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MICHAŁ IGIELSKI

Management of the cost-effectiveness of the energy mix in Poland

„Renewable energy sources are the choice of the future, which is already present today"

Barack Obama, former President of the United States

Abstract

Research background and purpose: The main purpose of the article is to analyze the share of renewable energy sources in Poland's energy mix and to assess the management of the cost-effectiveness of their use, with particular emphasis on their impact on energy production costs, energy system stability and CO_2 reduction.

Design/methodology/approach: To achieve the purpose of the article, the author used a triangulation of research methods, which included a literature and regulatory review, scenario modeling and three analyses: statistical data, cost and energy efficiency. By using the above methods, the study will allow a comprehensive assessment of the role of renewable energy sources in the Polish power system and their impact on its cost efficiency.

Findings: The share of RES in Poland is growing, but still remains lower than in many EU countries, despite the fact that the cost of producing energy from renewable sources is steadily falling, making it increasingly cost-effective. Key barriers are the lack of developed storage infrastructure and legal restrictions for onshore wind farms.

Value added and limitations: The article provides up-to-date and detailed data on the structure of renewable energy consumption, taking into account the latest trends, regulations and technologies. A unique contribution is the analysis of various RES technologies in terms of their profitability and impact on energy prices, which provides practical conclusions for policy makers and investors, as well as the author's interdisciplinary approach - combining economic, legal, technological and social aspects. In conclusion, the value of the article stems from its timeliness, comprehensive approach and the possibility to use the results to shape energy policy and investment strategies in Poland.

Keywords: *energy management; renewable energy sources (RES); energy mix, energy cost efficiency*

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Michał Igielski
Faculty of Management and Quality Sciences, Gdynia Maritime University, Morska 81-87, 81-225, Gdynia, Poland; email: m.igielski@wznj.umg.edu.pl
ORCID: 0000-0003-4680-3733

1. Introduction

The increasing importance of renewable energy sources (RES) in Poland is due to the growing requirements of the European Union's climate policy, the need to reduce CO_2 emissions and the falling costs of renewable technologies. Poland's energy transformation towards RES is progressing despite still encountering structural, legal and economic challenges. In 2024, the share of RES in the national energy mix will reach a record 29.6%, with the share of coal falling to 57.1% (Blaczkowska, 2024).

As for the definition of the energy mix, one can refer to the International Energy Agency's 2021 proposal, which states that it is the composition or distribution of different primary energy sources used to meet the energy needs of a region or country (International Energy Agency [IEA], 2021*)*. It includes both fossil and renewable forms of energy and is commonly expressed as a percentage or absolute value (TWh, PJ) over a specified period. Equally interesting for the purposes of this study is the European Commission's 2023 approach, which says that the energy mix is the structure of the share of different energy sources (primary or final) in the total energy production, consumption or supply of a country, region or energy system, over a specified period of time (European Commission, 2023a). It includes both fossil (e.g., coal, gas, oil) and non-fossil (e.g., RES, nuclear) carriers. Accordingly, a distinction is made (REN21, 2023):

1. Primary energy mix - the share of sources in energy production at the raw material level (e.g., coal, biomass).
2. Final energy mix - the structure of energy consumption by end-users (transportation, industry, household).
3. Electricity production mix - the share of different technologies in power generation.

Therefore, the key objective of the article is to analyze the share of renewable energy sources in Poland's energy mix and to assess the cost-effectiveness management of their use, with a particular focus on their impact on energy production costs, energy system stability and CO_2 emission reduction. Hence, in this publication the author discusses the share of RES in the national energy mix, identifies the main sources of renewable energy and analyses the management of the cost-effectiveness of their production compared to fossil fuels.

A sequence of research and theoretical argumentation was also carried out to verify the hypothesis that increasing the share of RES in Poland's energy mix contributes to improving the cost efficiency of the energy system by reducing variable costs in the long term and reducing dependence on fossil fuels.

The main conclusions that the author was able to formulate after the whole process are undoubtedly that although RES in Poland is growing dynamically, challenges related to costs, system stability and regulatory policy remain crucial. Further development requires synergies between technological innovation, legal reforms and long-term planning to ensure cost efficiency and energy security.

2. Theoretical background

2.1. Current state. Energy transition in Poland - key facts

The current energy structure in Poland does not lead to optimistic conclusions. In 2023, about 71.8% of electricity generation came from fossil fuels (including 60.3% from coal, 10.2% from gas) (Enerdata, 2025). Unfortunately, in this system, the share of RES was only 27.9% (including wind 14%, solar 6.8%, biomass 4.7%) (European Commission, 2025). Unfortunately, the following year did not bring much change - in 2024, the RES share rose to 30% of the electricity mix, with the share of coal falling to about 55 % (European Commission, 2025). [6]. However, the first half of 2025 brought a breath of hope, as according to the Energy Forum (Minder, 2025), in June RES generated 44.1% of electricity in Poland, surpassing the 43.7% from coal. This is the first such case in the country's history. Below, in tabular form, the author has presented the dynamics of RES development in Poland, taking into account strategic economic goals and undertaken/ planned investments in this area.

Table 1. **Dynamics of RES development in Poland in 2021-2025**

Type of renewable energy source	**Photovoltaic (PV)**	Installed PV capacity has reached 21.8 GW by early 2025, accounting for 30% of total system capacity. Year-on-year growth of 25-45% thanks to support programs (e.g., "My Current") and the growing number of prosumer installations - about 1.5 million micro-installations (12 GW share).
	Wind power	Onshore wind power capacity is about 10 GW (7.5% increase in 2024). Offshore: 5.9 GW projects by 2030, targeting 11-18 GW by 2040.
	Other RES	Biomass and biogas (4-5 % share). Hydropower (2-3 % share) - still small, though with growth potential.
Strategic targets and investments	**Policy framework**	Target: - 56% RES in the electricity mix by 2030, - 73% (RES + nuclear) by 2040, - Climate neutrality by 2050, - in 2040: 45 GW PV, 41 GW onshore wind, 18 GW offshore, 6-9 GW nuclear capacity (first reactor from 2033), a package of reforms including „cable pooling," simplification of connections and new investment zones for RES
	Investment and transition economics	Cost of transition to climate neutrality: about $450 billion, which could result in +4% GDP growth by 2050. Investment in grid modernization: ~PLN500 billion (~$16 billion) to connect RES and storage.

Challenges and social aspects	1. Connection blockages: more than 6,000 grid operator refusals (2015-2021) - blocked about 30 GW of potential capacity. 2. Long permitting times - up to 5-7 years for wind farms, up to 4 years for PV infolink-group.compveurope.eu. 3. Fair social mix: retrenchment program for miners, funds from the Just Transition Package (~€3.5 billion) for mining regions.

Source: own study based on data from European Commission (2024, 2025), Reuters (2025), Polish Ministry of Climate and Environment (2021a) and Infolink Consulting Group (2025)

2.2. Literature and regulatory review on RES in Poland and the EU

The development of renewable energy sources (RES) in Poland is strongly determined by national and EU policies that affect investments, support mechanisms and the cost-effectiveness of the energy system. Contemporary research on renewable energy sources (RES) focuses on various aspects of their implementation, ranging from cost-effectiveness to impact on power system stability to regulatory considerations. The following review discusses key scientific publications and reports that analyses energy policy, RES development trends and their impact on the economy.

Table 2. **Analysis of contemporary research on renewable energy sources**

No.	Publication Title	Scope of Research	Main Findings
1.	Exploring the Green Horizon: Recent Research on Renewable Energy in Poland-A Review	Overview of RES research in Poland	The share of PV and windmills in Poland's energy mix is growing. Regulatory barriers arising from current law are emerging. Optimistic Investment Trends
2.	Renewable Energy Investments in Poland: Goals, Socio-Economic Benefits and Development Directions	Economic and Social Benefits of RES	Investments in RES reduce energy poverty and create jobs
3.	Analysis of the Current State and Challenges of Renewable Energy Employment in Poland	Renewable Energy Employment Market	Poland is the leader in PV employment in the EU (~113,000 people) and there is an emerging need to adapt education
4.	Energy Transition in Poland - Assessment of the Renewable Energy Sector	Assessing the Status and Prospects of the Transition	In Poland, low grid flexibility prevails and connection problems hinder development

5.	Reviewing the Situation and Prospects for Developing Small Renewable Energy Systems in Poland	Small Renewable Energy Systems: PV and local turbines	The potential of micro-installations and local energy models has increased significantly in Poland
6.	Poland Solar PV Market Outlook 2025–2034	PV market trends and projections	In Poland, >4 GW were installed in 2004, and total PV capacity is ~20.8 GW
7.	Harmony Energy and EDF build Europe's largest battery storage in Poland (200 MW/400 MWh)	Energy storage	Flexibility infrastructure development - large-scale batteries

Source: own study based on data from Aydın et al. (2025), Dębicka et al. (2024), Pilipczuk et al. (2024), Pietrzak et al. (2021), Witkowska – Dąbrowska et al. (2023), Renewable Market Watch (2024) and Harmony Energy (2024)

There are theories setting an optimal time when the economy should switch to RES. Some forecasts even spoke of 2023 as the date when natural resources were already expected to be insufficient in meeting electricity demand. Despite such pessimistic sentiment, the transition of countries to RES energy production is not forced. Economic factors have less influence on energy management decisions. In fact, political factors are more important, motivating countries to make changes based on international agreements. An example of such influence is the European Union, which imposes certain standards to which member countries should respond (Malaczewski, 2017, pp. 39-43). In this case, the focus is on the dynamic development of RES and the reduction of coal energy. Therefore, the standards set are being raised on an ongoing basis - this is to respect the environment for future generations.

Renewable energy sources (RES) are nothing more than energy sources that renew themselves naturally in a relatively short period of time and do not deplete on a human lifetime scale. They are an alternative to fossil fuels and play a key role in the energy transition and the reduction of greenhouse gas emissions. We can include (Twidell & Weir, 2017, pp. 45-67):

1. Solar energy, which is used with photovoltaic (PV) panels to produce electricity and with solar panels to produce heat. It is dependent on solar insolation and requires energy storage or integration with other sources.
2. Wind energy - electricity production using wind turbines, can be used onshore (onshore) and offshore (offshore). Like solar energy, it is characterized by production instability, which requires flexible balancing systems.
3. Hydropower (hydropower), which includes run-of-river, dam and tidal hydropower plants. This is a more stable source of energy, but dependent on hydrological conditions.

4. Biomass and biogas, which is energy extracted from plants, organic waste and biogas. It can be used to produce heat, electricity and biofuels. However, it requires sustainable management of raw materials to avoid overexploitation of the environment.
5. Geothermal, which uses the Earth's heat to produce electricity and heating. Importantly, it can be used in both large power plants and local heating systems.

Among European countries, it is Poland that has the most polluted air. According to statistics, 3,500,000 people in the world die per year due to harmful compounds in the atmosphere. In Poland alone, 50,000 people die per year due to pollution (Najwyższa Izba Kontroli, 2018). Societies are putting pressure on states to protect the environment and thus improve the quality of life. This is referred to as energy democracy. The development should be described as dynamic due to green technologies, implemented policies and social activism. Dynamic developments in renewable energy sources have led to an economic transformation in which society is not only a consumer of conventional energy, but also realizes itself as a prosumer (Seroka, 2022, pp. 93-95).

Therefore, bearing in mind the benefits of RES, including those crucial to the fight against climate change, i.e., reductions in CO_2 emissions and reduced dependence on fossil fuels and imported raw materials, a number of documents regulating activities in this area have emerged, which the author of the article describes in Table 3.

Table 3. **EU and national regulations and policies on RES**

No.	Origin of the document	Document	Description
1	European Union	European Green Deal (European Commission, 2019)	– key EU strategy to achieve climate neutrality by 2050 – plans to reduce CO_2 emissions by 55% by 2030 (compared to 1990 levels) – promotes the development of RES, energy efficiency and hydrogen technologies
2		Renewable Energy Directive II (European Union, 2018)	– sets a target of at least 32% RES share in EU final energy consumption by 2030 – supports prosumers and the development of energy communities – Obliges Member States to simplify administrative procedures for RES projects
3		Fit for 55 (European Union, 2021)	– introduces changes to the EU ETS (CO_2 emissions trading), increasing the cost of emissions for the energy sector – raises the RES target to 45% of the EU energy mix by 2030 – introduces the Carbon Border Adjustment Mechanism (CBAM) to protect the European market from imports of carbon-intensive products

4	European Union	Regulation TEN-E - Trans-European Networks for Energy (European Union, 2022)	– supports the development of transmission infrastructure for renewable energy sources – finances electricity grid modernization projects under the CEF (Connecting Europe Facility)
5		EU ETS - Emissions Trading System (European Union 2005)	– CO_2 emission charges increase the cost of fossil fuel energy, making RES more competitive – high allowance prices accelerate the decarbonization process
6	Poland	Poland's Energy Policy until 2040 (PEP2040) (Ministry of Climate and Environment RP, 2021b)	Sets targets for the energy transition in Poland, including: – reduction of CO_2 emissions by 30% by 2030 – 50% share of RES in final electricity consumption by 2040 – development of offshore wind power (6-11 GW by 2040) – construction of first nuclear power plants (approx. 6-9 GW
7		Act on Renewable Energy Sources (Energy Regulatory Office, 2015)	– introduces an auction system for RES producers – regulates the status of prosumers and energy communities – introduces a system of feed-in tariffs (FiTs) and market premiums
8		Auction system for RES (Institute for Renewable Energy, 2019)	– support mechanism that allows RES producers to sell energy at a guaranteed price – auctions for different technologies (wind, PV, biomass) – system criticised for favouring large investors at the expense of smaller producers
9		Reform of the grid charge system (Ministry of Climate and Environment, 2021a)	– New dynamic tariffs to encourage energy consumption during hours of high RES production. – Increased grid charges for large RES producers.
10		Polish Hydrogen Strategy 2030-2040 (Ministry of Climate and Environment, 2021a)	– assumes construction of 2 GW of electrolysers by 2030 – promotes hydrogen as energy storage and fuel for industry
11		National Energy and Climate Plan (NERP, 2021) (Ministry of Climate and Environment, 2021b)	– document implementing EU targets at national level – provides for the development of RES technologies, improvement of energy efficiency and decarbonisation of industry

Source: own study

In summary, Poland faces a huge challenge that requires major changes (Table 4). However, with the right regulatory policy, it can become a leader in the energy transition in Europe. Going further, on the basis of a review of scientific literature and an analysis of normative acts, according to the author of the study, the future of the energy sector in the entire European Union, including Poland, depends on effective RES integration, grid flexibility and a long-term regulatory strategy (Bocciarelli et al., 2022, p. 338). In a similar vein, treating legal regulations and energy policy as key determinants for the rate of RES development, other researchers of the topic speak out, indicating that stable regulations are crucial to ensure an inflow of investment into the RES sector, while frequent changes in the law may discourage investors.

Table 4. **Summary of key conclusions, challenges and recommendations for RES management in Poland**

No.	Category	Main findings
1.	**Conclusions**	– EU regulations are forcing Poland to make a rapid energy transition – high CO_2 allowance prices are accelerating the shift away from coal, making RES more competitive – the RES support system needs further reform to ensure equal access for all investors
2.	**Challenges**	– upgrading the grid and developing energy storage technologies remains a key challenge – shortening of administrative procedures for RES investments - currently they are too time-consuming – development of hydrogen and energy storage technologies - key to system stability – implementation of dynamic energy tariffs - will increase the flexibility of the system – greater support for prosumers and local energy communities – integration of demand-side management (DSR) and smart grid systems
3.	**Recommenda-tions**	– the cost of energy production from RES is steadily decreasing - becoming more competitive with fossil fuels – integrating RES into the system requires investment in energy storage and grid flexibility – support mechanisms (e.g. RES auctions) have a key impact on the rate of development of the sector, but need to be optimized – EU regulations (EU ETS, Fit for 55) are significantly accelerating the energy transition in Poland – national policy must take into account the development of new technologies, such as hydrogen and smart grids, to ensure the stability and efficiency of the electricity system

Source: own study

In addition, there is a perception that the high price of emission allowances for environmentally harmful gases is forcing EU countries to phase out coal faster, which translates into a CO_2 price that under the EU ETS will exceed €100/t by 2030 - this is what will make RES the most competitive energy source (Ellerman et al., 2022, p. 219).

Unfortunately, on the other hand, after comparing RES support systems in different EU countries, we can conclude that the most popular auction mechanisms are the most cost-effective, but may favour large companies at the expense of smaller investors (Jenner et al., 2021) - such as in Poland, where the auction system needs to be reformed to increase its efficiency and accessibility for small energy producers. Besides, for which the author of the article particularly agrees , there are too few initiatives such as e.g. FiTs (Feed-in Tariffs), PPAs (Power Purchase Agreements) or the Fit for 55 package (Kitzing et al., 2022, pp. 7-15), which are crucial for stabilizing RES investments and could accelerate RES development by up to 30% by 2035.

Although numerous international studies have examined the cost efficiency of renewable energy sources (e.g., Aydın et al., 2025; Ellerman et al., 2022; Hirth et al., 2021), there is a lack of comprehensive and up-to-date analyses for Poland that would integrate three key dimensions: economic (LCOE and CAPEX/OPEX), regulatory (national vs. EU frameworks) and technological (energy storage and grid flexibility). Existing Polish research usually addresses these aspects separately.

This article therefore aims to fill that gap by creating an integrated model evaluating the cost-effectiveness management of the Polish energy mix, and by comparing its results with conditions observed in EU countries.

2.3. Research hypotheses

Based on the literature review and the identified research gap, the following hypotheses were formulated:

H1. An increase in the share of renewable energy sources (RES) in Poland's energy mix improves the overall cost-effectiveness of the energy system by reducing variable generation costs in the long term

H2. The financial benefits from RES expansion depend on the development of supporting infrastructure – primarily energy storage and grid modernization

H3. The effect of RES share on system cost efficiency is significantly influenced by regulatory stability, including national transposition of EU policies (e.g. EU ETS, the Renewable Energy Directive, the Fit for 55 package)

These hypotheses stem directly from the previous analyses showing partial evidence for each link between RES, cost reduction and policy mechanisms, yet lacking an integrated Polish assessment (cf. Aydın et al., 2025; Seroka, 2022; Kitzing et al., 2022).

3. Methods

Due to the fact that the main objective of the study is to analyze the share of renewable energy sources in Poland's energy mix and to assess the cost-effectiveness management of their use, with particular emphasis on their impact on energy production costs, energy system stability and CO_2 emission reduction, the author of the article used a triangulation of research methods for its implementation, which include:

1. Statistical data analysis - collection and analysis of data on the share of RES in Poland's energy mix based on reports from government institutions (URE, PSE, CSO), international organizations (IEA, Eurostat) and energy market operators.
2. Cost analysis - comparison of costs of energy production from various sources (RES vs. conventional) using indicators such as LCOE (Levelized Cost of Electricity), CAPEX, OPEX and analysis of subsidies and support mechanisms for RES.
3. Scenario modelling - the author developed scenarios for the development of Poland's energy mix until 2030 and 2050 with different levels of RES share, taking into account economic, technological and regulatory factors.
4. Energy efficiency analysis - assessment of the impact of RES on power system stability and cost efficiency in the context of energy storage, grid flexibility and demand-side management.
5. Literature and regulatory review - analysis of national and EU energy policies and legislation affecting the development and cost-effectiveness of RES in Poland.

The application of the above research methods will allow for a comprehensive assessment of the role of renewable energy sources in the Polish energy system and their impact on its cost effectiveness. The selection of sources was based on their topicality, reliability and relevance to the subject of the study. Peer-reviewed publications, official reports of international and national institutions, as well as contextual materials allowing for a broader view of RES issues were taken into account.

Despite the broad scope of the analysis, the study may face some limitations. First of all, the dynamics of change in the renewables sector means that data and strategies can change rapidly. In addition, the limited number of expert interviews may affect the completeness of conclusions.

To sum up, the empirical part of this study was based on secondary quantitative data obtained from the following public and institutional sources: Eurostat, the International

Energy Agency (IEA), the Energy Regulatory Office (URE), Polish Power Grid (PSE) and the Central Statistical Office (GUS).

The data sets from the above-mentioned institutions were filtered according to three criteria:

- relevance – only those sets that directly describe the structure of generation, consumption and capacity broken down by energy source were included;
- timeliness – they cover the period 2021–2024;
- comparability – all values were standardised in terms of units (TWh, GBP/MWh, Mt CO_2) and time frequency (annual data). All monetary values have been converted into euros at the average exchange rate for 2023 (1 USD = 0.91 EUR (European Central Bank, 2023).

The statistical data has been normalised using z-score standardisation to ensure that the indicators are comparable across years and sources. Outliers exceeding one standard deviation from the mean were manually verified based on the original data. Cost indicators (LCOE, CAPEX, OPEX) were calculated as weighted averages of values reported by the IEA and IRENA for Central Europe and compared with national data from the Institute for Renewable Energy (IEO).

On this basis, the author developed two scenarios described below:

1. Balanced Scenario (BS) and Progressive Scenario (PS).
2. Base year: 2023 (actual share of RES in electricity production = 30%).
3. Time horizons: 2030 (short term) and 2050 (long term).
4. Key variables:
   - share of RES in total energy production (%),
   - LCOE cost (EUR/MWh),
   - system stability index (measured based on the variability of the daily supply-demand balance in PSE data),
   - CO_2 emissions path (Mt) and total CAPEX (in billion EUR).
5. Analytical tools - calculations performed in MS Excel 2021 and R Studio (version 2023.12) using packages for regression analysis and trend forecasting.
6. Assumptions:
   - average decrease in LCOE for RES at 2.8% per annum (IRENA, 2023),
   - annual increase in energy storage capacity of approx. 15% (based on PSE forecasts),
   - a steady increase in the price of CO_2 allowances by EUR 5/t per annum (ETS reference scenario).

The use of these data processing procedures and the model parameters described, in the author's opinion, ensured consistency and allows for full replication of the research in the future.

In conclusion, the research methods used, in the author's opinion, will provide a comprehensive look at the issue of renewable RES and their importance in the context of sustainable development.

4. Results

For the purpose of further consideration, the author of this article, as a definition of the energy mix, adopted the proposal created by A. Cherp and V. Vinichenko (2021, p. 1137). Who state that it is the structure of the share of various energy sources in the overall energy balance of a country or region. It includes both electricity and thermal energy production, as well as the raw materials used to produce them.

The main components of the energy mix most often include:

1. Fossil fuels:
   - coal - traditionally dominant in Poland, but gradually reduced due to high CO_2 emissions,
   - natural gas - considered a transition fuel in the energy transition due to its lower carbon intensity than coal,
   - oil - mainly used in the transportation sector.
2. Renewable energy sources (RES).
3. Nuclear power - some countries, such as France and the US, play a key role in the energy mix.

The current structure of the European Union's energy mix is most influenced by climate policy.

From the point of view of today's priorities, the issues of the impact of human activity on changes in the Earth's climate are becoming the most relevant. A significant share of energy production for the Union is played by nuclear power and renewable energy sources (nuclear energy is 29%, RES is 28%). In Poland, on the other hand, as much as nearly 70% comes from fossil fuels, and RES account for a little over 30% of the country's energy structure. In Poland, renewable energy is derived primarily from solid biofuels, wind power and liquid biofuels. The share of RES by sector is not evenly distributed. Most clean energy comes from the electricity generation sector, while in the case of transportation, the share of RES energy in final consumption increased by only 0.28% in 2023. compared to 2016 (European Commission, 2023b).

There are many reasons for this situation. The first, and perhaps the most important, is the state of Poland's power grid, which, according to a report by the Polish Energy Institute (Institute for Renewable Energy, 2024), needs rapid modernization, combined with investments in energy storage, to avoid overloads and blackouts. This is supported by studies showing that the cost of electricity from solar and wind is already lower than from coal, and further investment in energy storage could accelerate the elimination of fossil fuels. The second, and perhaps equally important, is the lack of legislative support

- a report by the Energy Forum (2023) says that Poland can achieve 70-80% RES by 2050 with proper regulatory support, and a combination of nuclear and RES may be the most effective model for the country.

This is confirmed, among others, by data from the International Renewable Energy Agency (IRENA, 2023), according to which the average cost of electricity generation from photovoltaics and wind farms (LCOE) has fallen globally to around USD 30–45/MWh, which is lower than for coal-fired power (USD 65–120/MWh on average). Similar conclusions can be drawn from a report by the Jagiellonian Institute and the Polish Wind Energy Association (2023), which shows that in Poland, the cost of energy from new wind and PV installations ranges from PLN 250–300/MWh, while from coal-fired power plants it reaches PLN 400–550/MWh.

Taking into account the above arguments, as well as the identified determinants affecting the energy mix (energy policy - national and EU regulations; costs and availability of raw materials - e.g., gas imports from various directions; climate change and pressure to reduce emissions; technological progress - development of energy storage and electricity grids), the author of the study, based on the analysis of the collected materials, conducted a scenario modeling process - proposed two scenarios for the development of Poland's energy mix until 2030 and until 2050 (Table 5).

Table 5. **Scenarios for the development of Poland's energy mix up to 2030 and up to 2050**

SCENARIOS OF POLAND'S ENERGY MIX DEVELOPMENT UNTIL 2030		
In order to develop a scenario for the development of Poland's energy mix until 2030, the author considered three variants: **conservative, balanced and progressive**. Each variant differs in the rate of growth of the share of renewable energy sources (RES), investment in new technologies and the impact of national and EU regulations.		
Conservative scenario (RES share at 25%)	Assumptions	Moderate growth in RES share resulting from slow implementation of pro-climate policies and continued dominance of coal and gas
	Economic factors	High CO_2 costs, but on the other hand limited investment in renewable infrastructure
	Technologies	Dominance of coal (c. 45%) and gas (c. 25%), slight increase in photovoltaic and wind capacity
	Regulation	Implementation of EU obligations at minimum required level.
	Consequences	– Poland remains one of the EU countries with the highest emissivity of the electricity system – high energy prices due to CO_2 emission costs – limited energy independence and further dependence on gas imports

Balanced scenario (RES share at 40%)	Assumptions	Dynamic but gradual development of renewable energy sources, supported by EU and national policies
	Economic factors	Greater investment in electricity grid modernization and development of energy storage
	Technologies	Increase in photovoltaics and onshore wind power, development of offshore and energy storage technologies
	Regulation	Effective implementation of EU climate policy, development of support systems for RES investments (e.g. auctions, subsidies)
	Consequences	– moderate stability of energy prices due to diversification of sources – improved energy independence of Poland – decrease in emissivity of the energy sector - compliance with EU targets
Progressive scenario (RES share at 55%)	Assumptions	Agglomeration and industrial regions of Poland intensively develop photovoltaics and energy storage, and offshore development reaches an advanced stage
	Economic factors	High investment in modern technologies, but in the long term lower energy costs due to lower RES operating costs
	Technologies	Rapid development of offshore and onshore wind power, increase in photovoltaic installations and energy storage
	Regulation	Accelerated phase-out of coal-fired power plants, increased financial incentives for companies and prosumers
	Consequences	– high stability of the energy system through advanced demand-side management and development of energy storage – significant reduction in energy costs in the long term – meeting the EU's 2030 climate targets
Summary and recommendations		**Most realistic scenario:** **Sustainable** (40% RES in 2030), as it corresponds to current political and economic trends and is in line with EU requirements **Most favourable** long-term scenario: **Progressive** (55% RES), as it provides the greatest energy independence and reduces energy costs in the long term **Least favourable:** **Conservative** (25% RES), as it keeps energy costs and CO_2 emissions high, which can lead to economic and political problems It is therefore crucial to implement policies that favour the growth of RES and to invest in the flexibility of the electricity grid to optimise the use of renewable energy sources in Poland

SCENARIO OF POLAND'S ENERGY MIX DEVELOPMENT UNTIL 2050		
In order to develop a scenario for the development of Poland's energy mix until 2050, the author considered three variants: a conservative scenario, a balanced scenario and a transformational scenario. Each of them takes into account different growth rates of the share of renewable energy sources (RES), the level of investment in new technologies and the impact of national and EU regulations.		
Conservative scenario (RES share at 50%)	Assumptions	– Poland still relies heavily on fossil fuels, although it is gradually reducing CO_2 emissions – RES development is limited by a slower pace of investment and public resistance to certain technologies (e.g. wind farms) – gas-fired power plants play a key role in balancing the electricity system
	Economic factors	– high CO_2 costs make coal power increasingly unviable, but selected coal-fired power plants (mainly with CCS - CO_2 capture and storage technology) are still in operation – relatively low investments in modern grids and energy storage technologies result in limited flexibility in the electricity system
	Technologies	– 30% of the energy mix is still based on natural gas – nuclear power provides about 15-20% of energy – RES development is mainly limited to photovoltaics and onshore wind, with a moderate contribution from offshore
	Regulations	– Poland implements the minimum requirements of EU climate policy, but does not take aggressive steps towards decarbonisation – support mechanisms for RES are limited and regulations favour stable energy sources such as gas and nuclear
	Consequences	– high energy prices resulting from dependence on imported gas – continued dependence on fossil fuels, which increases geopolitical risks – reduced competitiveness of the economy due to the high carbon footprint of production
Balanced scenario (RES share at 70%)	Assumptions	– Poland gradually increases the share of RES, in parallel with the development of nuclear power infrastructure – investment in electricity grids and storage technologies allows for stable system operation
	Economic factors	– electricity costs gradually decrease due to greater market competition and storage technologies – Poland achieves partial energy independence by reducing gas imports – significant investment in transmission and distribution infrastructure (smart grids)
	Technologies	– industry and the transport sector are switching to electricity from RES – 50% of the energy mix comes from wind (including 20% from offshore) and photovoltaics – nuclear power provides about 15-20% of the energy – energy storage and demand-side response technologies are becoming key to system stability

Balanced scenario (RES share at 70%)	Regulations	– Poland is actively implementing EU climate policy, including climate neutrality by 2050 – the government supports the development of RES through subsidies, auction systems and tax incentives.
	Consequences	– decrease in the carbon intensity of the energy sector. – moderate energy prices, stability of supply. – increased competitiveness of the economy and development of new green energy industries.
Transformational scenario (RES share of 90-95%)	Assumptions	– Poland undergoes complete decarbonisation, with RES as the dominant energy source – the electricity system is fully digitalised, with developed energy storage and smart grids – gas and coal-fired power plants are completely phased out
	Economic factors	– significant savings due to low operating costs of RES and elimination of CO_2 emissions – Poland is becoming an exporter of cheap green energy – development of hydrogen industry and use of RES for production of synthetic fuels
	Technologies	– 70% of the energy mix comes from solar and wind power – developed energy storage infrastructure (batteries, pumped storage, hydrogen) – artificial intelligence and blockchain support energy supply and demand management
	Regulation	– Poland is pursuing an advanced climate neutrality strategy – significant subsidies and tax breaks for green technologies – high taxation of CO_2 emissions effectively removes fossil fuels from the market
	Consequences	– Poland achieves full energy independence – lowest energy prices ever thanks to cheap production from RES – expansion of Polish technology companies into foreign markets
Summary and recommendations		**Most likely scenario:** **Sustainable** (70% RES), as it is realistic in the context of current technological and political trends **Most desirable scenario:** **Transformational** (90-95% RES), as it ensures full energy independence and minimises energy costs **Least desirable scenario:** **Conservative** (50% RES), as it leads to high energy prices and continued dependence on fossil fuels

Note: The progressive (2030) and transformational (2050) scenarios should be interpreted as development goals rather than short-term forecasts. Their implementation would require substantial improvements in Poland's power infrastructure - in particular, rapid grid modernisation, large-scale energy storage deployment, and digital transformation of the electricity system. Current technical limitations of Poland's transmission network and insufficient storage capacity create a high-risk constraint that may delay or reduce the scale of the projected gains. The scenarios therefore represent aspirational pathways illustrating the upper potential of the Polish energy transition under optimal regulatory and investment conditions

Source: own study

Each scenario is based on the same categories of parameters, but takes different input values (e.g., RES share, electrification rate, CO_2 emission path). This makes it possible to compare their effects in terms of system decarbonization, generation costs, energy security, and go-ness with EU policies. In addition, the scenarios show different energy transition paths. The largest CO_2 reductions and greatest long-term security are provided by the progressive scenario, but it requires the largest investments. The balanced scenario offers a trade-off between cost, feasibility and compatibility with EU policies.

Interpretation for scenario modelling:

1. Financing and investment: reports show the real scale of needs (tens of billions of zloty/USD), which helps determine CAPEX in the Progressive and Balanced scenarios.
2. Regulatory and tax framework: a number of legal and tax changes reduce barriers to entry and increase the profitability of RES projects.
3. Infrastructure: grid modernization and energy storage projects (EIB, PSE, PGE) are indispensable for the connection of new RES capacity - affecting the possible implementation schedule.
4. Stability and public acceptance: new regulations (e.g., inclusion of prosumers, participation of local communities in projects) can increase acceptance and smoothness of investments.

The following chart illustrates the share of energy sources in each scenario for the years 2030 and 2050.

To sum up and based on the author's scenarios above, in order to achieve optimal results, the key, in the author's opinion, will be not only quick investments in energy storage and modernization of power grids, which will allow the gradual phasing out of coal and gas while developing nuclear and offshore energy, but also the implementation of intelligent energy management systems and the development of hydrogen technologies. Therefore, only a consistent decarbonization policy and support for new technologies will allow Poland to achieve competitiveness in the global energy market. All the more so, as the share of renewable energy sources (RES) in Poland's energy mix increases, new challenges and opportunities related to energy efficiency arise. After all, the stability of the electricity system and cost-effectiveness largely depend on three key factors: energy storage, grid flexibility and demand management.

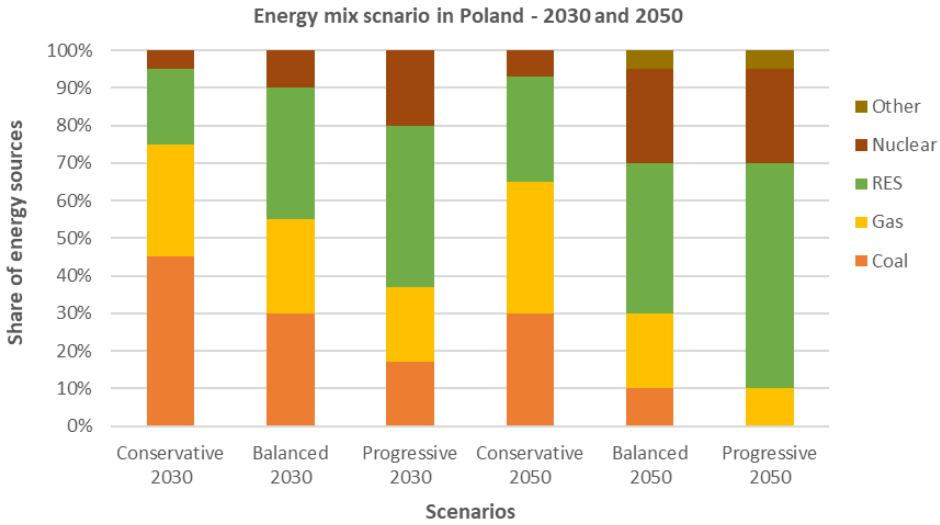

Figure 1. **Energy Mix in Poland visualization**

Source: own study

5. Discussion

According to a 2023 report by the International Renewable Energy Agency (IRENA), the cost of producing energy from RES, especially solar PV and wind, has fallen significantly in recent years, making them increasingly competitive with traditional energy sources. In Poland, the situation is similar, making them increasingly competitive with fossil fuels. In addition, an analysis by the Jagiellonian Institute and the Polish Wind Energy Association (2023) indicates that increased investment in RES infrastructure could result in savings for the Polish economy in the order of PLN 116 billion by 2040, which corresponds to a price of around PLN 34/MWh. This means that, based on the analysis of the above and other statistical data, a growing share of renewable energy sources can be observed in the Polish energy mix, with wind power and photovoltaics playing a dominant role. The decrease in the cost of energy production from RES and the potential savings for the economy emphasize the importance of further investment in these technologies in the context of cost efficiency and national energy security.

The analysis of the cost of generating electricity from different sources is crucial for assessing the economic efficiency of Poland's energy mix (Table 6). One of the commonly used indicators to compare the cost-effectiveness of different technologies is the Levelised Cost of Electricity (LCOE), which takes into account all costs associated with the construction, operation and decommissioning of an installation per unit of energy produced. Therefore, it should be borne in mind that the energy efficiency and stability of the power system in Poland will also depend on the implementation of modern technological solutions and appropriate market regulations.

Table 6. **Costs of energy production from RES in Poland - data for 2023**

No.	Energy source	Average cost [EUR/MWh]	Target cost [€/kWh]	Key factors influencing cost
1	Onshore wind power	33	0,04 – 0, 05	Mass production of wind turbines, improved efficiency, EU subsidies.
2	Offshore wind energy	75	0,04 – 0,05 (downward trend)	High investment and storage costs; integration challenges.
3	Photovoltaic energy	45	0,04 – 0, 05	Cost reductions due to scale, technology progress, and EU support programs.
4	Hard coal	≈ 64	-	Includes system stability costs (CCS, backup).
5	Natural gas	≈ 77	-	Costs influenced by fuel price volatility and CO_2 allowance prices.

Note: All cost values for fossil fuels originally expressed in USD have been converted to EUR using the average annual exchange rate for 2023 (1 USD = 0.91 EUR; source: European Central Bank)

Source: own study based on data from International Renewable Energy Agency (2023) and National Center of Nuclear Research (2023)

While renewable energy sources (RES) involve higher capital expenditure (CAPEX) at the investment stage, they are characterized by significantly lower operating costs (OPEX) compared to fossil-fuel-based power plants. RES have no fuel costs and are less exposed to commodity price fluctuations, although additional infrastructure and storage investments are required to ensure grid stability.

When comparing the costs of generating energy from RES and conventional sources, it is important to consider not only the direct costs of production, but also external costs, such as greenhouse gas emissions and impacts on public health. An analysis of the external costs of primary energy production in Poland shows significant differences in greenhouse gas emissions between different energy generation technologies. The conclusions of the cost analysis suggest that investments in renewable energy sources, especially onshore wind power, can be cost-competitive compared to traditional energy sources. In addition, taking into account environmental and social benefits, the development of RES can contribute to the long-term cost efficiency of the Polish energy system.

Below, in Table 7, the author presents a comprehensive analysis of the external costs of primary energy production in Poland, taking into account the differences in greenhouse gas (GHG) emissions between different energy production technologies. It includes emissions data, the social cost of CO_2 emissions (the so-called "external cost") and a comparative analysis. It is important to keep in mind that external costs are social and environmental costs that are not included in the market price of energy, such as greenhouse gas (GHG) emissions, air pollution (PM, NO_x, SO_2) or health and environmental damage. In the analysis, the author focused on CO_2eq emissions and climate costs in terms of EUR/MWh and EUR/t CO_2eq.

Table 7. Analysis of the external costs of primary energy in Poland

No.	Technology	CO_2eq emissions [g/kWh]	External climate cost* [EUR/MWh]	Notes	Conclusions
1.	Hard coal	820–1050	78–100	High emissions, outdated infrastructure	1. Lignite and hard coal have the highest external environmental costs - 8-10 times higher than RES. 2. Replacing 1 MWh from lignite with PV energy reduces the social cost of CO_2 emissions by about 90-95 EUR/MWh. 3. Emissions from natural gas are lower, but still significant - hence its role as transitional. 4. Wind, hydropower and PV have the lowest external costs - often <5 EUR/MWh. 5. Taking external costs into account changes the hierarchy of profitability of sources.
2.	Lignite	1000–1200	95–114	Highest emissions - dominant in Poland	
3.	Natural gas (CCGT)	350–490	34–46	Lower emissions, but still a fossil fuel	
4.	Biogas (from waste)	~100 (net ~0)	10–20	Potential for negative emissions (if counted as LCA)	
5.	Forest biomass	~200–400	18–38	Emissions dependent on source and transportation	
6.	Wind energy	12–14	~1	No operational emissions, trace life cycle emissions	
7.	Photovoltaic (PV)	20–60	2–6	Emissions mainly related to panel production	
8.	Hydropower	2–10	<1	Lowest emissions; limited availability in Poland	
9.	Nuclear	6–20	~1–2	Life cycle emissions only; high capital costs	

*Assuming social cost of CO_2 emissions: 95-100 EUR/t CO_2

Source: own study based on data from Polish Ministry of Climate and Environment (2021a), International Monetary Fund (2023), Intergovernmental Panel on Climate Change – IPCC (2021), Nguyn et al. (2025), Vivid Economics 2021 and European Commission (2023)

Unfortunately, it is also important to remember that renewable energy sources, such as photovoltaics and wind power, are characterized by variable generation that depends on weather conditions. This creates challenges related to voltage and frequency fluctuations in the grid and the need to maintain power reserves (e.g., gas-fired power plants or energy storage), which in turn can lead to the risk of grid overloads during periods of high generation. Therefore, the integration of RES into the power system is one of the key challenges for the energy transition. Just as the growing share of volatile sources, such as wind and solar, requires better demand management and the development of smart grids (Perez-Arriaga & Batlle, 2023 pp. 37-40).

Therefore, it is imperative to emphasize that RES integration costs can be and are high, especially in countries with unsuitable grid infrastructure (Lund et al., 2022, p. 77). This requires additional investments in grid stabilization. However, agreeing with Boccard (2022, p. 603), it should be assumed that RES development, which may seem very costly now, in the long term (up to 20 years), is much lower than the long-term maintenance of fossil fuels.

Of course, there are commercially available solutions to improve the stability of the system - such as energy storage (lithium-ion batteries, pumped storage or hydrogen storage). Unfortunately, they generate significant investment costs, which translate into the bottom line. In fact, so do other solutions that are gaining popularity around the world - e.g. smart grid technologies that enable dynamic matching of supply and demand (flexible grid management) and mechanisms that allow real-time adjustment of energy consumption (Demand-Side Response management).

This is in line with the current trend in science, which clearly shows that when the share of RES in the energy mix exceeds 50%, there is an increasing demand for technologies that support stability - such as energy storage and fast power reserves (Hirth et al., 2021, pp. 12-15; Hanh et al., 2020, pp. 148-149).

Further analyzing energy storage technologies and their cost-effectiveness in the context of the energy transition, it can be pointed out that:

- lithium-ion batteries are best for short-term grid balancing,
- pumped storage power plants remain the most cost-effective long-term solution,
- hydrogen as energy storage may become crucial after 2030.

To illustrate Poland's position, the average Levelized Cost of Electricity (LCOE) for onshore wind in 2023 amounted to about 43 EUR/MWh in Germany, 46 EURO/MWh in Spain and 56 EURO/MWh in Czech Republic, compared with ≈ 60 EUR/MWh in Poland (IRENA 2023; Enerdata 2025). For solar PV, the differences are similar (range 30–50 EUR/MWh), while coal-based generation remains above 90 EUR/MWh in all cases. This shows that Poland is approaching EU averages but still faces slightly higher cost levels due to grid limitations and higher financing costs. Such a comparison confirms that structural reforms (storage facilities, investment incentives) can bridge this gap and strengthen cost competitiveness within the EU energy market.

Table 8. **Comparative cost-effectiveness of energy generation in selected EU countries**

No.	Energy source	Indicator	Poland	Germany	Spain	Czech Republic	EU average
1.	Onshore wind	LCOE (EUR/MWh)	60	43	46	56	48
2.	Solar PV	LCOE (EUR/MWh)	50	38	32	47	40
3.	Coal-fired	LCOE (EUR/MWh)	95	92	90	88	>90
4.	Gas-fired	LCOE (EUR/MWh)	77	70	72	75	73
5.	Share of RES in electricity mix (%)	2023	30	52	55	27	47
6.	CO_2 emissions from power generation (Mt)	2023	95	165	181	34	N/A

Note: LCOE – Levelized Cost of Electricity; all values converted to EUR using average 2023 exchange rate (1 USD = 0.91 EUR)

Source: own study based on data from Enerdata (2025), International Renewable Energy Agency (IRENA) (2023), Eurostat (2024)

To broaden the European context, Table 8 compares Poland's energy cost-effectiveness and renewable share with selected EU countries. As shown, the LCOE values for onshore wind and solar PV in Poland remain slightly higher than the EU average, primarily due to grid and financing constraints. However, the gap is steadily narrowing, suggesting that with ongoing infrastructure modernization and policy support, Poland may reach EU cost parity before 2030.

The results of this research confirm the general pattern observed in recent international studies on renewable energy cost-effectiveness. According to IRENA (2023) and IEA (2023), the global average Levelized Cost of Electricity (LCOE) for onshore wind and solar photovoltaics continued to decline to around 45 EUR/MWh and 40 EUR/MWh respectively, while coal-based generation remained above 90 EUR/MWh. The findings for Poland presented in this paper - approximately 60 EUR/MWh for wind and 50 EUR/MWh for solar – are still 10-15 EUR/MWh higher than the EU average. This difference reflects higher financing costs and infrastructure constraints in the Polish market.

Comparative analyses reported by B. Aydın, K. Stecuła, P. Olczak, J. Kulpa and B. Stecuła, B (2025) for Central and Eastern Europe and M.B. Pietrzak, B. Igliński, W. Kujawski and P. Iwański for Poland also indicate that the reduction of variable costs from RES generation depends on grid modernisation and regulatory stability. Similar correlations are confirmed by other authors, who link the increase in the share of renewable energy with higher system efficiency only in countries with stable political frameworks and developed storage capacities (Kitzing et al., 2022).

In contrast to countries such as Germany or Spain – where rapid deployment of renewables brought a marked decline in marginal generation costs (Boccard, 2022) - Poland still faces an incomplete integration of renewable sources into the national power system.

Nevertheless, the trend lines identified in this study suggest that, the Polish market may reach cost parity with the EU by 2030.

It can therefore be concluded that the results of the author's study are consistent with the empirical findings of other authors, while also providing a regional perspective that emphasises the role of regulatory and technological factors in determining the rate of decline in RES costs in Poland.

In conclusion, analyzing scenarios for Europe, the article's author notes that grid flexibility and storage development can reduce system balancing costs by 30-40%. Especially since B. Zakeri and S. Syri (Zakeri & Sanna, 2022, p. 573) calculated that the cost of energy storage drops by 15% per year, making it likely that these technologies could become widespread in the next decade. On the other hand, smart grids, dynamic tariffs and automated demand management systems are gradually reducing the need for excessive investment in power reserves, improving the economic efficiency of the energy transition (Papadis & Tsatsaronis, 2020, p. 212).

6. Conclusion and recommendations

The share of RES in Poland is growing, but still remains lower than in many EU countries, despite the fact that the cost of producing energy from renewable sources is steadily falling, making it increasingly cost-effective. Key barriers are the lack of developed storage infrastructure and legal restrictions for onshore wind farms.

However, this does not affect the positive verification of the hypothesis posed at the outset, since the research process, carried out with the help of the methods and tools described, clearly proves that the variable costs of energy production from RES are lower than conventional sources in the long term. Besides, there can be no doubt that increasing the share of RES ultimately reduces expenditures on fossil fuels, and Poland can become independent of fossil fuel imports through the development of this sector.

However, for this to happen, certain conditions must be met and appropriate measures taken - the main recommendations for the future, according to the author, therefore include:

1. Increase investment in energy storage - crucial for system stability.
2. Investment in local grids and microgrids for greater system resilience (will enable autonomous energy management at the local level).
3. Faster adaptation of power grids to RES, which are not adapted to distributed generation. Most of the infrastructure in Poland was designed for centralized coal-fired power plants. Therefore, there is a need to modernize the transmission and distribution network - smart meters, automation and better monitoring systems are needed.
4. Integration of prosumers into the electricity system.
5. Automatic balancing of supply and demand.
6. Liberalization of regulations for onshore wind power - will enable development of new projects
7. Support for the development of offshore wind energy - great potential for Poland.
8. Support for innovation in the RES sector - e.g. hydrogen technologies.
9. Modernization of the grid and implementation of smart management systems.
10. Promoting demand flexibility through dynamic tariffs and Demand-Side Response (DSR) systems (e.g., the ability to temporarily reduce energy consumption by large industrial plants during peak hours and smart systems that allow households to adjust their power consumption).
11. Further reduce RES costs by supporting research into new technologies (e.g., reduction of transmission losses through smart grid systems and local power generation, dynamic tariffs that can encourage consumers to consume energy during periods of high RES generation, use of AI and predictive algorithms - this allows better forecasting and balancing of production.

Of course, the author is aware that despite the study providing a comprehensive analysis of the cost-effectiveness management of renewable energy sources in Poland, several limitations can be identified.

Firstly, there are methodological limitations – the study is based mainly on secondary data from institutional sources (Eurostat, IEA, PSE, URE). Although these sources are reliable, their dynamic and partially aggregated nature may limit the accuracy of cost trend estimates. The limited number of expert consultations reduced the scope of qualitative validation. Furthermore, scenario modelling was based on deterministic assumptions and did not include sensitivity analysis or non-Monte Carlo simulations, which could have strengthened the robustness of the results.

Other limitations relate to scope and time, as the analysis covers the period 2021–2024 and projections up to 2050. Future changes in EU and Polish energy policy, as well as price volatility in the energy market, may affect the relevance of the conclusions. Comparative data for selected EU countries have been averaged based on LCOE values, which may overlook regulatory and financial differences that are specific to individual countries.

As for the directions of further research, in order to deepen the analytical framework, further research should include empirical validation through expert interviews and comparative case studies between EU countries. The use of econometric methods (e.g. panel analysis or time series modelling) would make it possible to examine the causal relationships between the share of RES, energy cost structure and CO_2 emissions. Extending scenario analysis to include stochastic modelling and policy sensitivity assessment would allow for a deeper understanding of uncertainty factors and the long-term impact on energy security and competitiveness.

The integration of economic and social aspects within the model (e.g. employment effects, social acceptance, regional balance) also appears to be a promising direction. Research combining quantitative and qualitative approaches can strengthen policy recommendations and support the decision-making process for shaping Poland's renewable energy development strategy.

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