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Analysis of the energy source potential of the Polish economy

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ABSTRACT:
The Polish energy sector is undergoing a dynamic transformation driven by economic growth, climate policy, and the need to ensure long-term energy security. Historically dependent on coal-based generation, Poland is gradually increasing the share of renewable energy sources, particularly photovoltaics and wind power, which have recorded rapid growth in installed capacity and electricity production in recent years. Rising electricity prices, technological innovation and regulatory support have further accelerated this transition. However, the variability of renewable energy generation and limitations in energy storage technologies pose significant challenges to grid stability and reliability. In this context, nuclear energy is increasingly considered a strategic component of the future energy mix. Modern nuclear power plants, including advanced fast neutron reactors, offer high energy density, low greenhouse gas emissions and continuous electricity supply. The closed fuel cycle associated with fast neutron reactors significantly enhances fuel efficiency and reduces long-term resource constraints. This paper analyzes the current structure of the Polish energy sector, compares renewable and nuclear energy sources in terms of reliability, cost-effectiveness and environmental impact, and evaluates their role in ensuring sustainable economic development. The results indicate that a diversified energy mix combining renewable sources with nuclear power is essential for maintaining energy security, stabilizing electricity prices and achieving climate goals in Poland.

KEYWORDS:
Polish energy sector; renewable energy sources; nuclear power; fast neutron reactors; energy security; electricity costs; sustainable development

1. Introduction

Energy represents a key area of state activity in meeting the country's economic needs and development prospects. Currently, nuclear energy sources constitute a key source of energy in highly developed economies.

The Polish energy sector is still based primarily on fossil fuels, with particular emphasis on coal. In 2025, it accounted for 69.57 % of gross electricity production. At the same time, renewable energy sources (RES) play a significant role, generating 20.71 % of electricity in Poland in 2024. Their share is steadily growing, thanks in part to wind and photovoltaic energy. Among RES, the largest production in 2024 was recorded in wind energy, with the total installed capacity of wind farms reaching 10,391 MW. In the first half of 2025, global wind energy production increased by 7.7 % (+97 TWh), with growth dynamics in photovoltaics [1-5]. The price of electricity is a factor stimulating the development of this group of energy sources. During the years 2021-2022 in Poland the energy price doubled from PLN 282.97/MWh to PLN 566.33/MWh [6]. Poland's energy challenges in 2025 are characterized by the rapid development of renewable energy sources (RES), particularly in photovoltaics, which dominates the installed capacity.

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In June 2025, renewable energy sources (RES) reached a record high for Poland, accounting for 41.1 % of total electricity production [7]. The development of this industry is driven by innovations such as energy storage, smart grids and new forms of consumer support.

2. Assessment of the Polish energy sector

It is unknown when a so-called "blockade" will occur in Poland. According to literature, such a risk exists especially during planned shutdowns of old coal-fired power units, which can lead to long-lasting power outages [7]. Blockades are also possible due to extreme weather conditions.

Renewable energy sources are one way to save the Polish economy, but they are burdened with many drawbacks, including:
- high initial costs,
- long payback periods for investment costs,
- limited availability and harmfulness of risky renewable energy systems, including wind energy.

Among renewable sources, solar power plants achieved the best results, and are also the most desirable option near homes. The main drawbacks of such plants include the panels' exposure to sunlight, their dependence on weather conditions, which leads to inconsistent energy production, the need for large areas for panel installation and the need to store excess energy. The payback period for the investment is approximately ten years and their lifespan is estimated at 25 years. Our German neighbor's economy is not abandoning photovoltaics, but it is struggling with excess energy during periods of strong sunlight, leading to technological difficulties and problems with the profitability of this investment. This situation constitutes a so-called "development failure", requiring the development of new solutions, such as new markets or energy storage.

3. Which countries generate the most renewable energy

In 2024, China produced 32 % of its electricity from renewable sources. The United States produced 11 %, Brazil 7 %, Canada 4,7 %, and India 4,3 %. The next countries in the ranking of countries with the share of renewable energy were Germany, Japan, Russia, Norway, and Spain. Poland ranked 27th in terms of the amount of electricity produced from renewable energy sources [8].

Poland's energy sector is undergoing a global transformation with a decreasing share of coal and a significant increase in the share of renewable energy sources (RES), especially photovoltaics. Forecasts indicate a further increase in energy demand, challenged by electromobility, rising generation costs, the need for massive investments in RES and the need to build nuclear power plants to ensure energy security and achieve climate goals.

4. Nuclear power plants in the global assessment of electricity production

Nuclear power plants generate electricity by harnessing the energy derived from the fission of uranium-235 and plutonium atoms. In 2024, there were 440 nuclear power plants operating worldwide in 33 countries, with a total capacity of 390 GW.

The beginnings of nuclear power came in the 1950s, with the first 5 MW nuclear power plant built in 1954 in Obinsk, USSR. The early days of nuclear power focused on the production of enriched fissile material for nuclear weapons. The rapid development of nuclear power is due to the failure-free operation of the first nuclear power plants [9, 10].

The decline in interest in this energy source was influenced by two significant accidents in nuclear power systems: the first at Three Hilee Island in 1979 and the second at Chernobyl in 1986. The design and construction cycle for a nuclear power plant takes approximately 10 years, so the consequences of decision-making are often difficult. After 2020, many countries began to reconsider the possibility of building nuclear power plants due to commitments to limit carbon dioxide emissions, forecasts of rising fuel prices, difficulties resulting from the redistribution and demand for electricity, and the desire to diversify its sources. Nuclear energy is the most condensed energy source used by humans and is one of the cleanest forms of energy production currently known. Furthermore, uranium resources are estimated to be sufficient to meet humanity's energy needs for many thousands of years [9-11]. In the years 2024-2030, the construction of new power units is planned in Bangladesh (2), China (28), France (1), India (8), South Korea (2), Slovakia (1), Turkey (4), USA (1), Russia (3), Great Britain (2), Iran (1), Egypt (3) and Poland (1) [11-13].

A nuclear power plant operates through a nuclear fission reaction, which releases a large amount of heat, which is absorbed by water at high pressure (approximately 15 MPa) in the primary steam circuit. This circuit is operated using reactors (PWRs), which use ordinary, so-called light water. The water coolant serves as the working fluid in the reactor core. The PWR produces hot water at high pressure, which then flows to the steam generator (WP). In the second circuit, it releases heat at lower pressure, which is converted into dry saturated steam, typically at a temperature of 275 °C and a pressure of 6 MPa. This steam then expands in a steam turbine (TP), producing electricity via a generator. The PWR uses two water working fluid circuits to reduce the risk of radioactive leakage.

In power plants (PWRs), the net energy output is reduced by 6 % of the rated reactor power, where this energy is used to power all technological systems. New technologies and new nuclear reactors have recently emerged; so-called "fast neutron reactors" are nuclear reactors where energy is obtained in the active neutron spectrum, i.e., close to neutron fission (> 105 eV). The neutron energy is not slowed down, and the so-called "fast neutron energy", hence the name of the reactor type, is used. The neutron flow rate involved in nuclear fuel fission is cooled by liquid lead or metallic sodium [11].

5. Fast neutron nuclear reactors

Compared to the currently dominant neutron reactors (BWRs), the new type of reactor (BN) allows for an increased convertion ratio of the uranium-238 isotope to plutonium isotopes, which support the reaction, including with hydrogen derived from nuclear waste known as depleted uranium. The concept of mass-produced fast neutron reactors leads to a reduction in the uranium demand for their operation, a process known as a closed fuel cycle [14-16].

In September 2016, Russia tested a new professional power unit with a fast neutron reactor, the BN-Beloyansk-600, along with the launch of fuel production under the name MOX [16, 18]. Russia has become a leader in the transition to a closed-cycle nuclear fuel consumption, which will allow significant amounts of energy to be obtained from this new, innovative energy source due to the possibility of using fuel derived from recycled nuclear waste. Currently, to put it simply, uranium fuel accounts for only 3 % of its energy potential; this technology is used in conventional nuclear power plants. In fast neutron reactor technologies cooled by metallic sodium or liquid lead, 99 % of the energy potential of uranium or plutonium nuclear fuel is utilized [17, 18].

In a nuclear power plant with a fast neutron (FN) reactor, the reactor generates energy through a chain reaction involving the fission of uranium or plutonium nuclei, with neutrons being produced more quickly during the fission process. In conventional reactors (BWRs), neutrons are slowed by passing them through water to become thermally effective moderators. Fast neutron reactors do not have a neutron slowing system. In the active zone of the reactor (FN), the fission of fuel nuclei occurs, resulting in the release of fast neutrons, which cause the propagation of the nuclear fuel and can also transform unfissiled isotopes, such as uranium-238. This phenomenon will significantly expand the raw material base for nuclear energy. The new reactor system leads to a closed fuel cycle, one of the features of fast neutron reactors [17, 18]. Moreover, the operation of the reactor on so-called "fast neutrons" cooled by liquid lead is characterized by the fact that the heat exchanger is not water as in the reactors used so far (BWR), but liquid lead.

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The new technology generally increases the effective fuel supply, which can last for 2,000 years. The most important thing for this technology is the reactor structures (BN), which are relatively safe. These technologies use lead or metallic sodium instead of heated water operating at high pressure. Sodium becomes liquid at 100 °C and boils at 900 °C. In conventional nuclear reactors, the cooling system, which uses water at 15 MPa, increases the risk of system depressurization and large-scale accidents. Metallic sodium eliminates this problem because sodium's high boiling point allows the use of this type of coolant and heat exchanger at normal pressure, eliminating the risk of a large-scale accidents. Sodium, when in contact with oxygen and moist vapors, forms stable chemical compounds, which remain within the power plant in the event of an accident and prevent the spread of radioactive elements. The literature [17, 18] shows that Rosatom has commercial variants of the fast neutron (FN) reactor.

Rosatom is improving its technology and is currently actively working on the design and construction of another reactor, the BN-1200, which uses molten lead as a heat exchanger. Based on literature reports [15-18], the technology of nuclear power plants using fast neutrons cooled by liquid lead is expected to be one of the most efficient and safe nuclear technologies in the world in the coming decade. Another important direction is the construction of modular nuclear power plants with a fast neutron reactor (BN) with lower energy outputs, which will allow for more flexible management of the electricity generated in such plants.

6. Reliability, cost-effectiveness and the various aspects of electricity sources

In 2024, the global renewable energy sector will have 585 GW of new installed capacity, representing a 92.5 % share of global capacity and energy. The sector is not developing rapidly to meet the COP 28 target of doubling renewable energy capacity, with capacity forecast at 11.2 TW by 2030. What distinguishes 2024 is not only the scale of the performance but also its structure. In 2024, global renewable energy capacity will increase to 15.1 %, a result recommended by historical research. IRENA Director General Francesco La Camera notes that renewable energy capacity increases each year, demonstrating that renewable energy is one of the most economically and operationally viable sources for distribution. The disadvantage is that distribution sources are regional.

The reliability of renewable and nuclear energy is a key economic aspect that influences the stability and efficiency of energy systems. Renewable energy sources can be flexible and resilient to reliability issues, and when complemented by smart grids and energy storage, they aid in energy management. Nuclear energy, on the other hand, has its place in a flow-based energy mix, where a balanced approach to environmental protection, ensuring energy security during nuclear power plant operation, and managing radioactive waste remain key challenges.

Both different energy sources, renewable energy and nuclear energy, guarantee the country’s economic development, which has its place in the future energy mix, where environmental protection and energy security remain key. An important aspect of electricity source analysis is the economic outcome, i.e., the price of electricity, which only with clean energy technologies becomes a key element in achieving sustainable economic development. The renewable energy

sector impacts fragile economies. In nuclear energy, the costs of investment projects are crucial. However, to ensure the stability of energy grids, nuclear energy sources will constitute a stable base energy source, complementing the instability of renewable energy sources, thus improving the reliability of electricity access in the national economy. Reducing the negative environmental impacts of nuclear energy investments requires international cooperation on technology and the exchange of experience in the safety of its operation, which minimizes the risks associated with its construction and operation. The strengths of nuclear energy include:
- low thermal gas emissions during energy production,
- high energy efficiency relative to the amount of fuel and raw materials used,
- continuous energy supply.

Despite this, the risk of failure and the impact on local ecosystems cannot be ignored. The economic aspect of electricity sources also becomes crucial in the assessment. The foundation of commercial power generation has been, and should continue to be, a safe supply of electricity.

A dominant theme in the energy sector is the development of renewable technologies, which play a key role in transforming electricity production. Solar and wind energy are becoming increasingly common. The development of nuclear energy has also brought significant innovations. Modern reactors are safer, generate minimal waste, and advanced cooling and process control systems enable stable energy production from this source. The global energy sector has developed a system for assessing the profitability of electricity production from various sources [19]. The LCOE method is a method for assessing the profitability of obtaining electricity from various sources, allowing for a comparison of the costs of electricity production from different raw materials. It includes all costs related to the construction, operation and decommissioning of the installation, as well as the amount of energy produced during its useful life. This provides the average cost of generating 1 MWh of electricity, where Figure 1 presents the cost of energy from various sources of electricity generation [19]. The cost of electricity production varies depending on the technology used and the type of fuel. The LOCE method is a key indicator enabling comparison of the cost-effectiveness of different energy sources, allowing us to objectively assess which technologies are cost-effective over a given timeframe.

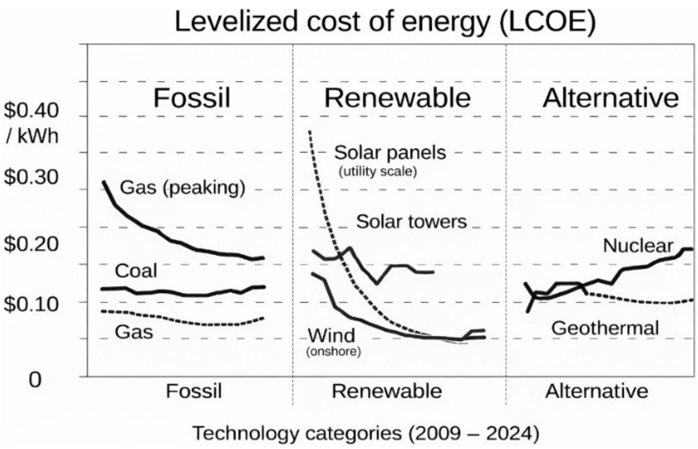

Fig. 1. Cost of generating electricity from various sources [19]

7. Conclusions

The development prospects for renewable energy in Poland are optimistic, with significant projected increases in installed capacity, especially in photovoltaics and small-scale wind energy. Key factors include falling technology costs, growing demand for clean energy, and regulatory changes. The core challenge in Poland is the development of energy storage technologies.

To ensure Poland's energy security, there is undoubtedly a need to build safe and efficient nuclear power plants as part of the security of the Polish energy system.

References

[1] Transformacja energetyczna w Polsce, Edycja 2025, Forum Energii, https://www.forum-energii.eu/transformacja-energetyczna-polski-edycja-2025.

[2] Pokrywiecki M., Stan polskiej energetyki – analiza i kierunki działań, Stowarzyszenie KoLiber, https://koliber.org/publikacje/stan-polskiej-energetyki-analiza-i-kierunki-dzialan/.

[3] Forum Energii, https://www.forum-energii.eu/.

[4] Energetyka24.com, https://energetyka24.com/.

[5] Olkuski T., Grudziński Z., Polityka energetyczna Polski – nowe wyzwania, Zeszyty Naukowe Instytutu Gospodarki Surowcami Mineralnymi i Energią PAN 2019, 108, 71-81, DOI: 10.24425/znigsme.2019.128670.

[6] Raporty za rok 2024, Polskie Sieci Elektroenergetyczne, https://www.pse.pl/dane-systemowe/funkcjonowanie-kse/raporty-roczne-z-funkcjonowania-kse-za-rok/raporty-za-rok-2024.

[7] Dashboard, Energetyczna mapa Polski, https://emp.pw.edu.pl/.

[8] Rocznik – dane o energetyce, Forum Energii, https://www.forum-energii.eu/rocznik-dane-o-energetyce.

[9] Elektrownia jądrowa, Wikipedia, https://pl.wikipedia.org/wiki/Elektrownia_j%C4%85drowa.

[10] Elektrownie jądrowe w świecie, Świadomie o atomie. Energia jądrowa w Polsce, https://swiadomieoatomie.pl/baza-wiedzy/elektrownie-jadrowe-na-swiecie/.

[11] Nuclear.pl, https://nuclear.pl/.

[12] Kwinta W., Największe elektrownie atomowe świata 2022 [RANKING TOP 15], inzynieria.com, https://inzynieria.com/energetyka/elektrownie_atomowe/rankingi/65704,najwieksze-elektrownie-atomowe-swiata-2022-ranking-top-15.

[13] Energetyka jądrowa w Polsce i na świecie, EY, https://www.ey.com/pl_pl/insights/consulting/energetyka-jadrowa-szanse-i-wyzwania.

[14] Atomnaya energetyka v mire, Rostatom, https://rosatom.ru/mediacenter/.

[15] Atomnaya energia, http://spravochnik.ru/.

[16] Reaktory na bystrych neutronach, Luch v Dzenie.

[17] Yadernye reaktory na bystrych neutronach, Yurithacher.com.

[18] Budushche yadernoi energetyki v Rosiji, https://techmaster.ru/.

[19] LCOE: Porównanie kosztów wytwarzania energii z konwencjonalnych i odnawialnych źródeł, PROWABLE, https://www.prowable.pl/lcoe-porownanie-kosztow-wytwarzania-energii/.

Analiza potencjału źródeł energii w gospodarce Polski

STRESZCZENIE:
Polski sektor energetyczny przechodzi dynamiczną transformację, wynikającą z rozwoju gospodarczego, polityki klimatycznej oraz konieczności zapewnienia długoterminowego bezpieczeństwa energetycznego. Tradycyjnie oparty na węglu system energetyczny stopniowo zwiększa udział odnawialnych źródeł energii, w szczególności fotowoltaiki i energetyki wiatrowej, które w ostatnich latach odnotowały szybki wzrost mocy zainstalowanej i produkcji energii elektrycznej. Wzrost cen energii, innowacje technologiczne oraz wsparcie regulacyjne dodatkowo przyspieszają ten proces. Jednocześnie zmienność produkcji energii z OZE oraz ograniczenia technologii magazynowania energii stanowią istotne wyzwania dla stabilności i niezawodności systemu elektroenergetycznego. W tym kontekście energetyka jądrowa coraz częściej postrzegana jest jako strategiczny element przyszłego miksu energetycznego. Nowoczesne elektrownie jądrowe, w tym zaawansowane reaktory na szybkich neutronach, charakteryzują się wysoką koncentracją energii, niską emisją gazów cieplarnianych oraz zdolnością do ciągłej produkcji energii elektrycznej. Zamknięty cykl paliwowy, typowy dla reaktorów prędkich, znacząco zwiększa efektywność wykorzystania paliwa i ogranicza długoterminowe problemy surowcowe. W pracy dokonano analizy struktury polskiego sektora energetycznego, porównano odnawialne i jądrowe źródła energii pod względem niezawodności, opłacalności ekonomicznej i oddziaływania na środowisko oraz oceniono ich rolę w zapewnieniu zrównoważonego rozwoju gospodarczego. Wyniki wskazują, że zdywersyfikowany miks energetyczny, łączący OZE z energetyką jądrową, jest kluczowy dla bezpieczeństwa energetycznego Polski, stabilizacji cen energii oraz realizacji celów klimatycznych.

SŁOWA KLUCZOWE:
sektor energetyczny Polski; odnawialne źródła energii; energetyka jądrowa; reaktory na szybkich neutronach; bezpieczeństwo energetyczne; koszty energii elektrycznej; zrównoważony rozwój