SILESIAN UNIVERSITY OF TECHNOLOGY PUBLISHING HOUSE

SCIENTIFIC PAPERS OF SILESIAN UNIVERSITY OF TECHNOLOGY 2026
ORGANIZATION AND MANAGEMENT SERIES NO. 244

MANAGEMENT OF ENERGY TECHNOLOGY SELECTION FOR STRENGTHENING POLAND'S ENERGY SECURITY

Cezary SZWED[1*], Klaudia PROCHACKA[2]

[1] Warsaw University of Technology, Faculty of Management; cezary.szwed@pw.edu.pl,
ORCID: 0000-0001-6140-8198
[2] Warsaw University of Technology, graduate of the Faculty of Management; klaudiaprochacka@gmail.com
*Correspondence author

Purpose: The objective of the present paper is to evaluate the energy technologies available and planned for implementation in Poland. This evaluation is conducted in the context of ensuring energy security (in the terminology used in the power sector: security of supply), the resilience of the power system, and compliance with political requirements.
Design/methodology/approach: The research methods employed encompass statistical data analysis, technological parameter assessment, cost analysis, emission indicators, installation lifetime, and energy transition scenarios. The presentation included an exposition of technological and political risk models, alongside comparative analyses of their various iterations.
Findings: The most significant element in enhancing Poland's energy security is to preserve the current technological mix and to incorporate high-power nuclear energy into it. The analysis demonstrated that the predominance of a particular technological approach was associated with an escalation in energy risk.
Research limitations/implications: The study is constrained by the long-term uncertainty of the regulatory environment, the absence of comprehensive data for new technologies, and the significant influence of political decisions.
Practical implications: The findings of the study have the potential to inform national energy policy, operator strategies, infrastructure development planning, enhanced decision-making processes by energy companies, and the formulation of national research and development programs.
Social implications: The energy transition is effecting profound changes to the structure of the energy sector, with consequences for the labor market and the development of local communities. It is imperative to furnish the public with reliable information regarding the planned changes and their effects on energy prices.
Originality/value: The paper integrates the results of technical analysis with strategic assessment and long-term energy development scenarios. The consideration of system resilience and political risks is also a factor in the overall assessment.
Keywords: security of supply, generation mix, generation technologies, energy transition, power sector management.
Category of the paper: Research paper.

1. Introduction

Energy security is a pivotal aspect of the functioning of industrialized countries, serving as a cornerstone of economic and social stability. In contemporary terms, this concept is not limited solely to ensuring the continuity of electricity supply, but also includes the resilience of energy infrastructure to geopolitical, economic, technological, and environmental disruptions. The extant literature on the subject increasingly emphasizes that energy security should be analyzed in systemic terms, taking into account both the supply and demand sides of the energy market (Schmitz et al., 2025).

In recent years, the definition of energy security has expanded significantly. In addition to the traditionally understood security of supply, key categories now include the system's resilience to various types of disruptions and physical and cyber attacks, flexibility of its operation in conditions of demand volatility and the use of weather-dependent sources, and adaptive capacity, i.e. the ability to respond to technological, regulatory and market changes. In the power sector, resilience is understood as an element of security of supply alongside power system reliability, consisting of grid and generation adequacy and operational security. The issue of diversifying domestic fuel and energy sources, and reducing dependence on imports of energy raw materials, such as gas, is also of particular importance. In the context of geopolitical tensions, this issue should become one of the priorities of state policy (Brown et al., 2018).

The present status of energy policy in Poland is such that the nation is undergoing a transformation of its energy sector. It is evident that the execution of this process has been undertaken in close conjunction with the European Union's energy and climate policy framework. The legislative package entitled "Fit for 55", the European Green Deal, and the reform of the emissions trading system (EU ETS) impose a number of political obligations on member states. These obligations include the requirement to systematically reduce CO_2 emissions and to develop so-called low- and zero-emission technologies. These requirements have a substantial impact on energy costs for the economy and municipal consumers (IEA, 2024).

Concurrently, global trends pertaining to the digitalization of the economy, the electrification of transport, and the automation of industrial processes are precipitating a systematic increase in electricity demand. These phenomena indicate that energy security is acquiring a strategic dimension, and investment decisions in the energy sector have long-term consequences for the competitiveness of the economy and the stability of the state (Schmitz et al., 2025).

The Polish power system continues to rely heavily on hard coal and lignite, which in recent years accounted for approximately two-thirds of domestic electricity production. This model guarantees stability of supply; however, it does not align with the directives and decisions of

EU climate policy. Concurrently, there has been uncontrolled development of renewable energy sources (RES), in particular photovoltaic including-prosumer photovoltaic sources and wind energy, with the observability and controllability of these sources not meeting the current standards in the commercial energy sector (Mrozowska et al., 2021).

Despite the rapid growth of RES, the share of stable, low-emission energy sources remains limited. The inherent variability of wind and solar energy production introduces additional challenges to the balancing of the power system, emphasizing the necessity to develop dispatchable sources, energy storage facilities, and modern grid infrastructure. In this context, the planned development of nuclear energy and technologies supporting system flexibility is of particular importance (Aldeman et al., 2023).

A pivotal component of energy security pertains to the effective management of technology within the energy sector. This concept encompasses the systematic planning, implementation, operation, and gradual phasing out of generation technologies over an extended timeframe. The energy sector is distinguished by the notably protracted life cycle of technical assets, which can span from several decades to even eighty years. Consequently, investment decisions must be made with consideration for not only the present market conditions, but also the future implications of regulatory, technological, and social developments. The management of energy technologies therefore requires a systemic approach that integrates engineering, economic, and strategic aspects (Musango, 2024).

In the context of the energy transition, it is imperative to coordinate the development of stable technologies, such as nuclear energy and high-efficiency coal-fired power plants, with the rapid development of renewable technologies and energy storage systems. Effective technology management also includes the assessment of technological and raw material risks, the ability to adapt network infrastructure, and the use of analytical tools to support decision-making, such as scenario analysis, technology life cycle assessment, and multi-criteria models. In this context, technology management has emerged as a pivotal instrument for implementing national energy policy, facilitating a compromise between security of supply, economic efficiency, and environmental objectives (Saini et al., 2025).

In the context of the aforementioned information, the impetus for this study is the necessity to revise the prevailing energy production model in Poland in the face of evolving geopolitical conditions, including the security crisis in Central and Eastern Europe, and increasingly stringent climate regulations. The decisions currently being made regarding the selection of energy technologies will determine the country's energy security for decades to come (Bani et al., 2025).

The objective of the present study is to preliminarily identify and evaluate energy technologies with the potential to form the future foundation of the Polish power system. In undertaking this task, the following criteria will be given due consideration: system adequacy, investment and operating costs, environmental impact, compliance with European Union policy, and technological and raw material risks. The paper constitutes an element of a prevailing tendency within research in the domain of engineering management and strategic analysis, with a particular emphasis on the optimal selection of technologies in the context of the resilience of critical national infrastructure.

The subsequent chapters are dedicated to the description of the research methods and techniques utilized (Chapter 2), the presentation of the quantitative and qualitative results obtained (Chapter 3), the discussion of these results (Chapter 4), and the summary of the results and the indication of directions for further research (Chapter 5).

2. Methods

The proprietary research methodology applied in this study is interdisciplinary in nature and was developed to enable a comprehensive assessment of energy technologies with regard to their suitability for ensuring Poland's long-term energy security. The methodology integrates relevant elements presented in the subject literature. The research was based on a combination of qualitative and quantitative methods, which made it possible to account for technical and economic aspects as well as strategic, regulatory, and environmental conditions.

The subsequent steps of the research methodology were as follows:

1. Identification of the research problem.
2. Classification of energy technologies.
3. Selection of technology assessment criteria.
4. Comparative analysis of energy technologies.
5. Scenario analysis of the energy mix development.
6. Synthesis of the obtained results.

The first stage of the methodology involved the identification of the research problem, consisting of defining the concept of energy security from a systemic perspective and identifying the key challenges faced by the Polish power sector. At this stage, geopolitical, regulatory, and technological conditions influencing the need for transformation of the energy mix were taken into account. The research problem was formulated as the need to select such energy technologies that ensure a balance between supply reliability, economic efficiency, and the reduction of environmental impact (Cherp et al., 2014).

In the next step, the identification and classification of energy technologies applicable to the Polish power system were conducted. The analysis covered conventional, low-emission, and renewable technologies, as well as supporting technologies such as energy storage systems. The classification was carried out with regard to the level of commercial technological maturity, the operational characteristics (fully dispatchable and non-dispatchable sources), and the potential role in the power system (IEA, 2023).

Subsequently, a set of criteria for the assessment of energy technologies was developed, encompassing four main areas: technical, economic, environmental, and energy security-related aspects. The selection of criteria was based on a review of the literature and recommendations of international institutions. This approach enabled a multidimensional evaluation of technologies, extending beyond traditional cost-based analyses (Musango, 2017).

The next stage consisted of a comparative analysis of energy technologies based on the previously defined criteria. The analysis considered, among others, investment and operational costs, emission intensity, dispatchability, and the impact on system adequacy. The comparative analysis made it possible to identify the strengths and weaknesses of individual technologies and to assess their suitability in the context of national system conditions (Lund et al., 2017).

An important element of the methodology was scenario analysis, aimed at identifying possible pathways for the development of the energy mix over the long term. The scenarios accounted for different rates of development of renewable energy sources, nuclear power, and energy storage technologies, as well as the variability of CO_2 emission allowance prices and technology costs. Scenario analysis enabled the assessment of the power system's resilience to uncertainty and external risks (Bogdanov et al., 2019).

The final stage of the methodology involved the synthesis of the obtained results and the formulation of observations of both cognitive and practical relevance. Based on the conducted analyses, the technologies that contribute most significantly to enhancing Poland's energy security were identified. This stage allowed for the integration of partial results into coherent aggregated findings (Markard et al., 2012).

3. Results

3.1. Identification of the research problem

The starting point of the research was a multifaceted analysis of the current state of the Polish power sector, which is presently at a critical tipping point. Empirical data confirms that Poland remains one of the few European Union member states that still rely heavily on fossil fuels – specifically hard coal and lignite – for their generation base. These resources, which are domestic in origin, are primarily utilized in large-scale system power plants and combined heat and power (CHP) plants. Consequently, the National Power System (NPS) is characterized by high sensitivity to the volatility of CO_2 emission allowance prices (EU ETS), the long-term dynamics of which are determined by political decisions at the European Union level.

Simultaneously, Poland is experiencing a dynamic expansion of distributed renewable energy sources (RES), with a particular emphasis on photovoltaic installations and onshore wind power. At the same time, strategic projects involving offshore wind farms, low-emission gas-fired sources, and large-scale electricity storage systems are in the early stages of development. A key component of the future generation structure is the construction of Poland's first nuclear power plant, which is currently in the preparatory phase. However, it must be emphasized that the evolution of the generation base necessitates a radical expansion of the national transmission and distribution networks.

The research problem was identified as the imperative to balance the so-called energy trilemma, which involves simultaneously ensuring security of supply, maintaining the cost competitiveness of electricity, and achieving policy-driven carbon emission reductions. In accordance with the updated National Energy and Climate Plan (NECP, 2024), Poland aims to achieve a high, several dozen percent share of RES in the energy mix by 2040. The analysis demonstrated that the technological barrier is no longer the primary inhibiting factor. Currently, the critical challenge lies in the pace of implementation and the integration of new capacities into the power system. This requires an advanced expansion of both the grid and the Information and Communication Technology (ICT) layers – specifically smart grid systems – necessary to manage distributed and highly weather-dependent energy sources.

Realizing such an ambitious transformation vision requires unprecedented capital expenditures (CAPEX). These cover not only the construction of new RES units but, above all, the costly redevelopment of grid infrastructure. The research shows that energy storage technologies, despite their crucial role in system stabilization, currently remain high-unit-cost solutions, which significantly impacts the total costs of the systemic transformation. Due to the high capital intensity and limited scalability of modern storage systems, it is considered essential to maintain, modernize, and further develop large-scale (centralized) power generation.

Large-scale generation units, including the planned nuclear power plants, will play a fundamental role as system stabilizers, guaranteeing continuity and reliability of supply during periods of reduced generation from renewable sources. This approach allows for the preservation of national energy security from a systemic perspective (Prochacka, 2025). Additional significant research challenges are associated with the decarbonization of the district heating sector and the need to adapt the grid to the dynamically increasing demand generated by electromobility.

3.2. Classification of energy technologies

In the second stage of the research, a detailed inventory and classification of available generation technologies were conducted. The analysis also incorporates the state's capacity to independently secure energy generation and delivery processes to end-users. For this reason, energy technologies can be categorized into two groups (Prochacka, 2025):

1. Technological solutions for which Poland possesses its own raw materials or fuel resources, namely: hard coal, lignite, and RES – primarily solar and wind energy (onshore and offshore).

2. Technologies requiring Poland to import raw materials, specifically: gas-fired power and nuclear energy.

Based on fuel types, according to the methodology proposed in this work, the technologies were divided into three main groups:

1. Conventional technologies (fossil fuels): hard coal and lignite power plants (the current baseload of the system) and combined-cycle gas units, serving as dispatchable (regulatory) sources.
2. Renewable technologies: onshore and offshore wind power, photovoltaics (PV), and, to a significantly lesser extent, hydropower, geothermal, and biomass energy.
3. Nuclear technology: traditional large-scale units – classified as zero-emission sources with high availability, remaining a prospective technology in the Polish context, and Small Modular Reactor (SMR) technologies, which have been under development for an extended period.

The classification accounted for the level of commercial technological maturity. Most technologies in use are at the highest level – commercial application is feasible (coal, gas, large scale nuclear, PV, onshore, and offshore wind). Technologies such as large-scale energy storage or SMRs are treated in the Polish context as implementation-stage technologies of potential strategic importance. Differences in commercial availability and construction lead times for individual technologies determine the possible dynamics of changes in the energy mix.

3.3. Selection of technology assessment criteria

To ensure the objectivity of the analysis, a multi-criteria evaluation model was adopted. The selection of criteria was based on a literature review and operational indicators crucial for the transmission system operator. The main areas of evaluation include:

1. Economic criteria.
2. Technical and operational criteria.
3. Environmental criteria.
4. Security and social criteria.

The basic stages of the life cycle of power generation sources are design, construction, operation, and decommissioning. Each of these stages is associated with a corresponding supply chain. In the energy sector, expenditures on so-called "hard infrastructure" dominate (CAPEX). These include outlays for land acquisition for construction, purchase of equipment, construction and assembly costs, and grid connection costs. On the other hand, operating expenditures (OPEX) in energy consist of fuel costs, service and maintenance, repairs, technical inspections, parts replacement, wages, taxes, and fees. An additional quasi-tax is the cost of CO_2 emission allowances. The indicator that provides the basis for comparing different technologies is the LCOE (Levelized Cost of Electricity). LCOE is the total cost of building and operating an energy installation, calculated for each unit of energy produced (typically 1 MWh) over its entire life cycle. However, LCOE does not take into account system management costs, including balancing and ancillary services or the costs of expanding the power grid.

An essential element of the evaluation was the analysis of technical parameters that determine the stability and reliability of the power system's operation, specifically the technical and operational criteria. A key indicator is the net efficiency, which defines the effectiveness of converting primary energy (fuel) into electricity delivered to the grid. An equally important parameter is the Capacity Factor, reflecting the real degree of unit utilization throughout the year. In an era of increasing shares of unstable RES, the flexibility of units – defined as the ability to rapidly increase or decrease generated power in response to fluctuations in demand and supply – becomes of critical importance.

Environmental criteria, which directly result from the European Union's climate policy goals, can also be utilized in the process of evaluating energy technologies. The primary indicator analyzed is the specific CO_2 intensity. Environmental criteria also include emissions of other pollutants, such as sulfur oxides (SO_2), nitrogen oxides (NO_X), and particulate matter, which significantly affect local air quality. An important, though often overlooked, aspect is land use requirements and the impact on ecosystems – in this context, RES technologies, such as wind or solar farms, require significantly larger areas per unit of installed capacity than centralized nuclear or coal units.

The final group consists of system security criteria and social conditions, which, in the Polish context, determine the feasibility of implementing specific technologies. Key importance was attributed to the dispatchability of supply, understood as the unit's ability to operate independently of external factors. Equally significant is the level of social acceptance, which is becoming a critical barrier for many investments. In this case, attention should be paid to the so-called NIMBY (Not In My Backyard) effect, particularly regarding onshore wind farms and the planned locations for nuclear power plants.

3.4. Comparative analysis of energy technologies

In the fourth step, a direct comparison of the selected technologies was conducted based on the chosen indicators. Within the economic criteria, this was the LCOE. The comparison results for the main technologies are presented in Table 1.

Table 1.
Selected economic parameters

No.	Technology	LCOE [USD/MWh] with CO_2 costs	LCOE [USD/MWh] without CO_2 costs
1.	Coal power plants	90-140	45-85
2.	Gas power plants	80-120	50-80
3.	Nuclear power plants	N/A	70-130
4.	Hydroelectric power plants	N/A	100-160
5.	Solar power plants	N/A	35-55
6.	Onshore wind farms	N/A	30-45
7.	Offshore wind farms	N/A	75-95

Source: authors' own elaboration based on (IRENA, 2025; NREL, 2024).

Unit costs for conventional power plants assume high capacity utilization (baseload operation). Under lower utilization factors, unit costs may significantly exceed the presented ranges due to the distribution of fixed costs. The comparison of average levelized costs of electricity (LCOE) reveals significant economic disparities among the analyzed technologies, primarily driven by emission-related charges and the specific structure of capital expenditures. In the case of renewable energy technologies (onshore wind and photovoltaics), despite exhibiting the lowest LCOE values, investment costs are largely front-loaded, with the vast majority of expenditures incurred during the construction phase. A different cost structure characterizes gas-fired power generation, which features relatively low capital expenditures (CAPEX) but a high sensitivity to variable costs, particularly fuel prices. Nuclear power and offshore wind energy, in turn, are associated with very high entry costs and substantial upfront investment requirements. For coal-fired power plants, capital expenditures for new units are currently subject to the highest financial risk, largely due to the necessity of incorporating high emission-related costs into project budgets.

Among the technical and operational criteria presented in Table 2, the comparison focuses on plant lifetime and the annual number of operating hours.

Table 2.
Selected technical and operational parameters

No.	Technology	Operational lifetime [years]	Availability Factor [h]	Relative Availability Factor [%]
1.	Coal power plants	40	7000	79,91
2.	Gas power plants	30	7000	79,91
3.	Nuclear power plants	60	8000	91,32
4.	Hydroelectric power plants	80	4000	45,66
5.	Solar power plants	25	900	10,27
6.	Onshore wind farms	25	2300	26,26
7.	Offshore wind farms	25	3100	35,39

Source: authors' own elaboration based on (Prochacka, 2025).

The Availability Factor parameter determines the technical availability of power, not the actual time of power utilization (Utilization Factor), which is significantly lower for renewable energy sources. The presented data indicate significant differentiation among technologies in terms of infrastructure lifetime and their availability within the power system. Hydropower plants (80 years) and nuclear power plants (60 years) exhibit the longest lifetimes, which, combined with the very high capacity factor of nuclear energy, defines these sources as the backbone of stable -generation. In contrast, renewable energy technologies such as photovoltaics and wind power are characterized by shorter lifecycles and substantially lower annual operating hours, resulting from their dependence on weather conditions.

From a technical perspective, a key distinction is made between weather-dependent generation sources and dispatchable (controllable) units, which include only coal-, gas-, and nuclear-fired power plants. Unlike the intermittent generation from wind farms or photovoltaic installations, these technologies offer full controllability, allowing the system operator to precisely adjust electricity production to current demand levels.

Among the environmental criteria, land-use requirements for the construction of generation facilities were selected for comparison. The results are presented in Table 3.

Table 3.
Selected environmental parameters

No.	Technology	Land use per MWh per year
1.	Coal power plants	11-23
2.	Gas power plants	0,2-1,3
3.	Nuclear power plants	0,1-0,5
4.	Hydroelectric power plants	24-40
5.	Solar power plants	1,1-35
6.	Onshore wind farms	8,4-247
7.	Offshore wind farms	N/A

Source: authors' own elaboration based on (Ritchie, 2025).

The analysis of the environmental criterion regarding land use reveals drastic differences in the energy density of individual sources. Nuclear and gas power plants exhibit the highest spatial efficiency. Within the category of conventional sources, coal power plants show a significantly higher demand for land, which is associated with extensive infrastructure for fuel storage and mining waste. Particular attention should be paid to the results for renewable technologies, which are characterized by the largest data dispersion. Solar power plants require a moderate amount of land, whereas onshore wind energy shows extremely high upper-end requirements. Such high values for wind result from the necessity of maintaining large buffer zones between turbines, although it should be noted that this land can often be co-used for agricultural purposes. Offshore wind energy does not occupy any land area, which constitutes a significant advantage in countries with limited availability of free investment sites. However, it should be remembered that occupying water areas limits their use for other purposes. In future studies, the catalog of environmental indicators should be expanded to include other parameters, such as the carbon footprint of component production and the demand for critical raw materials, which will allow for a more complete assessment of the ecological cost of the transition.

Among the security and social criteria, the dispatchability of supply – understood as the unit's ability to operate independently of external factors – was selected for comparison. The results are presented in Table 4.

Table 4.
Selected security and social parameters

No.	Technology	Dispatchability level	Reliance on external factors
1.	Coal power plants	Very high	Negligible
2.	Gas power plants	Very high	Moderate (fuel)
3.	Nuclear power plants	Very high	Negligible
4.	Hydroelectric power plants	High	Moderate (hydrological conditions)
5.	Solar power plants	Low	Total (weather-dependent)
6.	Onshore wind farms	Low	Total (weather-dependent)
7.	Offshore wind farms	Low	Total (weather-dependent)

Source: authors' own elaboration based on (Prochacka, 2025).

Table 4 highlights the particularly low dispatchability of solar power plants and wind farms compared to the reliable operation of coal and gas units. This underscores the structural necessity of maintaining dispatchable units or expanding energy storage capacity to balance the system during periods lacking weather-dependent generation.

The analysis of dispatchability must be considered alongside fuel security, which alters the strategic assessment of individual sources. Hard coal and lignite remains the only sources fully based on domestic resources, guaranteeing the highest degree of sovereignty in crisis situations. Nuclear power, despite the necessity of fuel imports, offers a high level of strategic security – the small volume of fuel rods allows for the accumulation of reserves sufficient for several years of plant operation, making the system resilient to sudden disruptions in supply chains. For simplicity, the distinction between run-of-river, reservoir, and pumped storage hydroelectric power plants has been omitted. Low dispatchability level should be understood as none, unless combined with storage.

The situation for gas power is entirely different. Due to the lack of significant domestic resources and the difficulties in storing gas quantities sufficient for long-term power generation purposes, this technology exhibits the highest sensitivity to geopolitical factors and price fluctuations on global markets. Further analysis requires consideration of additional socio-economic aspects, in particular the degree of control over technology supply chains, the potential for involvement of domestic industry (so-called local content), and the impact of investment location on the labor market and public acceptance.

3.5. Scenario analysis of the energy mix development

Based on the methodology proposed in the study (Prochacka, 2025) and the results discussed in the previous section, three scenarios for the transformation of the Polish energy sector have been proposed:

1. Continuation Scenario (Business as Usual – BAU).
2. Radical RES Scenario (Green Transition).
3. Balanced Scenario (Nuclear-RES Mix).

The Continuation Scenario assumes maintaining the dominant role of hard coal and lignite as primary sources, with a moderate increase in the share of RES. Utilizing existing domestic resources ensures high fuel sovereignty and high security; however, it generates the highest systemic costs regarding the LCOE indicator when including CO_2. High emissions and potentially low acceptance from parts of society make this variant difficult to accept from a political perspective.

The Radical RES Scenario assumes maximizing the share of photovoltaics and wind energy (onshore and offshore) with the total phase-out of coal and not building nuclear power. Its advantages include low unit costs of energy production and political acceptance. The drawbacks are the highest land-use requirements and critically low source dispatchability. This scenario would require building massive capacity in gas-fired power plants as a backup, which in turn increases dependence on fuel imports. Alternatively, building massive energy storage capacity would be necessary, which would radically increase energy costs for the economy. Based on an analysis of the forecasts contained in (NECP, 2024), maintaining stability with such a generation profile would require, in Polish conditions, at least several GW of reserve capacity in gas sources. In addition, it would also be necessary to implement at least several GW of energy storage facilities with an operating time of at least 4-6 hours. Without such a profound, costly, and addictive infrastructure modernization, it would not be possible to ensure the security of supply, and the levels of forced curtailment of RES generation could reach from several to several dozen percent of annual production, which would drastically reduce the profitability of investments and the efficiency of RES use.

The Balanced Scenario assumes stable nuclear generation alongside the development of offshore wind and photovoltaics. Nuclear power provides stable base-load operation, replacing decommissioned coal units. At the same time, it allows for the role of gas to be limited exclusively to balancing functions, which minimizes geopolitical risks associated with raw material imports. This variant optimizes the energy trilemma: costs, security, and ecology (Prochacka, 2025). In practice, such effects result from the diversification of the national energy mix (nuclear energy, RES, regulatory gas sources or storage, and fuel-secure coal sources).

3.6. Synthesis of the obtained results

The synthesis of the collected technical-economic data and the scenario analysis allows for the formulation of the following findings:

Unit Economic Efficiency vs. Systemic Costs. The results indicate a cost dualism. Although RES technologies offer the lowest LCOE, their integration in the "Radical RES" scenario generates high indirect costs stemming from the necessity of building backup capacity in gas or capital-intensive energy storage. Significant expansion of the power grid, control systems, and ensuring cybersecurity are also required. Conversely, the "Continuation" scenario exhibits the highest direct costs due to the burden of CO_2 emission fees on coal. It should be emphasized that RES do not offer the same product as dispatchable sources, because RES offer energy only at selected times depending on weather conditions, while dispatchable sources offer energy on demand.

Spatial and Environmental Optimization. There is a strong negative correlation between the degree of dispatchability and land use. Stable technologies (nuclear, gas) require minimal area, whereas low-dispatchability technologies (wind, solar) require areas tens to hundreds of times larger. The synthesis indicates that the "Balanced Scenario" best resolves land-use conflicts by utilizing the high power density of nuclear energy.

Security and Energy Sovereignty. The analysis showed that fuel sovereignty is highest in the case of coal (domestic resources) and nuclear (the possibility of long-term fuel storage). A scenario based exclusively on RES, despite no fuel requirement, paradoxically increases geopolitical risks due to the need to balance the system with imported natural gas.

Balancing the Energy Trilemma. A comparison of the scenarios proves that only the "Balanced Scenario" (a nuclear-RES-gas/coal mix) allows for the simultaneous achievement of three strategic goals: emission reduction (a political goal referred to as ecological), maintaining security of supply through dispatchable sources and guaranteed fuel availability (the security goal), and avoiding extreme energy storage costs and risks associated with gas price volatility (the economic goal).

4. Discussion

The results of this analysis cast new light on the structural and systemic challenges facing the Polish power system amidst advancing decarbonization. Particularly significant is the distinction between the unit Levelized Cost of Electricity (LCOE) and the total cost of power system operation, which also includes the costs of balancing, power reserves, grid expansion, and maintaining security of supply. With high shares of RES in the mix, actual costs can be substantially higher than LCOE would suggest. The lack of constant RES dispatchability necessitates investment in backup sources and storage. In public debate and some policy analyses, this distinction is often overlooked, leading to oversimplified conclusions regarding the competitiveness of individual technologies.

The low dispatchability (regulatability) and high variability of RES production, particularly evident in photovoltaics, significantly limit or even eliminate their ability to contribute to ensuring the country's energy security. Weather-dependent sources are unable to serve as a stable foundation for the power system without the mass deployment of energy storage technologies or support from dispatchable sources – currently coal-fired, and in the future, gas-fired as well.

The analysis confirms the economic necessity of moving away from coal as the base of the national energy mix if CO_2 emission costs in the EU ETS system are included in the energy price. Poland, characterized by one of the highest emission intensity rates in the European Union, is also particularly vulnerable to fluctuations in emission allowance prices. Consequently, energy sovereignty understood as possessing one's own fuel resources becomes, in a sense, an economic trap, causing funds collected as CO_2 emission costs to flow from the energy sector to other sectors via the state budget (in part), in accordance with political decisions, and to the EU ETS system (in part – currently at least several billion PLN). On balance, from participation in the EU ETS system alone, Poland therefore loses significant amounts of money. This implies that the reasons for this state of affairs are purely political in origin and are unrelated to the operational efficiency of the power sector.

These conditions necessitate a redefinition of the concept of energy security: from a model based on raw material availability to a model based on access to advanced low-emission generation technologies with high power density. In this context, the discussed balanced scenario, in which nuclear energy serves as the stable pillar of the power system, takes on special significance. The analysis showed that despite high investment outlays, nuclear power plants offer exceptionally high dispatchability and very low land use. Nuclear power plants with Long-Term Operation (LTO) achieve the lowest generation costs among all low-emission technologies. These parameters are crucial not only for security of supply but also for social acceptance.

In the discussion regarding the NIMBY phenomenon, the spatial argument carries particular weight. The construction of a single centralized nuclear power plant, located in a limited area, may prove more socially acceptable than the necessity of installing thousands of wind turbines scattered across large areas of the country, or dozens of SMR plants once that technology reaches commercial maturity. This aspect is often marginalized in purely cost-based analyses, despite being a significant barrier to RES development in practice.

The radical RES scenario, which assumes a mix based almost entirely on renewable sources, also requires critical reflection. Poland's specific climatic conditions – including low solar irradiation in winter and seasonal wind variability – mean that a lack of nuclear energy would have to be compensated for by a significant increase in capacity from gas-fired power plants. Excessive reliance on a single source of uncertain raw materials is difficult to accept. Dependence on gas increases the system's vulnerability to price spikes and regulatory changes (CO_2 allowance prices). Furthermore, burning gas still generates CO_2 emissions, and its extraction process can cause methane leaks – a potent greenhouse gas. This leads to a transformation paradox: in striving for decarbonization, the system becomes increasingly dependent on natural gas imports, which increases risks to national energy security in the context of an unstable geopolitical situation. Natural gas, despite its flexibility and relatively lower emission intensity, should serve as a transition and regulatory fuel rather than a long-term foundation of the energy mix.

The considerations are supplemented by an analysis of the sensitivity of key parameters, which allows the resilience of individual scenarios to market volatility to be determined. The most critical factor for the continuation scenario remains the volatility of CO_2 emission allowance prices in the EU ETS system, which directly determines the costs of production in coal-fired units and may transform fuel sovereignty into an "economic trap." In turn, the radical RES scenario shows the highest sensitivity to fluctuations in natural gas prices on global markets and to the rate of decline in energy storage technology costs (learning curves), as the lack of a stable basis forces the use of fossil fuels as a necessary system backup. In the case of nuclear energy, which is a pillar of the sustainable scenario, the key parameters of uncertainty are the cost of capital (WACC) and the risk of exceeding the budget during the construction phase (CAPEX), but once operational, these units offer the lowest and most predictable generation costs in long-term operation. Taking the above uncertainties into account confirms that diversifying the mix within the sustainable scenario best mitigates the risks arising from the unpredictability of commodity markets and climate policy, providing the best response to the energy trilemma. Consequently, the energy mix must be balanced. Strategic discussion should not focus on a dichotomous choice of "RES or Nuclear", but on determining the correct proportions between technologies. Synergy between low LCOE but unstable renewable sources and nuclear energy – which is costly to build but stable and spatially efficient – allows for maintaining acceptable energy prices for industry and households. This combination of technologies allows for the limitation of total system costs while ensuring continuity of supply amid variable RES shares. As a result, the energy transition appears not as a purely technological process, but as a multidimensional optimization of the energy trilemma, in which security of supply, the politicization of climate, and economic competitiveness must be treated as equals.

5. Conclusions

As part of this paper, a comprehensive comparative analysis of generation technologies in the Polish energy sector was conducted, based on a multi-criteria synthesis of economic, technical, environmental, and security indicators. Utilizing an original methodology, three transformation scenarios were evaluated: continuation, radical RES, and balanced, which allowed for the identification of a desirable energy mix capable of meeting the needs of the national economy. By integrating factual data with security analysis, directions for further transformation planning were formulated, demonstrating the synergy between nuclear energy and renewable energy sources. Thus, the analyses carried out have made it possible to identify the desired direction of transformation, although it should be noted that the ultimate effectiveness of the selected scenarios will depend, among other things, on the dynamics of CO_2 emission allowance costs and the pace of commercialization of energy storage technologies.

The scientific value of the paper and the proposed methodology lies in a holistic approach to the energy trilemma, extending beyond the standard framework of purely cost-based analysis. In relation to previous studies, which often focus in isolation on the LCOE indicator or exclusively on climate aspects, this work introduces a link between technical dispatchability, energy density, and fuel sovereignty. Such an approach allows for more precise modeling of real systemic costs, representing a significant contribution to the development of energy economics theory under the conditions of transforming mono-technological systems into diversified systems.

The utilitarian value of the paper is reflected in the possibility of its direct use by the management of energy companies, market analysts, and government administration bodies responsible for shaping the state's energy policy. The presented syntheses of technical-economic parameters can serve as a ready-made tool supporting decision-making processes regarding investment portfolio selection and risk assessment related to raw material availability. Demonstrating the high spatial efficiency of nuclear energy can be utilized in educational campaigns aimed at increasing social acceptance for large-scale energy investments.

Despite the broad scope of the analysis, there are certain limitations in the application of the presented results, primarily resulting from the high dynamics of market variables. The study did not include a detailed account of the costs of modernizing transmission and distribution networks, which, in the case of the radical RES scenario, may significantly affect the final energy price for the end consumer. Furthermore, the analysis does not account for the volatility of the weighted average cost of capital (WACC) over time, which, in the case of long-term investments such as nuclear power plants, may modify the final LCOE indicator. The analysis also does not consider potential technological breakthroughs in the field of commercial long-cycle energy storage.

Future research directions should focus on three levels. Researchers should strive to develop power system models that account for real-time system balancing costs and the impact of digitalization on mix efficiency. For economic practitioners, it will be essential to study the possibilities of sector coupling, which could utilize surpluses from RES. Politicians, on the other hand, should focus on creating stable regulatory frameworks conducive to long-cycle investments, such as nuclear power, while simultaneously developing mechanisms to support local acceptance for fully controllable, weather-independent distributed energy sources.

References

1. Aldeman, M.R., Jo, J.H., Loomis, D.G., Krull, B. (2023). Reduction of solar photovoltaic system output variability with geographical aggregation. *Renewable and Sustainable Energy Transition*, *3*. doi:10.1016/j.rset.2023.100052
2. Bani Ahmad, A., Ooi, C. A., Ali, O., Charin, C., Maharum, S.M.M., Swadi, M., Salem, M. (2025). Renewable integration and energy storage management and conversion in grid systems: A comprehensive review. *Energy Reports*, *Vol. 13,* doi: 10.1016/j.egyr.2025.02.008
3. Bogdanov, D., Farfan, J., Sadovskaia, K., Aghahosseini, A., Child, M., Gulagi, A., Oyewo, A.S., de Castro, G., Breyer, C. (2019). Radical transformation pathway towards sustainable electricity via upwards convergence. *Nature Communications, Vol. 10, Iss. 1, No. 1*, pp. 1-14, doi: 10.1038/s41467-019-08855-1

4. Brown, T., Schlachtberger, D., Kies, A., Schramm, S., Greiner, M. (2018). Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system. *Energy, Vol. 160*, doi: 10.1016/j.energy.2018.01.001
5. Cherp, A., Jewell, J. (2014). The concept of energy security: Beyond the four As. *Energy Policy, 75,* doi: 10.1016/j.enpol.2013.09.019
6. IEA (2023). *International Energy Agency. World Energy Outlook 2023,* https://iea.blob.core.windows.net/assets/86ede39e-4436-42d7-ba2a-edf61467e070/WorldEnergyOutlook2023.pdf, 30.11.2025.
7. IEA (2024). *International Energy Agency, Energy Technology Perspectives*, https://iea.blob.core.windows.net/assets/34511d5d-8dc8-42a2-8faf-b83606cffced/EnergyTechnologyPerspectives2024.pdf, 30.11.2025.
8. IRENA (2025). Renewable Energy Statistics 2025. *International Renewable Energy Agency*, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2025/Jul/IRENA_DAT_RE_Statistics_2025.pdf, 30.11.2025.
9. Lund, H., Østergaard, P.A., Connolly, D., Mathiesen, B.V. (2017). Smart energy and smart energy systems. *Energy, Vol. 137, Iss. 1, No. 1*, pp. 556-565, doi: 10.1016/j.energy.2017.05.123
10. Markard, J., Raven, R., Truffer, B. (2012). Sustainability transitions: An emerging field of research and its prospects. *Research Policy, Vol. 41, Iss. 6, No. 1*, pp. 955-967, doi: 10.1016/j.respol.2012.02.013
11. Mrozowska, S., Wendt, J.A., Tomaszewski, K. (2021). The Challenges of Poland's Energy Transition. *Energies, 14(23)*, 8165. doi:10.3390/en14238165
12. Musango, J.K. (2017). Sustainability of technology-society systems: The case of electricity in South Africa. *Energy Policy, Vol. 105, Iss. 1, No. 1*, pp. 73-86, doi: 10.1016/j.enpol.2017.02.030
13. Musango, J.K. (2024). Energy technology assessment in managing sustainable energy transitions: A bibliometric analysis. *Sustainable Energy Technologies and Assessments, 72*. doi:10.1016/j.seta.2024.104021
14. NECP (2024). National Energy and Climate Plan for 2021–2030. *Ministry of Climate and Environment*. https://www.gov.pl/web/klimat/krajowy-plan-na-rzecz-energii-i-klimatu, 30.11.2025.
15. NREL (2024). *2024 Standard Scenarios Report: A U.S. Electricity Sector Outlook*. National Renewable Energy Laboratory. https://docs.nrel.gov/docs/fy25osti/92256.pdf, 30.11.2025.
16. Prochacka, K. (2025). *Selection of energy technologies in the context of Poland's energy security (in Polish).* Master's thesis. Warsaw: Warsaw University of Technology, Faculty of Management.
17. Ritchie, H. (2025). *How does the land use of different electricity sources compare?* OurWorldinData.org. https://archive.ourworldindata.org/20251125-173858/land-use-per-energy-source.html, 30.11.2025.

18. Saini, K., Saini, M., Kumar, A., Saini, D.K. (2025). Performance analysis and optimization in renewable energy systems: a bibliometric review. *Discover Applied Sciences*, *Vol. 7, No. 178,* doi: 10.1007/s42452-025-06585-2
19. Schmitz, R., Flachsbarth, F., Plaga, L.S., Braun, M., Härtel, P. (2025*).* Energy security and resilience: Revisiting concepts and advancing planning perspectives for transforming integrated energy systems. *Energy Policy, Vol. 207,* doi:10.1016/j.enpol.2025.114796