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Development of offshore wind energy in Poland—Opportunities and threats

Anna Kokorniak[1]✉, Urszula Gabriel-Półrolniczak[2]

[1] https://orcid.org/0000-0001-8091-1805
[2] https://orcid.org/0000-0002-7371-2231

Maritime University of Szczecin, Faculty of Engineering and Economics of Transport
11 H. Pobożnego St., 70-507 Szczecin, Poland
e-mail: [1]a.kokorniak@pm.szczecin.pl, [2]u.polrolniczak@pm.szczecin.pl
✉ corresponding author

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Abstract

Faced with the European Union's growing expectations regarding the intensification of energy generation from renewable sources, Poland, like many other European countries, has encountered the enormous challenge of introducing energy produced by offshore wind farms (OWFs) into the energy market. This article aims to present the current state of development of offshore wind farms (OWFs) in Poland and to identify the main opportunities and threats associated with the further development of this sector in the domestic and international context. The direction of the current rapid investment growth in this area stems from decisions of the European Parliament and the European Council, which require intensified efforts to increase the share of energy obtained from renewable sources in the energy mix. At the same time, the creation of an energy base in the form of offshore wind farms in Poland contributes to energy diversification and improves the country's energy security. Several projects are currently underway in the Polish Baltic Economic Zone, the largest of which include Baltica 2 and Baltica 3, led by PGE Polska Grupa Energetyczna and the Danish company Ørsted. The construction of offshore wind farms encounters several barriers that hinder project implementation; however, long-term energy production can bring numerous benefits to Poland. This paper highlights the key advantages of offshore wind farm development, including Poland's energy sovereignty, job creation, and strengthened efforts to reduce greenhouse gas emissions. The greatest threats, however, include an underdeveloped local supply chain, unpredictable legislative changes, and the risk of delays due to environmental requirements. Considering the limitations associated with the lack of production continuity and the ability to fully utilize the electricity generated by offshore wind farms, solutions for industrial-scale electricity storage are presented, including conversion to compressed air using compressed air energy storage (CAES) technology, and the conversion of electricity into chemical energy in the form of hydrogen (H_2).

Introduction

The rising standard of living, advancing digitalization, expanding access to modern technologies, and the growing diversity of available products have all contributed to the intensification of consumerism. As a result, a continuous increase in the production of goods and services can be observed. At the same time, industrial development, demographic growth, and dynamic urbanization processes are directly driving higher demand for electricity. For decades, the global energy system relied predominantly on fossil fuels, which served as the main source for generating electricity. The long-term dominance of fossil fuels shaped an energy mix based largely on coal. In 2024, the structure of the energy mix in electricity production in Polish power plants was as follows: hard coal (69,112 GWh, 41.4%), lignite (35,844 GWh, 21.5%), natural gas (16,768 GWh, 10.0%), hydropower (3057 GWh, 1.85%), and wind farms and other renewables (42,208 GWh, 25.3%) (Rynek Elektryczny, 2025). According to data from the Polish Power Grid (Polskie Sieci Elektroenergetyczne), the total electricity production in 2024 amounted to 166,989 GWh, while demand reached 168,956 GWh (Rynek Elektryczny, 2025). The absence of a sustainable approach to production management, combined with the intensive exploitation of natural resources, has contributed to the deepening of the global climate crisis. Over the years, ongoing climate destabilization has directly affected not only human and animal health but also the condition of the natural environment, particularly accelerating the depletion of the Earth's resources. Consequently, countries around the world have been compelled to introduce comprehensive systemic reforms aimed at identifying new and technologically safer methods of electricity generation. Of particular importance is the need to ensure not only the economic efficiency of energy production but also the reliability of its transmission within both national and international power systems. Thus, a key condition for the success of the energy transition is a global shift in approach toward systematically increasing the share of energy derived from alternative and low-emission sources.

In the next five years, offshore wind farms are expected to play a crucial role in advancing global energy transformation processes. The development of this sector in Poland will contribute not only to increasing the share of renewable energy sources in the national energy mix but, above all, to reducing the dependence of electricity generation on fossil fuels. Favorable wind conditions in the Baltic Sea ensure stable energy production, while planned investments highlight the sector's significant production potential. Moreover, the expansion of offshore wind energy strengthens national energy security and stimulates economic growth through the creation of new industries within the maritime and energy sectors. In response to the intensive exploitation of natural resources and the escalating greenhouse effect, the world's largest economies, such as China, the United States, and in Europe, Germany, the United Kingdom, and Norway, have undertaken extensive measures to enhance the efficiency of electricity use, modernize existing energy infrastructure and, above all, intensify efforts toward the development of alternative energy technologies. The complexity of transformational processes and the necessity of structural reform within the energy sector require long-term planning. Given that the energy sector is a significant contributor to the intensified greenhouse effect, a key priority has become the design and implementation of new technological solutions that support the use of renewable energy sources, while aiming to minimize the time required for implementing changes. In terms of the share of renewables in total electricity consumption, Sweden was the clear leader among European Union countries in 2022, reaching 66%, followed by Finland at 47.9% and Latvia at 43.3%. Among the 27 EU member states, Poland ranked 22nd, with a share of 16.9% (Parlament Europejski, 2024).

An unexpected factor directly accelerating the energy transition in Europe was Russia's invasion of Ukraine in February 2022. As a result of this war, European countries faced the necessity of reassessing their level of sovereignty, including in the field of energy. The European Union (EU) imposed numerous sanctions on Russia within a few months in an attempt to force it to cease military actions. However, these did not significantly affect Russia's continued aggressive operations. Therefore, accelerating efforts to reduce dependence on Russian energy resources became an essential goal for European states. In Poland's case, it became necessary to update the government's current policy through flexible and dynamic changes to existing regulations, which often hinder the development of renewable energy.

European Union institutions, such as the European Parliament (EP) and the Council of the European Union (CEU), have established energy-related obligations for their member states—which include Poland—primarily by emphasizing the need to intensify efforts aimed at achieving the designated targets regarding the share of energy derived from renewable sources. The directives issued by the EP explicitly define the role of renewable energy sources (RES) in supplying Europe with electricity. The energy sector alone accounts for three-quarters of the total greenhouse gas emissions within the European Union. Consequently, on 18 October 2023, the EP and the CEU adopted Directive (EU) 2023/2413, which advocates for strengthening the role of renewable energy sources as a means of reducing greenhouse gas emissions. The Directive underscores both the legitimacy and necessity of achieving the target of a 55% reduction in emissions by 2030 relative to 2019 levels, and of attaining climate neutrality by 2050.

The purpose of this study is to assess the current state of offshore wind energy development in Poland and to identify the main opportunities and risks associated with its further expansion. The article examines both national and global trends in the offshore sector, the potential for integrating offshore wind farms with hydrogen technologies, and provides a SWOT analysis of selected aspects of implementing offshore wind energy within Poland's economic zone in the Baltic Sea.

The World Wind Energy Association reported that, in 2023, the global leaders in installed wind power capacity were China (470 GW), the United States (150.5 GW), and India (44.7 GW). In Europe, the leading countries were Germany (69.5 GW), Spain (30.7 GW), and the United Kingdom (30.2 GW). Poland reached 9.4 GW of installed wind capacity, placing it among the top ten European countries (Teraz Środowisko, 2024). According to WindEurope, European wind farms reached a total capacity of 285 GW in 2024, of which 87% (237 GW) was onshore and 13% (34.2 GW) offshore (WindEurope, 2025). Polish investors plan to introduce 6 GW of offshore capacity by 2030, capable of supplying approximately 8 million households annually, and to expand this figure to 11 GW by 2040, covering the electricity needs of around 15 million Polish households (Morska Energetyka Wiatrowa, n.d.b).

The paper is based on the hypothesis that the development of offshore wind energy in Poland depends primarily on effectively harnessing its potential and on minimizing barriers and risks arising from technical, environmental, and regulatory conditions.

Methodology

In order to prepare this article, a review of the literature and industry reports concerning the offshore wind energy market was conducted, with particular emphasis on the conditions shaping the development of this sector in Poland as well as in the global context. The relevance of the topic is increasing due to the rapidly evolving geopolitical situation and the intensification of pressures from the European Union aimed at expanding the share of renewable energy sources in the energy balance of individual member states. At present, fossil fuels dominate the Polish energy system; however, the offshore wind sector demonstrates considerable potential both in accelerating the energy transition in Poland and in enhancing the country's energy security. To achieve a clearer understanding of the dynamics governing the development of the offshore wind sector, a trend analysis method was applied, as it provides a transparent means of illustrating directions and changes occurring over time.

This method makes it possible to capture the current situation in the context of potential and anticipated long-term actions. It was selected due to its capacity to employ statistical data and forecasts for the graphical representation of phenomena, the assessment of the rate of change within the sector under study, and the comparison of their trajectories over time. Its primary aim is to identify the key directions in the development of offshore wind energy in Poland, considering both European and global trends. In addition, the SWOT analysis method was applied, encompassing strengths, weaknesses, opportunities, and threats. The use of this approach allowed for the identification of the most significant factors influencing the operation of offshore wind farms in Poland, taking into account both their potential energy capacity and the risks facing this sector. The analyses were based on data obtained from leading industry organizations and statistical institutions, including WindEurope, the Polish Wind Energy Association, and the Global Wind Energy Council (GWEC), as well as from information provided by investors involved in Baltic Sea offshore wind projects.

Current state of the development of offshore wind farm investments in Poland

The favorable natural conditions of the Baltic Sea constitute the primary foundation for offshore wind farm (OWF) investments. Relatively stable wind patterns, shallow waters, and low salinity make this basin highly suitable and offer substantial potential for further projects. In the first quarter of 2022, out of 15 permits issued by the President of the Energy Regulatory Office (URE) for the construction and operation of artificial islands intended for OWF development, seven were approved for Phase I and received administrative decisions granting support to cover the negative balance. This support took the form of a so-called contract for difference (CfD), which ensures that the price of electricity generated by offshore wind farms and supplied to the grid does not exceed the level established by the Minister of Climate and Environment in the regulation of 30 March 2021. This mechanism involves covering the difference between the market price of electricity and the cost of its generation for a period of up to 25 years. All Phase I projects that were approved are listed and described in Table 1, while Figure 1 presents their exact locations. The differences between support for Phase I and II projects result strictly from the method of covering the negative balance. In subsequent years, support for Phase II projects will be granted under the already established auction mechanism. The planned auction schedule foresees allocations of 4 GW in 2025, 4 GW in 2027, 2 GW in 2029, and 2 GW in 2031. This mechanism requires a minimum of three participants to submit bids, and the bidder offering the lowest electricity price is declared the winner by decision of the President of the Energy Regulatory Office (URE) (Morska Energetyka Wiatrowa, n.d.c; Polskie Stowarzyszenie Energetyki Wiatrowej, 2024). Currently, following the submission of the first application for a given area, the Ministry of Infrastructure announces that, for the next 60 days, other interested parties may submit their applications for the same location. Approximately 130 investors have expressed interest to date.

To promote the use of modern technologies, restrictions have been introduced concerning the age of wind farms on OWFs. Under these regulations, any farm applying for support must ensure that, on the date electricity is first generated, the OWF device was manufactured no more than 72 months earlier, that is, it cannot be older than six years.

The largest investor in the Polish Exclusive Economic Zone of the Baltic Sea is the partnership of PGE, the largest electricity producer in Poland, and Ørsted, the global leader in the offshore energy sector. The project encompasses an area of more than 300 km^2 designated for two offshore wind farms (Baltica 2 and Baltica 3), with a combined installed capacity estimated at 2.5 GW. By 2027, these farms are expected to generate electricity sufficient to power up to four million households. It is projected

Table 1. Offshore wind farm projects in numbers

Project name	**MFW Baltyk II**	**MFW Baltyk III**	**Baltica 2**	**Baltica 3**	**Baltic Power**	**FEW Baltic II**	**BC Wind Polska**
Investor	Polenergia/ Enquinor (Norway)	Polenergia/ Enquinor (Norway)	PGE/ Orsted (Denmark)	PGE/ Orsted (Denmark)	Baltic Power (Orlen/ Northland Power (Canada))	Baltic Trade and Invest Sp. z o.o. (RWE)	Ocean Winds (EDPR/ ENGIE)
Farm area	122 km^2	119.52 km^2	190 km^2	130 km^2	130 km^2	41 km^2	90 km^2
Power indicated in PSZW	720 MW	720 MW	1500 MW	1500 MW	1200 MW	440 MW	500 MW
Supported power	720 MW	720 MW	1498 MW	1045 MW	1197 MW	350 MW	369.5 MW
Distance from the shore	37 km	22 km	40 km	25 km	23 km	50 km	23 km
Sea depth at the location	23–41 m	25–39 m	30–40 m	30–40 m	up to 45 m	30–50 m	35–60 m
Number of households powered	2,000.000		4,000.000		1,500,000	350,000	720,000
Number of turbines in the farm/height of a turbine	50 turbines, Siemens Gamesa SG 14-236 DD (approx. 15 MW for each turbine)	50 turbines, Siemens Gamesa SG 14-236 DD (approx. 15 MW for each turbine)	107 turbines, Siemens Gamesa (approx. 15 MW for each turbine)	50 turbines (approx. 15 MW for each turbine)	76 turbines, Vestas (max. 100), with a height of 270 m (approx. 15 MW for each turbine)	25 turbines, Siemens Gamesa SG 14-236 DD (approx. 15 MW for each turbine)	Up to 34 turbines (13 MW for each turbine)
Start of construction	2024		2024		2024	2024	2024
Commissioning	2027	2027	2027	2030	2026	2027	2027–2028
Operational period	25–30 years	25–30 years	30 years	30 years	25 years	25–30 years	25–30 years
Service base	Port in Łeba	Port in Łeba	Port in Ustka	Port in Ustka	Port in Łeba	Port in Łeba	Port in Władysławowo
	(Polenergia, n.d.)	(Polenergia, n.d.)	(Balica Energy, n.d.)	(Balica Energy, n.d.)	(Balic Power, n.d.)	(RWE, n.d.)	(BC Wind, n.d.)

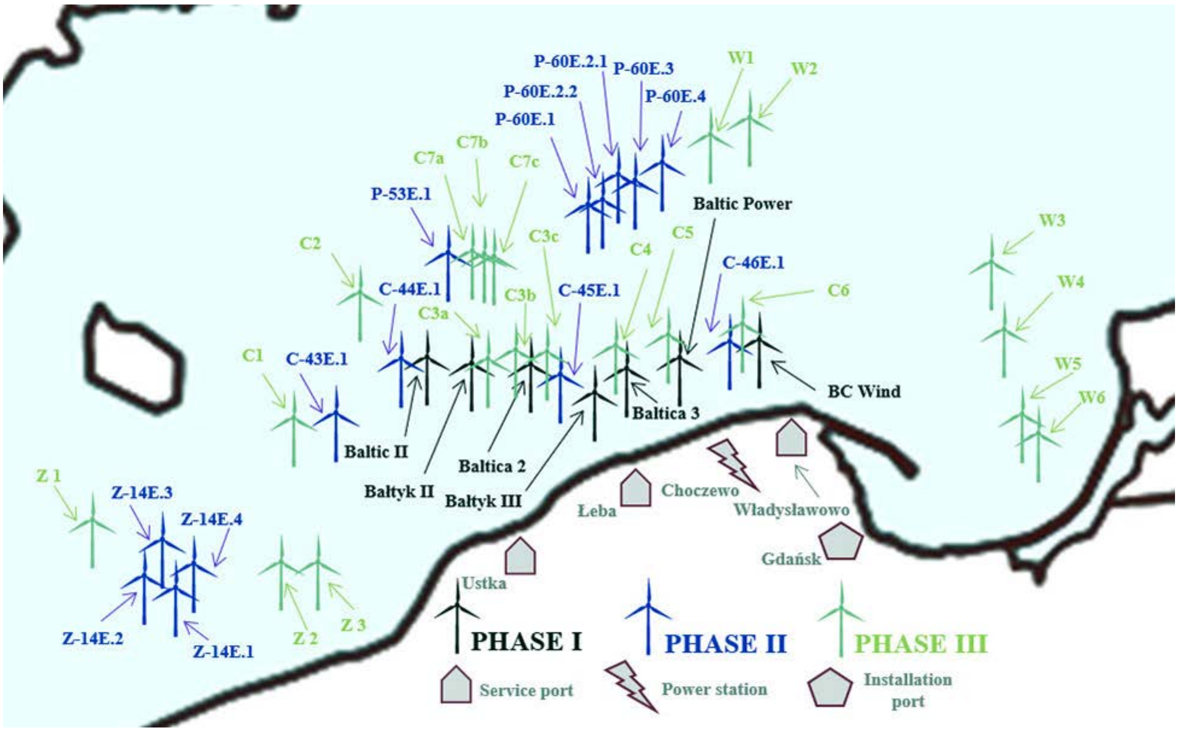


Figure 1. Locations of the offshore wind farm projects in the Baltic Sea (based on data from Baltic Wind EU, 2023)

that, by 2027, this venture will comprise the largest number of wind turbines among all Phase I projects. According to data from Statistics Poland, household electricity consumption in Poland in 2023 amounted to 29,774,532,800 kWh, while the average per capita consumption was 789.8 kWh (Główny Urząd Statystyczny, 2025).

The second-largest project in terms of generating capacity is the offshore wind farm being developed through the cooperation of two investors: Polenergia, the largest private energy group in Poland, and the energy company Equinor. The projects of these investors (MFW Bałtyk I and MFW Bałtyk II) are designed to generate 1.44 GW of electricity across an area of approximately 250 km^2. However, these are not the only planned investments of this consortium. Another project, MFW Bałtyk I (P-53.E.1), located about 80 km from the shoreline, is to be constructed on an area of approximately 128.53 km^2 and will have a capacity of 1560 MW. This will be the most distant offshore wind farm. According to the investor, the three projects combined will supply electricity to up to six million households. This is currently the largest planned investment.

The two smallest projects, considering primarily the amount of electricity that can be generated, are FEW Baltic II, developed by Baltic Trade and Invest Sp. z o. o. (RWE), and BC Wind Polska, developed by Ocean Winds (EDPR/ENGIE). FEW Baltic II is the westernmost project that, with a capacity of 350 MW, will be able to supply 350,000 households. It is also the smallest wind farm, with a planned area of about 40 km^2. The BC Wind Polska project has a planned capacity of 400 MW, which will result in electricity generation sufficient for 700,000 households. It is noteworthy that RWE and Siemens Gamesa have also signed a cooperation agreement with the Maritime Academy in Szczecin (currently the Maritime University of Szczecin), which focuses on activities and opportunities supporting student education and possibly even cooperation in selected research projects. Figure 1 presents the planned location of projects in Phases I, II, and III of the support scheme. The Phase I projects are listed in Table 1. The potential of installed capacity foreseen in the subsequent areas of the Polish Exclusive Economic Zone of the Baltic Sea includes the following locations:

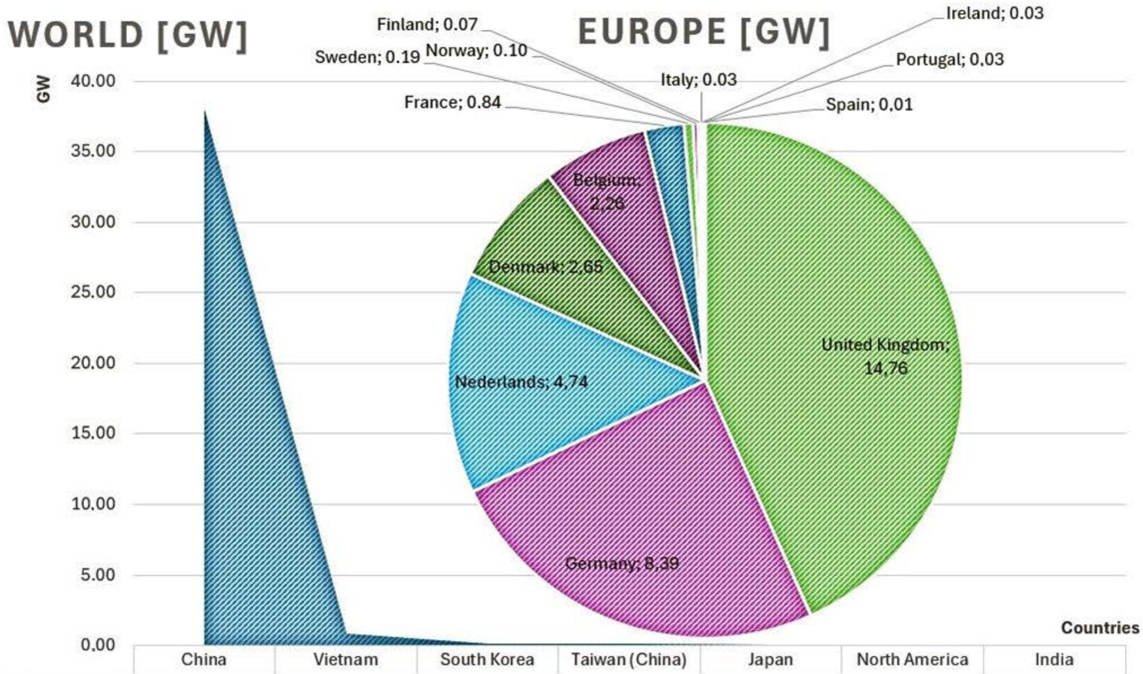
- western area (Z) – Pomeranian Bay for phase II is as follows: Z-14.E.1 (0.8 GW), Z-14.E.2 (0.9 GW), Z-14.E.3 (1.2 GW), and Z-14.E.4 (1.2 GW). For phase III: Z1 (0.6 GW), Z2 (0.7 GW), and Z3 (1.2 GW) (Morska Energetyka Wiatrowa, n.d.a; Polskie Stowarzyszenie Energetyki Wiatrowej, 2022a),
- central part (C) – Słupsk Bank, including locations for phase II: C-43.E.1 (1 GW), C-44.E.1 (1 GW), C-45.E.1 (0.2 GW), and C-46.E.1 (1 GW). For phase III: C1 (2.1 GW), C2 (2.7 GW), C3a (0.2 GW), C3b (0.5 GW), C3c (0.5 GW), C4 (0.4 GW), C5 (0.3 GW), C6 (0.1 GW), C7a (0.4 GW), C7b

(0.1 GW), and C7c (0.1 GW) (Morska Energetyka Wiatrowa, n.d.a; Polskie Stowarzyszenie Energetyki Wiatrowej, 2022a);

- northern area (P) – Southern Middle Bank is the location for phase II: P-53.E.1 (1.6 GW), P-60.E.1 (1.6 GW), P-60.E.2 (0.9 GW), P-60.E.3 (1.2 GW), and P-60.E.4 (0.5 GW). For phase III (W): W1 (0.8 GW), W2 (2.6 GW), W3 (1.2 GW), W4 (1.5 GW), W5 (0.7 GW), and W6 (1.0 GW) (Morska Energetyka Wiatrowa, n.d.a; Polskie Stowarzyszenie Energetyki Wiatrowej, 2022a).

From the perspective not only of implementing a specific project, but also of supporting regional development, the Baltic Power project, arising from the joint venture between Orlen Group and Northland Power, deserves particular attention. This is a highly advanced investment, with a capacity of 1.2 GW and the potential to supply electricity to 1.5 million households. On 3 October 2022, Baltic Power announced that the first installation terminal in Poland would be established in the Port of Świnoujście, which is scheduled to begin operations in 2025. Ultimately, the terminal was commissioned in June 2025, while components for Vestas wind turbines have been manufactured since January 2025 at the turbine factory located in Szczecin. The planned workforce is expected to reach 600–700 employees by the end of 2025 (Ledzinska, 2025). The installation terminal, constructed by Orlen Neptun, covers an area of 20 hectares and includes 250 meters of quay. It is designed to accommodate components for the construction of wind farms, including Vestas-manufactured turbines. The facility provides an optimal base for storing and transporting large-scale components by means of specialized jack-up vessels onto the designated wind farm sites. Employment at the terminal is expected to generate an additional 100 jobs (Orlen Neptun, n.d.b). Another installation terminal is planned in Gdańsk, and a service port in Ustka is expected to be operational by the end of 2025. Poland's plans to launch approximately 6 GW of electricity generation from offshore wind farms by 2030 create an opportunity for the country to enter the offshore wind market in the Baltic Sea region dynamically and strengthen its position. According to data presented in Figure 2, based on the WindEurope report, the total installed capacity of offshore wind energy in Europe reached 34.09 GW by the end of 2023.

By the end of 2024, the total installed wind power capacity in Europe amounted to 285 GW, of which approximately 37 GW derived from offshore wind farms and 245 GW from onshore installations. Alongside China, Europe maintained its position as a global leader in the offshore sector. Within the European Union alone, installed capacity reached around 251 GW, including approximately 21 GW offshore and 230 GW onshore (WindEurope, 2025).



	China	Vietnam	South Korea	Taiwan (China)	Japan	North America	India
WORLD [GW]	38.00	0.87	0.15	0.10	0.07	0.04	0.00

Figure 2. Total European offshore installations until the end of 2023 (based on data from WindEurope, 2025; Global Wind Energy Council, 2024)

The detailed distribution of offshore capacity by country at the end of 2024 is as follows: the United Kingdom at approximately 16 GW (largest farms: Hornsea One and Two), Germany at approximately 9 GW (largest farms: Merkur, Hohe See), the Netherlands at approximately 5 GW (largest farms: Borssele 1&2), Denmark at 3 GW (largest farms: Kriegers Flak, Horns Rev), and Belgium at 2 GW (largest farm: SeaMade) (WindEurope, 2025).

Looking ahead to 2030, further expansion of the European offshore wind sector is anticipated through the implementation of additional projects, as illustrated in Figure 3. An analysis of the collected numerical data makes it possible to identify key development trajectories of offshore wind energy, for instance, in a temporal perspective. The data presented in Figure 3 indicate a consistent growth in installed offshore wind capacity. The assumptions underlying the planned investments indicate that the United Kingdom will remain the clear leader of the offshore sector by 2030, reaching an energy output of 35.5 GW. The second-largest capacity is projected for Germany, expected to attain 18.29 GW. The Netherlands ranks third, with a systematically increasing offshore capacity from 2026 to 2029, followed by a slight decline in 2030, ultimately reaching 10.41 GW. By the end of 2030, Poland is expected to achieve a generation capacity of approximately 6 GW, thereby surpassing France, which plans to reach 3.82 GW by that year. Belgium, in turn, does not envisage any new investments in 2026, maintaining a stable capacity of 2.26 GW. Other countries forecast offshore energy capacities by 2030 at the following levels: Bulgaria (0.01 GW), Finland (0.25 GW), Ireland (1.05 GW), Italy (0.04 GW), Lithuania (0.63 GW), Portugal (0.02 GW), Spain (0.3 GW), Norway (0.88 GW), and Sweden (0.54 GW) (WindEurope, 2025).

Figure 3 also illustrates that, by 2026, countries such as the United Kingdom, Germany, Poland, and France will achieve stable increases in generation capacity. Subsequently, in the years 2027–2028, a temporary slowdown is expected, followed by renewed growth projected to continue through 2030.

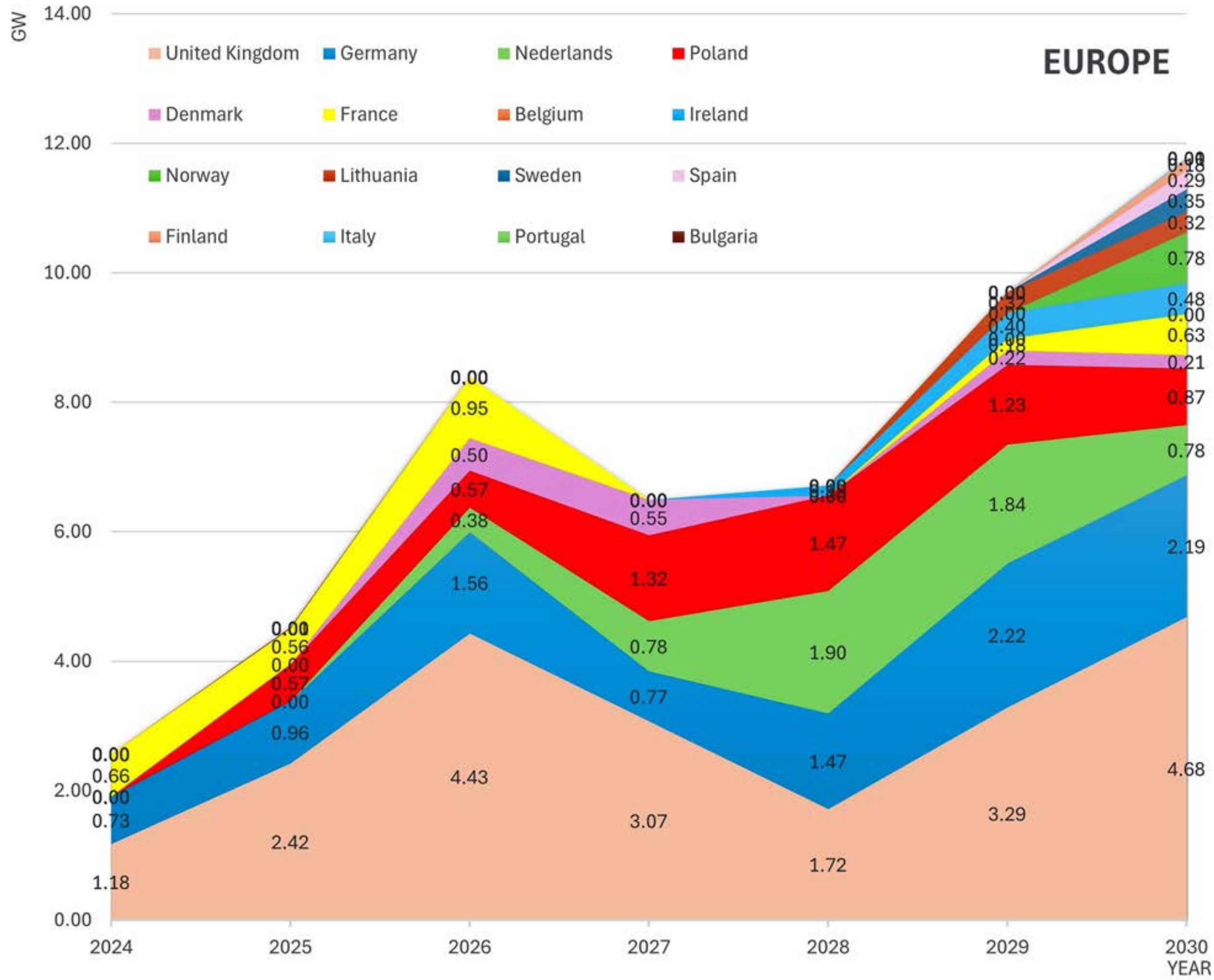


Figure 3. Europe offshore wind growth to 2030 (based on data from WindEurope, 2025)

Compared with other countries, Poland's production capacity is set to increase steadily from 2026 to 2028 while, in 2029–2030, it is expected to maintain a stable level of new investments. Within just five years, Poland has the opportunity not only to enter the European offshore wind energy market but also to become one of the key players in this sector in the Baltic Sea (WindEurope, 2025).

In the following section of this study, the situation of European countries is further analyzed in comparison with the largest global investors engaged in the offshore sector. According to earlier data (Figure 2), at the end of 2023, Europe and China demonstrated comparable levels of offshore energy generation, amounting to 34 GW and 38 GW, respectively. Forecasts, however, indicate that this situation will shift in the coming years in favor of China. In 2024 alone, the country planned to expand its generation capacity by 12 GW, followed by an average annual increase of 15 GW from 2025 onward, ultimately reaching 104 GW by the end of 2030 (Global Wind Energy Council, 2024). In comparison, European countries are projected to increase their installed offshore wind capacity to 84.12 GW by 2030, enabling them to maintain their position as one of the two global leaders in the offshore market (WindEurope, 2025). Figure 4 visualizes the global efforts of states to maximize offshore energy production.

The graphical comparison presented in Figure 4 also highlights the involvement of North America (including Canada) in the development of the offshore wind sector. By the end of 2023, this region possessed installations with a total capacity of 0.04 GW (see Figure 1). According to the latest forecasts, capacity is expected to increase to 15.22 GW by 2030, representing a significant expansion. A third global center projected to make a substantial entry into the offshore market is Taiwan, with a forecasted capacity of 10.69 GW by 2030. In the European context, Poland, assuming the full implementation of planned investments, is expected to rank fourth, reaching an installed capacity of 6 GW, thereby consolidating its position among the leading countries advancing offshore wind energy worldwide. Other states included in Figure 4 project offshore capacities by 2030 at the following levels: South Korea (6.105 GW), Japan (4.347 GW), Vietnam (2.612 GW), and India (2 GW) (Global Wind Energy Council, 2024).

Considering Poland's position within the Baltic Sea region, the country has become a key and rapidly developing hub for offshore wind energy investment,

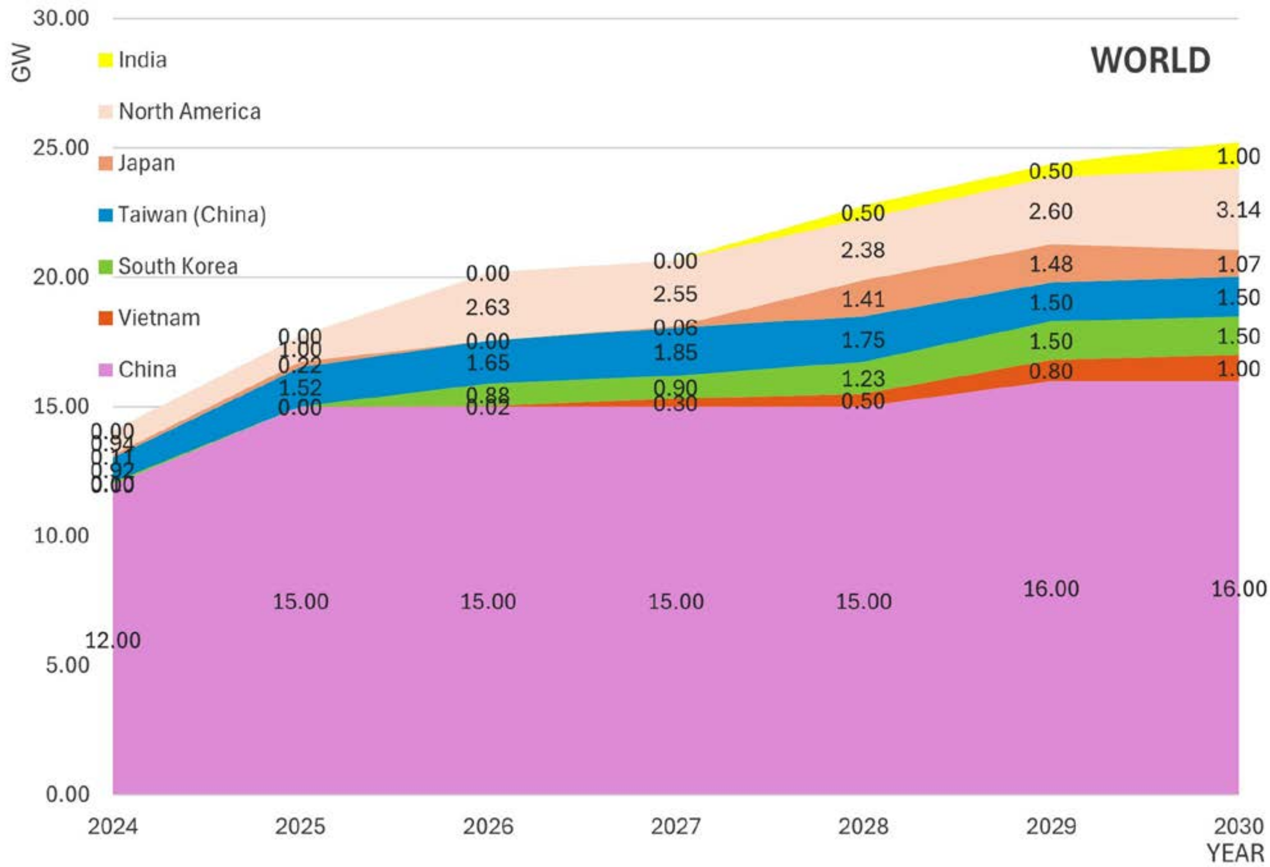


Figure 4. World offshore wind growth to 2030 (based on data from the Global Wind Energy Council, 2024)

characterized by significant technical potential and expanding infrastructure. In recent years, Poland has shifted from merely planning offshore infrastructure investments to actively developing its own supply chain as well as technological and logistics capabilities. With an estimated potential of 12 GW, it ranks among the countries with the highest technical capacity in the region (Pronińska & Księżopolski, 2021). Although Poland does not yet possess an industrial base as mature as that of Germany or Denmark, the rapid expansion of offshore projects, increasing involvement of foreign investors, and the development of ports (Gdynia, Łeba, Ustka) position it as a key hub for the future growth of offshore wind energy in Central and Eastern Europe (Kosek et al., 2025).

Compared with Lithuania, Latvia, and Estonia, Poland demonstrates a much higher level of project maturity and a significantly larger domestic market, enabling it to serve as a regional service and production center (Pronińska & Księżopolski, 2021). Despite the leading role of Germany and Denmark, Poland's favorable geographic conditions, competitive investment costs, and strategic importance for regional energy security suggest that it may join the group of the most advanced countries in the Baltic Sea offshore energy sector within the next decade.

Offshore Wind Energy – the possibility of energy management

Currently, electricity in Poland is primarily generated from hard coal and lignite in utility power plants, which accounted for 67.95% of total production in 2023 (Polskie Sieci Elektroenergetyczne, 2023). However, the energy sector is increasingly focusing on electricity generation from RES, which accounted for 21.52% of the national electricity output in 2023 (wind farms and other renewable energy sources). Electricity from RES, as a renewable energy sector using offshore wind energy is, to some extent, an ecological alternative to fossil fuels and, additionally, allows for increasing the country's energy independence. Unfortunately, despite being one of the fastest-growing energy markets in the world, offshore wind energy has certain limitations relating to the lack of continuity of production and the possibility of full use of energy.

An alternative that allows for increasing the possibility of using the vast amount of energy produced, leading to covering shortages during increased demand, is its storage. While the possibility of direct storage of electrical energy on an industrial scale is limited, the possibility of its conversion to another form of energy that is easier to store becomes an opportunity. Such conversion concerns the possibility of storing energy using compressed air or converting electrical energy to chemical energy in the form of hydrogen H_2 (Figure 5).

On an industrial scale, one of the existing solutions is storing electrical energy by converting it into compressed air energy storage (CAES). This is the storage of energy in a mechanical form, where the engine, drawing electrical energy from the network, drives a compressor that compresses the air. During compression, mechanical energy is converted into the internal energy of the gas, which results in an increase in the temperature of the compressed air that, when compressed to 70 atm, has a temperature of around 1000 K (727 °C) (Odnawialne Firmy, 2015). Therefore, to avoid failure and leakage, the compressed air is cooled in a heat exchanger and then pumped into pressure tanks or geological caverns, e.g., depleted salt mines. During peak energy demand, the compressed air is pumped out of the storage (the tank and cavern) and directed to the

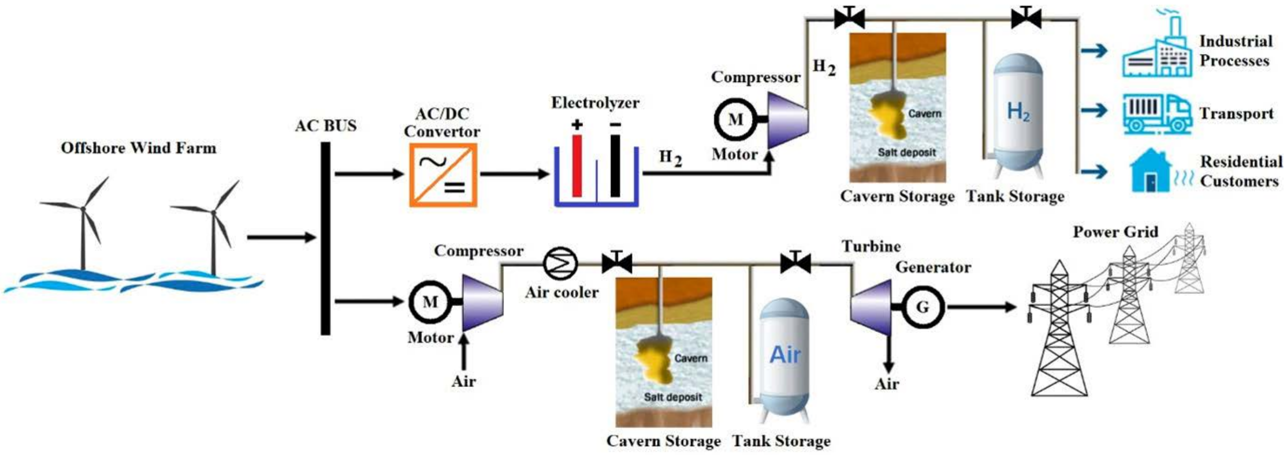


Figure 5. Schematic diagram for energy storage systems from offshore wind farms

turbine, where it enters the combustion chamber, where natural gas is burned. The exhaust gases heat the air, causing it to expand, and the pressure generated as a result of the expansion rotates the turbine blades that, through the shaft, drive the generator, generating electricity. The CAES energy storage system has been used on an industrial scale for many years. The first commercial installation of CAES technology was built in 1978 in Germany at the Huntorf power plant with a capacity of 280 MW (Crotogino, Mohmeyer & Scharf, 2001). In 2022, the Chinese Academy of Sciences announced the connection to the grid of the world's largest CAES energy storage system to date in Zhangjiakou, Hebei Province, in northern China, which can store over 132 million kWh of electricity per year (Energetyka Rozproszona, 2022).

In the second case, taking into account the high calorific value of hydrogen equal to 120 MJ/kg, the storage of a large amount of energy of about 33 kWh/kg, and the possibility of easy storage in large capacities, hydrogen becomes an ideal medium for energy accumulation in the period of production surpluses (Bartosik et al., 2016). At the same time, hydrogen is used on an industrial scale in various sectors, including the chemical industry (ammonia and methanol synthesis), the refinery industry (hydrorefining and hydrocracking), the food industry (fat hardening), metallurgy (iron ore reduction), as an energy carrier in transportation, and in heating systems for residential buildings, highlighting its significant demand and utility. Taking into account the properties and possibilities of using hydrogen, the Council of Ministers of the Republic of Poland adopted, by resolution no. 149 of 2 November 2021, the document "Polish Hydrogen Strategy until 2030 with a perspective until 2040," which defined the main goals of the development of the hydrogen economy in Poland (Ministry of Climate and Environment, 2021). One of the goals presented in the document is the production of hydrogen from electricity from offshore wind farms, as well as its efficient and safe transmission, distribution, and storage. In order to produce the so-called low-emission hydrogen (carbon footprint below 5.8 kg CO_2 eq/kg H_2), it is possible to use technology based on water electrolysis in an electrolyzer, powered by electricity from offshore wind farms (green hydrogen), and allowing it to obtain H_2 at a purity level of 99.9999%.

Electricity from offshore wind farms initially passes through a rectifier system, which allows for the conversion of alternating current to direct current, which can directly power the electrolyzer. In the simplest terms, water electrolysis is the process of splitting water into hydrogen and oxygen molecules under the influence of an electric current flow, which can be described by the chemical equation at the cathode (reduction reaction) as $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$, at the anode (oxidation reaction) as $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$, and in total as $2H_2O \rightarrow 2H_2 + O_2$. Currently, various types of electrolyzers are used in the water electrolysis process, including polymer electrolyte membrane (PEM) electrolyzers, alkaline electrolyzers (AEL), solid oxide electrolyzers (SOE), or anion exchange membrane (AEM) electrolyzers. The basic operating and performance parameters for individual types of electrolyzers are presented in Table 2 (Trattner et al., 2021; Kumar & Lim, 2022; Nasser et al., 2022; Sahin, 2024).

Based on the data presented in Table 2, a comparison of electrolyzers was made (Table 3), which

Table 2. Comparison of the different types of water electrolyzers

Specification	PEM	AEL	SOE	AEM
Charge carrier	H^+	OH^-	O^{2-}	OH^-
Electrolyte	Solid polymer	KOH/NaOH (10–40%)	Solid ceramic	Solid polymer
Anode material	Pt, Ir, Ru	Ni	LSM-YSZ, $CaTiO_3$	Ni-based alloy
Cathode material	Pt, Pt-C	Ni alloys	Nicermets	Ni, Ni-Fe, $NiFe_2O_4$
Operating temperature [°C]	70–90	65–100	650–1000	50–70
Operating pressure [bar]	< 70	1–30	< 30	< 35
Current density [A/cm^2]	1–3	0.2–0.6	0.3–1	0.5–2
Voltage range [V]	1.4–2.5	1.4–3.0	1.0–1.5	1.4–2.0
Stack lifetime [hr]	60,000	50,000–80,000	< 40,000	> 10,000
Efficiency [%]	67–84	62–82	~90	up to 68
H_2 purity [%]	99.9–99.9999	99.5–99.9998	99.9	99.9–99.9999

Note. LSM denotes lanthanum strontium manganate and YSZ signifies yttria-stabilized zirconia

Table 3. Advantages and disadvantages of typical water electrolysis technologies

Electrolysis technology	Advantages	Disadvantages
PEM	• Commercialized technology • High purity of the gases • High current density	• Noble metal electrocatalysts • Acidic environment corrosion
AEL	• Well-established technology • Commercialized for industrial applications • Noble metal-free electrocatalysts • Long-term stability	• Low current density • Corrosive liquid electrolyte
SOE	• Very high efficiency • Noble metal-free electrocatalysts	• Laboratory-phase technology • High working temperature • Low current density
AEM	• Noble metal-free electrocatalysts • High purity of the gases	• Laboratory-phase technology • Low current density • Low efficiency

shows that the alkaline electrolyzer AEL is currently the most desirable in the hydrogen production process.

Hydrogen storage on an industrial scale after the electrolysis of water, similarly to air, can be carried out under pressure in post-mining salt caverns and in above-ground pressure tanks. Storage in this form is based on physical methods, mainly on gas compression. The low density of hydrogen in the gas phase under normal conditions (0.0882 kg/m^3) means that it must be stored under high pressure. Storing hydrogen in geological structures allows for long-term and safe storage of this gas on a large scale at relatively low costs, under high pressure and with high energy density, without affecting the natural environment. Additionally, the physical properties of salt mean that the caverns are air-tight for the stored gas and are characterized by long-term stability and high flexibility in terms of injection and withdrawal (Ligęza & Narloch, 2023).

At room temperature, hydrogen is stored under pressures ranging from 150 to 800 bar (Szymak, 2011). Currently, four types of above-ground pressure tanks are used for storing hydrogen in its gaseous phase. Steel or aluminum tanks allow storage at approximately 200 bar, while metal tanks reinforced with glass or carbon fiber enable storage at around 300 bar. Tanks with a metal liner and a full composite wrap made of glass or carbon fiber allow hydrogen storage at pressures of about 430 bar. Fully composite tanks, where the internal liner is reinforced with a composite wrap of glass or carbon fiber, enable hydrogen gas to be stored at pressures of up to 660 bar (Sieć Badawcza Łukasiewicz – Instytut Organizacji i Zarządzania w Przemyślе, 2023).

In parallel, to some extent, hydrogen storage in the liquid phase is realized by using cryogenic tanks. The energy density of liquid hydrogen is much higher than in the case of compressed hydrogen and is 70.9 kg/m^3. However, taking into account the boiling point of hydrogen, which is −253 °C, the process of liquefying and storing liquid hydrogen is very energy-intensive and requires a high energy input. The total energy consumption in the case of storing liquefied hydrogen is about 35% of the energy content of the stored hydrogen; therefore, storage in this form is usually limited to aviation and space applications (Ligęza & Narloch, 2023).

Opportunities and threats for the development of offshore wind energy

The development of offshore wind energy in Poland brings numerous opportunities but is also associated with certain risks. On the one hand, national offshore wind farm projects provide the potential to enhance energy security, reduce greenhouse gas emissions, and create new jobs. On the other hand, the implementation of these projects faces multiple challenges, including difficulties relating to high investment costs, lengthy administrative procedures, and the risk of insufficient transmission infrastructure in relation to the growing energy output. The following sections outline the factors that may determine either the success or the impediment of offshore wind energy development in Poland, taking into account both the potential benefits and the challenges concerning future investments in this sector. The SWOT analysis of the offshore wind energy sector in Poland (presented below) enables a comprehensive assessment of the current situation and the identification of key factors influencing the development of offshore wind farms in Poland.

Strengths

- *Low emissions and compliance with the goals of the green transition*

Offshore wind farms are well aligned with the trend of the green transition, which has a positive effect on the perception of this sector. This stems primarily from the fact that electricity generation from wind, in contrast to conventional power plants, does not result in the emission of greenhouse gases or air pollutants such as sulfur dioxide, nitrogen oxides, or particulate matter. According to the Intergovernmental Panel on Climate Change (IPCC), the median life-cycle value of CO_2 emissions for offshore wind farms is approximately 12 gCO_2eq/kWh (Schlömer et al., 2014), while a detailed analysis by Chipindula et al. indicates a range of 6–9 gCO_2eq/kWh (Chipindula et al., 2018). Another advantage of offshore wind farms is that they do not consume water for cooling and do not generate toxic or radioactive waste.

- *Stable potential of wind energy generation in the Baltic Sea*

The Baltic Sea offers exceptionally favorable conditions for the construction of wind farms due to its shallow waters, low waves, and minimal tides, combined with advantageous wind speeds (Nowak et al., 2024). The average depth of the Baltic is approximately 55 m, while the average wind speed at 100 m above sea level ranges from about 8 to 10 m/s, with increasingly favorable values toward the south (Orlen Neptun, n.d.a). According to experts, the most attractive areas are located near the Pomeranian Bay, north of the Słupsk Bank, and around the Southern Middle Bank. The estimated offshore wind potential of the Baltic Sea is 93 GW, of which Poland alone accounts for 33 GW—an amount that could cover nearly 60% of the country's electricity demand (Polskie Stowarzyszenie Energetyki Wiatrowej, 2022c). Compared with onshore energy generation, the Baltic Sea, owing to higher wind speeds and greater wind stability, offers a more consistent and efficient potential for energy production, which makes offshore wind farms an attractive source of renewable energy (Polskie Stowarzyszenie Energetyki Wiatrowej, 2022b).

- *Development of port infrastructure in Łeba and Ustka for servicing offshore wind farms (OWF)*

The development of port infrastructure supports the servicing of offshore wind farm projects by providing an appropriate logistical base for the transport and installation of turbines. The ports of Łeba and Ustka are undergoing comprehensive modernization in order to adapt them to serve as service bases for offshore wind farms. In Łeba, an investment worth 132 million PLN is scheduled for completion in August 2026, resulting in the creation of a service terminal for 100 wind turbines located 22 km offshore (Starostwo Powiatowe w Lęborku, 2021). Ustka, where the official construction of the PGE Baltica operations and maintenance base commenced in June 2025, will serve a similar function, acting as a service port for the offshore sector (Offshore Wind Poland, 2025). Infrastructure supporting offshore wind energy is also being intensively developed in the West Pomeranian Voivodeship. In Szczecin, a modern Vestas factory is being established to assemble nacelles and hubs for 15 MW turbines (Ledzinska, 2025), and the construction of a blade manufacturing facility is also planned. Combined, these investments are expected to create approximately 1800 jobs (Offshore Wind Poland, 2024). Moreover, the Szczecin–Świnoujście port is implementing Poland's first installation terminal dedicated to offshore wind farms that, starting in 2025, will service specialized installation vessels and enable the assembly of up to 80 turbines annually (Port Szczecin–Świnoujście, 2022).

- *Favorable locational conditions and low spatial interference*

In contrast to onshore wind farms, which require large areas and often face restrictions arising from regulations concerning minimum distances from residential buildings, offshore wind farms provide significantly more favorable locational conditions. Onshore wind power plants are frequently criticized for their impact on the landscape, the noise they generate, and conflicts with spatial development plans, particularly in densely populated areas. The siting of offshore wind farms (OWF) at a considerable distance from the shoreline, typically within the exclusive economic zone, more than 20 km from land, substantially reduces their visibility from the perspective of coastal observers. Although under favorable weather conditions, turbine structures may still be visible from land, their impact on the landscape is relatively minor compared with onshore wind farms (Polskie Stowarzyszenie Energetyki Wiatrowej, 2023). Consequently, OWFs present a lower risk of social conflicts related to landscape intrusion.

- *Enhancing Poland's energy security*

The development of OWFs significantly strengthens Poland's energy security by reducing dependence on imported fossil fuels and supporting the pursuit of carbon neutrality. According to the forecasts included in the Polish Energy Policy until 2040 and the draft of the National Energy and Climate

Plan, the planned installed capacity of offshore wind farms is expected to reach approximately 5.9 GW by 2030 and around 18 GW by 2040 (Polskie Stowarzyszenie Energetyki Wiatrowej, 2022d).

Through local wind energy production and the gradual reduction of reliance on energy supplies from Russia and other countries, it is also possible to avoid fluctuations in raw material prices on world markets. Thanks to the large installed capacities in OWF, the share of renewable energy sources in the national energy mix is increasing, which is of fundamental importance for building energy independence. Offshore wind energy, as a stable source of power, thus becomes not only a key tool for decarbonization but also a strategic element in strengthening energy sovereignty.

- *Application of modern turbines*

The Polish offshore wind energy sector is developing on the basis of the most advanced turbine technologies available, such as the 15 MW Vestas V236 turbines installed in the Baltic Power project (Northland Power, 2025) and the Siemens Gamesa SG 14-236 DD turbines with a capacity of 14.4 MW ordered for the Bałtyk II and III projects (Portal Morski, 2024). These are characterized by extremely large rotor diameters, vast swept areas, and high energy efficiency (Portal Morski, 2024; Northland Power, 2025). Such advanced turbines enable efficient electricity generation even under variable weather conditions, with a single rotor rotation capable of meeting the energy needs of an average household for several days (Portal Morski, 2024). Their deployment enhances Poland's prospects of establishing itself as one of the leading actors in offshore wind energy in Europe.

- *Development of integrated power grids*

The integration of offshore wind farms into complex transmission systems contributes to the development of next-generation power infrastructure, encompassing the construction of dedicated cable connections, substations, and networks based on HVDC technology, which enables efficient long-distance energy transmission with minimal losses. One of the potential added values is the possibility of storing surplus energy through Power-to-X technologies, particularly hydrogen production, which makes it possible to eliminate the problem of overgeneration, and additionally increases energy independence while fostering the integration of sectors such as power (energy storage), transport (as fuel), and industry (applications of green hydrogen) (Polskie Stowarzyszenie Energetyki Wiatrowej, 2022c; Bałamut & Przygoda, 2025).

Weaknesses

- *Infrastructure barriers*

For Poland to fully exploit the estimated potential of installed capacity in offshore wind energy, it is essential to remove critical infrastructure barriers that may delay or even obstruct planned investments in this sector. A major challenge remains the lack of connection points and the insufficient capacity of the national transmission infrastructure to accommodate offshore wind energy (OWE) projects. The Polish transmission grid, particularly in the northern part of the country, will require extensive modernization to cope with the increased electricity flows once offshore farms are commissioned. Polish Power Grids (Polskie Sieci Elektroenergetyczne) indicate the need for new substations, connection points with adequate capacity, and the construction of a strategic north–south HVDC transmission line (Polskie Sieci Elektroenergetyczne, 2024).

At the same time, the development of OWE requires investments in installation ports and a network of service ports, the use of which would help reduce project costs and create a competitive supply chain at both regional and European scales. Investments are also necessary in land-based access infrastructure to enable efficient logistics for deliveries. In addition, the Polish Wind Energy Association (Polskie Stowarzyszenie Energetyki Wiatrowej) points out that the limited availability of specialized fleets for the construction and servicing of offshore wind farms (OWFs) may become a significant "bottleneck" for the entire investment process (Polskie Stowarzyszenie Energetyki Wiatrowej, 2022c).

- *Negative environmental impacts*

Despite the benefits they offer, offshore wind farms (OWFs) are also associated with certain adverse effects on the Baltic Sea environment. During the construction phase, underwater noise, particularly from pile driving, can have a significant impact, leading to the displacement of or health risks for marine fauna, including critically endangered harbor porpoises. Long-term negative effects include bird collisions with turbine rotors, disturbances to marine habitats, and changes in species composition around artificial structures, which may disrupt local ecosystems. An additional risk is the potential leakage of petroleum derivatives from service vessels or turbines, which could adversely affect biodiversity and the state of marine ecosystems. Life-cycle analysis of OWFs indicates that negative environmental impacts occur primarily during the production and material extraction phases, where intensive use of steel, copper, and concrete results in high burdens in categories such as ecosystem toxicity, mineral extraction, and resource depletion (Chipindula et al., 2018). Furthermore, during the decommissioning phase, a significant environmental challenge lies in the limited recyclability of composite turbine blades, which are most often sent to landfills. This leads to the accumulation of hard-to-process materials and increases environmental burdens at the end of the installation's life cycle. Given that this remains a relatively new and developing technology, the predictability of environmental impacts, particularly over the long term, remains limited due to the scarcity of long-term observations. This highlights the need for continued research and monitoring of marine ecosystems (Li et al., 2022).

When analyzing environmental factors likely to generate the greatest social opposition, the most significant concerns include the visual impact of offshore wind energy (OWE) developments on the landscape, effects on coastal and marine protected areas, impacts associated with transmission infrastructure, restrictions on access to fishing grounds, and the resulting decline in revenues from fisheries and tourism (Biniek, 2017).

- *High investment costs*

Offshore wind farms (OWFs) generate substantial initial investment costs for all investors, stemming from their exposure to extreme weather conditions, the expenses of transporting and installing turbines, and the need to deploy transmission infrastructure. The construction of offshore wind farms, together with associated transmission systems, requires considerable capital expenditure, often amounting to billions of PLN for a single project. Network-related investments are also highly costly; this includes the construction of new substations, 400 kV lines, and HVDC connections, without which the efficient integration of electricity into the national grid would not be possible.

High implementation costs are further accompanied by significant financial risks, which may limit the number of investors willing to pursue such projects. Consequently, the profitability of investments depends largely on state support, well-designed legislative provisions, and legal stability.

- *Lengthy and complex investment procedures*

One of the most significant challenges is the complex and time-consuming process of obtaining permits and administrative decisions. Lengthy and complicated project preparation and permitting procedures have been identified as key factors hindering the development of offshore wind energy (OWE), as noted in the 2022 report of the Supreme Audit Office (NIK) and in materials prepared by the Foundation for Sustainable Energy (Stryjecki, 2023). Each offshore wind farm (OWF) project requires extensive environmental studies, often lasting around two years, which directly translates into enormous costs amounting to tens of millions of PLN.

Moreover, the project preparation process typically involves a team of approximately 100 people on the investor's side, working in cooperation with numerous consulting firms. Securing the necessary permits for a single OWF project includes 4–5 construction permits and 6–8 location decisions, each requiring the acquisition of several opinions and approvals. In total, 100–200 administrative processes involve more than 30 different offices and institutions. Accordingly, the NIK report emphasizes that offshore legislation should be directed at reducing the risk of investors failing to obtain favorable decisions by simplifying procedures, for example, in selected areas (Najwyższa Izba Kontroli, 2022).

- *Limited capacity of the domestic market for installation and maintenance services in OWE*

The lack of a sufficiently large and adequately qualified operational workforce constitutes another challenge for the development of offshore wind energy (OWE) in Poland, particularly in view of the scale of planned investments. At present, Poland has only one operational installation port, while the availability of specialized equipment, vessels, and companies with the necessary expertise remains inadequate. There is also a shortage of specialized technical and maintenance staff, which results in dependence on foreign contractors, prolongs project timelines, and increases operating costs. This situation weakens the position of the Polish market within the supply chain and reduces the potential economic benefits of OWE development. Without strengthening domestic installation and service capabilities, offshore wind expansion may face significant delays and operational constraints. The low level of employment in the maritime sector underscores the urgent need for investments in intensive training and education programs to meet the requirements of this rapidly developing market.

Opportunities

- *The prospect of achieving Poland's long-term energy sovereignty*

Offshore wind farms (OWFs) in Poland create an opportunity to strengthen the country's energy sovereignty by enabling local electricity generation and reducing dependence on imported resources such as oil, gas, and coal. In the long term, the development of the sector may contribute to Poland's complete independence from fossil fuels, which is of strategic importance in the context of national energy policy. This, in turn, provides Poland with the prospect of becoming a significant producer of renewable energy, thereby supporting an energy transition aligned with decarbonization objectives.

- *Development of higher education through the creation of specialized study programs*

The development of the offshore wind energy sector in Poland encourages domestic universities to adapt their educational offerings in order to train specialized personnel essential for the implementation of ambitious offshore wind farm development plans. Institutions such as Gdańsk University of Technology, the University of Gdańsk, and the Maritime University of Szczecin, in response to the growing needs of the industry, are launching new study programs and postgraduate courses dedicated to offshore wind energy. An example is the master's program Smart Renewable Energy Engineering, supported by PGE Baltica, which combines engineering knowledge with managerial and digital competencies (Politechnika Gdańska, 2025). The Maritime University of Szczecin offers a program unique at the national level, known as Industrial Engineering and Offshore Wind Power Plants, under which students obtain international certifications relating to occupational safety on wind turbines, as well as the operation and servicing of devices located inside wind power plants (Wiadomości Szczecin, 2024). In addition, within the logistics program (second-cycle studies) at the Faculty of Engineering and Economics of Transport, a specialization in offshore logistics is offered, preparing students to work in the maritime economy sector by developing competencies in logistics, offshore project management, renewable energy technologies, and the implementation of innovative solutions in transport and energy (Politechnika Morska, n.d.). Through investments in the offshore sector, universities gain the opportunity to modernize curricula and build long-term partnerships with industry, which in the longer term strengthens the quality of technical education in Poland.

- *Development of energy storage technologies*

The increase in investments in the offshore sector and the growing demand for green energy are driving the intensification of infrastructure and technology development relating to energy storage. At present, a national grant program for large-scale battery projects worth €980 million is being implemented, which foresees the creation of more than 5.4 GWh of new storage capacity by 2028 (Green Dealflow, 2025). The grants may be allocated to the construction of electricity storage facilities with a minimum power output of 2 MW and a capacity of no less than 4 MWh and the development of grid connections and accompanying infrastructure, as well as the configuration and adaptation of storage (Gram w Zielone, 2024). In addition, EDF Renewables has launched the construction of Poland's first commercial large-scale energy storage facility with a capacity of 50 MW, intended to stabilize the grid by absorbing surpluses and releasing them during periods of increased demand (Polski Przemysł, 2025). The ongoing energy transition is stimulating the advancement of storage technologies, which play a vital role in strengthening grid flexibility, ensuring stability and enabling the effective integration of variable renewable resources.

- *Economic growth and new jobs*

Investments in this sector have an additional positive impact on local labor markets, both during the construction and operational phases, by creating new jobs in the installation, maintenance, and servicing of wind farms. According to the PSEW report (2024), the full exploitation of Poland's offshore wind energy (OWE) potential could meet as much as 57% of national electricity demand and reduce CO_2 emissions by approximately 102 million tons annually. Investments in 33 GW of OWE capacity could generate more than 100,000 jobs and contribute 178 billion PLN in gross value added during the development phase and 46 billion PLN annually during the operational phase. The Wind Industry Report (2024) indicates that the expansion of wind farms to 36 GW by 2040 could result in a GDP growth of 70–133 billion PLN, supply chain orders worth 80 billion PLN, and up to 97,000 new jobs (Wind Industry, 2024). Similarly, a McKinsey analysis estimates that by 2030 the offshore sector could generate 60 billion PLN for Poland's GDP, 77,000 jobs, and 15 billion PLN in revenues for the state budget and local governments (Kosek, 2025). Taken together, these reports demonstrate that the development of OWE could become one of the key drivers of economic growth in Poland.

Threats

- *Growing geopolitical tensions limiting investment willingness*

Escalating geopolitical tensions in the region, such as the war in Ukraine and the growing strain in EU–Russia relations, may lead to infrastructure investments in Poland being perceived as high-risk projects, thereby discouraging investor activity. An unstable geopolitical environment can affect both the physical security of infrastructure and the stability of energy supplies, regulatory frameworks, and support guarantees for renewable energy sources. As a result, it may hinder the further development of the offshore wind energy (OWE) sector.

- *Dependence on foreign supply chains*

The development of offshore wind energy is characterized by a strong reliance on foreign suppliers for components such as turbines, cables, and foundations. This dependency increases vulnerability to global logistical disruptions and raises the risk of delays in component deliveries. Dependence on imports also heightens exposure to fluctuations in global prices of raw materials, transportation, and manufacturing, thereby increasing project investment costs and potentially reducing profitability.

In the event of armed conflicts or international sanctions, this reliance may result in disruptions to the import of materials and components, or even a complete loss of access to them. Strong dependence on foreign suppliers also limits the ability to respond quickly to changes in project schedules or technical problems, thereby raising the risk of prolonged downtime.

- *High financial risk associated with rising costs, economic shifts, and regulatory changes*

Rising interest rates, inflation, and economic uncertainty increase the cost of financing investments and heighten the risk to their long-term profitability. As a result, investors may withdraw from planned ventures or reduce their scale, diminishing overall project viability. The development of offshore wind energy (OWE) in Poland is also burdened by the unpredictability of the regulatory environment. Frequent legislative changes, unclear regulations, and lengthy administrative procedures complicate the implementation of ongoing projects and discourage the initiation of new ones. Combined with rising interest rates, inflation, and economic uncertainty, these factors significantly increase overall financial risk.

- *Hybrid threats*

Investments in offshore wind farms (OWFs) are exposed to risks associated with criminal activities aimed at disrupting systems that are critical to the state's energy security. Continuous monitoring of irregularities in the operation of wind farms is essential to ensure their safe and efficient exploitation. The distance of OWFs from land creates a direct vulnerability to various types of external attacks, including potential acts of sabotage targeting specific installations. Kinetic actions against OWFs may involve, for instance, disrupting the construction process through hazardous maneuvers near the installation fleet or, at later stages, unauthorized boarding of service vessels. There may also be direct attempts to damage, for example, transmission cables by dragging anchors along them, or wind turbines themselves through false technical servicing. However, hybrid tools such as cyberattacks may likewise be employed, potentially leading not only to the malfunction of a single turbine but also threatening the integrated electricity transmission system. This entails a direct risk of compromising the ability to control and operate OWFs, thereby preventing the supply of electricity necessary to meet a country's energy needs.

Sabotage, in a broader sense, may therefore encompass not only external but also internal attempts to destabilize both the construction and subsequent operation of OWFs. Internal elements of sabotage may include, for example, deliberate breaches of procedures by employees, manipulation of data within device controllers, or even obstruction of information flows between departments. The most dangerous scenario for maintaining energy independence is, thus, the combination of multiple methods of destabilizing OWF operations. For this reason, consistent and systematic monitoring and the implementation of new turbine surveillance solutions, as well as the observation and analysis of vessel traffic within all OWFs located in the Polish sector of the Baltic Sea, together with cooperation with units from other Baltic Sea states, may yield the expected security outcomes in the field of international collaboration (Miętkiewicz, 2025).

Conclusions

Increasing the share of renewable energy sources (RES) through investment in their development offers the world a key means of mitigating the greenhouse effect and ensuring sustainable conditions for future generations. By harnessing renewable energy and simultaneously working to improve technologies for its generation, countries (including Poland) contribute not only to a cleaner environment but also, and more importantly, to the stable growth of RES in pursuit of a green energy transition. Wind energy plays a central role in accelerating this process in Poland. Both the potential of the Baltic Sea within

Poland's exclusive economic zone and the strong interest of numerous enterprises in offshore wind farm investments provide promising opportunities to take a milestone step toward ensuring the country's energy security. In the long term, the establishment of offshore wind farms in Poland is expected to bring multiple benefits, such as significant support in meeting the European Union's climate goals, the creation of new jobs, and the development of port infrastructure and the entire service base, as well as the use of wind power for hydrogen production to increase the efficiency of the farms. However, every investment entails future challenges that must be addressed by the investors ultimately responsible for building wind farms in the Polish section of the Baltic Sea. These include the high initial investment costs required for the construction of wind farms, lengthy permitting procedures, regulatory frameworks in need of revision, and the necessity of carefully assessing the long-term impacts of wind farms on ecosystems and local communities.

Poland's current energy situation stands in contrast to environmentally sustainable approaches to energy generation. Given the uncertainty associated with continuing traditional modes of production, a transformation of economic policy has become necessary. Wind energy has the potential to substantially increase the share of RES in Poland and reduce reliance on imported energy by generating domestic electricity in line with the Green Deal guidelines. Therefore, Poland's energy policy should consistently aim to support the development of the entire offshore wind sector, streamline administrative procedures, and ensure the efficient transmission and storage of electricity generated by wind farms.

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