

MEASURING ENERGY POTENTIAL IN THE CONTEXT OF ENVIRONMENTAL TRANSFORMATION – PROPOSED METHODOLOGY, PROSPECTS AND CHALLENGES

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Purpose: The theoretical goal of this article is to present a model for measuring countries' energy potential based on the definition of potential derived from physics. The empirical goal is to conduct analyses assessing the dynamics of changes in Poland's energy production structure and the state of Poland's energy balance, to calculate Poland's energy potential for 2018-2024, to critically assess Poland's energy self-sufficiency, and to draw conclusions and recommendations regarding Poland's energy security in the coming years given the threats of the modern world.

Design/methodology/approach: A time-dependent concept of a country's energy potential was defined, allowing for the analysis of the availability of domestic and foreign energy resources. A model for measuring energy potential was proposed and its advantages and disadvantages were discussed. The empirical analysis was based on source data for Poland for the years 2018-2024.

Findings: Energy potential was defined based on a physical formula and using the concept of economic potential (income and population). The terminology was adapted to the energy market. The value of the potential depends on the adopted measure. The research results can be applied to analyses of the country's energy resources, the diversification of energy sources, and energy security.

Practical implications: The formula allows for calculating a country's energy potential and analyzing its energy security, categorizing its own energy security and its dependence on other countries in a given period. It can be used to assess a country's energy security, assess the diversity of energy sources, and assess energy self-sufficiency.

Originality/value: The methodology described in this article is innovative when applied to the energy market. It proposes a formula for measuring energy potential. Physical concepts are adapted to the topic of energy security. The advantages and disadvantages of this method, as well as research limitations, are outlined.

Keywords: economy, management, energy market, energy potential, energy balance, energy security.

Category of the paper: Research paper.

1. Introduction

Energy generation is a crucial and irreplaceable element of every country's economy. Depending on geographic location, availability of energy resources, and technological progress, energy generation varies. Some countries are self-sufficient, energy independent, and able to obtain energy from their own natural resources. However, not all countries are self-sufficient in this regard. Some countries are dependent on other entities, and Poland is in this situation as well.

With the development of technology and environmental awareness, the structure of energy sources is also changing. In many countries, fossil fuels were the primary energy source for many decades. However, with technological advances and an awareness of environmental pollution, the approach to energy generation and environmental issues has changed significantly in the 21st century.

Energy security is a key topic of public debate in the 21st century, as the entire global economy relies on energy resources. This is particularly important in the European Union, whose member states are largely dependent on imports of these resources. The reliability and security of these imports will underpin the future development of these economies, which is why analyzing the energy balance of the European Union as a community and of each country individually is so crucial. EU member states' dependence on energy imports is not uniform. A growing demand for energy is noticeable.

To a large extent, the economies of many countries are shifting away from fossil fuels in favor of ecological energy sources, including nuclear power. This approach justifies environmental protection as one of the factors of a sustainable and responsible economy.

Given geopolitical and military threats and armed conflicts, diversification of energy sources is also crucial. Climate change, the increasingly visible environmental pollution and its impact on public health, and technological advancements imply changes in energy sources. The share of renewable and nuclear energy is increasing, while the share of energy obtained from fossil fuels is decreasing.

2. Theoretical background

Much attention is paid in the literature to the issue of energy security as the foundation of the functioning of the state in a dynamically and stochastically changing economic environment.

The literature can be divided into three subgroups. In macroeconomics, the importance of energy balance in the economic development of countries has been discussed by Baldwin (2022), Baldwin and Forslid (2023), Begg, Fischer, and Dornbusch (1992). Particular attention was paid to energy self-sufficiency in the works by Campling and Selwyn (2018), Diebold and Yilmaz (2015), Fronczek (2018), Gorynia (2019), while dependence on foreign suppliers and the related problems were described in the works by Hegerty (2016), Kocot (2007), and Kołodko (2003). Rynarzewski and Zielińska-Głębocka (2006), Trautwein, H.-M. (2022) strongly emphasize the importance of self-sufficiency, including self-sufficiency in the energy market in competition, in the global economy at all levels of cooperation.

Another group of studies includes methodological works that model selected economic variables Beckmann and Czudaj (2014), Diebold and Yilmaz (2009), explain concepts Mastalerz-Kodzis (2018), define correlations, and examine dynamics Greene (2003) and Silvennoinen and Thorp (2013).

The third group encompasses works on the energy market, its laws, trends, and regulations. These include works by Abdelradi and Serra (2015), Cabrera and Schulz (2016), and Izadyar, Ong, Chong, and Leong (2016). These are works in the field of energy acquisition, its processing and use in the economy: Marques, Fuinhas and Pires Manso (2010), Mensi, Hammoudeh, Nguyen and Yoon (2014), Mensi, Beljid, Boubaker and Managi (2013) and Drożdż and Mróz-Malik (2020).

The energy policies of countries and their natural resources are also an important issue, as this significantly influences the structure of energy production. Discussions on energy policy can be found in the works Papież, Śmiech and Frodyma (2021), Bijańska and Wodarski (2024).

The aim of this article is to derive a formula for measuring the country's energy potential, analyze the dynamics of changes in the structure of energy production in Poland, and calculate Poland's energy potential for 2018-2024. The paper also presents a critical assessment of Poland's energy self-sufficiency and draws conclusions and recommendations regarding Poland's energy security.

3. Methods

3.1. Territorial unit potential – definition and measurement methodology

Originally, the concept of potential comes from physics, then it was used by economists in Geographical Economics, and in this work, based on physical concepts, the methodology for measuring energy potential will be presented.

3.2. Potential as a physical concept

In physics, potential is a quantity used to describe a physical field. A field of physical quantities is a set of functions characterizing points in space and other parameters. For a given system of physical units, the partial potential P_{ij} is used to analyze the interactions of units ($i, j = 1, \dots, n; n \in N$). For any two units, it is determined according to the formula:

$$P_{ij} = \alpha_0 \frac{P_i P_j}{d_{ij}} \quad (1)$$

The value of the partial potential is interpreted as the amount of energy between units i and j per unit mass, P_i, P_j is the mass of the units, d_{ij} the distance between the units, α_0 and is a parameter.

3.3. Economic potential

Potential is defined in economics as the resource of capabilities, possibilities, or performance that can be assigned to a given territorial unit. As early as 1970, G. Dutton introduced the concept of income and population potential and their quotient, which has become a measure of socioeconomic development. The potential of a region, area (territorial unit), or state is a multidimensional concept, as it depends on many different, often interdependent factors. Potential defines an entity's capabilities based on the abilities, competencies, and efficiency possessed by a given organization, and also measures the ability to use these resources and those of its environment.

Based on the definition of partial potential, the concept of the potential of a territorial unit (e.g., a state) is constructed. It is assumed that the territorial division system consists of n objects – spatial units ($n \in N$). The potential of each unit is dependent on all other units, albeit to varying degrees. The model of the potential of the i -th spatial unit ($i = 1, 2, \dots, n, n \in N$) in a given time period (year, quarter, month) is written as:

$$V_i = \alpha_0 \sum_{\substack{j=1 \\ j \neq i}}^n \frac{B_j^{\alpha_{1,j}} P_j^{\alpha_{2,j}}}{d_{ij}^\beta} \quad (2)$$

where:

B_i - weight of the i -th spatial unit,

$\alpha_0, \alpha_{1,j}, \alpha_{2,j}$ - structural parameters of the model,

β - distance parameter, remaining symbols as above.

According to the spatial potential model, the capabilities of a territorial unit (state) depend on the condition of the unit itself, but also on the unit's location within the considered space and the adopted metric. This can be a geographical space, in which the distance between units is

measured as the Euclidean distance between the geographical coordinates of distinguished points. Road distance (shortest, fastest) can also be considered, as can the availability of connections between units. Another interesting approach is to consider the metric as an economic quantity.

The components of the above formula can have an economic interpretation.

In geographical economics, the mass of a unit can be considered as production, GDP, population, employment, foreign trade turnover, and investment volume. The mass weight of a given spatial unit can be the occupational structure of the population, age, gender, income, or investment volume per capita. Weights can be adopted arbitrarily or calculated based on statistical data. Distance metrics between units include temporal, physical, Euclidean, and economic distances. Model parameters are determined using the least squares method.

The dependent variable V_i is interpreted as the total impact on the i -th spatial unit, while the total potential of the i -th unit is the sum of the partial potentials of all units in the system. Economic potential can be interpreted as the intensity of the impact of all states (regions) of the system on a selected state (region). Potential is the sum of two components: the system's own potential and the potential of the surroundings. Geographic location has a significant impact on the value of the surroundings' potential. In economics, the following spatial potential models can be distinguished: income, population, and location (accessibility of the region to residents of other regions). These models of geographical economics are described in detail in Mastalerz-Kodzis (2018).

3.4. Energy potential

For the purposes of this article, a country's energy potential is defined as its ability to generate energy from available sources, but also in the context of obtaining energy from other countries. This paper proposes a methodology for determining energy potential, taking into account fossil fuels, renewable energy (wind, photovoltaics), and nuclear energy, and incorporating the time parameter into formulas for calculating countries' energy potential.

Let us assume the following notations:

$EP_i(t)$ - total energy potential in the i -th territorial unit in period t ,

$E_i(t)$ - value of energy produced in the i -th territorial unit in period t (own potential),

$Z_i(t)$ - total energy consumption in the i -th territorial unit in period t ,

d_{ij} - distance between units i and j ,

$\sum_{\substack{j=1 \\ j \neq i}}^n \frac{E_j(t)}{d_{ij}}$ - energy potential of the surroundings of the i -th territorial unit (ambient potential).

In practice, a metric can be binary. If a given country is neighboring the country under study, the value in the distance matrix is 1; if it is not neighboring, the value is assigned to 0. It can also be a binary matrix when considering agreements between countries regarding the

purchase and sale of energy or its carriers. In general, the greater the distance between countries, the more expensive the transmission, meaning the lower the profitability of buying and selling energy. The concept of a metric can also be applied to the distance between countries. Of course, the value of the potential depends on the adopted metric.

Total energy potential is defined as the sum of the internal and external potentials:

$$EP_i(t) = E_i(t) + \sum_{\substack{j=1 \\ j \neq i}}^n \frac{E_j(t)}{d_{ij}} \quad (3)$$

Potential is a measure of a region's spatial accessibility. It determines the intensity of interactions between regions, taking into account economic values and distances between regions. In formula (3), it is divided by the distance between units, as the greater the distance, the smaller the impact on the analyzed characteristics. Energy storage facilities are not included in the formulas. In order to meet a country's energy needs, its total energy potential should be higher than its consumption. A country is safe when its total energy potential is greater than its demand in a given period of time.

The ratio of the i -th unit's own potential in period t to the demand is given by the formula:

$$EE_i(t) = \frac{E_i(t)}{Z_i(t)} \quad (4)$$

If the value $EE_i(t)$ is greater than 1, it means that the country's total energy potential is greater than its energy demand in a given time period, meaning the country is self-sufficient. If the value $EE_i(t)$ is less than 1, the demand exceeds consumption, meaning the country is dependent on other entities.

In turn, the quotient

$$FE_i(t) = \frac{EP_i(t)}{Z_i(t)} \quad (5)$$

provides information about energy availability, taking into account the surrounding environment. If this quotient is greater than one, it means that the capacity to produce and obtain energy exceeds consumption, so consumption can be covered by the country's own resources and those of other territorial units. However, if the value were less than one, it would indicate a critical situation in which the country lacks sufficient energy resources, and even assistance from neighboring (or further) countries would not solve the energy shortage. This is a critical situation.

Potential is a measure of a region's spatial accessibility. It determines the intensity of interactions between regions, taking into account economic values and distances between regions. Energy storage facilities are not included in the formulas. This value $EE_i(t)$ changes over time, so it is possible to consider the dynamics of changes in the energy potential of countries and assess whether changes in the energy generation structure are positively impacting the energy independence of territorial units.

4. Results and discussion

4.1. Energy transformation in Poland – changing the structure of energy production in the years 1970-2024

For decades, hard coal was the primary energy source in Poland. Since the 1980s, hard coal extraction and consumption have been steadily declining (Figure 1). Until 2009, extraction exceeded consumption, but since 2010, consumption has exceeded extraction. A significant decline in hard coal consumption in the Polish economy has been recorded. Compared to 2023, the decline is 14%, and compared to 2015, it is a staggering 33%.

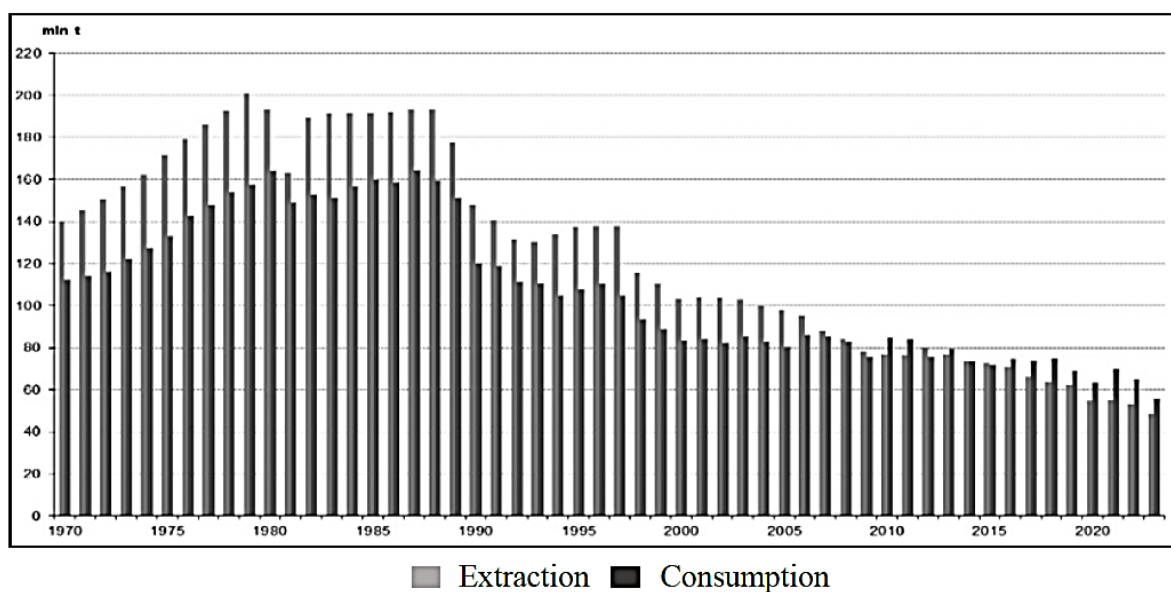


Figure 1. Hard coal extraction and consumption in the years 1970-2024 (mln t).

Source: Own elaboration.

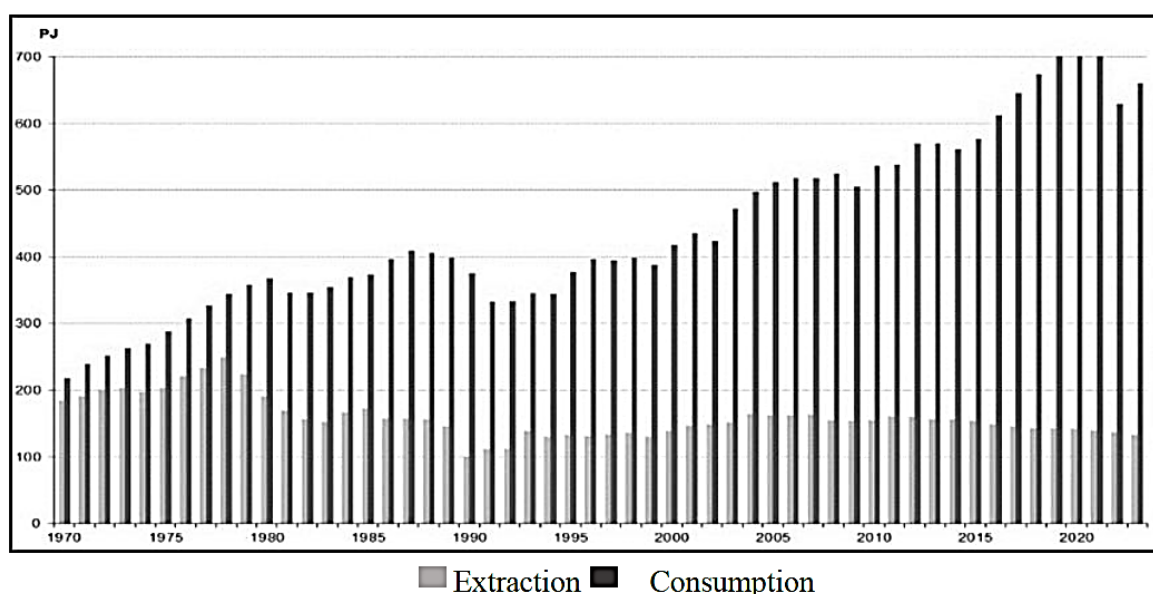


Figure 2. Production and consumption of natural gas in the years 1970 – 2024 (PJ).

Source: Own elaboration.

The total share of coal in electricity production is declining. In 2024, it reached 56.2%, a 4.3 percentage point decrease compared to 2023. Meanwhile, gas consumption is steadily increasing. Dependence on renewable energy imports (primarily biofuels and biomass) hovers around zero (Figure 2).

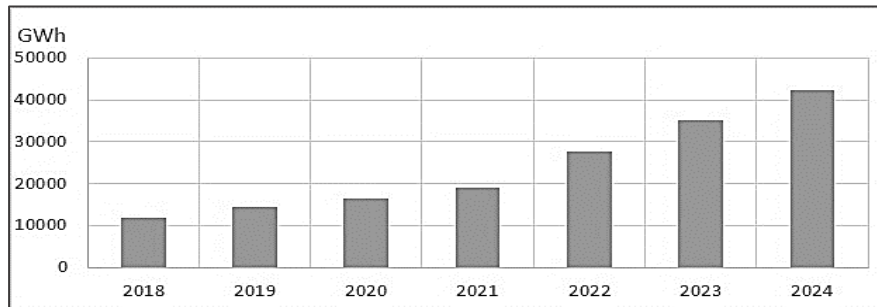


Figure 3. Renewable energy production in 2018-2024 in Poland (GWh).

Source: Own elaboration.

In the 20th and early 21st centuries, renewable energy sources received little attention. It wasn't until the 1920s that significant changes were made. Renewable energy from various ecological sources is becoming increasingly important (Figure 3).

4.2. The structure of energy production in Poland in 2024

Electricity is produced primarily by utility power plants. In 2024, these facilities generated 124,781 GWh, representing almost 75% of total production. The remainder came from wind farms and other renewable energy sources (42,208 GWh) – data are included in Table 1 and Figure 4. It's worth noting that the percentage of installed capacity from commercial and renewable sources is not the same as their percentage of electricity production. Green sources account for 44.08% of installed capacity, but only 25.3% of production.

Table 1.

The structure of energy production in Poland in 2024

Energy source	GWh
hard coal-fired power plants	69 112
hard coal power plants	35844
gas power plants	16768
wind farms and other renewable energy sources	42208
hydroelectric power plants	3057

Source: Own study based on data.

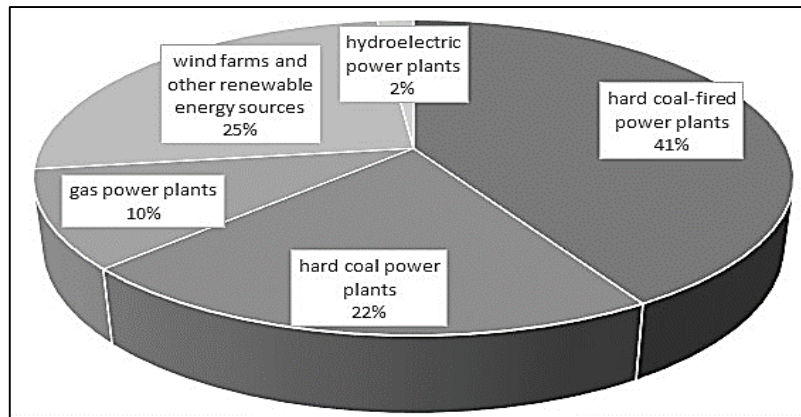


Figure 4. Share of energy production in Poland in 2024.

Source: Own elaboration.

However, the share of coal in energy production is still significant, accounting for over 57 percent (Figure 5).

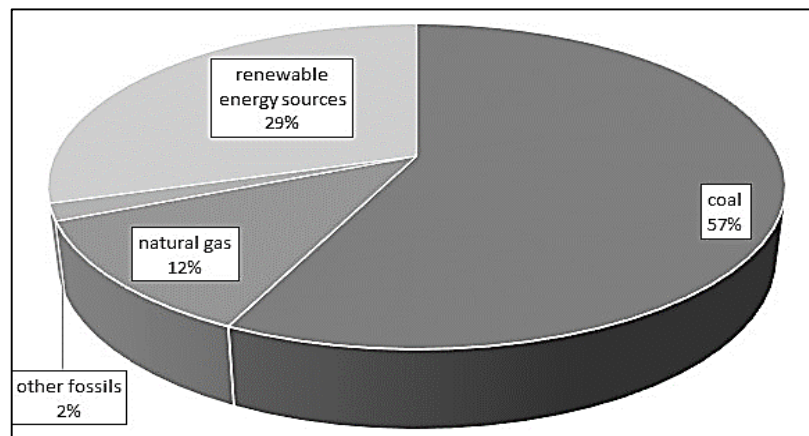


Figure 5. Energy mix in Poland in 2024 year.

Source: Own elaboration.

The 2024 report prepared by the Energy Forum shows a gradual shift in the share of coal-fired sources in Poland's energy mix. Last year, they accounted for 57.1% of electricity production, marking a record low for the combined share of hard coal and lignite in total energy generation. At the same time, the share of renewable energy sources increased again, reaching a historically high 29.6%.

4.3. Poland's energy dependence

Currently, Poland is energy dependent on other countries. Figure 6 shows energy production and consumption from 1970 to 2024. Energy dependence is visible in 1988-1989, in 2014, and since 2016 (Figure 6).

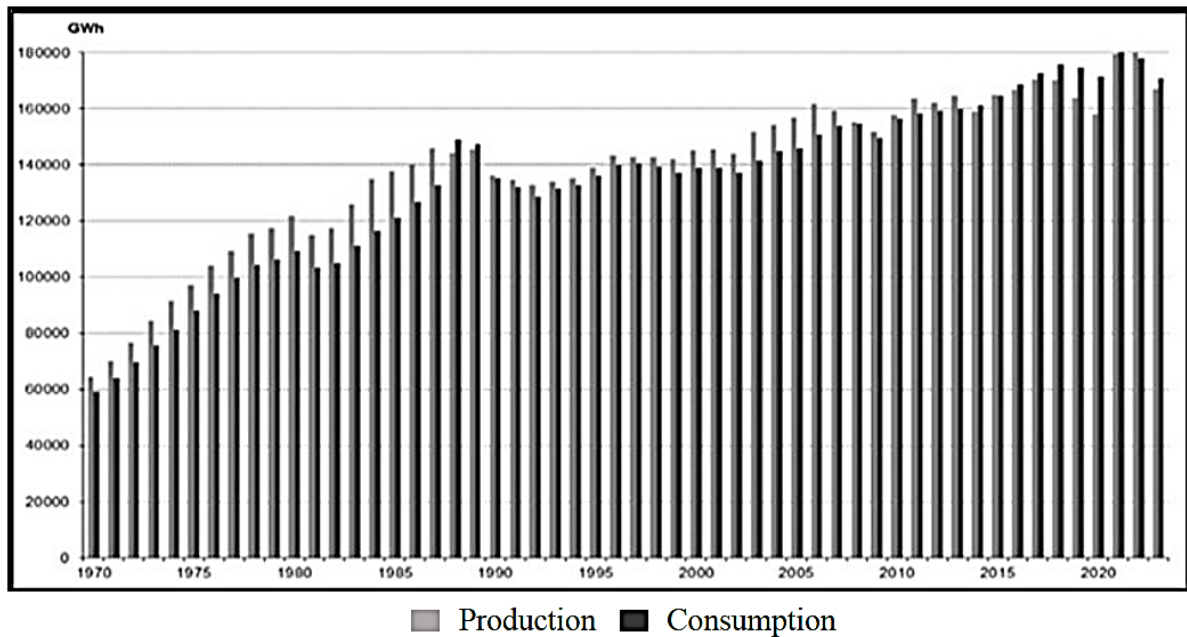


Figure 6. Electricity production and consumption in Poland 1970-2024 (GWh).

Source: Own elaboration.

Poland's dependence on raw material imports is steadily growing, primarily due to the increasing share of oil and its derivatives in the structure of raw material consumption (Figure 6, Figure 7). In 2023, the total dependence reached 45%, compared to 29% in 2014. However, supply diversification, necessary for national security, is taking place. The total cost of raw material imports in 2024 was approximately PLN 112 billion. Since the beginning of the Russia-Ukraine armed conflict, Poland's dependence on raw materials from Russia has steadily declined. By the end of 2024, Poland completely cut off its fuel and raw material supplies from Russia. Poland paid the most for fuel and raw materials from Saudi Arabia (29%), Norway (18%), and the United States (17%).

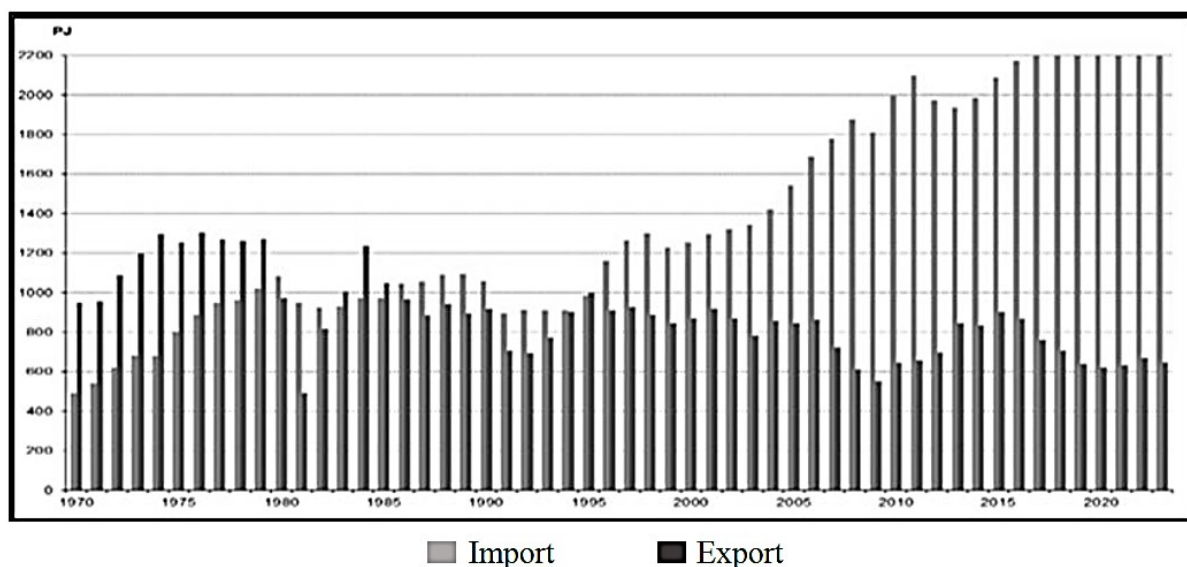


Figure 7. Total energy in Poland - import and export in the years 1970-2024 (PJ).

Source: Own elaboration.

The Polish economy's dependence on energy imports increased from 29% to 45% between 2014 and 2023. For years, the highest import dependence has been observed for crude oil. As much as 96-97% of the oil consumed in Poland comes from abroad. In 2024, dependence on natural gas imports reached 82%. This is 2 percentage points more than in 2023 and 9 percentage points more than 10 years ago. Thermal hard coal imports in 2024 covered 10% of domestic consumption. The decrease compared to 2023 is due to record low consumption of this raw material. Over the past decade, dependence on thermal hard coal imports has increased by 13 percentage points.

Poland's energy deficit is recorded in Table 2 and shown in Figure 8.

Table 2.
Energy deficit in Poland in 2018-2024 (in GWh)

Year	Electricity production	Electricity consumption	Energy consumption deficit
2018	165214	170932	-5718
2019	158767	169391	-10624
2020	152308	165532	-13224
2021	173583	174402	-819
2022	175157	173479	1678
2023	163629	167518	-3889
2024	166990	168956	-1966

Source: Own elaboration.

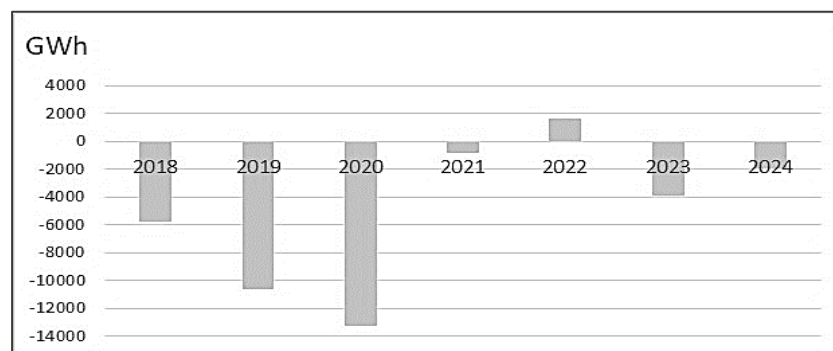


Figure 8. Energy deficit in Poland in 2018-2024 (in GWh).

Source: Own elaboration.

In summary, electricity production in 2024 was lower than domestic consumption. Consequently, the foreign exchange balance amounted to 1,966 GWh. Poland was dependent on foreign suppliers. EU energy import dependency rate stood at 58.4% in 2023. The energy deficit is covered by exports. Exports depend on the metric defined in point 3.4

4.4. Poland's energy potential in 2018-2024

Based on the data, Poland's domestic energy potential was calculated for the years 2018-2024.

Table 3.*Poland's domestic energy potential for the years 2018-2024*

Year	$EE_i(t)$
2018	0,967
2019	0,937
2020	0,920
2021	0,995
2022	1,010
2023	0,977
2024	0,988

Source: Own elaboration.

Only in 2022 the value was greater than 1, so only in this period was Poland energy self-sufficient. In other years, dependence on other countries (not just those within the European Union) was significant. This is a very dangerous phenomenon for the Polish economy and for Poles.

4.5. Energy independence of the European Union. Impact of energy transformation on climate and environmental change – prospects and challenges

The European Union imports more than half of the energy it consumes – primarily in the form of fossil fuels such as oil and natural gas, which generate the majority of its energy. Nuclear energy accounts for 13%, and over 15% of its energy comes from renewable sources. For several years, the popularity of renewable energy has been steadily increasing in both Poland and the EU.

Energy transformation allows for a reduction in the use of fossil fuels in overall energy production. This has a positive impact on the environment, resulting in less pollution and reduced climate change (global warming). Further research plans to include the "energy storage" variable in the energy potential formulas in theoretical and methodological analyses, as well as modify the metric to account for long-term contracts and commitments regarding energy procurement from external entities, as well as the CO₂ environmental pollution variable. The authors believe that taking these factors into account will allow for a more precise determination of countries' economic potential and will also enable potential forecasts for future periods. This is a crucial element of countries' energy security and influences their stable and sustainable development.

The goal should be to achieve a situation in which the total energy potential exceeds demand. If the country's own potential does not meet demand, the country's energy policy should be adjusted so that the surrounding potential covers the remaining portion necessary for the proper functioning of the country. Selecting the metric can be a challenging optimization problem when there are many options for obtaining energy from external sources. Such an optimization task will pose a challenge for the authors in further analyses.

The issue of energy security in European Union countries, particularly in the face of the Russia-Ukraine war crisis, is a particularly significant topic in the current literature. Works by Brodny and Tutak (2023), Dunlop and Völker (2023), Kaczmarek (2022), and Loewen (2022) highlight the importance of energy independence and a balanced energy policy. Studies by Pietrzak et al. (2021), Ahn et al. (2021), and Bowen and Saha (2023) highlight the importance of diversifying energy sources in the 21st century, while works by Brzóska et al. (2022), Kaczmarek et al. (2022), and Jonek-Kowalska (2022) demonstrate a shift away from fossil fuels towards renewable and nuclear energy. It is clear that this course of action is optimal in today's global economic reality.

Another interesting and important aspect for Poland's sustainable and stable economic development is determining the economic potential of its surroundings in the long term. However, this potential depends on metrics (distance, transmission costs, agreements between suppliers, and sanctions imposed on countries). Such an analysis would undoubtedly provide a broader perspective on energy independence for Poland and other countries. This will undoubtedly be the subject of future research and analysis.

5. Summary

The energy potential of each country is a factor influencing its security in the rapidly changing economic environment and the very difficult political situation currently prevailing worldwide. Dependence on other countries can adversely affect security, especially in the face of armed conflicts and the associated restrictions on the flow of goods, including energy resources.

Every country should strive for energy self-sufficiency. However, this is sometimes impossible due to the unavailability of energy resources and the inability to switch energy sources, such as nuclear power plants, wind farms, or photovoltaics.

Measurement of energy potential is a crucial element of a country's development strategy. However, the measurement methodology leaves researchers with many parameters, such as the distance matrix. Depending on its value, relationships, agreements, and availability, the values of countries' energy potential may vary. However, analyzing the dynamics of change allows for an assessment of the direction of change and the provision of guidelines and recommendations for the energy security of the country and its inhabitants.

The direction of further analyses is to compare the energy potential of European countries, show the possibilities of cooperation in the exchange of energy resources and energy itself, and provide recommendations for further strengthening Poland's energy position in Europe.

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