment rate ($X_{10}$), and, unfortunately, $CO_2$ emissions per km from new passenger cars ($X_{16}$). At the same time, they have the lowest level of renewable energy sources ($X_4$) and the gross value added in environmental goods and services ($X_9$) (Table 12). Relatively low ecological burdens and a high degree of investment should contribute to achieving the set energy goals. Still, it will require significant changes in infrastructure and the mentality of inhabitants.

The third cluster consists of five countries: Austria, Belgium, France, Germany, and Netherlands (grey on Figures 5 and 6). They are characterized by the highest degree of innovation (variable $X_{11}$ and $X_{12}$), use of circular material ($X_7$), and levels of wealth ($X_{14}$). The largest degree of energy dependence ($X_5$) may constitute a problem in these countries. The third cluster consists of countries with the lowest waste generation ($X_8$) as well as $CO_2$ emissions from the industry and passenger cars. All the above factors prove that the five countries mentioned will certainly achieve their energy targets. The only aspect that innovation and investment should focus on is increasing energy independence (mainly from Russia), which, in fact, already takes place by investing in hydrogen-based energy.

The fourth cluster is formed by the Nordic countries: Denmark, Finland, Sweden, and Estonia (Figures 5 and 6). They are characterized by tremendous potential for a smooth transition in the energy transformation process. These countries have the highest share of renewable energy (variable $X_4$), investment in GDP ($X_{10}$), and inhabitants with higher education ($X_{13}$). They are also countries with the lowest greenhouse gas emissions ($X_4$), energy dependence ($X_5$), and the proportion of inhabitants who have problems with maintaining a proper temperature in their homes ($X_6$). The lowest energy productivity in this group ($X_2$) results from a high share of renewable energy sources. However, taking into account the small population of these countries, renewable energy sources completely fulfil their role and effectively supply the inhabitants and industry with the necessary energy; all this makes them the countries with the highest potential for a smooth energy transition and fully achieving energy goals.

Table 12 summarizes the mean values for individual diagnostic variables. In the vast majority of cases, significant differences can be noticed between the average levels of diagnostic variables in the selected clusters, which proves the high separability of clusters and the high quality of the presented groups. The Kruskal–Wallis test additionally confirmed this. Table 13 shows the results of the Kruskal–Wallis test for the holistic approach in our analysis. The juxtaposition of variables revealed slightly worse discriminatory properties than in the case of two aspects separately, i.e., smart and efficient energy systems and macroeconomic heterogeneity. This time, statistically significantly different medians occurred only in the case of eight individual variables. However, similarly to the first analyzed aspect, also at this point, maintenance of all individual variables is logically justified. Variables $X_3$, $X_5$, $X_8$, $X_9$, and $X_{13}$ clearly distinguish the fourth cluster from other groups. Variable $X_{10}$ separates cluster 2 from the rest, while variables $X_{10}$ and $X_{16}$ distinguish the appropriate clusters 1 and 3, respectively.

**Table 13.** Kruskal–Wallis test results—holistic approach.

| **Test Chi-Squared** | $X_1$ | $X_2$ | $X_3$ | $X_4$ | $X_5$ | $X_6$ | $X_7$ | $X_8$ |
|---|---|---|---|---|---|---|---|---|
| Statistics | 8894 | 2202 | 2585 | 9424 | 4452 | 16.140 | 14.337 | 1284 |
| *p*-value | 0.031 | 0.532 | 0.460 | 0.024 | 0.217 | 0.001 | 0.003 | 0.733 |
| **Test Chi-Squared** | $X_9$ | $X_{10}$ | $X_{11}$ | $X_{12}$ | $X_{13}$ | $X_{14}$ | $X_{15}$ | $X_{16}$ |
| Statistics | 3805 | 5063 | 16.614 | 14.929 | 3894 | 15.362 | 7958 | 4062 |
| *p*-Value | 0.283 | 0.167 | 0.001 | 0.002 | 0.273 | 0.015 | 0.047 | 0.2548 |

Source: Authors' study based on [75].

The grouping consistency obtained based on taxonomic analyses of various aspects was also investigated using the chi-square test of independence. In the case of smart and efficient energy systems and macroeconomic heterogeneity, the test statistic was 3.5911 (p = 0.31), which indicates that the results obtained in the first and second grouping are not consistent. Therefore, there is no association between the analyzed aspects. However, when studying the potential for the energy transition and the aspects above, the null hypothesis should be rejected in each case, meaning that there is an association between the potential for the energy transition and the emission intensity ($\chi^2 = 37.82; p = 0.00$), as well as the potential for the energy transition and the strength of the economy ($\chi^2 = 17.07, p = 0.001$).

## 5. Discussion and Conclusions

The article presents a discussion focusing on the implementation of the energy transition in the European Union. Such a transformation is currently taking place in all economies and results from many processes that have overlapped since the beginning of the 1990s. Globalisation, which increased the interdependence between countries in social, economic, and institutional terms, contributed to the shape of the energy transformation to the greatest extent [8,9,105]. Systematically developing globalization facilitated significant socio-economic development and the related increase in the wealth of societies [14,106,107]. Positive socio-economic changes were also influenced by the parallel dynamic growth of innovation, foreign direct investment, and significant institutional progress [10–13,15,108].

Additionally, significant changes in consumers' attitudes and the labor market have also taken place [16–19,109]. All these processes allowed for the commercialization of technologies related to the production of electricity and heat, which are currently available to households in retail sales [110]. Commonly available technologies generating energy from renewable sources for households and enterprises solve problems associated with the systematic increase in energy demand and a limited amount of traditional energy sources, which are becoming increasingly expensive and cause significant environmental degradation [3,4]. All the above indicates that the problem of energy transformation is a key issue related to the possibility of further development of world economies.

The analysis of the EU's member states presented in this scientific paper constitutes an interesting research problem due to this process's institutional and legal determinants. In the EU, legal acts were adopted that to oblige all member states to introduce assumptions regarding the energy transformation within strictly defined deadlines. The discussion entails a question about the success of this process in the case of all countries, as all countries are obliged to carry out the energy transition. Failure to meet the adopted transformation conditions by one country or a group of countries may hinder the assumed energy transition process and lead to a change in the assumed conditions or even withdrawal of the entire European Union from the undertaken path. In the light of such information, the research questions posed by the authors, i.e., how to effectively carry out the desired process of energy transformation and how to measure it appears to be important from the perspective of further development of the EU in the upcoming years. To obtain an answer to such questions, the article proposes an innovative method of assessing European Union countries in terms of energy transformation. The analysis of member states was conducted based on the selection of individual Sustainable Development Goals and related diagnostic variables. It allowed the authors to focus on studying two distinct aspects related to energy transformation processes. The first "smart and efficient energy systems" concerns the nature of energy and heat consumption by economies of the member states. The second aspect, "macroeconomic heterogeneity", allows for assessing countries in terms of their economic potential necessary to carry out the energy transformation effectively.

The assessment of member states in the light of these two aspects allowed for the grouping of European economies according to of their ability to achieve goals related to the energy transformation. In the study, the countries were first evaluated in terms of "smart and efficient energy systems", which enabled the identification of four clusters. The second step considered the "macroeconomic heterogeneity" aspect, and countries were assigned to only two clusters. Finally, a country analysis was performed by taking into account both elements, resulting in the division of countries into four groups.

The analysis revealed that Estonia, Denmark, Finland, and Sweden were countries in which the energy transformation should proceed smoothly and, at the same time, translate into further economic growth. Countries involving a risk of non-compliance with conditions provided for in the applicable EU legal acts were also identified. These are: Bulgaria, Croatia, Greece, Latvia, Lithuania, Romania, and Portugal. This indicates that the EU policy should take into account possible difficulties with the implementation of required environmental criteria by some countries or certain regions. Specific guidelines related to instruments supporting the achievement of energy transformation goals should also be included in subsequent legal acts issued by the EU.

In the article, an evaluation of the generally understood readiness of countries to go through the energy transformation in the long term has been made. The proposed approach to assessing the energy transition is to combine the concept of the energy transition with sustainable development and growth. Authors do not want to benchmark countries on their fulfillment of energy transition and climate goals but attempt to assess the readiness of countries to effectively implement the energy transition. The presented perspective is new because countries may be leaders in energy transformation, but their economies may not be prepared for the related changes, which, in the long term, may translate into a deterioration of the socio-economic situation of selected countries. The direction of further research of the authors will be an attempt to confront the obtained results regarding the readiness of countries to go through the energy transformation with the actual state of implementation of selected tasks of sustainable development or selected aspects of these tasks by these countries. The conclusions will provide a basis for determining the likely long-term development paths of the EU member states, both in the context of the energy transformation processes and the level of sustainable development. This will allow us to answer the question, to what extent the selected EU member states will be able to implement simultaneously processes related to energy transition and challenges of sustaining sustainable economic development.

Finally, the authors want to emphasize the fact that there is a significant problem related to the implementation energy transformation of the EU member states. The situation in the community is specific because the entire transformation is strongly surrounded by institutions and legislation that obliges countries to meet the next conditions related to the energy transformation and the implementation of the Sustainable Development Goals. The issue of achieving the goals of the European Union's energy transformation is a process subordinated to the goals set out in legal documents. The goals pursued in this way may differ significantly from the capabilities of economies, enterprises, households, and social acceptance. Undoubtedly, the functioning of all economies is based on energy, and the functioning of households and the costs of living and possible inflation are related to it. Meanwhile, there are regions in the EU (regions within countries) where the energy transition is too expensive from an economic point of view, where a significant percentage of households are doomed to energy poverty, and where social opposition to green transformation is slowly emerging. In such regions, the processes of energy transformation may be slowed down or even stopped from below. The authors want to emphasize the need to include energy justice in transformation processes and that the transformation should result from or be combined with grassroots initiatives at the local level, and that such an approach has the greatest sense in the long-term implementation of the EU energy strategy [111–114]. It should be emphasized that it is not possible to determine what effect energy transformation will bring for the economy and societies in the future. It may turn out that the suspension of the energy transformation processes will move from the one region to the entire member state, or that the economy of one of the countries or a group of countries will undergo a serious economic crisis. In such a situation, some countries will go back to the starting point, and the entire EU project will end in failure.

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# Forecasting Crude Oil Consumption in Poland Based on LSTM Recurrent Neural Network

**Anna Manowska** [1,*] **and Anna Bluszcz** [2]

[1] Department of Electrical Engineering and Automation in Industry, Faculty of Mining, Safety Engineering and Industrial Automation, Silesian University of Technology, 44-100 Gliwice, Poland
[2] Department of Safety Engineering, Faculty of Mining, Safety Engineering and Industrial Automation, Silesian University of Technology, 44-100 Gliwice, Poland; anna.bluszcz@polsl.pl
* Correspondence: anna.manowska@polsl.pl

**Abstract:** Primary fuels, i.e., crude oil, natural gas, and power coal, dominate the total global demand for primary energy. Among them, crude oil plays a particularly important role due to the universality of applications and the practical lack of substitutes in transport. Crude oil is also one of the main sources of primary energy in Poland and accounts for around 30% of the energy consumed. Poland covers only 3% of its needs from domestic deposits. The rest is imported from Russia, Saudi Arabia, Nigeria, Great Britain, Kazakhstan, and Norway. Due to such a high import of raw material, Poland must anticipate future demand. On the one hand, this article aims to analyze the current (2020) and future (2040) crude oil consumption on the Polish market. The study analyzes the geopolitical and economic foundations of the functioning of the energy raw-materials market, the crude oil supply, the structure of Poland's energy mix, and assumptions about the energy policy until 2040. On the other hand, conclusions from the research were used to build a model of crude oil consumption for the internal market. It has been also shown that the consumption of crude oil on the Polish market is a nonlinear phenomenon with a small set of statistical data, which makes it difficult to build an accurate model. This paper proposes a new model based on artificial neural networks that includes long-term memory (LSTM). The accuracy of the constructed model was assessed using the MSE, Theil, and Janus coefficients. The results show that LSTM models can be used to forecast crude oil consumption, and they cope with the nonstationary and nonlinear time series. Many important contemporary problems posed in the field of energy economy are also discussed, and it is proposed to solve them with the use of modern machine-learning tools.

**Keywords:** crude oil consumption; crude oil trade; energy markets; machine learning; LSTM

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## 1. Introduction

Over the last century, there has been a significant technological development encompassing virtually all aspects of human life. This development has resulted in a rapid improvement in living conditions in the vast majority of countries. Such a favorable development would be impossible without energy, and the growing demand for energy has led to the discovery of new sources [1–4] and the development of new energy technologies [5–7]. Access to energy is the basis of global economic growth and societal development [8–12]. The transport sector also plays a vital role in accelerating economic activity for economic development [13]. Most of the significant changes result from globalization processes. These processes have resulted in a significant increase in the interdependence between all markets [14–17], and, additionally, have influenced change in consumption patterns [18–21] and the labor market [22–27]. In addition, many countries in Europe and around the world are rebuilding their energy systems under the influence of the increasingly stronger impact of globalization processes, which include shaping national energy strategies aimed at European Union (EU) climate and energy policy, including its long-term vision of striving for EU climate neutrality by 2050, and regulatory mechanisms stimulating the achievement of such effects in the coming decades [28]. Achieving a reliable energy supply and environmental sustainability have become a global effort [29,30]. Achieving the EU's 2020 and 2030 climate and energy goals is key to a low-carbon energy transition, and this also applies to the transport sector, which is in the process of leading shifts in an attempt to alleviate the problems of climate change and air pollution [31]. In connection with the implementation of the ambition to decarbonize, the EU is also notable regarding the trend connected with the development of entrepreneurship directed to the production of green energy [32–43]. Undoubtedly, an important role is played here by business angels and the creation of sustainable start-ups [44–50]. The second course of action is to focus on grassroots civic initiatives. Adequately targeted activities at the local level can play a key role in the community's approach to develop energy production [51–54]. Renewable energy cannot replace fossil fuels in all sectors of society. Currently, barriers in the transport sector mean that crude oil will remain the dominant fuel.

As an important component of energy structure, the production and consumption of oil can drive or inhibit economic development. Poland is a strongly developing country in terms of economic growth, with changes in the structure of its consumption expenditure, but also with the development of and an increasing dependence on oil resources [55–59]. The imbalance of supply and demand for crude oil is becoming more and more apparent. Moreover, there are no reliable studies related to the forecasting of crude oil consumption on the Polish market. Forecasting the demand for crude oil is an important part of developing a strategy for the development of the market for this commodity, so reasonable and accurate analyses of crude oil consumption are needed, not only to protect Poland's energy security [60] but also to effectively prevent bottlenecks in supplies and for the implementation of the Polish crude oil supply [60]. Sustainable and rapid development will have a significant impact on these processes. Rapidly growing energy consumption in Poland and structural changes still threaten the security of raw material supplies. Therefore, it is expected that effective methods of meeting the demand for crude oil will become the basis for formulating the policy of security for the energy supply and will directly affect the stability of social production and national energy security. They will also help Poland establish an independent oil- and energy-sector-forecasting mechanism, to achieve an effective market transformation. These are the main research questions that can be found in the literature on the subject, and the answers to them can be found in this article.

The demand for crude oil, which is one of the most important strategic raw materials in the world, has always been treated as a very difficult research task that has attracted the interest of scientists, practitioners, and many research institutions. The size of this demand depends on the price, supply [61,62], and irregular and unpredictable events [63]. Many factors, such as gross domestic product growth, stock levels, exchange rates, technology development, and substitute primary fuels, affect its size [64–67] and make the process non-stationary [68,69].

Most crude oil consumption is in the transport and heating sectors. Therefore, crude oil supplies must be undisturbed, and this poses a challenge to the modern management of the Polish resource economy. Forecasting oil consumption is fundamental to natural fuel management. Unfortunately, there are no studies related to forecasting crude oil consumption in the domestic and international literature. Okulski et al. [70] discussed the factors influencing the Polish and global crude oil markets. They indicated that almost all oil in Poland is imported, despite the fact that Poland has its own deposits. Kamyk et al. [71] analyzed the possibilities of domestic oil production and the directions of diversification of imports to Poland. The remaining research is related to the analysis of the primary structure of the energy mix, though the latest research comes from 2017 [72–74].

In order to narrow these gaps, in this article we present a model for forecasting crude oil consumption on the Polish market.

The research hypothesis adopted in this article is the development of a reliable model of crude oil consumption on the Polish market, which can be used to forecast the demand for the raw material. This model will allow for the development of credible strategies for the further development of the oil sector, as well as the energy sector.

The available forecasts will allow for effective management of the operational efficiency of the fuel sector and will contribute to the reduction in operating costs.

The novelties of this study are:

- the development of an innovative model based on LSTM artificial neural networks used to forecast oil demand;
- according to the authors' knowledge, this is the first study that uses deep learning methods to forecast the demand for crude oil on the Polish market;
- this is the first study to confirm that LSTM artificial neural networks can be used to predict mal-numerical, non-stationary statistical datasets.

The document is organized as follows: the second chapter describes the geopolitical and economic foundations of the energy-raw-materials market, the third chapter describes the supply of primary energy, the fourth chapter describes the crude oil market, and the energy structure of Poland is analyzed in chapter five.

## 2. Geopolitical and Economic Foundations for the Functioning of the Energy-Resources Market

The main trend in the global energy market is the increase in energy demand, as shown in Figure 1. World energy consumption is expected to increase by 29% over the period 2021–2050 [75]. The distribution of global energy demand will vary. A steady level of demand will be maintained in most European countries, Japan, South Korea, and North America, and there will be a large increase in consumption in the rest of Asia (60% of the global increase in demand), Africa, the Middle East and South America. Moreover, according to these forecasts, by 2050 the share of individual energy resources in global production is to change from the current state, in which 31.3% is crude oil [76], 27.2% hard coal, and 24.7% natural gas, to the same in which global energy production will be divided into almost equal parts between oil, natural gas, hard coal, and low-carbon energy sources. This means that demand for natural gas will grow at the fastest rate of all fossil fuels, by more than half, and the increasingly flexible global trade in liquefied natural gas (LNG) will offer some protection in the event of a supply disruption. The main regions that will increase global demand for natural gas are forecasted to be China and the Middle East, and unconventional gas is expected to account for almost 60% of global production growth. On the other hand, the use of coal in the future, despite its large resources and occurrence on all continents, may be gradually reduced due to steps being taken to tackle the problem of environmental pollution and reduce $CO_2$ emissions. Even so, global coal demand will increase by 15% by 2040. Similarly, the global demand for oil will increase (by less than 14%).

In 2020, primary energy consumption fell by 4.5%, the first decline in energy consumption since 2009. The decline was mainly driven by oil (−9.7%), which accounted for almost three-quarters of the decline. The consumption of all fuels decreased, except for renewable energy (+9.7%) and water (+1.0%). Consumption declined in all regions, with the largest declines in North America (−8.0%) and Europe (−7.8%). The lowest decline was in the Asia-Pacific region (−1.6%) due to growth in China (+2.1%), the only country where energy consumption increased in 2020. In other regions, consumption fell by −7.8% in South and Central America and fell to −3.1% in the Middle East, as shown in Figure 2.

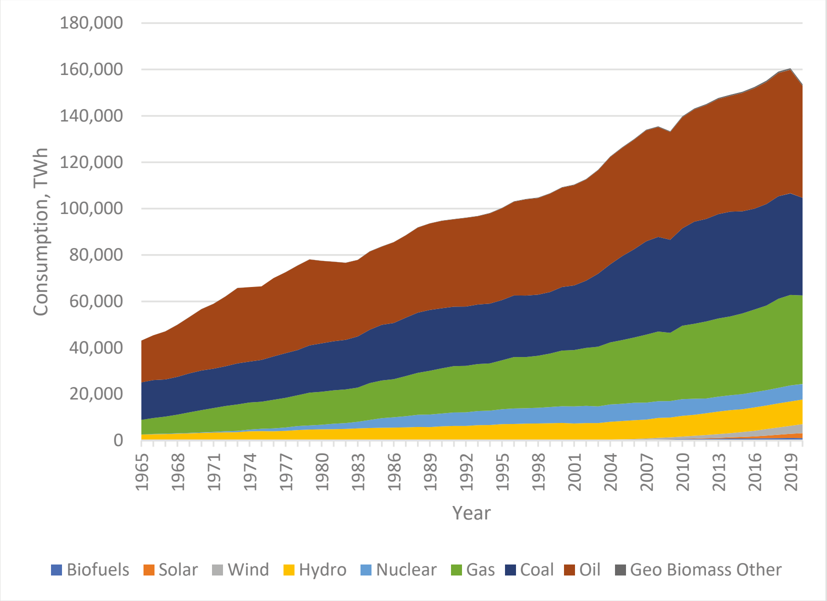

**Figure 1.** Consumption of energy resources in the world, own study based on [77].

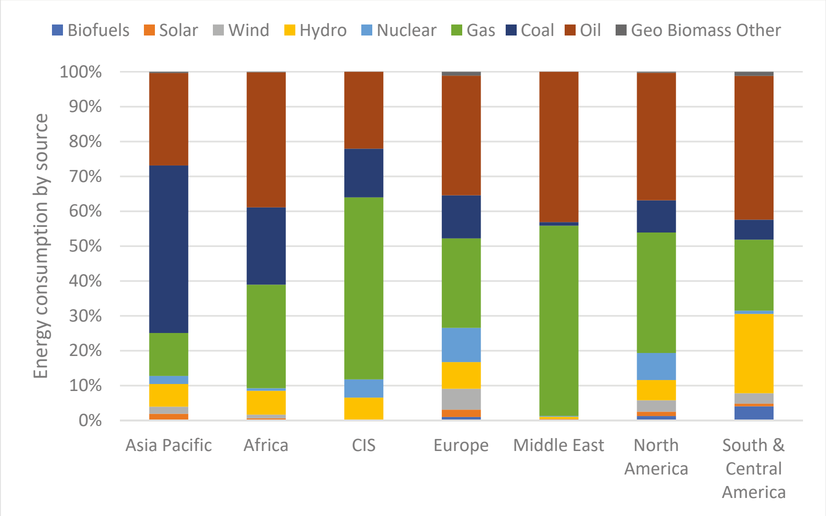

**Figure 2.** Global energy consumption in 2020, own study based on [77].

The presented forecasts show that despite the growing demand for energy resources, the structure of the trade in them will not change. Currently, the (net) import of energy resources on a global scale covers about 25% of the total demand for them, while the import of crude oil covers 55% of the demand for this raw material in the world, the import of natural gas covers 30% of the demand for natural gas, and the share of coal imports in the total demand for coal accounts for 18% [77].

### 2.1. Primary Energy Supply

In the global primary energy balance, the main sources of energy are oil, coal, natural gas, nuclear energy, and renewable energy. In 2020, the world consumption of primary energy amounted to 557.10 exajoules (EJ) [77] and, compared to 1990, it increased by 52%, while compared to 2019, it decreased by 5%. The increase in the total supply of primary energy in the period 1990–2020 is mainly due to its increase (by over 90%) in non-OECD countries. In contrast, in OECD countries in the years 1990–2020, this increase was only 16%. Until 2008, a systematic increase in the total supply of primary energy in these countries could be observed, and it declined after 2008, probably due to the global economic crisis and the decline in GDP. Another factor contributing to the reduction in the demand for primary energy may be the improvement of energy efficiency. A similar tendency in the supply of primary energy could be observed in European Union countries. In 1990, the supply of primary energy was 254 EJ, in 2019—606 EJ. Table 1 presents the volume of primary-energy demand in the years 1990–2020, broken down by individual types of energy carriers. In turn, Table 2 presents the share of individual energy carriers in the total primary-energy supply in the years 1990–2020. The share of individual energy carriers in the total world demand for primary energy in 2020 was as follows: crude oil constituted the source of approx. 31% of primary energy, coal—29%, natural gas—approx. 21%, nuclear energy—approx. 5%, and renewable energy sources—around 13%.

**Table 1.** Primary energy supply in particular years of the period 1990–2020.

| Energy Resource [EJ] | 1990 | 2000 | 2010 | 2020 |
|---|---|---|---|---|
| Coal | 93 | 96.9 | 153 | 162.4 |
| Oil | 135.3 | 153.6 | 167.6 | 187.4 |
| Natural gas | 69.6 | 86.6 | 114.4 | 140.8 |
| Nuclear energy | 22 | 28.3 | 30.1 | 30.5 |
| Hydro | 7.7 | 9.4 | 12.4 | 12.5 |
| Biofuels and waste | 38.2 | 41.5 | 49.1 | 15.2 |
| Other | 1.8 | 2.6 | 4.7 | 16.5 |
| **Total** | **367.6** | **418.9** | **531.3** | **568** |

Source: (own elaboration).

**Table 2.** The share of individual energy carriers in the total primary-energy supply (in %) in particular years of the period 1990–2020.

| Energy Resource [EJ] | 1990 | 2000 | 2010 | 2020 |
|---|---|---|---|---|
| Coal | 25% | 23% | 29% | 29% |
| Oil | 37% | 37% | 32% | 33% |
| Natural gas | 19% | 21% | 22% | 25% |
| Nuclear energy | 6% | 7% | 6% | 5% |
| Hydro | 2% | 2% | 2% | 3% |
| Biofuels and waste | 10% | 10% | 9% | 3% |
| Other | 0% | 1% | 1% | 3% |

Source: (own elaboration).

In the years 1990–2020, the share of crude oil in the demand for primary energy decreased from 37% to 33%. This decrease concerned both non-OECD countries, OECD countries, and the European Union. However, despite the decline in the share of crude oil in the supply of primary energy, in the years 1990–2020 in non-OECD countries the demand for primary energy obtained from crude oil increased by as much as 68%. On the other hand, in the case of OECD and European Union countries, until 2008 the share of crude oil in the demand for primary energy was growing year by year, and after 2008 it was systematically dropping. On the other hand, contrary to the energy policy expressed in the Kyoto Protocol, aimed at limiting $CO_2$ emissions, which should reduce the use of coal as a primary energy source, there has been an increase in the share of coal in the demand for primary energy. In the years 1990–2020, this share increased from 25% to 29%. However, it should be noted that the indicated increase was in countries outside the OECD area. In these countries, the share of coal as a primary energy source increased from 28% in 1990 to 37% in 2012. In 1990, the total supply of primary energy obtained from coal was 1150.1 Mtoe and increased in 2012 to 2858.6 Mtoe, i.e., by about 150%. On the other hand, in OECD countries, the share of coal in the demand for primary energy decreased from 24% in 1990 to 17% in 2020. An even greater decline in the share of coal as a primary energy source can be noticed in European Union countries: from 28% in 1990, it dropped to 14% in 2020. Nominally, the demand for primary energy from coal also decreased by about 35%, from 455.6 Mtoe in 1990 to 294 Mtoe in 2012. This is probably related to the energy policy in the European Union concerning the reduction in $CO_2$ emissions. The share of gas as a source of primary energy in the world in the years 1990–2020 remained at a similar level and amounted to approximately 21%. In 2020, the global demand for primary energy obtained from natural gas reached 25% and increased by about 6% compared to 1990. This increase was mainly due to the increase in demand for primary energy obtained from natural gas in non-OECD countries. In OECD countries, this increase was lower, and in European Union countries, the demand for primary energy obtained from natural gas increased until 2010, to fall below the level recorded in 2000 in the last two years. As in the case of natural gas, the share of nuclear energy and energy from renewable sources in the total supply of primary energy remained at a constant level in the years 1990–2010. The share of nuclear energy was about 6%, and energy from renewable sources was 10%.

### *2.2. Crude Oil Market*

Currently, conventional and unconventional crude oil resources are estimated at 331 trillion tons, which is only 3.4% of the world's energy resources [78], including 161 trillion tons of conventional crude oil (1.3%) and 170 trillion tons of non-conventional oil resources (2.1%). In turn, crude oil reserves amount to 217 trillion tons, which accounts for 23.7% of the world's reserves of energy resources, of which 168.7 trillion tons are conventional reserves (17.7%), and 47.9 trillion tons are unconventional reserves (5.0%). It was estimated in 2013 that the largest reserves of crude oil (conventional and unconventional) are located in Venezuela (17.7% of the world's resources in 2013) [77] and in the Middle East (Saudi Arabia—15.8%, Iran—9.3%, Iraq—8.9%, Kuwait—6.0%, United Arab Emirates—5.8%, and Qatar—1.5%). This means that the Persian Gulf countries belonging to OPEC account for 47.2% of the world's crude oil reserves, and the remaining six OPEC countries account for 24.7% of the world's crude oil reserves. Large oil reserves in 2013 are also in Canada (10.3%) and Russia (5.5%). The group of countries where the percentage share in the world's crude oil resources ranges from 1% to 3% includes: Libya—2.9%, the United States—2.6%, Nigeria—2.2%, Kazakhstan—1.8%, and China—1.1% [79].

World crude oil production in 1990–2020 was systematically increasing year by year (except for declines in 2002, 2007, 2009, and 2020). In 2020, it amounted to 4141 Mt and, compared to 1990, it increased by about 30%, while compared to 2000, it increased by about 14%. In the years 2000–2020, OPEC countries produced about 42–44% of global crude oil, thanks to which they had a decisive influence on the international crude oil market. On the other hand, in recent years, the production of crude oil in OECD countries was at the level of about 21–23% of world production. In 2020, US oil production (17% of global production in 2020) decreased by 3.4%, further widening the gap with Saudi Arabia as the largest oil producer, with the US producing 42% more oil than Saudi Arabia. Overall, oil production fell −8.8% in the Middle East, including −7% in Saudi Arabia, 8.6% in Russia and 14% in Nigeria. In Canada, it fell by 4.5%, but it increased by 1.6% in China and 7.1% in Brazil [80]. Figure 3 shows the volume of world oil production in particular years.

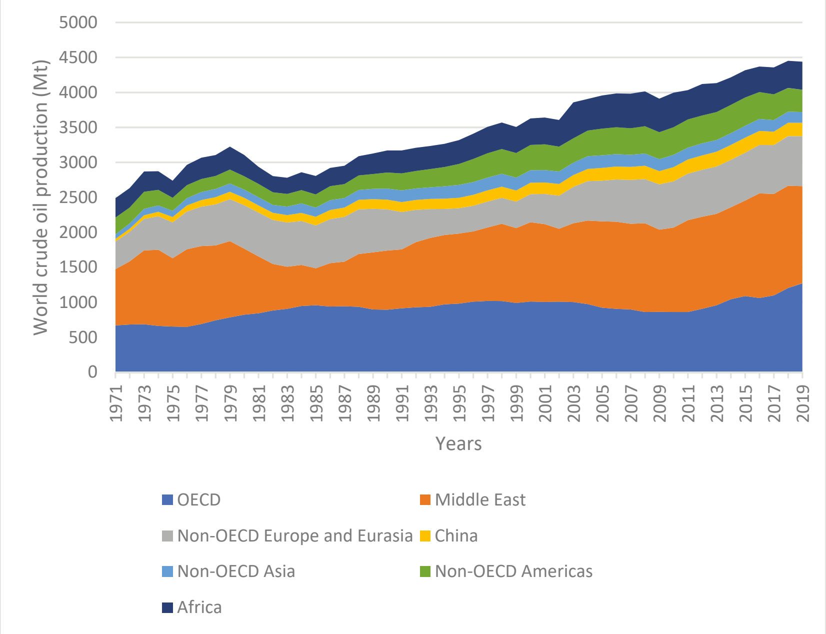

**Figure 3.** World crude oil production in particular years of the period (Mt), own study based on [77].

Crude oil production is concentrated in the Persian Gulf region, mainly in Saudi Arabia (16.2% in 2020) [81], Iran (9.5%), the United Arab Emirates (6%), Iraq (8.7%), and Kuwait (6%). This means that in 2020 the share, in the total production, of the five largest oil producers among the OPEC countries was approximately 30%. The top ten producers also include Russia, the United States, China, Canada, and Mexico. The total share of the 10 largest crude oil producers in the world production in 2020 was approximately 65%. This share was also at a similar level in 1990—67.5% and in 2000—61.6%. Crude oil turnover on international markets in the years 2000–2020 accounted for approximately 53–55% of the world's crude oil supply. In 2020, the world exports of crude oil amounted to 2174.6 million tons and, compared to 1990, its value increased by 41%, and compared to 2000—only by 10%. It is worth noting here that in the years 2000–2008 an increase in exports was observed, then its decline, caused by the global financial crisis, and a renewed increase after 2010. The main oil exporters were non-OECD countries, and the volume of these countries' exports accounted for approximately 83% of total exports. On the other hand, the recipients were OECD countries, in particular the United States, European countries and Japan. It should also be emphasized that the volume of exports of the 12 countries belonging to OPEC in the years 2000–2012 ranged from 54–58% of total exports. The main crude oil suppliers in the world in 2020 were the countries of the Persian Gulf region (Saudi Arabia—352 Mt, Iraq—195 Mt, United Arab Emirates—148 Mt, Kuwait—102 Mt). These countries mainly supplied oil to the American, Japanese, Chinese, Western European and Southeast Asian markets. The second largest exporter of crude oil was Russia (269 Mt). It supplied rope to the European, Chinese and American markets. The group of big exporters in 2020 also includes: Canada (154 Mt), Nigeria (99 Mt), Angola (63 Mt) and Kazakhstan (70 Mt). The exports of the 10 largest suppliers of crude oil in the years 1990–2020 amounted to approximately 67–70% of world exports. In turn, the largest recipients of crude oil in 2020 were China (505 Mt), India (227 Mt), the United States (202 Mt), Japan (149 Mt), and South Korea (145 Mt). European countries also had a significant share in the import of crude oil, including Germany, Italy, Spain, Great Britain, and the Netherlands.

Various types of crude oil are traded on international markets, differing in both their quality and access to markets. From the point of view of global economic (and financial) turnover, the most important are the following types of oil, which are assigned price indices: Brent, WTI, and the so-called OPEC basket, followed by Dubai Fateh and Russian crude oil. Brent crude oil consists of several types of crude oil extracted in the North Sea region. Its sulfation is slightly greater than that of WTI. This crude oil is refined in northern Europe, in the Mediterranean, and on the US East Coast. Brent's blend is listed, inter alia, on the London LSE and the International Oil Exchange (IPE) in London, and Brent oil futures are also traded on the NYMEX New York Stock Exchange. West Texas Intermediate (WTI) is a very high quality, low sulfur crude oil. Its quality and place of occurrence (i.e., Texas) mean that it is refined in the United States. Crude oil of the WTI type is listed on the New York Stock Exchange NYMEX [82]:

- The OPEC Reference Basket is the weighted average of crude oil types sourced from OPEC countries. The basket includes: Saharan Blend (Algeria), Minas (Indonesia), Iran Heavy (Iran), Basra Light (Iraq), Kuwait Export (Kuwait), Es Sider (Libya), Bonny Light (Nigeria), Qatar Marine (Qatar), Arab Light (Saudi Arabia), Murban (United Arab Emirates), and BCF 17 (Venezuela).
- Dubai Fateh (Dubai Crude) is oil extracted from Dubai. Until June 2005, it was part of the OPEC basket. It is also used as a reference price for the export of raw materials to the Far East.
- Ural oil is one of the four types of Russian oil. It is a mixture of deposits, mainly from Western Siberia, the Ural Mountains, and the Volga region, and is a reference point for establishing the export price of Russian crude oil. It is listed on the Russian stock exchange. The counterpart of Ural crude oil, listed on the New York Stock Exchange NYMEX, is Rebco crude oil (Russian Export Blend Crude Oil). Brent, WTI, and Dubai Fateh oil prices play a major role.

### *2.3. Poland's Energy Structure*

The European Union (EU) currently has (as of June 2021) greenhouse gas (GHG)-emission-reduction targets adopted in the energy and climate framework until 2030. GHG-emission-reduction targets have been set in such a way that the EU is on the on the road to a low-carbon economy, as presented by the European Commission (EC) in its Communication on a long-term vision for 2050. The EU level target of reducing GHG emissions in 2030, by at least 40% by 2030 compared to 1990, was declared as an EU contribution (NDC) under the Paris Agreement. On 12 December 2019, the European Council adopted the Communication European Green Deal (European Green Deal, EU Green Deal, EGD). In total, it covers 48 activities in various fields—from the energy sector, through agriculture and transport to society's participation in the fight against climate change. The main goal was to achieve climate neutrality in the European Union by 2050. According to the above document, the new GHG-emission-reduction target for the European Union for 2030 should be in the range of 50% to 55% compared to 1990. Such an approach was repeated in the draft European Climate Law, published on 4 March 4 2020. During subsequent discussions in 2020 and 2021, both the Council and European Parliament increased the target value for 2030. As part of the consensus reached in April 2021, the provision on the target by 2030 says at least a 55% net emission reduction compared to 1990, clearly spelling out both emission reductions and removals. Poland, as an EU member state, on the one hand has the right to shape its energy mix in an autonomous way, while on the other hand must submit to the requirements of the energy and climate policy developed within the EU. In Poland, the key strategic document of the government that tries to reconcile these challenges is the Energy Policy of Poland (PEP), prepared on the basis of the Energy Law of 10 April 1997 (Journal of Laws of 2021, item 716, as amended) [83]. The last document of this type was adopted by the Council of Ministers in 2021. "Poland's Energy Policy until 2040 (PEP2040)" includes in its assumptions the necessity to ensure energy security, fair transformation, sustainable development of the economy, and strengthening of its competitiveness [60].

In addition, as part of the obligation imposed on the EU Member States, the National Energy and Climate Plan for 2021–2030 (NECP) [79] was developed. The development of the NECP results from the Regulation of the European Parliament and of the Council (EU) 2018/199911.

Poland's primary energy structure is definitely different from other European Union countries due to the significant share of coal. The most important factors that determine the shape of Poland's energy balance are the following factors [60]:

- natural—the dominance of hard coal and lignite resources;
- political—no long-term coherent vision of energy policy;
- systemic—fully immature market economy;
- external—participation in world trade and transport of energy carriers;
- economic—relatively high prices, factors of electricity;
- technical and technological—an extensive mining base of solid fuels and new technologies of fuel use.

In the years 1990–2018, the production of primary energy has a moderate growing trend, as shown in Figure 4. The highest level of 104.96 Mtoe was recorded in 2018, while the lowest was 89.02 Mtoe in 2002. The current shape of the Polish energy mix is the result of socio-economic changes that were introduced after 1988 and pertained in particular to the mining sector.

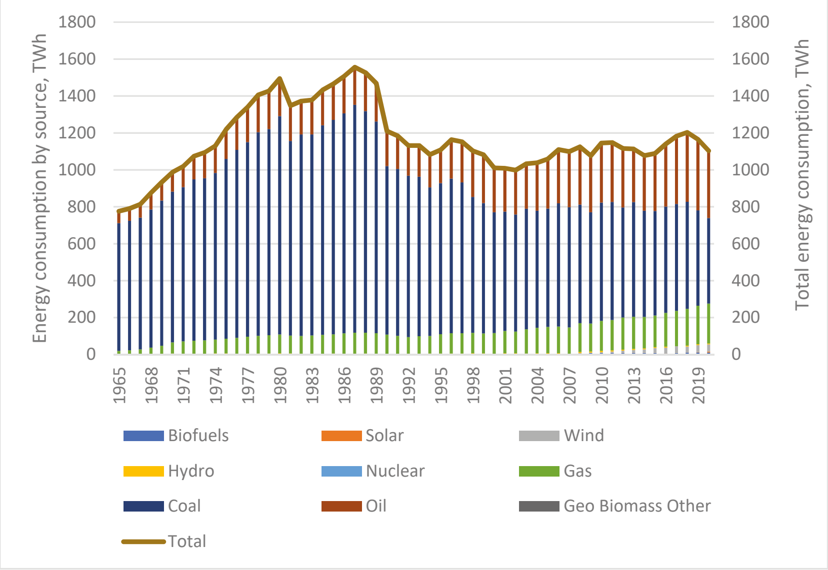

**Figure 4.** Primary energy production in Poland, own study based on [77].

The Polish resource base potential allows for domestic satisfaction of the demand for hard coal, lignite, and biomass, while the demand for natural gas and crude oil must mostly be covered by imports. Initiatives are currently underway to diversify the directions and sources of supplies, and efforts are still being made to search for domestic (also unconventional) deposits in order to replace the supply from depleted deposits. Part of the demand for crude oil and natural gas will be limited by the growing importance of biofuels and alternative fuels (including electricity, LNG, CNG, biomethane, hydrogen) [56]. Poland is to the greatest extent dependent on imported crude oil, therefore, in the short term it is necessary to ensure good conditions for crude oil reception and an efficiently functioning internal infrastructure. The possibilities of deliveries by sea will be increased thanks to the expansion of the Pomeranian Oil Pipeline and the storage bases of crude oil and liquid fuels. Deliveries of petroleum products depend on a properly developed network of pipelines, especially in the southern part of Poland, which will also be expanded, e.g., the Boronów-Trzebinia pipeline [60].

## 3. Materials and Methods

In the literature, many publications can be found related to forecasting the demand for fossil resources, but only a small part of the articles concern forecasting the demand for crude oil. There are many ways of forecasting the demand for energy resources, autoregressive and moving average (ARMA) models [84,85], generalized ARCH model [86], models of the stochastic effective function [87], and methods of forecasting time series through artificial neural networks [88–90]. Table 3 summarizes existing research on fossil fuel consumption forecasting.

**Table 3.** A summary of existing studies on forecasting of natural gas consumption.

| Autor(s) | Goal | Method |
|---|---|---|
| Wang et al. [87] | A new method of oil price forecasting | A combination of the FNN model and the stochastic time-effective function-WT-FNN |
| Wu et al. [91] | A new method of oil price forecasting | Social media information was used in convolutional neural network, which can finely reflect oil market factors and exogenous factors, such as conflicts and political instability. |
| Zhang et al. [92] | Predicted the predictability of market returns on oil futures | A principal component analysis (PCA) |
| Hamdi et al. [93] | They showed that the use of neural networks is the right choice due to the non-linear nature of crude oil prices | They compared traditional methods with econometric models and with artificial neural networks. |
| Anik et al. [94] | They forecasted the demand for primary energy, with particular emphasis on the demand for crude oil. | They used the Cobb–Douglas function for forecasting. |
| Manowska [88–90] | They analyzed the use of mathematical models to forecast fossil resources | In their works, they paid special attention to the non-stationarity of processes and the non-linear nature of their wear. They proposed the use of LSTM artificial neural net-works, which are highly effective in forecasting small-scale, non-linear data sets |

Artificial neural networks were used to forecast crude oil consumption. The model was selected after statistical analysis and determination of the characteristics of the time series. The statistical data were verified with the Augmented Dickey–Fuller (ADF) test, which is a standardized unit root test, and its results are interpreted by observing the $p$-value of the test. If the statistic is in the range of 1–5%, the null hypothesis is rejected, i.e., there is no unit root and the series is stationary. If $p$ is greater than 5%, the analyzed time series has a unit root, the series is non-stationary and will need to be differentiated to achieve this stationarity. The summary of the analysis is shown in Table 4. The $p$ value for all performed tests exceeds the adopted significance level of 5%, which means that there are no grounds to reject the null hypothesis. The analyzed time series does not meet the conditions of stationarity.

**Table 4.** Extended Dickey–Fuller test for oil-consumption time series.

Extended Dickey–Fuller test for the crude oil consumption process
the significance of the delay from the order of 10 was tested for the AIC criterion
sample size 51
Null hypothesis: unit root a = 1 exists; process I (1)

test with constant
for an order delay of the 4th process (1-L) of the crude oil consumption series
model: (1-L) y = b0 + (a − 1) ∗ y (−1) + . . . + e
the estimated value of (a − 1) is: −0.0094344
Test statistic: tau_c (1) = −0.432418
**asymptotic *p*-value = 0.9014**
First-order residual autocorrelation: 0.002
delayed differences: F (4, 45) = 5.135 [0.0017]

with a constant and a linear trend
for the first-order process delay (1-L) of the crude oil consumption series
model: (1-L) y = b0 + b1 ∗ t + (a − 1) ∗ y (−1) + . . . + e
the estimated value of (a − 1) is: −0.164256
Test statistic: tau_ct (1) = −3.03071
**asymptotic *p*-value = 0.1237**
First order residual autocorrelation: −0.056

with a constant, linear trend and square trend
for an order 2 (1-L) delay of the crude oil consumption series
model: (1-L) y = b0 + b1 ∗ t + b2 ∗ t ˆ 2 + (a − 1) ∗ y (−1) + . . . + e
the estimated value of (a − 1) is: −0.206229
Test statistic: tau_ctt (1) = −3.3558
**asymptotic *p*-value = 0.1539**
First-order residual autocorrelation: 0.014
delayed differences: F (2, 47) = 9.160 [0.0004]

The analysis was made in Gretl software for the adopted level of significance α = 0.05.

The consumption of crude oil on the Polish market is also a very complex issue related to the functioning of the energy-resources market. Anticipating factors influencing this consumption require many links between the constitutive elements and many feedback loops resulting from the actions taken, e.g., economic or political decisions with specific effects. All these features are characteristic of nonlinear time series [95]. In such a situation, a dynamic description of these data is usually very difficult, and sometimes impossible [96,97]. Artificial neural networks that allow non-linearities to be fully accounted for are helpful.

Machine learning is a subset of artificial intelligence that allows to perform the process of predicting outcomes without having to program them explicitly. In machine learning, algorithms are trained to find patterns and correlations in datasets and to make the best decisions and make predictions based on the results of such analysis. Machine learning—and its components, i.e., deep learning technology and neural networks—are concentrically overlapping subsets of AI [98–100]. AI processes data to make decisions and make forecasts. Machine-learning algorithms allow AI to additionally learn from this data and develop intelligence without the need for additional programming. Artificial intelligence is an overarching category over all subsets of machine learning. The first subset is machine learning, the next is deep learning, and within that are neural networks. A recursive neural network (RNN) is a type of artificial neural network that uses sequence data or time series data. These deep-learning algorithms are commonly used to solve order or time problems. Recursive neural networks are used to forecast time series. They use training data for learning. They are distinguished by "memory" because they retrieve information from previous inputs to influence the current input and output. While traditional deep neural networks assume that inputs and outputs are independent of each other, the outputs of recursive neural networks depend on prior elements in the sequence. While future events would also be helpful in determining the output of a given sequence, unidirectional recursive neural networks cannot account for these events in their predictions. One variation of RNN architecture is long-term memory (LSTM), which is specifically designed to avoid long-term dependency problems. Although LSTM is similar in structure to the RNN, the vanilla LSTM has three gates (i.e., input, forget, and output), block input, single cell, output activation function, and peephole connections [96]. LSTM was the first repeating network architecture to overcome the problem of gradient disappearance and explosion. The LSTM-forgetfulness gate determines what information is to pass through or is ejected from the cell state, the input gate determines what new information should be stored in the cell state, while the output gate regulates what each cell produces. Moreover, it will depend on the cell state, regarding filtered and newly added data.

The LSTM network computes the mapping from the input sequence x = (x1, . . . , xT) to the output sequence y = (y1, . . . , yT), by computing the network unit activation using the following iterative equations from t = 1 to T [101]:

$$f_t = \sigma_g(W_f x_t + U_f h_{t-1} + b_f) \quad (1)$$

$$f_t = \sigma_g(W_f x_t + U_f h_{t-1} + b_f) \quad (2)$$

$$o_t = \sigma_g(W_o x_t + U_o h_{t-1} + b_o) \quad (3)$$

$$\bar{c}_t = \sigma_h(W_c x_t + U_c h_{t-1} + b_c) \quad (4)$$

$$c_t = f_t \times c_{t-1} + i_t \times \bar{c}_t \quad (5)$$

$$h_t = o_t \times \sigma_h(c_t) \quad (6)$$

where conditions W and U are weight matrices, the b conditions are polarity vectors (bi is the input gate polarization vector), σ is the activation function, and i, f, o and c are input gates, forgotten gates, output gates and cell activation vectors, respectively, all of which are the same size as the activation vector of the starting cell, i.e., the result of the vectors.

Each theoretical model built depends on three factors:

- correct estimation of model parameters;
- applying the appropriate inference principle;
- make the right starting assumptions.

The correctness of the above-mentioned factors can be verified by assessing the accuracy and accuracy of the forecasts.

The degree of accuracy of the forecast will be measured using mean square error of ex post forecasts of formula [102]:

$$\mathrm{MSE} = \sqrt{\frac{1}{n}\sum_{t=1}^{n}(y_t - \hat{y}_t)^2} \quad (7)$$

n — number of observations of the forecast variable y;
$y_t$— actual value of the y variable in the period t = 1,2, . . . , n;
$\hat{y}_t$— forecast of the variable y determined in the period t.
Absolute error of ex post forecasts [102]:

$$\Delta_t = |y_t - \hat{y}_t| \quad (8)$$

Another frequently used factor to determine the quality of a prognostic model is Theil's coefficient, which is used to calculate the total relative forecast error during the testing period. It is expressed by the following formula [102]:

$$I^2 = \frac{\sum_{t=m+1}^{n}(y_t - \hat{y}_t)^2}{\sum_{t=m+1}^{n} y_t^2} \quad (9)$$

Theil's coefficient was broken down into factors.

The first factor informs about errors due to the bias of forecasts (failure to guess the average value of the forecast variable):

$$I_1^2 = \frac{\left(\bar{y}_t - \bar{y}_t{}^*\right)^2}{\frac{1}{n-m}\sum_{\tau = m+1}^{n} \bar{y}_t^{\cdot 2}} \tag{10}$$

where

$\bar{y}_l^{\cdot}$—average of crude oil consumption volume in the verification period;

$\bar{y}_l{}^*$—average of the forecasted crude oil consumption volume in the verification period.

The second factor informs about errors due to insufficient flexibility (failure to guess the fluctuations of the forecast variable):

$$I_2^2 = \frac{\left(s_r - s_p\right)^2}{\frac{1}{n-m}\sum_{t = m+1}^{n} y_t^2} \tag{11}$$

where

$s_r$—standard deviation of the actual values within the verification interval;

$s_p$—standard deviation of the forecast values in the verification range.

The third factor informs about errors due to insufficient compliance of the forecasts with the actual direction of changes of the forecast variable (failure to guess the direction of the development trend):

$$I_3^2 = \frac{2 \cdot s_r \cdot s_p \cdot (1 - r_w)}{\frac{1}{n-m}\sum_{t = m+1}^{n} y_t^2} \tag{12}$$

where

$r_w$—linear correlation coefficient between the actual and forecasted value in the verification interval.

Janus coefficient [102]:

$$J^2 = \frac{\frac{1}{n-m}\sum_{t = m+1}^{n}\left(y_t - \hat{y}_t\right)^2}{\frac{1}{n}\sum_{t=1}^{n}\left(y_t - \hat{y}_t\right)^2} \tag{13}$$

This coefficient determines the degree of adjustment of the forecasts and the model to the actual data in the verification interval. If its value is $J^2 \leq 1$, then it can be concluded that the current forecasts are correct and the model can be used for forecasting. The determination of the prediction errors shows that they are random variables. This means that they have their own probability distributions and their own distribution parameters.

## 4. Results and Discussion

In recent years, the demand for crude oil has increased along with the sustained and rapid development of the national economy in Poland. Poland does not have enough oil deposits to fully meet the demand. Since the 1990s, crude oil consumption has grown at an average annual rate of 5.77%. Oil self-sufficiency has become an important source of the imbalance between the supply and demand for crude oil in Poland.

The article analyzes the geopolitical and economic foundations of the functioning of the energy raw materials market, crude oil supplies, the structure of Poland's energy mix and the assumptions of the energy policy until 2040. The conclusions from the research were used to build a model of crude oil consumption in the internal market.

The analysis was conducted on the annual crude oil consumption data for Poland from 1965 to 2020. Table 5 shows the descriptive statistics of the analyzed phenomenon. The average crude oil consumption for Poland is 18.51 Mtoe, and it is close to the median of 17.51 Mtoe. The analyzed phenomenon has a platokurtic distribution. The entire dataset is positively skewed.

**Table 5.** Descriptive statistics.

| **Measures** | |
|---|---|
| Mean | 18.51 |
| Standard error | 0.92 |
| Median | 17.51 |
| Standard deviation | 6.74 |
| Sample variance | 45.42 |
| Kurtosis | −0.51 |
| Skewness | 0.09 |
| Range | 27.28 |
| Minimum | 5.54 |
| Maximum | 32.82 |
| Quantity | 55.00 |
| The largest | 32.82 |
| The smallest | 5.54 |
| Confidence level (95.0%) | 1.84 |

Source: (own elaboration).

The theoretical model of oil consumption was built on the LSTM artificial neural network, and it was used in place of the traditional recursive networks as this architecture overcomes the limitations of traditional time-series-forecasting techniques. Each LSTM block runs at a different time step and forwards its output to the next block, until the last LSTM block produces the sequential output. The core element of an LSTM network are memory blocks, which were invented to deal with fading gradients by remembering network parameters over a long period of time.

Data from 1965–2009 were used as a modeling sample. Meanwhile, in order to verify the predictive performance of the model, the actual data from 2010–2020 will be used as the comparative data for the performance of the model.

The crude oil consumption data were entered into the model as vertical vectors of the form:

$$\mathbf{X_{we}} = \begin{bmatrix} x_o \\ \vdots \\ x_n \end{bmatrix} \tag{14}$$

The statistical data has been divided into two sets: the training dataset and the test dataset (70%, 30%). These data were transformed into an input data matrix of the form:

- training data:

$$\mathbf{X_{we}} = \begin{bmatrix} x_0 & \cdots & x_{n\,-\,t} \\ \vdots & \vdots & \vdots \\ x_{k\,-1} & \cdots & x_{n\,-\,t\,+\,k\,-1} \end{bmatrix} \quad \mathbf{Y_{wy}} = \begin{bmatrix} x_k \\ \vdots \\ x_{n\,-\,k\,-1} \end{bmatrix} \tag{15}$$

- test data:

$$\mathbf{X_{wet}} = \begin{bmatrix} x_{n\,-\,t\,+1} & \cdots & x_{n\,-\,k} \\ \vdots & \vdots & \vdots \\ x_{n\,-\,t\,+\,k} & \cdots & x_{n\,-1} \end{bmatrix} \quad \mathbf{Y_{wy}} = \begin{bmatrix} x_{n\,-\,k} \\ \vdots \\ x_n \end{bmatrix} \tag{16}$$

where:

n—absolute number;
k—delay;
t—number of test data.

The network was implemented in the TensorFlow environment. The statistical data are entered into the LSTM network, according to the dependencies (15) and (16). The model is designed from the input LSTM and the hidden dropout to the output dense layer, according to Table 6.

**Table 6.** Model: "sequential".

| Layer (Type) | Output Shape | Param |
|---|---|---|
| lstm (LSTM) | (None, 3, 3) | 60 |
| dropout (Dropout) | (None, 3, 3) | 0 |
| lstm_1 (LSTM) | (None, 1) | 20 |
| dense (Dense) | (None, 1) | 2 |

Total params: 82; trainable params: 82; non-trainable params: 0.

The key to LSTM is the state of the "Ct" cell. This state is modified by the forget function, according to the dependence (1), and the input functions "it", "xt", and "c$\bar{t}$", according to the dependencies (2)–(4). The cell output is derived from the cell state "ct" using the output relationship (5). The model was trained on 40 pieces of data using cross entropy and Adam's optimization over 24 epochs. In total, 30% of the data were used for model validation. After obtaining a statistically significant match, ex post forecasts were generated. The network results were analyzed according to the dependences (7) and (8). If this stage is successful, long-term forecasts can be generated and checked for statistical correctness in accordance with the dependencies (10)–(12). Moreover, in order to relate the theoretical results to the current state of the process and relate them to a common-sense horizon, the ex post forecasts were analyzed using the Janus coefficient (Formula (13)).

Table 7 shows the program code that was written for the LSTM network. The next steps of the algorithm are presented in the left column.

**Table 7.** Program listing.

**A Recurrent Neural Network (LSTM) Implementation Using TensorFlow Library**

Loading and reading the data file

```
from google.colab import files
uploaded = files.upload()
df = pd.read_csv(io.BytesIO(uploaded['XXX.csv']))
df.head()
```

Function that sets the training vectors according (15) and (16)

```
def univariate_data(dataset, start_index, end_index, history_size, target_size):
data = []
labels = []
start_index = start_index + history_size
if end_index is None:
end_index = len(dataset)-target_size
for i in range(start_index, end_index):
indices = range(i-history_size, i)
Reshape data from (history_size,) to (history_size, 1)
data.append(np.reshape(dataset[indices], (history_size, 1)))
labels.append(dataset[i + target_size])
return np.array(data), np.array(labels)
```

The amount of historical data downloaded for training

```
tf.random.set_seed(13)
uni_data = df['Crude Oil']
TRAIN_SPLIT = uni_data.shape [0]−1
uni_data.index = df['Year']
univariate_past_history = 3
univariate_future_target = 0
uni_data.head()
print(TRAIN_SPLIT)
uni_data.plot(subplots = True)
uni_data1 = uni_data
uni_data = uni_data.values
```

**Table 7.** *Cont.*

**A Recurrent Neural Network (LSTM) Implementation Using TensorFlow Library**

Network training

```
train_univariate = tf.data.Dataset.from_tensor_slices((x_train_uni, y_train_uni))
train_univariate =
train_univariate.cache().shuffle(BUFFER_SIZE).batch(BATCH_SIZE).repeat()
val_univariate = tf.data.Dataset.from_tensor_slices((x_val_uni, y_val_uni))
val_univariate = val_univariate.batch(BATCH_SIZE).repeat()
simple_lstm_model = tf.keras.models.Sequential([
tf.keras.layers.LSTM(3, input_shape = (x_train_uni.shape [1],x_train_uni.shape [2]),
return_sequences=True),
tf.keras.layers.LSTM(1, input_shape = (x_train_uni.shape [1],x_train_uni.shape [2]),
return_sequences=False),
tf.keras.layers.Dropout(rate = 0.03),
tf.keras.layers.LSTM(1,activation = ‘relu’),
tf.keras.layers.Dropout(rate = 0.3),
tf.keras.layers.Dense(1)
])
simple_lstm_model.compile(optimizer = ‘adam’, loss = ‘mae’)
simple_lstm_model.fit(train_univariate, epochs = EPOCHS, steps_per_epoch =
EVALUATION_INTERVAL, validation_data = val_univariate, validation_steps = 50,
callbacks = [tensorboard_callback])
```

Prediction for test data

```
result = []
print(“Model prediction on test data “)
for i in range(x_train_uni.shape [0]):
for j in range(univariate_past_history):
x_val_uni [0,:,0] = x_train_uni[i,:,0]
val_univariate = tf.data.Dataset.from_tensor_slices((x_val_uni, y_val_uni))
val_univariate = val_univariate.batch(BATCH_SIZE).repeat()
x,y = val_univariate.take(2)
predykcja = simple_lstm_model.predict(x [0])
wynik = np.append(wynik,predykcja [0])
print(predykcja [0])
pandaresalt = pd.DataFrame(resalt)
pandaresalt.plot(subplots = True)
uni_data2 = uni_data1[univariate_past_history:uni_data1.shape [0]−1]
uni_data2.index = pandaresalt.index
uni_data2.plot(subplots = True)
```

Proper prediction

```
print(“Proper prediction “)
for k in range(35):
for m in range(univariate_past_history−1):
x_val_uni [0,m,0] = x_val_uni [0,m + 1,0]
x_val_uni [0,univariate_past_history−1,0] = predykcja [0]
val_univariate = tf.data.Dataset.from_tensor_slices((x_val_uni, y_val_uni))
val_univariate = val_univariate.batch(BATCH_SIZE).repeat()
x,y = val_univariate.take(2)
predykcja = simple_lstm_model.predict(x [0])
resalt = np.append(resalt,predykcja [0])
print(predykcja [0])
print(“Resalt “, i + 1, “forecasting”)
pandawynik = pd.DataFrame(resalt)
pandawynik.plot(subplots = True)
```

Figures 5 and 6 show the learning parameters of the network. Figure 5 shows the number of epochs that were used to learn the network. In total, 24 epochs were used and an error of 2% was obtained.

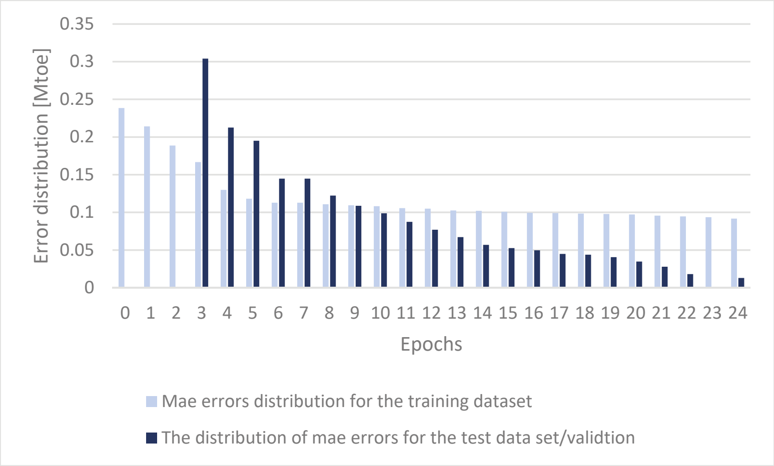

**Figure 5.** Distribution of LSTM network learning errors, own study.

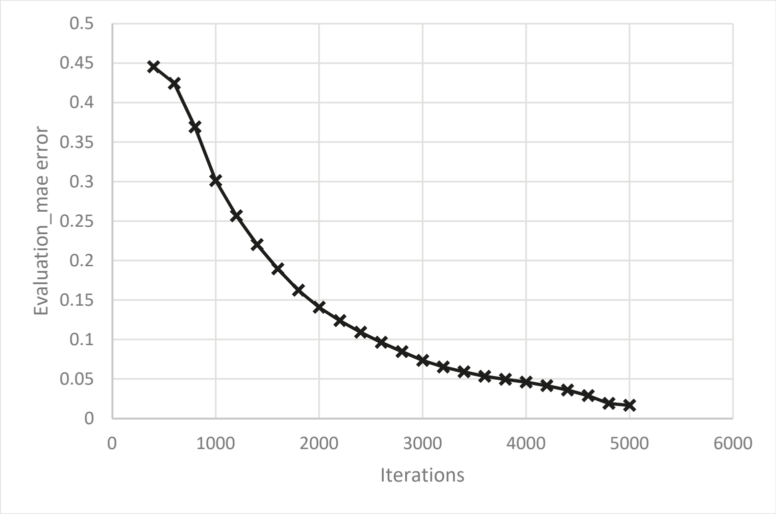

**Figure 6.** Evaluation loss vs. iterations, own study.

Figure 6 presents the reduction in the error as a result of successive iterations. We can see that this error decreases, which confirms that there has been no overfitting or reduction in the performance of the model.

The comparison of the theoretical and real values and the error distribution are shown in Figure 7.

The validity of the constructed model was assessed using the tools described in the Section 3. The average forecast error is −0.0505 Mtoe, which means that the forecasts are on average too high (overestimated). The mean absolute error of the ex post forecasts is 0.3069 Mtoe, while the root mean square error is 0.3995 Mtoe. The difference between the errors is 24%, which proves a significant variation in values. The average percentage error is 2%, which means that the model largely models the real course of crude oil consumption. The relative forecast error during the testing period is 0.16 Mtoe. The value of the Janus coefficient is 0.6, which means that the model can be used for forecasting until 2040. The forecasts generated by the model are shown in the Figure 8.

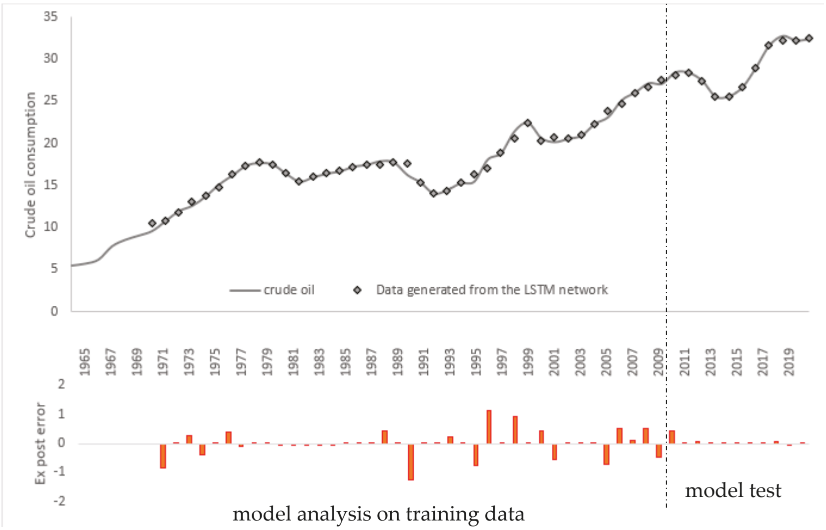

**Figure 7.** Theoretical model of crude oil consumption with analysis of errors, own study.

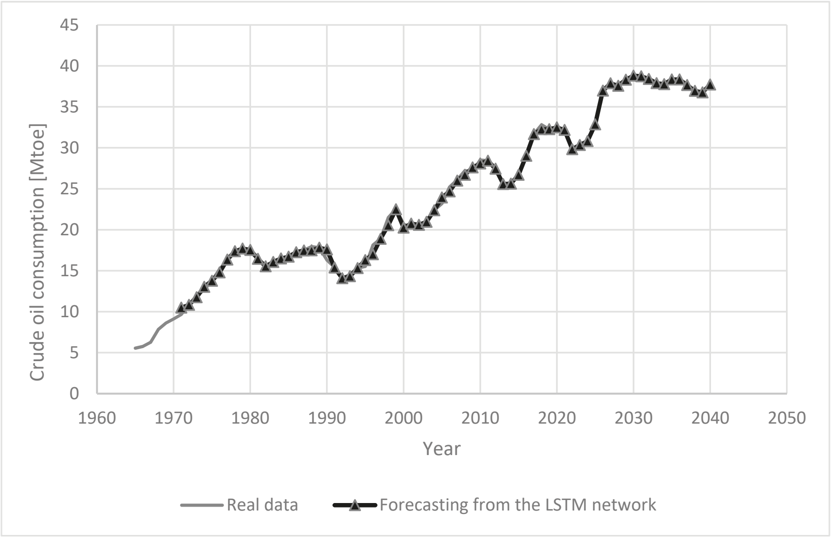

**Figure 8.** Forecasting crude oil consumption, own study.

The forecast of the demand for crude oil was developed until 2040 and with assumptions resulting from external conditions, via the government project of Poland’s energy policy—PEP2040, taking into account the specificity of the domestic resources held. The forecast assumes the implementation of the main goal, which is to increase the degree of diversification of the crude oil supply sources, understood as obtaining crude oil from different regions of the world, from various suppliers using alternative transport routes, and by building warehouses with capacities to ensure the continuity of supplies. According to the forecasts prepared, the demand for crude oil is growing. This is mainly due to the fact that there are no alternative fuels in the primary-energy mix that could reduce this demand. The issue of oil demand is currently one of the most important determinants of future oil price trends. The sharp increase is visible until 2030. The level of around 39 Mktoe remains until 2035 and then declines by around 6%, reaching the level of 37 Mktoe in 2040. Developed forecasts of oil consumption will allow for a rational transformation of the Polish primary-energy mix.

## 5. Conclusions

Forecasting the demand for crude oil is an important part of Poland's energy security and crude oil market-development strategy. A thorough analysis of crude oil needs can protect the country by providing an effective way to solve the oil-bottleneck problem. Taking into account the non-linear nature of the phenomenon of Polish crude oil consumption, a model based on artificial neural networks was proposed for forecasting. An LSTM structure was used, which is a type of recursive network that takes into account the time dependencies between the statistical data. As a result, these networks can be used for series forecasting. LSTM has three gates (i.e., input, forget, and output), block input, a single cell, an output-activation function, and peephole connections. LSTM is the first repeating network architecture to overcome the problem of gradient disappearance and explosion. The LSTM-forgetfulness gate determines what information is to pass through or be ejected from the cell state, and the input gate determines what new information should be stored in the cell state, while the output gate regulates what each cell produces. Moreover, it will depend on the cell state, regarding filtered and newly added data. On this basis, the consumption of crude oil in Poland in the years 1965–2040 was forecasted. The forecasts presented in this study are based on the business-as-usual scenario, meaning that the forecasts are based on the observed trend and do not take into account future changes due to the political regime. On the basis of the obtained forecast results, the demand for crude oil will increase in Poland until 2030, to 39 Mktoe. Thereafter, it will moderately decline by around 2%, reaching 37 Mktoe in 2040.

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