

Estimating the costs of replacing conventional energy in the era of energy transformation – the example of Poland

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Abstract

This article analyses the costs of replacing conventional energy sources in Poland in the context of the ongoing energy transition. The article aimed to determine the capital expenditures required to replace conventional sources with renewable technologies, such as wind power and photovoltaics. The article also presents the potential costs associated with maintaining renewable energy installations (*OPEX*), based on available literature. Based on available source data, both the construction costs of new installations and their potential economic profitability were estimated. This analysis included indicators such as *NPV*, *IRR*, and *LCOE*. The analysis demonstrated that all considered technologies could be profitable, but their profitability depends on the assumptions adopted. Based on the assumptions adopted in the article, wind energy (onshore) performed best, characterised by the lowest capital expenditures and the shortest payback period. The results indicate that replacing conventional energy is possible, but requires a differentiated investment approach and consideration of the specific characteristics of individual renewable technologies.

Keywords

energy transition, decarbonisation, renewable energy deployment, investment needs



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Introduction

The ongoing energy transition is transforming electricity systems worldwide. It has become a central pillar of economic and energy policy development across the European Union. The energy transition process in the European Union is being reinforced by a regulatory framework aimed at achieving climate neutrality by 2050 and ambitious climate goals (the 20-20-20 package, the "Clean Energy for All Europeans" strategy, the European Green Deal, the "Fit for 55" initiative, and REPowerEU) (Salim et al., 2026; International Energy Agency, 2023; REN21, 2024; European Commission, 2023; European Commission, 2022; Bluszcz & Manowska, 2020; Gajdzik et al., 2024; Manowska, 2018; Li et al., 2020; United Nations, 1997; Directive 2009/28/EC, 2009; Directive (EU) 2018/2001, 2018; Fetting, 2020; European Commission, 2019; Schlacke et al., 2022). Investments in renewable energy technologies, driven by the need to reduce greenhouse gas emissions and increase the share of renewable energy sources (International Energy Agency, 2023; REN21, 2024; Al Khaffaf et al., 2024; Stancu et al., 2025; Pietrzak et al., 2021; Myszczyzyn & Suproń, 2021), have now become a central element of energy policy and market development.

Poland is one of the largest producers and users of coal in the EU, making it a particularly relevant case study due to its historically high reliance on coal-fired electricity generation and the resulting structural challenges associated with decarbonisation (International Energy Agency, 2022; Kardaś, 2023; Rybak et al., 2024; Marciniuk-Kluska & Kluska, 2025). Despite the dynamic development of renewable energy sources in recent years, the transformation of the Polish energy system is still limited by existing infrastructure, regulatory conditions, and cost factors.

In this context, the economic evaluation of renewable energy investments plays a key role in supporting decision-making processes. Metrics such as net present value (*NPV*), internal rate of return (*IRR*), and levelized cost of electricity (*LCOE*) are commonly used to assess the profitability and cost-competitiveness of energy projects (International Energy Agency, 2020; IRENA, 2022).

Although existing research addresses various aspects of energy transition and renewable energy development in Poland, integrated analyses combining multiple economic indicators in current market conditions are lacking. In particular, limited attention has been paid to the simultaneous use of *NPV*, *IRR*, and *LCOE* in investment feasibility assessment; these analyses are often sector-specific (Pietrzak et al., 2021; Simionescu et al., 2023; Simionescu, 2025; Simionescu & Cifuentes-Faura, 2023).

This study aims to assess the economic profitability of renewable energy investments in Poland using a combined approach based on financial and economic analysis indicators. In addition to universal indicators such as *NPV* and *IRR*, the Levelized Cost of Electricity (*LCOE*), a specialised indicator for the energy industry, was used, allowing for the assessment of the profitability of a generation source and for comparative analysis across technologies. The study contributes to the literature by providing a comprehensive assessment framework applicable to investment decisions in the context of the energy transition. This publication examines three renewable energy sources: solar, wind, and water.

The article consists of nine chapters. In addition to the Introduction and Literature Review, it presents the study's methodology, investment costs, and operating and maintenance costs. It also presents an analysis of the potential of selected energy sources and a comprehensive analysis of the investment profitability using several indicators in combination. The article also includes a Discussion and Conclusions.

Literature review

Renewable Energy Transition and Investment Needs

The growing importance of renewable energy sources (RES) is widely recognised in the literature as a key element of the global energy transition. Growing concerns about greenhouse gas emissions, combined with technological advances and falling costs of renewable technologies, have accelerated the deployment of RES in power systems. In the European Union, this trend is further reinforced by the regulatory framework aimed at achieving climate neutrality by 2050, including binding renewable energy targets and carbon pricing mechanisms. As a result, investments in renewable energy infrastructure have become a central element of both energy policy and market development, with significant capital flows directed towards wind and solar technologies (International Energy Agency, 2023; REN21, 2024; European Commission, 2023; European Commission, 2022).

At the same time, the literature emphasises that the scale and effectiveness of investments in RES are strongly dependent on country-specific conditions, including regulatory stability, market structure, and existing generation structures. This highlights the importance of case studies in understanding the economic feasibility of RES projects in different national contexts (REN21, 2024; European Commission, 2023; European Commission, 2022).

Specificity of the Polish Energy Sector

Poland is a particularly relevant case for analysing renewable energy investments due to the structural characteristics of its energy sector. The Polish power system has historically been dominated by coal-fired power generation, resulting in high emissions and significant reliance on fossil fuels. Despite recent growth in renewable energy capacity—especially photovoltaics—the transition process is still limited by existing infrastructure, regulatory uncertainty, and the need to ensure system stability (Pietrzak et al., 2021; Myszczyżyn & Suproń, 2021; Brauers & Oei, 2020).

Existing research emphasises that the transformation of the Polish energy sector is shaped by both internal and external factors. On the one hand, ageing coal-fired power plants and rising operating costs create a structural need for modernisation (Pietrzak et al., 2021). On the other hand, the European Union's climate policy, including the EU Emissions Trading System (EU ETS), has significantly changed the economic conditions for electricity generation by increasing the costs of high-emission technologies. Therefore, the development of renewable energy in Poland is not only a technological shift but also a response to changing economic and regulatory conditions (Pietrzak et al., 2021; Myszczyżyn & Suproń, 2021).

Economic Evaluation Methods in Energy Investments

The economic evaluation of energy investments is a well-established field, with several indicators used to assess project feasibility and efficiency. The most commonly used indicators include net present value (*NPV*), internal rate of return (*IRR*), and levelized cost of electricity (*LCOE*). *NPV* measures the overall profitability of an investment by discounting future cash flows, while *IRR* reflects the rate of return that balances the present value of revenues and costs. *LCOE*, in turn, represents the average cost of generating electricity over the project's lifetime and is widely used to compare different energy technologies (IEA, 2020; Thom et al., 2025; Stolarski et al., 2024).

Although these indicators are frequently used in the literature, they reflect different dimensions of economic efficiency and are subject to specific limitations. For example, *NPV* and *IRR* depend on assumptions about discount rates and future price trajectories, whereas *LCOE* does not account for system integration costs or the market value of electricity. Therefore, a comprehensive assessment of renewable energy investments requires the combined use of multiple indicators rather than relying on a single indicator (Ranosz et al., 2026).

Applications of Economic Indicators in Renewable Energy Studies

Numerous studies have used economic indicators to assess the feasibility of renewable energy projects, particularly in the context of solar and wind technologies. The scientific literature confirms that declining technology costs and supportive policy frameworks have improved the competitiveness of renewable energy relative to conventional power generation. However, results vary significantly depending on location-specific factors such as resource availability, market prices, and regulatory conditions (IEA, 2023; Thom et al., 2025).

In the context of Central and Eastern Europe, and Poland in particular, existing analyses often focus on selected technologies or individual indicators (Stolarski et al., 2024; Olkiewicz et al., 2023; Niekurzak, 2021). While some studies assess the cost competitiveness of renewable energy using *LCOE*, others focus on financial performance indicators such as *NPV* and *IRR*. This fragmented approach limits the ability to draw comprehensive conclusions regarding investment profitability, especially in dynamically changing market conditions (Ranosz et al., 2026; Camilo & Santos, 2023).

Research Gap

Despite the growing number of publications on renewable energy development and economic evaluation methods, integrated analyses combining multiple evaluation metrics within a single analytical framework are still lacking. In particular, limited attention has been paid to the simultaneous use of *NPV*, *IRR*, and *LCOE* in assessing renewable energy investments in Poland under current market conditions (Ranosz et al., 2026; Camilo & Santos, 2023).

This gap is particularly significant in the context of the ongoing energy transition, where investment decisions must consider both financial performance and cost competitiveness. In response to this limitation, this study adopts a combined approach to assessing the economic viability of renewable energy projects, providing a more comprehensive basis for decision-making.

Methodology

Extensive secondary data analysis was conducted, followed by the necessary calculations, which allowed for the determination of investment costs for constructing a 1 MW installation for various renewable energy sources.

The assessment of the effectiveness of investments in renewable energy sources was conducted in several stages (Fig. 1).

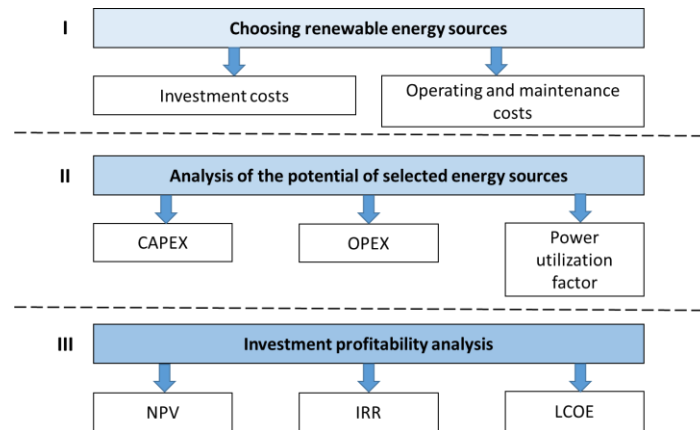


Fig. 1. Stages of research on the profitability of investments in renewable energy sources. Source: own study

First, three energy sources were selected: solar, wind, and water. In addition to the photovoltaic power plant, two wind farms were considered: onshore and offshore. Then, using publicly available data, a list of costs comprising the total investment cost for constructing a 1 MW installation was presented for selected renewable energy sources, and approximate CAPEX and OPEX values were estimated for each (for a 1 MW installation). The installed capacity utilisation factor (1) was also calculated, where time is defined as the total number of hours in a calendar year. This indicator allows for assessing the efficiency of a given plant's nominal capacity.

$$\text{Power utilization factor} = \frac{\text{Energy produced (GWh)}}{\text{Installed power (GW)} \cdot \text{Time(h)}} \quad (1)$$

In turn, three indicators were used to conduct the profitability analysis:

- **NPV (Net Present Value)** stands for net present value and is the sum of discounted cash flows from an investment, reduced by the initial outlays. In practice, NPV allows a comparison of the capital expenditures required for an investment and the cash flows it will generate in the future. The formula for calculating NPV can take various forms, with two of the most common: a basic formula, in which the approach assumes the separation of capital expenditures from financial flows, and a specific formula, in which the outlay is assumed to be consistent with the sum of cash flows, where it is treated as a cash flow derived from the zero term. The basic formula, included in this publication, is as follows (2) (Bzunek, 2018; Encyklopedia Zarządzania, n.d.):

$$NPV = \sum_{i=1}^n \frac{CF_i}{(1+r)^n} - I_0 \quad (2)$$

Where:

- CF_i – financial flows,
- I_0 – value of initial outlays,
- n – number of periods,
- r – required rate of return; the rate of return imposed by an investor over a single cash flow period;

- **IRR (Internal Rate of Return)** is a method of finding the discount rate for which the discounted financial flows reach the value of investment expenditures. This technique is directly related to the NPV model, because the IRR determines the discount rate for which the NPV is 0. To determine the NPV, a modification of equation 2 can be used, in which the value of this indicator is assumed to be 0, and in relation to this, the corresponding discount rate d is sought. Profitability can be assessed by equating the IRR value with the discount rate, and the interpretation is as follows (Brealey et al., 2020):

- $IRR > d$ – profitable investment, $NPV > 0$,

- $IRR = d$ – neutral investment, $NPV = 0$,
- $IRR < d$ – financially unprofitable investment, $NPV < 0$.

- **LCOE** (ang. *levelized cost of electricity*) – the levelized cost of electricity (Garrison & Noreen, 2021; Biernaciak, 2023) is a translation of the net present value of the cost of producing a unit of electricity during the operation of a given energy plant. The calculations include all incurred costs: investment, renovation, operating, and fuel costs, as well as the outlays required to repay any debts. The summed costs are divided by the volume of electricity produced, taking into account the discount rate and the installation's service life, i.e., the time during which the installation can be effectively used before it becomes unprofitable or technically unsuitable for further operation. The obtained value is most often converted to kilowatt-hours [kWh], megawatt-hours [MWh], or gigawatt-hours [GWh], which makes the unit universal and facilitates the comparison of results from different technologies (Sikorski, 2019). The most universal equation for calculating the LCOE coefficient was used (3) (IRENA, 2019):

$$LCOE = \frac{\text{total costs in the total period}}{\text{amount of electricity in the total period}} = \frac{\sum_{t=1}^n \frac{CAPEX_t + OPEX_t}{(1+r)^t}}{\sum_{t=1}^n \frac{E_t}{(1+r)^t}} \quad (3)$$

Where:

$CAPEX_t$ – investment expenditure per year t ,

$OPEX_t$ – operating costs per year t ,

E_t – amount of electricity produced per year t ,

r – annual effective discount rate,

n – installation service life.

The necessary calculations were performed using an EXCEL spreadsheet.

Results

Investment costs

Capital expenditures, also known as *CAPEX (Capital Expenditure)*, are not universal, as the costs they include depend directly on the type of investment. However, several types of costs are specific to each project, including (Kucharczyk, 2017): real estate acquisition costs (including land and facility purchases), construction and modernisation costs (including renovations), purchase of machinery and equipment, research and development costs related to the development of new products or technologies, and costs related to the construction or modernisation of supporting infrastructure, such as power grids.

Below is a cost estimate of individual investment components for a hypothetical 1 MW photovoltaic installation (Table 1).

Tab. 1. List of costs that make up the total investment cost for the construction of a 1 MW photovoltaic installation

	Investment component	Price [PLN]
1	Purchase of a plot of land with an area of 1.6 ha	86 000
2	Site preparatory work	440 000
3	Project execution	164 000
4	Photovoltaic panels; 540 [PLN/pcs.]	1 199 880
5	Inverters (inverters); 12 410 [PLN/pcs.]	210 970
6	Components supporting the operation of the system	30 000
7	Ground installation tables/roof mounting systems; 2 200 [PLN/pcs.]	396 000
8	Wiring	266 200
9	Installation of PV modules, inverters, and mounting tables/systems	279 828
10	Accessories (distribution boxes, controllers, etc.)	36 000

11	Transformer with connection	250 000
12	Facility monitoring	30 000
13	Fencing the facility	70 000
TOTAL		3 458 878

Source: own study based on (Kwestarz, Merle & Obrębska, 2021)

Table 2 presents financial outlays for photovoltaic installations based on the 2023 report by the Institute for Renewable Energy.

Tab. 2. The structure of turnover on the photovoltaic market in Poland in 2023

PV market segments	Increase in new PV capacity [MW]	Average investment cost [PLN million/MW]	Electricity production from PV [GWh]
Micro-installations (<50 kW)	2 022	4.0	9 820
Installations < 1 MW	1 676	3.1	3 142
Farms > 1 MW	963	2.5	1 071
Suma	4 662	-	14 032

Source: own study based on (Ciula et al., 2023)

With respect to the above data, the basis for the calculations will be the average investment cost, reflecting the average CAPEX incurred for the implementation of a single project. The common cost figure for all PV market segments was determined by a weighted average, based on the percentage share of each installation type in total PV market electricity production in 2023, and the estimated value was **3.68 [PLN million/1 MW]**.

Table 3 is a summary of data obtained from various sources on the total investment outlays in the field of solar energy for a 1 MW photovoltaic installation, along with the obtained arithmetic mean.

Tab. 3. Capital expenditures for the implementation of a 1 MW photovoltaic power plant

Data source	CAPEX [PLN/ 1 MW]
Raport IEO (2023)	3 680 000
Kwestarz, M. et al., Gaz, Woda i Technika Sanitarna (2021)	3 458 878
Rackiewicz, M. ARE S.A (2019)	4 585 800
AVERAGE	3 908 226

Source: own study based on (Kwestarz, Merle & Obrębska, 2021; Ciula et al., 2023; Rackiewicz, 2019)

The next section presents data on the second unconventional energy source under consideration, i.e., onshore and offshore wind energy. The estimated structure of investment expenditures for 1 MW of installed capacity in an onshore wind farm, developed by PWEA (Energetyka Wiatrowa w Polsce Raport 2024, 2023) in its published report, is presented in Table 4.

Tab. 4. Estimated structure of capital expenditures for 1 MW of installed capacity in an onshore wind farm in 2023

Average investment costs for 1 MW of installed capacity in 2023	Cost [PLN million]
Turbines	4.7
Site preparation/purchase of rights to implement the project	1.4
Main Power Point and Wiring	1.0
Construction work	0.6
Connection fee	0.2
TOTAL	7.9

Source: own study based on (Energetyka Wiatrowa w Polsce Raport 2024, 2023)

Table 5 is a summary of data obtained from various sources on the total investment outlays in the area of onshore wind energy for a 1 MW farm, together with the obtained arithmetic mean.

Tab. 5. Capital expenditures for the implementation of a 1 MW onshore wind farm

Data source	CAPEX [PLN/1 MW]
Raport PSEW (2023)	7 900 000
Białynicki-Birula, P. (2020)	4 468 741
Czepło, F. (2022)	6 700 000
AVERAGE	6 356 247

Source: own study based on (Energetyka Wiatrowa w Polsce Raport 2024, 2023; Białynicki-Birula, 2020; Czepło, 2022)

Offshore wind farms (OWFs) require a separate cost estimate because the components that shape costs differ in this sector. The structure of the share of individual CAPEX components for offshore wind farms is presented in Fig. 2, based on data developed by Baker Tilly TPA (Energetyka Wiatrowa w Polsce Raport 2024, 2023).

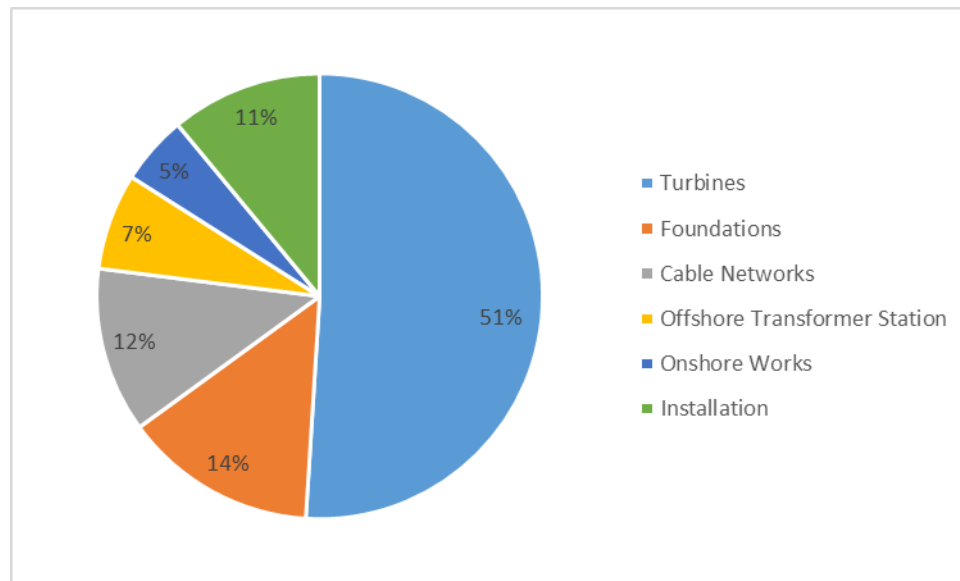


Fig. 2. Percentage share of individual CAPEX investment expenditures in the construction of offshore wind farms in Poland. Source: own study based on (Energetyka Wiatrowa w Polsce Raport 2024, 2023)

The above diagram is only an estimate due to the lack of currently operating Polish offshore wind farms (OWFs) with actual data on incurred expenditures. However, this does not mean a lack of historical data on the construction of offshore wind farms in the Baltic Sea, as currently operating offshore wind farms in other Baltic countries are operated by Germany, Denmark, Switzerland, and Finland. Based on these and domestic estimates from PWEA, the potential investment outlays for the development of offshore wind energy in Poland in 2023 were estimated at PLN 12.4 million per **1 MW**. Historical data from foreign countries came from eight separate farms, while the actual investment outlays for OWFs commencing production in 2024 - 2026 are expected to be in the range of PLN 8.3–12.5 million per 1 MW (Energetyka Wiatrowa w Polsce Raport 2024, 2023). The differentiation is mainly because the value of expected expenses for newly built farms is lower than for existing farms, due to technological progress in the form of larger and more efficient turbines or better project management processes, which directly affects lower construction costs (Lee & Zhao, 2022).

In determining the target CAPEX value for the profitability analysis, preliminary predictions regarding the size of investment outlays for the implementation of the first Polish offshore wind farm under the Baltic Power project were used. According to preliminary estimates by PWEA, investment outlays will amount to approximately PLN 18.16 million per 1 MW (Baltic Power, n.d.). A summary of estimated investment outlays from both sources mentioned above, along with the average value, is presented in Table 6.

Tab. 6. Capital expenditure for the implementation of offshore wind energy

Data source	CAPEX [million PLN/1 MW]
Raport PSEW - hypothetical farm (2024)	12 400 000
PSEW – Baltica Power (2026)	18 166 666
AVERAGE	15 283 333

Source: own study based on (Energetyka Wiatrowa w Polsce Raport 2024, 2023; Baltic Power, n.d.)

To summarise the gathered information, the highest *CAPEX* per 1 MW of installed capacity is associated with offshore wind energy technology, for which the average costs amount to PLN 15 283 333. These costs are significantly higher than those that could be incurred for the construction of the onshore wind energy sector, for which the average *CAPEX* was set at PLN 6 224 685.25/1 MW. The lowest *CAPEX* per 1 MW of installed capacity is for a photovoltaic installation, at PLN 4 263 369.50.

Operating and maintenance costs

OPEX (Operating Expenditures) includes costs associated with day-to-day operations, meaning all expenses, excluding capital expenditure, incurred to run a given business. Operating expenses include, among others, (Garrison & Noreen, 2021): costs of materials and raw materials, labor costs (including salaries, bonuses, and employee benefits), maintenance and operating costs, expenses arising from the need to maintain facilities, machinery, and other resources (including energy costs, maintenance, and potential repairs), administrative and management costs, costs related to company management, including office costs, accounting and legal services, and sales and marketing costs (financing promotions, advertising, and all other customer acquisition activities).

The following data present a cost estimate of individual operating expenses incurred during the implementation of a hypothetical 1 MW photovoltaic installation over the course of one year (Table 7).

Tab. 7. List of costs that make up the total annual operating costs for the implementation of a 1 MW photovoltaic installation

OPEX element	Cost [PLN/1 MW/1 year]
Service fee	30 000
Land tax	13 580
Energy consumption	2 160
Insurance	24 852
TOTAL	70 592

Source: own study based on (Kwestarz, Merle, & Obrębska, 2021)

Table 8 presents *OPEX* values in a manner analogous to the *CAPEX* data summary (Table 3), coming from the same sources and referring to the same 1 MW photovoltaic installations. The costs refer to the annual operation.

Tab. 8. Annual operating costs for the implementation of 1 MW of photovoltaic installation

Data source	OPEX [PLN/ 1 MW/1 year]
Raport IEO (2023)	51 250
Kwestarz, M. et al., Gaz, Woda i Technika Sanitarna (2021)	70 592
Rackiewicz, M. ARE S.A (2019)	72 109
AVERAGE	64 650

Source: own study based on (Kwestarz, Merle, & Obrębska, 2021; Ciula et al., 2023; Rackiewicz, 2019)

The remainder of this section is devoted to characterising operating costs for onshore and offshore wind energy. A cost estimate of average annual operating expenses for an onshore wind farm, prepared by PWEA based on data from several different companies, is presented in Table 9.

Tab. 9. List of costs that make up the total annual operating costs for the implementation of a 1 MW onshore wind farm

OPEX element	Cost [PLN/1 MW/1 year]
Operation and maintenance costs	123 500
Property tax	49 400
Lease rent	22 230
Insurance, wind farm management fees, and administrative costs	51 870
TOTAL	247 000

Source: own study based on (Energetyka Wiatrowa w Polsce Raport 2023)

In line with the presentation of operating cost data in the solar energy sector, the averaged *OPEX*, along with the average annual *OPEX* for onshore wind farms, was based on the relevant *CAPEX* sources for the same project. The data are summarised in Table 10.

Tab. 10. Operating costs for the implementation of a 1 MW onshore wind farm in 1 year

Data source	OPEX [PLN/ 1 MW/1 year]
Raport PSEW (2023)	247 000
Białynicki-Birula, P. (2020)	125 753
Czepło, F. (2022)	Brak danych
AVERAGE	186 377

Source: own study based on (Białynicki-Birula, 2020; Czepło, 2022; Energetyka Wiatrowa w Polsce Raport 2023)

The operating cost structure of offshore wind farms is similar to their onshore counterparts in terms of the share of operation and maintenance costs, such as monitoring and maintenance, as well as service costs, including repairing potential failures, structures, and cabling. Rescue operations at sea that pose a foreseeable threat to workers' health or lives constitute an additional element. Therefore, the *OPEX* calculation should also include the operation of service ports in the event of an immediate rescue operation.

PSEW estimated *OPEX* for offshore wind farms using several sources, including historical data from the German Baltic 2 wind farm, launched in 2015, and current data from several farms in European waters. Based on this, the average annual operating costs for a Polish offshore wind farm were determined at **PLN 380 000/1 MW**. Due to the scarcity of data on these costs, this value will serve as the sole basis for further calculations as part of the offshore wind energy profitability analysis.

To summarise the collected information, offshore wind farms are characterised by the highest operating costs, with annual costs expected to be PLN 380 000 per 1 MW. *OPEX* for onshore wind farms is PLN 247 000/1 MW annually, and photovoltaic installations are associated with costs for this period of PLN 77 624.50/1 MW.

Analysis of the potential of selected energy sources

This section will provide a theoretical analysis of the potential for replacing conventional energy with the renewable sources under consideration. Table 11 presents a summary of average *CAPEX* and *OPEX* data for the analysed technologies, and based on this, graphs were created showing the relative costs of both types of costs for each technology compared to the remaining solutions (Fig. 3 and Fig. 4).

Tab. 11. Summary of average *CAPEX* and *OPEX* values for selected technologies

Energy harvesting technology	CAPEX [PLN/ 1 MW]	OPEX [PLN/ 1 MW/1 year]
Photovoltaic installations	3 908 226	64 650
Onshore wind farms	6 356 247	186 377
Offshore wind farms	15 283 333	380 000

Source: own study

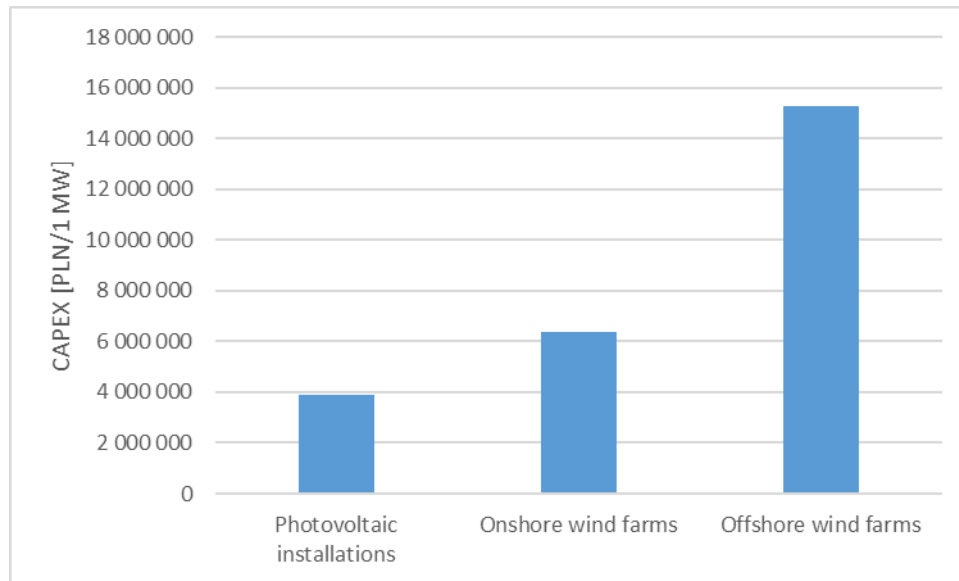


Fig. 3. Averaged CAPEX for photovoltaic installations and onshore and offshore wind farms.
Source: own study

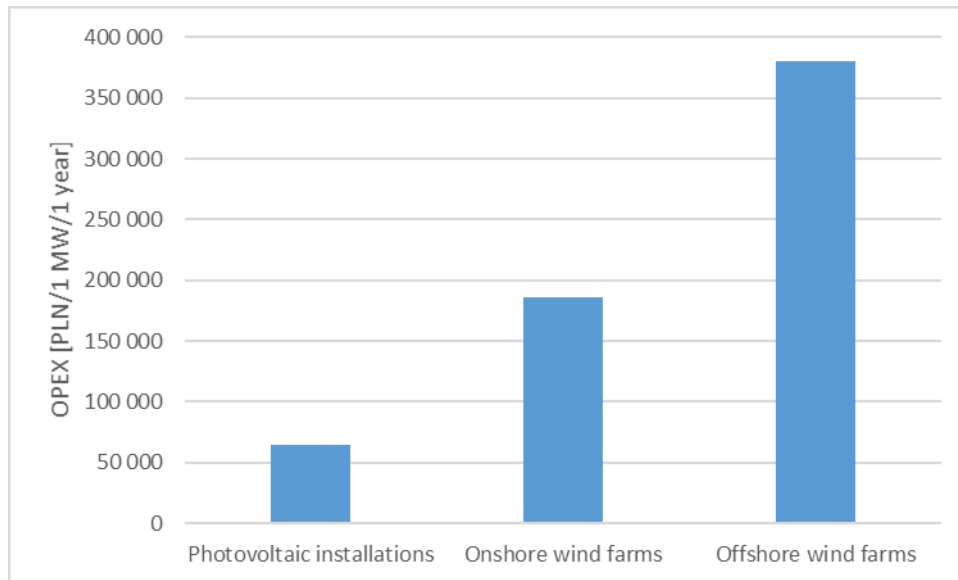


Fig. 4. Annual average OPEX for photovoltaic installations and onshore and offshore wind farms.
Source: own study

Based on the table and the above graphs, both the average *CAPEX* and *OPEX* values for a single year show an upward trend in the following order: photovoltaic installations, onshore wind farms, and offshore wind farms. It is also worth noting that the investment in an offshore wind farm is more than twice that for other technologies, and that the annual *OPEX* for onshore wind farms is, on average, twice as high as the corresponding *CAPEX* for other technologies.

To perform calculations to assess the profitability of individual sources based on installed capacity and energy production, the installed capacity utilisation factor (formula 1) will be used as an additional tool. Table 12 presents the installed capacity of power plants, the amount of electricity produced, and the average capacity utilisation factor for the currently most frequently used electricity sources in Poland as of the end of 2023, as well as data for the implementation of the first offshore wind farm, Baltic Power, which will be commissioned in 2026.

Tab. 12. The structure of installed power plant capacity and electricity produced in them for the largest electricity sources in Poland in 2023 and for the Baltic Power project

Source of electrical energy	Installed power plant capacity [GW]	Average capacity utilisation factor [%]	Amount of energy produced [GWh]
Conventional sources			
Hard coal	25.1	34.8	76 607
Lignite	8.3	47.6	34 571
Natural gas	4.7	32.9	13 650
Unconventional sources			
Solar energy	17	8.9	13 323
Wind energy – onshore power plants	9.3	28.2	23 000
Wind energy - Baltic Power offshore farm (2026)	1.2	38	4000

Source: own study based on (Informacje o projekcie Baltic Power, n.d.; Polskie Sieci Elektroenergetyczne, n.d.)

According to data from the Polish Power Grid, energy from coal and natural gas accounted for over 76% of total production in 2023, reaching 124.8 TWh (Polskie Sieci Elektroenergetyczne, n.d.). Mine sources are characterised by a high capacity utilisation factor due to their ability to operate at full capacity regardless of weather conditions, which poses the greatest challenge for renewable sources. Solar energy has the lowest capacity utilisation factor due to changes in solar radiation throughout the day, when production is zero at night, as well as seasonal changes and the resulting cloud cover in autumn and winter. Wind energy offers significantly better capacity utilisation, as the time of day does not limit the potential to utilise moving air masses, but wind intensity and frequency still carry the risk of unpredictability. In response, offshore wind farms were constructed, creating conditions that intensify both wind speed and frequency. This stabilisation ensures a 38% capacity utilisation rate, comparable to the potential of fossil fuels.

Based on the information presented in this section, estimated capital expenditures were calculated for replacing 124.8 TWh of electricity produced from fossil fuels with unconventional sources, taking into account the capacity utilisation factors of the technologies. The results are presented in Table 13.

Tab. 13. Estimated capital expenditures for specific types of installations to replace current electricity production from fossil fuels

Energy harvesting technology	Target energy production [TWh]	Power utilisation factor [%]	Necessary installed power [GW]	Total CAPEX [PLN billion]
Photovoltaic installations	124.8	8.9	160	625
Onshore wind farms	124.8	28.2	50.5	321
Offshore wind farms	124.8	38	37.5	573

Source: own study

The estimated CAPEX for the above-mentioned sources of fossil fuel replacement is highest for photovoltaic installations, at PLN 625 billion, while simultaneously requiring the highest installed capacity, due to a significantly lower capacity utilisation factor compared to other solutions. A similar capital expenditure of PLN 573 billion is associated with the construction of offshore wind farms, which have the highest capacity utilisation factor among the analysed sources, as reflected in the lowest required installed capacity. The construction of onshore wind farms has CAPEX more than half that of the above-mentioned sources, at an estimated PLN 321 billion, with the required installed capacity 26% higher than for offshore wind farms and 68% lower than for photovoltaic installations.

Investment profitability analysis

This subchapter analyses the profitability of investments in the considered renewable sources using NPV, IRR, and LCOE indicators. The installed capacity of individual types of installations was selected so that the total electricity production corresponded to 124.8 TWh of energy produced from fossil fuels in 2023 (Polskie Sieci Elektroenergetyczne, n.d.). The assumption included in the PEP2040 document, predicting 11 GW of total installed capacity for offshore wind farms in 2040, was adopted, as well as the optimistic scenario for the 10H distance act; according to it, if a minimum distance of 500 m for wind installations from residential buildings is established, the potential installed capacity for this energy source will reach a maximum value of 40.41 GW.

Each power plant type was treated separately, maintaining certain parameters with a common value despite possible actual deviations for individual solutions, including the discount rate and the plant's operational period. The energy sales price was determined based on PSE data on the monthly market price of electricity (RCEm), which averaged approximately PLN 450/MWh in 2023. The discount rate of 8.2% was established as a reference point based on the 2023 PWEA report on offshore wind energy, given the project's technologically complex and high-budget nature, consistent with conservative assumptions for other technologies. Both the operational and construction periods of the power plant are average values based on the specifications for individual installation types (Table 14).

Tab. 14. Parameters of individual types of installations included in the profitability analysis

Calculation parameter	Photovoltaic installations	Onshore wind installations	Offshore wind farms
Installed power [GW]	17	30.3	11
Power utilisation factor [%]	8.9	28.2	38
Electricity production [TWh/year]	13.3	74.9	36.6
CAPEX [PLN billion]	66	192	168
OPEX [PLN billion]	1.1	5.6	4.2
Market price of energy [PLN/MWh]	450	450	450
Discount rate [%]	8.2	8.2	8.2
Installation construction time [years]	3	3	3
The life of the installation [years]	25	25	25

Source: own study

The above assumptions indicate that the total cost of replacing conventional energy with selected renewable sources, with the assumed installed capacity structure, is **PLN 426 billion**. Based on the above data, the *NPV* and *IRR* for each type of installation were first determined using an EXCEL spreadsheet. In accordance with the adopted assumptions, the *NPV* for photovoltaic power plants was determined at PLN -25.52 billion with an *IRR* of 3.3%. Both a negative *NPV* and an *IRR* below the assumed 8.2% discount rate clearly indicate the project's unprofitability. For investments in onshore wind farms, the result was PLN 40.85 billion with an *IRR* of 9.5%, demonstrating the consistency of the calculations and the investment's profitability, with a return recorded after just four years of operation, based on aggregate cash flows. Offshore wind farms proved to be the most unprofitable project, with a profitability of PLN -66.3 billion and an *IRR* of 5.3%. The summary of results is presented in Table 15.

Tab. 15. NPV and IRR profitability indicators for individual renewable energy technologies

Type of installation	NPV [PLN]	IRR [%]
Photovoltaic installations	-25 520 000 000	3.3
Lądowe farmy wiatrowe	40 850 000 000	9.5
Morskie farmy wiatrowe	-66 300 000 000	5.3

Source: own study

To provide a visual comparison of the investment profitability of the technologies under consideration, we used the *LCOE* indicator, developed specifically to assess the costs of generating electricity from various sources. The calculated values are visualised using a graph (Fig. 5).

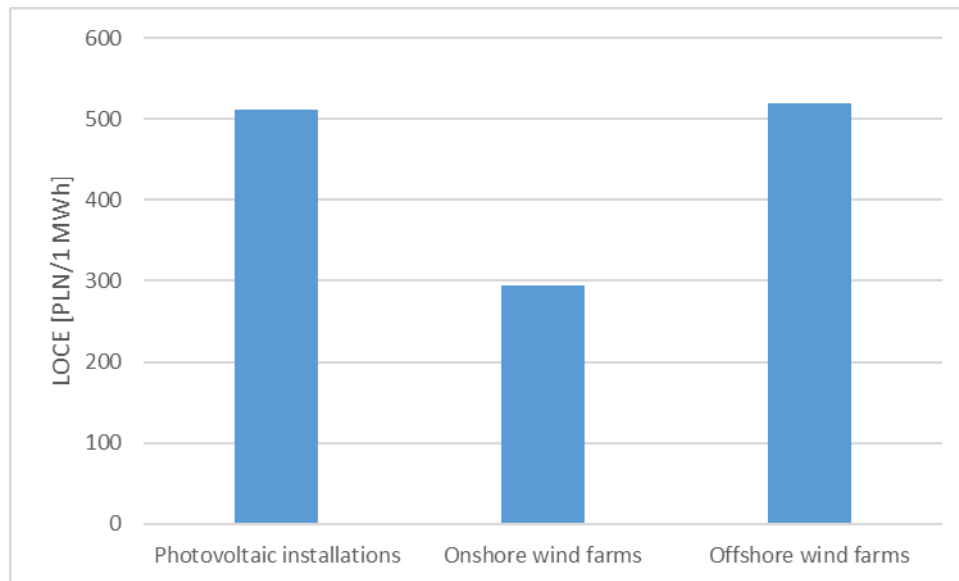


Fig. 5. LCOE for the technologies considered in the analysis of the profitability of using renewable sources.
Source: own study

The assumed market energy price was set at PLN 450/1 MWh. The chart above clearly shows that the lowest average unit cost of energy over the plant's operating life is attributed to onshore wind farms, at PLN 296/MWh. The highest *LCOE* among the technologies considered is for offshore wind farms, at PLN 516/MWh, while for photovoltaic installations it reaches a similar value of PLN 511/MWh. In terms of investment profitability, the lower the *LCOE*, the higher the profitability. Therefore, onshore wind farms demonstrate the highest profitability, followed by offshore wind farms and photovoltaic installations, significantly lower.

Discussion

This article aimed to estimate the costs of replacing conventional energy in Poland and the cost-effectiveness of individual technological solutions. Of the three renewable energy sources considered: solar, wind, and water, solar and wind energy were selected for analysis, while hydropower was rejected as a less promising energy source in Poland in the coming years. Within wind energy, onshore and offshore energy were separated and treated as separate investment projects.

In the research section, the average capital and operating expenditures for each technology were first determined, expressed as PLN/1 MW and PLN/1 MW annually. Using the installed capacity utilisation factor, based on the estimated capital expenditures for each technology and the volume of electricity production from conventional sources in 2023, a theoretical calculation was made to replace the current 124.8 TWh of energy produced from these sources with selected renewable sources. The calculations revealed the highest *CAPEX* for photovoltaic installations at PLN 625 billion, with a capacity utilisation factor of 8.9%. Slightly lower expenditures were associated with investments in offshore wind farms, amounting to PLN 573 billion, with the highest capacity utilisation factor of 38%. The lowest *CAPEX* was associated with the implementation of onshore wind farms, amounting to PLN 321 billion and utilising 28.2% of installed capacity.

Next, a profitability analysis of selected sources was undertaken, with calculation parameters based on current statistical data on energy sales prices and the current volume of energy production from fossil fuels, as well as on the assumptions for the future years until 2040 in the context of the structure of installed capacity utilisation of individual unconventional sources. The total capital expenditure for the assumed installed capacity of individual technologies was estimated at approximately PLN 426 billion. First, financial analysis indicators were used: *NPV* and *IRR*, which were calculated using EXCEL software, and the following results were obtained:

- for photovoltaic installations, *NPV* equal to PLN -25.5 billion after 25 years of operation and *IRR* below the adopted discount rate (8.2%) with a value of 3.3%, thus demonstrating the unprofitability of the investment,
- for onshore wind farms, an *NPV* of over PLN 40.8 billion was obtained after 25 years of operation and *IRR* = 9.5%, with the return on investment established after 4 years of operation,
- for offshore wind farms, the *NPV* result was PLN -66.3 billion with an *IRR* of 5.3%, thus demonstrating the highest unprofitability of the investment among the technologies considered.

Finally, the *LCOE* index was calculated, reflecting the unit cost of energy during the operation of the power plant, and the following results were obtained: for photovoltaic installations, the *LCOE* was PLN 516/MWh, which was the highest result and exceeded the assumed average energy sales price of PLN 450/MWh, a slightly lower *LOCE* value of PLN 511/MWh was obtained for offshore and onshore power plants, and the lowest *LCOE*, not exceeding the assumed value, was for onshore wind installations and amounted to PLN 296/MWh.

The results presented incompletely can be compared with others, because the literature on the subject lacks publications that include calculations of transformation costs and analyses of the profitability of replacing conventional energy with unconventional energy.

Conclusion

Many factors, both economic and geopolitical, influence the cost estimate for replacing conventional energy in the era of energy transformation. It's also important to remember that, in addition to the costs associated with construction and operation, the consequences of these costs should be considered, including potential negative social and environmental impacts, such as resettlements, land-use changes, noise from wind turbines, and ecosystem disruptions. Only a thorough economic analysis, taking into account the factors described above, should provide the basis for implementing the planned investment. This publication is a strictly budgetary analysis; however, additional aspects will also be considered in the conclusion. The key conclusions drawn from the analysis are as follows:

1. To replace current electricity production from conventional sources, which account for 76% of Poland's energy demand, onshore wind energy has the lowest investment requirement at PLN 321 billion.
2. Alternative renewable energy production cannot rely on a single source, as it is highly dependent on weather and location conditions. Therefore, an energy mix of complementary energy sources is necessary to maintain the country's energy security.
3. The cost of replacing conventional energy with unconventional energy, taking into account the proposed share of solar and wind energy sources, was estimated at PLN 426 billion.
4. The *NPV* cost-effectiveness analysis showed that only investment in onshore wind installations is profitable after 25 years, with a return on investment after 4 years of operation. Photovoltaic installations and offshore wind farms proved unprofitable under the adopted assumptions, with offshore wind farms the least profitable technology.
5. The reasons for the unprofitability of both energy sources are different: the main reason for the unprofitability of photovoltaic installations is the low capacity utilisation factor resulting from fluctuating solar radiation levels across successive seasons with varying degrees of cloud cover, while for onshore wind farms, it is the high capital expenditure.
6. The *IRR* analysis proved consistent with the *NPV* results for the assumed discount rate and demonstrated profitability only for onshore wind installations. The *IRR* obtained for offshore wind farms was higher than for photovoltaic installations, despite the lower *NPV*. This may indicate that this technology, despite its high costs, has greater potential to improve profitability than photovoltaic installations if capital costs prove lower or if market conditions improve, for example, higher energy prices.
7. The availability of data sources is crucial for estimating capital expenditures. Capital expenditures for offshore wind farms were averaged based on only two sources, with relatively wide volume spreads, due to the lack of historical data for this sector in Poland, which may be a weaker reflection of the average actual *CAPEX* compared to other technologies.
8. The *LCOE* indicator showed profitability only for onshore wind farms, and the results indicate that this technology will generate profits at a lower energy price than assumed in the calculations. For both photovoltaic installations and offshore wind farms, the *LCOE* was similar, reaching a value slightly higher than the market energy price. This may indicate that energy production from these sources is nearly competitively priced.
9. However, it should be remembered that *LCOE* is a measure commonly used in scientific research but does not account for all factors that determine the final cost of electricity production. Non-financial aspects, such as environmental costs resulting from CO₂ emissions or the structure of energy demand across months and seasons, are equally important.
10. Legal regulations play a significant role in estimating the costs of replacing conventional energy and analysing its profitability; the proposed structure of installed capacity may be completely different, assuming no amendment to the Wind Energy Act, according to which the maximum total installed capacity for onshore wind farms will not reach the value assumed in the calculations.

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