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Potential and profitability of wind farms in Poland in the light of regulatory and technological changes

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Abstract— **Wind energy is one of the innovative, modern sources of renewable energy. In recent years, the Polish energy sector has been undergoing a process of transformation, mainly determined by the European Union. The development of renewable energy has a positive impact on both the environment and energy security. It is conducive to the creation of a favorable business climate, which is why the analysis of wind energy efficiency assessment is particularly important in this context. The purpose of this article is to identify factors influencing investment in wind energy. It is shown that the profitability of wind farms is mainly influenced by factors such as the location of wind farms, the development of technology in terms of innovation of wind turbines, the creation of favorable legal and administrative regulations and the creation of mechanisms in terms of financial support. This paper reviews literature, legislation and reports on the development and efficiency of wind power. The analysis shows that there are legal, administrative, climatic, technical and social barriers that affect the development of the wind energy sector in Poland. Wind farms are becoming increasingly cost-competitive compared to conventional sources, especially with rising CO_2 emission costs and electricity prices.**

Keywords— renewable energy, wind energy, wind farms, offshore wind farms

I. INTRODUCTION

One of the goals of the energy transition is to move from centralised fossil fuel-based energy to distributed renewable energy production. This transition has been made possible by technological developments as well as financial support offered by the European institutions (European Wind Charter, 2023). This fosters a favourable business climate by combining innovative renewable energy technology with a positive impact on the environment from which the energy is generated. The European Union (EU) is actively involved in the energy transition, as renewable energy sources make it possible to create emission-free energy systems. However, this requires the development of technology, the expansion of the energy grid infrastructure of individual EU countries (Wyrobek et al., 2021)

According to the accepted assumptions of the European Green Deal and the Paris Agreement, the energy transition should take place by 2050. This will avoid the negative effects of climate change. The adopted strategy will require individual countries to develop decarbonisation plans for the energy system that will reduce carbon emissions. Achieving this will require innovative technologies to make the world's new energy system more efficient (Sobieraj, 2017). The main pillars of the energy transition include technical infrastructure, factors enabling the implementation of climate policy, the development of appropriate legal regulations, and the acquisition of the relevant skills and knowledge to implement the new energy system. By 2021, expenditure on technical infrastructure amounted to approximately USD 300 billion, and this amount is expected to double by 2050 (IRENA, 2023). In Poland, PLN 85 billion is planned to be allocated to the modernization of the power infrastructure. The investment is to be financed by PLN 15 billion in subsidies from EU programmes and PLN 70 billion in loans from the National Reconstruction Programme (Ministry of Climate and Environment, 2024). In 2023, the European Union introduced a change in the share of renewable energy in total electricity consumption from 42.5% to 45%. This will require an increase in wind energy production to meet the target and ensure security of supply (European Wind Charter, 2023). Public support for this initiative also plays an important role in the energy transition. Public acceptance of the changes being introduced in the energy sector is possible by ensuring transparency in planning, implementation and ongoing activities.

The geopolitical situation in the world, and in Europe in

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particular, has significantly accelerated the development of renewable energy. The main reason for this was Russia's invasion of Ukraine. This highlighted the risks of excessive dependence on a single foreign supplier of fossil fuels (European Commission, 2023). As a result, European countries have begun to implement ambitious plans for renewable energy sources in real actions to achieve energy security.

II. Literature review

Forecasts for energy development have been presented by the International Renewable Energy Agency (IRENA). A report published by IRENA (IRENA, 2023) outlines a plan for the global energy transition that reflects the goals of the Paris Agreement. It presents a plan to limit the temperature increase to 1.5oC and CO2 emissions to zero by 2050. Two scenarios for energy transition are presented, namely the 1.5°C Scenario and the Planned Energy Scenario (PES). The basic reference point is the Planned Energy Scenario, which presents plans for the development of the energy systems of individual countries, with particular emphasis on the G20 countries. The 1.5°C Scenario, on the other hand, assumes a reduction in global average temperature increase to 1.5°C by the end of this century. This is a very ambitious goal, which is to be achieved through the development of modern technological solutions.

Table 1. Required average annual investments in renewable energy technologies under the Planned Energy Scenario and 1.5°C Scenario, 2023-2050 (USD 2021 billion)

	Historical	PES 2023-2050	1.5°C Scenario 2023-2050
Bioenergy (total)	24	52	93
Concentrated solar power (CSP)	1	9	89
Geothermal	6	9	27
Hydro- all (excl. pumped)	40	103	138
Ocean/Tide/Wave	0	6	63
Solar PV (utility and rooftop)	130	160	333
Wind onshore	57	139	283
Wind offshore	95	159	356
Total	353	637	1382

Source: IRENA (2023), World Energy Transitions Outlook 2023: 1.5°C Pathway, International Renewable Energy Agency, Abu Dhabi, pp. 148.

Table 1 presents the average investment expenditure on renewable energy sources planned worldwide until 2050 according to the PES and the 1.5°C Scenario. In the Planned Energy Scenario, average annual investment in renewable energy sources will amount to approximately USD 637 billion by 2050. However, according to the 1.5°C Scenario, they will be more than twice as high. Increased investment is necessary due to higher demand for electricity and higher initial capital costs for renewable energy sources. Wind and solar energy are seen as having the greatest potential due to their rapid development, which is why the largest share of investments is allocated to these sectors. By 2050, investments in the onshore wind sector will amount to approximately USD 283 billion, and in offshore wind farms to USD 356 billion. Photovoltaics will require investments of USD 333 billion by 2050. Following investments in renewable energy sources, energy network infrastructure is being developed. Investments in this sector are estimated at approximately USD 800 billion (IRENA, 2023).

Among renewable energy sources, the wind energy industry is experiencing the fastest growth. Wind energy is considered a widely available and safe source of energy, and in some parts of Europe it is the cheapest source of energy (Georgakaki et al., 2023). Global wind energy capacity is expected to increase by 791 GW between 2024 and 2028. In turn, 652 GW is planned to be installed on land, while 139 GW is planned for offshore wind energy, with Europe accounting for 42 GW of capacity (Baker Tilly TPA Report, 2023).

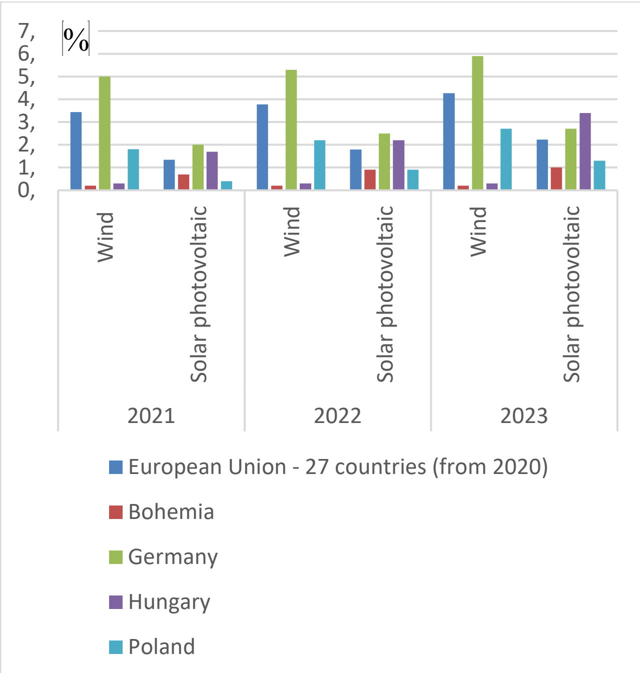
Poland's climate and energy strategy is primarily influenced by EU policy, which sets the energy transition path for 2030 and defines long-term actions to move towards EU climate neutrality by 2050. In December 2020, the European Council endorsed a plan to reduce net greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels, an increase on the existing reduction target of 40% (Council of the EU, "Ready for 55", 2023). The EU wants to achieve the set targets taking into account the economic conditions of individual member states and their capabilities to reduce greenhouse gases, as well as respecting the principle of sovereignty in shaping the national energy mix. The framework for Poland's energy transition is set out in the Polish Energy Policy to 2040 (PEP2040) (Obwieszczenie Ministra Klimatu i Środowiska, 2021), which includes strategies for selecting technologies to build a low-carbon energy system. According to the assumptions of PEP2040, the energy transition should be carried out in a fair and participatory manner, strive for zero-emission development of the country, and improve air quality.

The PEP2040 has set a target for the development of renewable energy sources. This development is intended to reduce the use of fossil fuels and increase the country's energy security by reducing fuel imports. In the long term, the use of RES will have a beneficial effect on reducing energy prices and environmental and health costs (Obwieszczenie Ministra Klimatu i Środowiska,, 2021).

Compared to other EU countries, Poland has a lower share of wind energy consumption compared to Germany and the EU countries overall, although the trend is increasing. Other Central European countries such as the Czech Republic and Hungary rely more on solar energy. Poland is the leader in wind energy production in this part of Europe due to its favourable climatic conditions for wind energy.

Figure 1 shows the share of renewable energy sources in total gross final energy consumption in selected EU countries. Poland declares to achieve a 23% share of RES in gross final energy consumption in 2030, taking into account energy consumption in electricity, heating and cooling and for transport purposes. By 2040, RES is estimated to increase to 28.5% (Obwieszczenie Ministra Klimatu i Środowiska, 2021). Poland plans to achieve higher RES energy capacity through the implementation of offshore wind energy, which it has adopted as the main strategic objective of PEP2040 within the framework of renewable energy development.

FIGURE 1. SHARE OF RENEWABLE ENERGY SOURCES IN TOTAL GROSS FINAL ENERGY CONSUMPTION (IN %)



Source: own study based on Statistics Eurostat (accessed on 23.04.2025).

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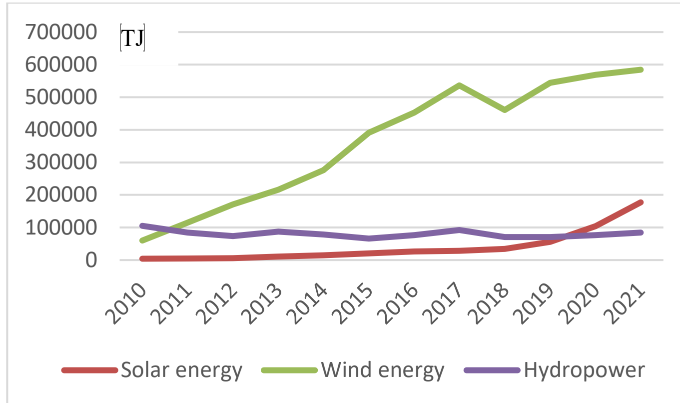
FIGURE 2. ENERGY GENERATION FROM SELECTED RENEWABLE SOURCES IN POLAND IN 2010-2021 (IN TJ)



Source: own study based on GUS (accessed on 25.04.2025).

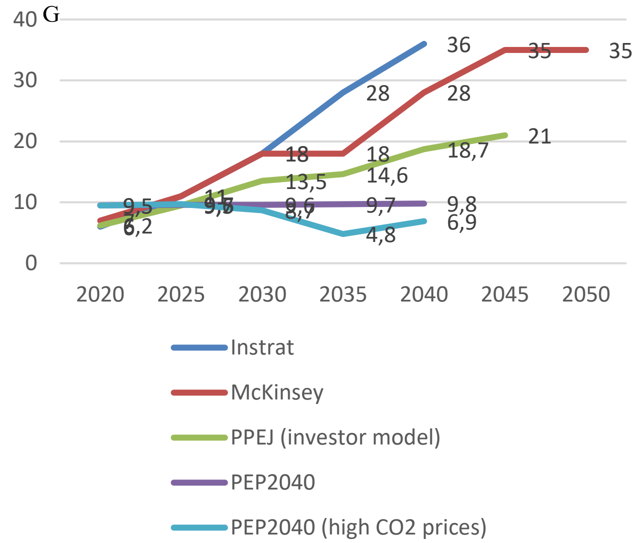
Based on the graph above, it should be noted that Poland obtains most of its renewable energy from wind power. This decreased in 2018, but the upward trend has been maintained. From 2019 onwards, an increase in solar energy can be seen, which was due to the government subsidies introduced.

III. RESEARCH METHODS AND RESULTS

The assessment of energy efficiency based on wind farms is primarily determined by atmospheric factors in terms of wind speed and frequency. The amount of electricity produced by wind farms depends on the strength of the wind at any given time. Poland has a transitional climate, which requires long-term observations due to the occurrence of large differences in measurements (Zalewska et al., 2021). Wind speed is lowest near the ground surface and increases with height. The most efficient installations are considered to be those installed at a height of approximately 100 m. The minimum wind speed for large wind turbines is 4 m/s and the maximum is 30 m/s. Once the maximum designated wind speed is exceeded, the torque of the turbine can cause damage. The appropriate wind speed for a wind farm is 15-20 m/s. The construction of a wind turbine requires several years, or preferably a series of ten years, of wind measurement studies in the area. Such an investment is considered viable when the optimum wind speed occurs for more than 2000 hours per year (Juszczak & May 2020). Analysis of atmospheric conditions indicates that the Polish territorial sea and coastal zones have the most favourable climatic conditions for wind energy development. The technical potential offshore is 20 GW, but due to environmental constraints and in particular the Natura 2000 area, it can be reduced to 7.5 GW (Brzezińska-Rawa & Goździewicz-Biechońska (2014). The limitations on the development of offshore wind energy are also related to the economic use of these areas, in particular fishing, as well as existing shipping routes and ensuring the safety of navigation. In addition, a significant part of the Baltic Sea area is of military importance

(Kotowicz & Kwiatek, 2019). Favourable locations for onshore wind farms are mentioned in addition to coastal areas, also mountainous areas, the area of central Poland (Brzezińska-Rawa & Goździewicz-Biechońska, 2014). The total installed capacity of wind farms in Poland is 10.8 GW at the end of Q2025 (PSE).

FIGURE 3. PROJECTIONS FOR THE DEVELOPMENT OF INSTALLED CAPACITY IN ONSHORE WIND FARMS IN POLAND (IN GW)



Source: compiled on the basis of Mierzwinski et al. (2021).

Figure 3 presents forecasts for the development of onshore wind farm capacity in Poland. Most forecasts of onshore wind farm development present an upward trend, only the plan developed by PEP2040 forecasts a downward trend (Mierzwński et al. 2021).

In addition to determining the right location to exploit wind potential, access to transmission infrastructure must also be taken into account in the development of wind farms. Due to its dependence on weather conditions, wind energy is characterised by unstable production and significant fluctuations in the amount of energy generated, which can have a negative impact on the functioning of the energy system. Therefore, priority access to the grid and the need for other generation units to adjust their production play an important role. The instability of weather conditions in wind energy can lead to problems with maintaining adequate energy quality, voltage levels and system stability. Areas considered to be the most favourable locations for wind farms are characterised by a low level of transmission network infrastructure development (Bandzul, 2005). The transmission network development plan prepared by Polskie Sieci Energetyczne (PSE S.A.) for 2025-2034 provides for a thorough modernization of the network at a cost of approximately PLN 64 billion by 2034. The aim of the transmission network development is to enable the transmission of 18.9 GW from offshore wind farms, approximately 19 GW from onshore wind farms and 45 GW from photovoltaic power plants. In total, this will enable the transmission of up to 160 TWh of renewable energy per year. The plan includes the construction of approximately 4,700 km of new 400 kV lines. In addition, there are plans to build new transmission stations and modernise existing ones (Thomson Reuters, 2025). The previous development plan for PSE S.A., set out on 17 December 2020 in the Act on the promotion of electricity generation in offshore wind farms, provided that offshore power plants located in the Baltic Sea with a total capacity of 10.9 GW would be connected to power stations in the northern part of the country. In 2023, the above Act was amended as a result of the introduction of the Act on Renewable Energy Sources of 17 August 2023, which provides for a long-term increase in the potential of offshore wind energy to 17.9 GW, which involves the expansion of the existing power grid. The PSE plan sets out a path for the development of offshore wind farms. It is assumed that by 2034, the expansion of the transmission network should enable the connection and introduction of approximately 13 GW of capacity. Connecting more power generated by wind farms will require the expansion of energy infrastructure through the construction of new connection points for offshore wind farms. A concept for the development of a transmission network ensuring the integration of the full power volume of offshore wind farms into the power system has also been developed. Most of the new capacity is to be located in the Ławica Odrzana area and will be connected to a new power station located in Western Pomerania (PSE, 2024).

Programmes covering the development and digitisation of energy networks are also being implemented. Energa Operator, a company belonging to the ORLEN Group, has obtained funds from the National Recovery Plan in the amount of over PLN 7.5 billion for the modernisation and digitisation of the transmission network in northern and central Poland. The plan includes the reconstruction of 21,000 km of the network to enable the connection of up to 9 GW of renewable energy sources and energy storage facilities, which will reach a target capacity of 1.4 GW. This programme will increase network reliability for 3.5 million customers and enable better use of renewable energy (BalticWind.EU, 2025). The transmission network experienced significant congestion between 2015 and 2021, resulting in the rejection of 6,000 connections by network operators. This rejection blocked approximately 30 GW of capacity, mainly from renewable energy projects (Zbronski & Mandrek, 2024).

The assessment of wind power efficiency is influenced by the level of the unit cost of electricity generation, which varies depending on the location of the wind farms. A study by Zalewska et al. (2021) shows that the fastest return on investment occurs in a zone located in the coastal belt area, a period estimated at 13 years. Two other locations were analysed in this study, i.e. lowland and foothills. The least favourable location in terms of weather conditions was found to be the lowland area. The payback period is estimated at more than 57 years and the average unit cost of generating 1 kW costs EUR 0.70/kWh, while in the coastal area it was estimated at EUR 0.16/kWh. The foothill location also shows a long payback period and is over 40 years. Also Bukala et al. (2015) investigated the profitability of wind energy production in three locations in Poland. They found that a traditional wind turbine with blades and a horizontal axis of rotation was the most cost-effective, offering the shortest payback period. The profitability of the investment depended on the location, with coastal areas showing the highest rate of return.

Another important parameter determining the profitability of wind farm investments is the innovation of the technologies used. Reduction of wind energy production costs will be determined by advances in wind turbine technology. Important parameters affecting their more efficient operation are the rotor diameter. Larger rotors with better efficiency increase the capacity factor and will allow areas with lower wind speeds to be used. A reduction in the number of components is sought, which will reduce the cost of wind energy production and increase the reliability of wind turbine operation. Currently, onshore turbines with a capacity of 6 Mw and a rotor diameter of 170 metres have already appeared (Mierzwinski et al. 2021). Research is continuing into the design and materials used for rotor blades. Currently, the material used for their manufacture is carbon fibre composites due to their higher stiffness-to-weight ratio. Carbon fibre has replaced aluminium and other metals. The use of carbon fibre enables the design of longer and more robust blades, which increase the energy capture of wind turbines. These materials also help to reduce turbine loads and extend the life of the turbines, helping to increase the economic viability of wind power projects. The industry continues to look for sustainable solutions based on natural fibres such as flax, bamboo or hemp embedded in bioresin. These materials are both renewable and require less energy to produce. Furthermore, they are more environmentally friendly (Ankit & Rinawa, 2021; Firoozi et al., 2024). The use of innovative materials contributes to wind energy's cost-effectiveness and competitiveness. Wind turbine performance is also influenced by aerodynamic innovations that address trailing edge adaptation. Flaps that dynamically adapt to wind conditions increase energy production and extend the life of turbine components. Also, the introduction of segmented blades increases the efficiency of wind turbines. They allow the construction of larger blades that capture more wind energy, which contributes to higher efficiency and lower costs (Firoozi et al., 2024).

Adequate government support and the creation of a favourable business environment the introduction of favourable regulations will contribute to a shorter payback period for wind energy investments. One of the most important regulations that will significantly contribute to the development of wind farms is the introduction of the Law of 9 March 2023 on wind power investments. This law introduced changes to the rules for the location of wind turbines. The 10H rule has been retained, which stipulates that the minimum distance of a wind turbine from buildings corresponding to 10 times the total height of the windmill including blades is to be maintained. However, the amendments to the rules have made windmill mounting distances more flexible by giving more power to municipalities within the planning procedure of local zoning plan amendments (Lipinski, 2023). Municipalities can allow wind turbines to be located closer than the prescribed distance, but it cannot be closer than 700 metres after meeting certain requirements. These changes have created new locations for wind farms, but further liberalisation of the regulations is necessary for the energy transition. In particular, abandoning the 10H rule and reducing the distance from 700 metres to 500 metres would increase the available land for wind farms in Poland from 2% to 4% (Baker Tilly TPA Report, 2024).

Offshore wind farms relative to onshore wind farms are remote from populated areas, so the noise from the equipment is not a nuisance and does not directly affect community life. Also, the capacity utilisation rate of offshore wind turbines is higher compared to onshore. From the same installed capacity offshore and onshore, more energy can be produced per year from offshore wind farms. The main challenge for offshore wind development is the high construction costs, which will decrease over time. It is estimated that by 2040 these costs will decrease by 40% and offshore wind power will be competitive with other renewable energy sources (Juszczak & Maj, 2020).

The consulting firm McKinsey & Company (McKinsey & Company, 2016) has attempted to estimate the impact of the construction of a 6 GW offshore wind farm on the Polish economy. The estimated cost of building the power plant is approximately PLN 70 billion. On the other hand, the cost of developing the transmission infrastructure for the energy produced was set at PLN 3 billion. The development of wind energy has an impact on Poland's GDP and employment. It is estimated that with the implementation of the above investment, a significant part of the supply chain could be located in Poland, which could generate an additional PLN 60 billion by 2030, of which PLN 47 billion would be generated by activities related to the preparation and implementation of the investment, and the remaining PLN 13 billion would result from additional exports of Polish-based companies operating in the supply chain and from investments in onshore power assets. Furthermore, the planning and construction of 6 GW of offshore farms could create 70000 jobs by 2030. In turn, 7000 jobs would be created in connection with the operation and maintenance of the investments.

An important factor determining the profitability of investment in wind farms is government support in the form of subsidies or other forms of funding. In Poland, the system of financial support for RES investments includes a system of subsidies. These funds are granted by government institutions, local governments, these are also EU funds and funds granted by Narodowy Fundusz Ochrony Środowiska i Gospodarki Wodnej (NFOŚiGW). Other sources of funding include preferential loans and credits granted by banks, loans granted by bank consortia, green bonds, tax concessions for individual customers and RES energy producers, feed-in tariff system, bonus system, i.e. market price subsidy system, auction system, green certificate system (Przygodzka et al., 2023).

Among the most sought-after forms of support are subsidies of all kinds. In 2024, the NFOŚiGW launched a grant under the “Moja Elektrownia Wiatrowa” programme aimed at individuals who want to produce electricity for their own needs using wind power. Funds can be used to subsidise the purchase and installation of backyard wind micro-installations and wind energy storage facilities. The subsidy is up to 50% of the costs, up to a maximum of PLN 30000 for a micro-installation and up to PLN 17000 for an energy store (NFOŚiGW, https://mojaelektrowniawiatrowa.gov.pl/o-programie/). NFOŚiGW has also launched a support programme for larger investments and enterprises. Grants can range from 30% to 65% of eligible costs, depending on the technology and investor. NFOŚiGW support also includes preferential loans covering up to 100% of the investment value (Metropolis, 2025). The available subsidies for wind energy producers in Poland offer significant financial support, both for private individuals and for companies. The choice of the appropriate programme depends on the scale of the planned investment and the type of investor. Augustowski & Kułyk (2024) studied the efficiency of 10 kW wind turbines for residential use in the area of Zielona Góra, Szczecin and Gdansk, assuming a subsidy of 50% of the investment costs. It was shown that the investment is most profitable in the coastal areas (Szczecin and Gdansk), with a payback period of approximately 9 years. However, with 50% financial support, this period is halved, which significantly increases the attractiveness of the investment.

Another form of support is the auction system. This system allows RES producers to obtain a guaranteed sale price for a limited period of time. Currently, it is the main way to support larger wind power investments (Ministerstwo Aktywów Państwowych, 2021). The advantage of the auction system is its stability and predictability. Financial stability involves the investor receiving predetermined support for a period of no more than 15 years. Predictability involves the maintenance of an electricity sale price that applies throughout the support period and is derived from the winning bid in the auction, which is then indexed annually for inflation (Baker Tilly TPA Report, 2024). Since January 2025, the cumulative global clean energy capacity auctioned was 1280 GW, wind energy has accounted for 31% of the allocated capacity since 2003. Due to changing market realities, indications are that the auction system will need to undergo reform. Rising material costs, wages, delays in permitting and bottlenecks in supply chains mean that the auction system no longer reflects the real price of energy production. Increasingly, the auction system also includes other criteria than just the production price. The system has come under particular criticism for projects with large capital outlays and long lead times, such as offshore wind. Although the cost of renewable energy production has recently declined, capital costs, inflation and increasing disruptions in supply chains are rising sharply, raising the cost of wind energy projects, and this is not reflected in the price set by the auction system (Global Wind Report, 2025).

IV. Conclusions

This paper presents the technical, environmental as well as economic aspects associated with the operation of wind power plants. One of the important variables determining the profitability of wind energy investments are atmospheric factors, in particular the frequency and speed of winds. Therefore, the efficiency of wind farms will depend on location and terrain. Based on the literature, the fastest payback period is obtained from wind farms located in coastal areas. Climatic conditions in the Baltic Sea are favourable for offshore wind farms, but investments in such projects require additional expenditures in transmission infrastructure and construction costs are much higher. However, the efficiency of offshore wind farms is significantly higher than onshore wind farms. Technological innovations in wind turbines also play an important role in the cost-effectiveness of wind farms. Research work is directed towards increasing the feasibility of wind turbines at lower wind speeds and in terms of more ergonomic rotor blade design and materials used for their production.

An important role in the development of wind energy is played by legal regulations and an appropriate political climate in the energy transition underway. The existing 10H distance rule, which, despite its partial liberalisation, is still a constraint to the development of wind power. Also, government support in the form of grants or other forms of subsidies will increase their profitability and contribute to a shorter payback period for wind energy investments.

Undoubtedly, the development of wind farms in Poland is of key importance for achieving climate goals and ensuring energy security. However, it is necessary to create a stable legal framework and investments in transmission infrastructure to fully exploit the potential of wind as a renewable energy source. This study can serve as an important source of information for investors, policymakers, and financial institutions, as it identifies key factors influencing the profitability of investments in wind energy. An analysis of the mechanisms supporting the development of wind energy—such as feed-in tariffs and subsidies—highlights ways to enhance project profitability and underscores the need for further optimization.

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