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Review

Wind Energy in Transition: Development, Socio-Economic Impacts, and Policy Challenges in Europe

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Abstract: Wind energy has emerged as a strategic pillar in the global energy transition, offering both environmental and economic benefits. This comprehensive review explores the development of wind energy with a focus on the regulatory, socio-economic, and technological challenges that shape its deployment in Europe, particularly in Poland. The study highlights disparities between countries in terms of both total and per capita installed capacity, emphasizing the importance of equitable access to renewable energy. Denmark and Germany outperform larger economies like China and India in per capita terms, indicating the significance of effective policy frameworks and public engagement. The article presents detailed case studies of successful wind farm projects across the EU alongside economic evaluations including cost structures, return on investment, and local development impacts. Additionally, the role of innovation—such as floating offshore wind farms and AI-based energy management—is discussed in the context of improving efficiency and overcoming infrastructure and environmental barriers. The analysis is supported by quantitative comparisons, graphical representations, and policy reviews, culminating in practical recommendations for future growth. Wind energy's expansion depends on integrated strategies that combine policy reform, technological advancement, economic viability, and community participation.

Keywords: wind energy; renewable energy transition; energy policy; per capita wind capacity; floating offshore wind; community engagement; wind energy economics; Poland; European Union; energy infrastructure

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Academic Editor: Davide Astolfi

Received: 25 February 2025
Revised: 24 March 2025
Accepted: 2 April 2025
Published: 28 May 2025

Citation: Wojtaszek, H.; Borowski, P.F.; Handschke, M.; Miciuła, I.; Stecyk, A.; Bielawa, A.; Ozdyk, S.; Kowalczyk, A.; Czepło, F. Wind Energy in Transition: Development, Socio-Economic Impacts, and Policy Challenges in Europe. *Energies* **2025**, *18*, 2811. https://doi.org/10.3390/en18112811

1. Introduction

Wind energy is one of the key pillars of the energy transition and the pursuit of climate neutrality. Both globally and in Europe, countries are investing in the development of wind farms to enhance energy security, reduce greenhouse gas emissions, and support socio-economic growth [1–5].

Numerous literature reviews on wind energy have been conducted to date, focusing on various aspects of this sector. Particular attention has been paid to technological issues, including the development of wind turbines, energy storage solutions, and measures supporting the stability of power grids [6–8]. Research has also focused on analyzing energy potential and the administrative and legal barriers that hinder wind energy project development in Europe and globally [9–11]. Significant attention has also been devoted to social acceptance of wind farms, the impact of installations on local communities, and challenges related to public participation in renewable energy projects [12–14].

In particular, in the case of Poland, these topics have been extensively discussed in the scientific literature, covering both legal and administrative aspects [15–17], as well as detailed analyses of the current state and future development prospects of the wind energy market [18–22]. These publications provide a comprehensive overview of the challenges and potential inherent in the domestic wind energy sector.

However, this article stands out due to its comprehensive approach, integrating a detailed analysis of regulatory and administrative challenges of wind farm development with an assessment of their socio-economic impact at local and national levels [23–25]. The article also presents the latest technological innovations, such as floating wind farms, advanced energy management systems, and weather forecasting solutions, which have significant potential to shape the future of the industry [1,20,21]. Additionally, the article includes unique case studies of selected wind farms in Poland and European Union countries, illustrating practical solutions for effectively overcoming investment and social barriers (e.g., Potęgowo, Margonin, Horns Rev 3, or Gode Wind farms). Consequently, this work constitutes a valuable addition to the existing literature, providing not only a comprehensive overview of current issues but also practical recommendations for future development [1–21].

Modern energy policies focus on generating power from low- or zero-emission sources. To maintain its leadership in climate neutrality efforts and remain competitive in the global market, the European Union has introduced a range of initiatives and regulations aimed at accelerating the energy transition. Increasing the share of wind energy in each country's energy mix significantly strengthens energy security and positively impacts socio-economic development at both local and national levels. Recent policy documents clearly highlight the role of wind power as a crucial element of decarbonization and the energy transition. Programs such as the Net Zero Industry Act, Electricity Market Design, and the European Wind Power Action Plan aim to accelerate the growth of wind energy in Europe by simplifying administrative and legal procedures [6–12].

Wind energy already plays an essential role in Poland's energy mix and will remain one of its fundamental components. This year, onshore wind farms may become the second-largest source of electricity in Poland, surpassing lignite. The updated Polish Energy Policy aims to achieve 14.5 GW of installed wind turbine capacity by 2030. Meanwhile, the National Energy and Climate Plan projects approximately 15.8 GW from onshore wind farms and 5.9 GW from offshore wind power. The government recognizes the need to adjust these plans to the sector's dynamic growth, and implementing the right regulations could boost optimism within the industry. According to the Polish Wind Energy Association (PSEW), if the full potential is realized, wind power capacity could reach around 18 GW by 2030 [26–29] (Figure 1).

This forecast illustrates the dynamic growth of the wind energy sector in Poland, considering the objectives outlined in the updated Polish Energy Policy (PEP2040), as well as the long-term development potential up to mid-century. Starting from approximately

8.5 GW in 2024, a steady increase is projected, reaching around 15.8 GW by 2030. In the following decades, further substantial growth is anticipated, driven by technological advancements, expansion of transmission infrastructure, and innovative offshore wind solutions, such as floating wind farms, combined with advanced energy management systems.

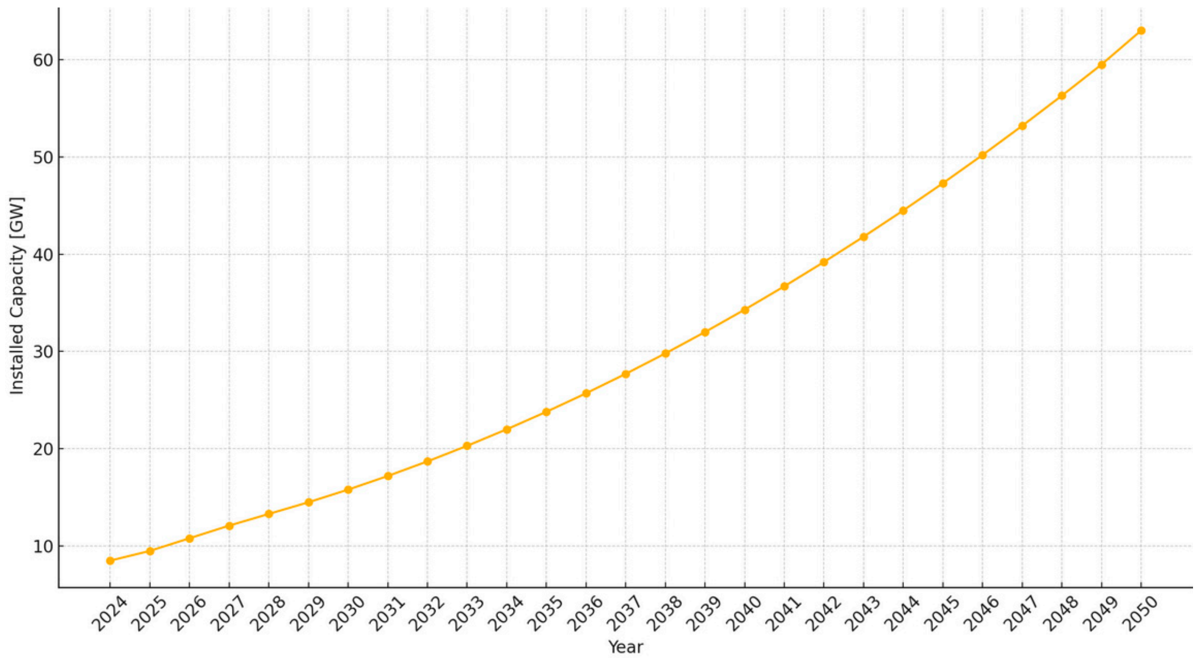

Figure 1. Forecast of Installed Wind Energy Capacity in Poland up to 2050 [GW]. Source: authors' own elaboration.

From 2030 to 2050, the growth rate may accelerate further due to the increasingly stringent climate objectives set by the European Union, stimulating member states to boost investments in renewable energy sources. Administrative process improvements and rising social acceptance will additionally facilitate this development. Consequently, the total installed wind capacity in Poland could exceed 60 GW by 2050, significantly contributing to national and European climate and energy targets. This long-term development strategy will also enhance energy security, create new employment opportunities, foster regional economic development, and support environmental sustainability through greenhouse gas emission reductions.

However, for onshore wind energy in Poland, location restrictions remain the biggest challenge. Increasing the minimum distance between wind turbines and residential buildings from 500 to 700 m last year has significantly reduced the availability of land for new investments, lowering potential installed capacity by 60–70%. Returning to a minimum distance of 500 m could open new opportunities for wind energy development while maintaining social acceptance and best practices. Such changes are not only expected by investors but also by local governments, which anticipate higher tax revenues from new wind farms [30–36].

Another obstacle to investment growth is the lengthy process of obtaining permits for onshore wind farms—one of the longest in Europe. Current administrative procedures are time-consuming, slowing down new projects and preventing full utilization of Poland's wind energy potential [37,38].

The main challenges for onshore wind energy development in Poland are location restrictions and lengthy administrative procedures. The introduction of a 700-m minimum distance requirement in 2023 significantly reduced potential installed capacity by approximately 60–70%. Reducing this distance to 500 m could accelerate industry growth, benefiting both investors and local governments through increased tax revenues [39,40].

Currently, the permitting process for wind farms in Poland is among the longest in Europe, taking up to 10 years. Simplifying these procedures and shortening project implementation timelines to 2–3 years would allow for more effective utilization of renewable energy sources (RES), in line with the EU's RED III directive [41–43].

Additional barriers include grid connection issues, as well as solutions such as cable pooling and direct power lines, which require further refinement. Collaboration between grid operators and the industry could enhance the efficiency of existing infrastructure [44].

Offshore wind energy is also developing, with new plans targeting 18 GW of installed capacity by 2040, marking significant progress compared to previous assumptions. The first wind farm in the Baltic Sea is set to start producing energy in 2026 [45–48].

2. Materials and Methods

This study employs a mixed-method approach combining qualitative and quantitative analyses to assess the development of wind energy, its challenges, and economic implications. The methodology is structured into three key sections: data collection, data analysis, and case study evaluation. The data for this research were gathered from multiple sources, including official reports and policy documents, such as those from the European Commission, Polish government energy policies, and regulatory frameworks, which were reviewed to assess policy and legislative impacts on wind energy development. Statistical data from the International Energy Agency (IEA), Eurostat, and the Polish Wind Energy Association (PSEW) were utilized to examine wind energy capacity, economic indicators, and employment statistics. Industry publications and scientific articles, including peer-reviewed journals and industry white papers, were consulted to incorporate the latest technological advancements and economic evaluations in wind energy. Additionally, selected case studies of wind farm projects in Poland and the European Union were analyzed to identify best practices and challenges in wind energy deployment [49–52].

The collected data were analyzed using both qualitative and quantitative techniques. Descriptive statistical analysis was employed to examine key economic and energy indicators using statistical methods to assess trends in wind energy development. Comparative analysis was conducted to evaluate regulatory policies, investment costs, and economic benefits of wind energy in Poland and other European countries. A SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis was performed to assess the current and future potential of wind energy development. Furthermore, economic viability was assessed using Levelized Cost of Electricity (LCOE) calculations, taking into account investment costs, operational expenses, and expected revenues [53].

A case study approach was used to examine specific wind energy projects, including Potęgowo Wind Farm in Poland (219 MW), where the analysis focused on its impact on local employment, tax revenues, and community acceptance; Margonin Wind Farm in Poland (120 MW), which was assessed for its financial and economic benefits for the local economy; Horns Rev 3 in Denmark (407 MW), where the socio-economic and environmental aspects of offshore wind energy were investigated; and Gode Wind in Germany (582 MW), where the study examined regulatory frameworks and technological innovations in offshore wind farms [54].

No human or animal intervention studies were conducted in this research. All data utilized were obtained from publicly available sources and official reports. Any proprietary datasets used have been appropriately cited, and the data processing methods adhere to ethical research guidelines. By integrating multiple data sources, analytical methods, and case study evaluations, this study provides a comprehensive overview of wind energy development, highlighting key challenges and opportunities for future expansion [55,56].

3. Dominant Countries in Wind Energy

In 2024, wind energy continues to play a pivotal role in the global energy transition, with leading countries achieving dominance through sustained investments in both onshore and offshore wind farms. China remains the undisputed leader in the global wind energy market, with an impressive installed capacity of 500 GW. This remarkable achievement underscores China's commitment to leveraging its vast geographical potential and investing in the rapid development of wind power infrastructure. The country's ability to scale both onshore and offshore wind farms at an unparalleled rate has positioned it as a global powerhouse in the renewable energy sector. Its aggressive policies and financial incentives have driven significant advancements, ensuring its leadership in both installed capacity and technological development [57,58].

The United States holds the second position globally, with a total installed wind power capacity of 160 GW. The U.S. wind energy sector is characterized by the extensive use of onshore wind farms, particularly in regions with high wind potential, such as Texas, the Midwest, and the Great Plains. These areas have capitalized on favorable wind conditions and robust state-level policies supporting renewable energy. Federal incentives, including production tax credits, have also played a key role in driving investments in the wind sector. Despite the focus on onshore wind, offshore wind projects are gaining traction, particularly along the eastern seaboard, where states such as New York and Massachusetts are pioneering large-scale offshore wind farms to diversify the country's renewable energy portfolio [54,59–66].

Germany, as Europe's leader in wind energy, has achieved an installed capacity of 73 GW, reflecting its strong commitment to renewable energy as part of its Energiewende (energy transition) strategy. Germany's efforts to expand both onshore and offshore wind capacity are driven by its ambitious climate goals, which aim to phase out coal and nuclear power while significantly reducing greenhouse gas emissions. Offshore wind farms in the North and Baltic Seas have become a cornerstone of Germany's energy policy, with state-of-the-art technology ensuring high efficiency and reliability. The German wind energy sector also benefits from robust grid infrastructure and innovative solutions for integrating intermittent renewable energy sources into the national grid [67–71].

India, with an installed capacity of 47 GW, continues to be a strong player in the wind energy market, especially in the context of Asia. The country has focused on scaling its wind energy capacity to meet its growing energy demand and reduce its dependence on fossil fuels. States such as Tamil Nadu, Gujarat, and Rajasthan are leading the way in onshore wind power development, supported by favorable policies and investments from both domestic and international stakeholders. India's renewable energy ambitions are aligned with its broader objectives of achieving energy security and fulfilling its commitments under the Paris Agreement [72–74].

Spain, with an installed capacity of 32 GW, has solidified its position as a leader in onshore wind energy. The country's commitment to renewable energy is evident in its well-established wind farms, which contribute significantly to its national energy mix. Spain has prioritized the development of wind energy to enhance energy independence and reduce reliance on imported fossil fuels. Meanwhile, the United Kingdom remains a global leader in offshore wind energy, with an installed capacity of 31 GW. The UK's innovative approach to floating offshore wind farms, combined with strong government support and a clear regulatory framework, has allowed it to maintain its leadership in this segment of the industry. Offshore projects such as Dogger Bank and Hornsea Wind Farm exemplify the UK's ambitious vision for renewable energy [75–77].

Brazil, with an installed capacity of 30 GW, stands out as the leader in Latin America's wind energy sector. The country has tapped into its vast wind resources, particularly in regions like the northeast, where consistent wind speeds create ideal conditions for wind farm development. Brazil's wind energy sector has benefited from competitive auctions and favorable financing mechanisms, which have attracted significant investments from private and public entities alike [78–80].

France, with 25 GW of installed capacity, is intensively developing its offshore wind sector, focusing on expanding its renewable energy capacity to meet ambitious climate targets. Offshore projects in the Atlantic and Mediterranean regions are expected to play a crucial role in France's energy transition strategy. The Netherlands is another key player in the European wind energy market, with cutting-edge offshore wind projects such as Hollandse Kust demonstrating its commitment to innovation and sustainability. Denmark, a pioneer in wind energy, continues to lead in terms of the highest share of wind energy in its national energy mix, with wind accounting for an impressive 56% of its electricity consumption. Denmark's early adoption of wind energy technologies and its focus on integrating renewable energy into the grid have made it a model for other countries to follow [72,74,81–83].

Europe, as a whole, plays a central role in the advancement of wind energy, leveraging advanced technologies, regulatory support, and collaborative efforts among member states. Countries like Germany, the United Kingdom, Spain, Denmark, and The Netherlands are at the forefront of innovation, setting global benchmarks for the deployment and integration of wind energy. European leadership in this sector is driven by a shared commitment to decarbonization and sustainable development, with wind energy serving as a cornerstone of these efforts (Figure 2) [84–86].

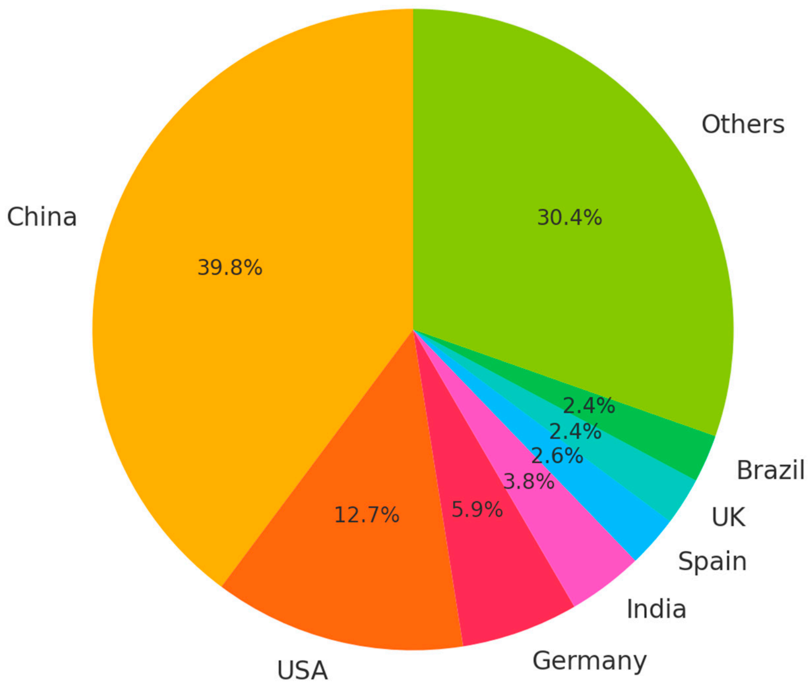

Figure 2. Installed Wind Power Capacity Worldwide (2024). Source: authors' own elaboration.

The global dominance of countries like China, the United States, and Germany in wind energy reflects their ability to capitalize on geographic potential, implement supportive policies, and foster technological innovation. Meanwhile, European nations, with their advanced infrastructure and commitment to renewable energy, continue to shape the future of the wind energy sector. The accompanying chart highlights the global distribution of installed wind power capacity in 2024, showcasing the countries that are driving growth and innovation in this critical area of renewable energy development [80,87–90].

The installed wind power capacity worldwide in 2024 is illustrated in the second chart, showcasing the countries with the largest capacities in this sector.

Although the absolute values of installed capacity confirm the dominance of countries such as China and the United States, it is equally important to analyze the installed wind power capacity per capita, which reflects actual access to renewable energy for citizens. This perspective reveals that smaller, highly developed nations, such as Denmark and Germany, achieve significantly higher per capita performance despite lower total capacity. A detailed analysis and comparison are presented below (Figure 3).

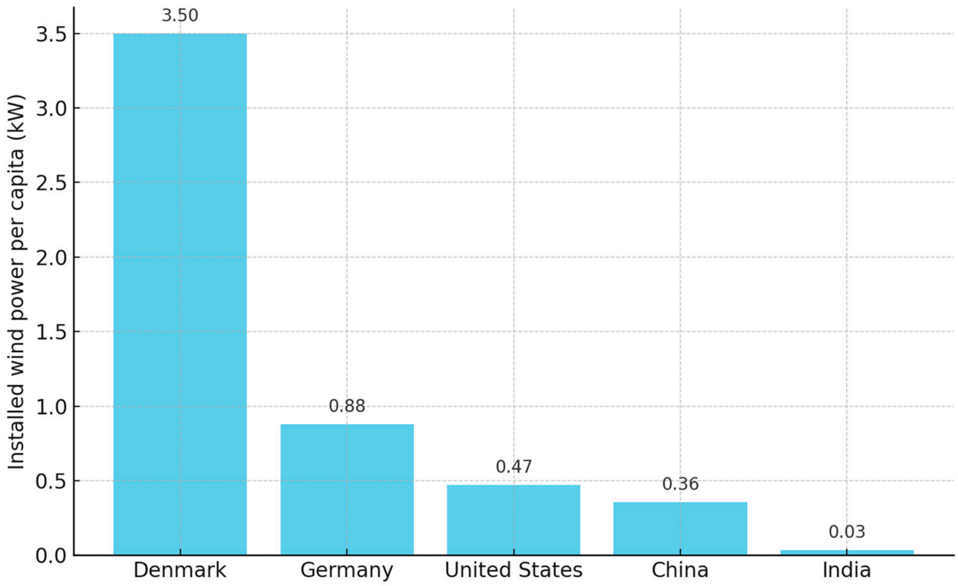

Figure 3. Comparison of wind energy availability per capita in Denmark, Germany, the United States, China, and India (2024). Source: authors' own elaboration.

In 2024, the global wind energy market was dominated by several key countries that stood out both in terms of total installed capacity and the pace of renewable infrastructure development. China led the way with an impressive 500 GW of installed capacity, significantly surpassing other nations. The United States ranked second with 160 GW, followed by Germany with 73 GW. Other major European contributors included Spain (32 GW), the United Kingdom (31 GW), France (25 GW), Denmark (21 GW), and the Netherlands (23.5 GW).

However, total installed capacity alone does not provide a full picture of investment efficiency. A more meaningful comparison requires analyzing installed capacity per capita, which accounts for population size and better reflects the actual availability of wind energy for citizens. In this regard, smaller, highly developed countries demonstrate significantly higher performance despite lower overall capacity.

Denmark, for example, with a population of approximately 6 million and 21 GW of installed wind power, achieves 3.50 kW per capita—the highest among the compared countries. Germany follows with 0.88 kW per capita, based on 73 GW of capacity and 83 million inhabitants. The United States reaches 0.47 kW per person with 160 GW of capacity and a population of around 340 million. China, despite its global leadership in total capacity, reaches only 0.36 kW per capita due to its large population of 1.4 billion.

Lastly, India, with 47 GW of installed capacity and the same population size as China, records the lowest per capita figure at just 0.034 kW.

The data clearly show that while China leads in total wind energy investments, on a per capita basis, it lags behind smaller, more developed countries. Nations like Denmark and Germany have integrated wind energy more effectively into their local systems, providing better access to clean energy for citizens. India, despite having a total installed capacity of 47 GW, has a per capita figure close to zero (0.034 kW), highlighting the imbalance between population size and the scale of renewable investments.

In conclusion, per capita analysis reveals substantial differences in wind energy accessibility between countries, allowing for a more balanced assessment of energy policies' effectiveness from a population-centered perspective.

Leading the ranking is China, which, with an impressive capacity of 500 GW, remains the undisputed global leader in wind energy. The United States follows in second place with 160 GW, reflecting the significant role of wind energy in its energy transition strategy. In third place is Germany, with a capacity of 73 GW, maintaining its position as the leader of the European wind energy market.

Further down the ranking, other European countries such as Spain (32 GW) and the United Kingdom (31 GW) demonstrate continued strong investments in both onshore and offshore wind farms. The list also includes Brazil (30 GW), which is characterized by a rapidly growing wind energy sector, and France (25 GW), which places a strong emphasis on developing offshore wind energy. The Netherlands (23.5 GW) and Denmark (21 GW) also feature prominently, with Denmark achieving the highest share of wind energy in its national electricity mix at 56%. These data highlight the pivotal role of wind energy in the global effort to transition towards more sustainable energy systems (Figure 4).

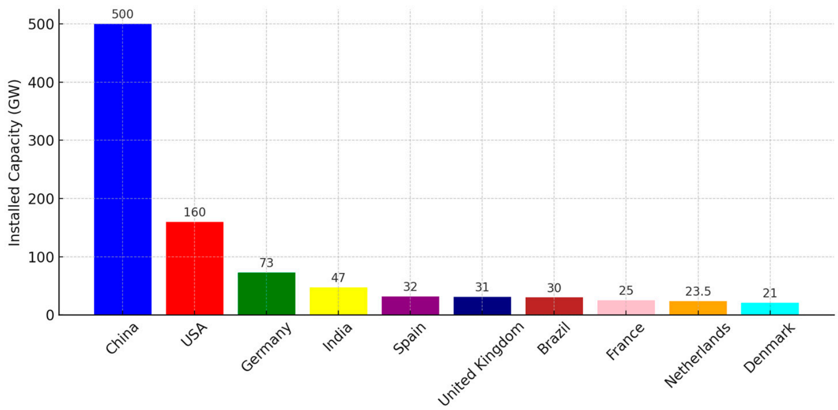

Figure 4. Installed Wind Power Capacity by Country (2024). Source: authors' own elaboration.

In 2024, the global wind energy sector was dominated by a single country, accounting for more than half of the total installed capacity, highlighting its massive investments in renewable energy. The second-largest contributor has a share more than three times smaller, emphasizing the scale of disparity between the leaders. The third position is held by a European country, which, although significantly behind the top economies, still plays a crucial role in the market. The remaining nations have considerably lower capacities, with their contributions to the global total not exceeding a few percent (Figure 4).

As a region, Europe maintains a strong position in the wind energy sector, although no single economy matches the global leaders. At the same time, emerging markets are showing increasing potential, steadily expanding their investments and share in wind energy production. The percentage analysis reveals the clear dominance of one country, a significant but much smaller presence of the second and third, and a relatively balanced distribution of smaller shares among the rest. These trends indicate a growing concentration of the sector in a few dominant hubs while new players gradually strengthen their position in the renewable energy market.

4. Challenges in the Development of Wind Energy

Wind energy faces several challenges, including location restrictions, complex administrative processes, social barriers, and the variability of weather conditions. In Poland, one of the main obstacles is the regulation regarding the minimum distance between turbines and residential buildings, which significantly limits available areas for investment. This regulation has greatly reduced the potential land for projects, thereby restricting the possible installed capacity. It is estimated that the current 700-m limit reduces the investment potential by approximately 60–70% compared to more flexible regulations, such as a minimum distance of 500 m.

Additionally, the lengthy process of obtaining permits for the construction of new wind farms remains a significant challenge. Administrative procedures in Poland are among the longest in Europe, causing delays in project implementation and increasing costs. The lack of digitization and the formal complexity of these processes further hinder the development of the sector.

Social aspects also pose barriers, such as the lack of acceptance from local communities due to concerns about noise, impact on the landscape, or potential decreases in property values near wind farms. To address these issues, it is crucial to conduct public consultations and educate communities about the benefits of wind energy.

Another challenge is the variability of weather conditions, which necessitates the development of energy storage systems and technologies that support grid stability. These include battery storage, hydrogen, and Power-to-X systems, which can mitigate the effects of intermittent energy generation.

Table 1 presents key economic aspects related to the development of wind energy, taking into account both investment and operational costs for onshore and offshore wind farms. The data also include estimated payback periods, potential revenues, and the impact on local economies, such as job creation and tax revenues. This analysis highlights the economic benefits of wind energy development and its importance for the sustainable development of regions where wind farms are established [88,91–93].

Table 1. Key economic aspects related to the development of wind energy [1–26,92].

Category	Details
Cost of building onshore wind farms	1.2–1.5 million EUR/MW
Cost of building offshore wind farms	2.5–3 million EUR/MW
Operational and maintenance costs onshore	30,000–50,000 EUR annually/MW
Operational and maintenance costs offshore	20–30% higher than onshore
Return on investment time (onshore)	8–12 years
Return on investment time (offshore)	12–15 years
Annual revenue of an onshore farm (50 MW)	6–8 million EUR annually
Jobs during the construction phase (per 1 MW)	10 jobs
Permanent jobs during the operational phase (per 1 MW)	0.3–0.5 jobs
Tax revenues per 1 MW of capacity	50,000–100,000 EUR annually

Source: authors' own elaboration.

An economic analysis of wind energy is presented in Table 1.

Table 1 outlines the financial specifics associated with the development and operation of wind farms, highlighting the differences between onshore and offshore installations as well as the economic impact, including job creation and tax revenues.

5. Social Acceptance of Wind Energy

Despite its numerous advantages, wind energy often faces concerns from local communities. The primary issues are related to landscape aesthetics, potential noise generated by turbines, and the impact on property values. An additional challenge is the lack of sufficient information about the benefits of such investments. To address these challenges, the European Wind Power Action Plan emphasizes improving transparency and community involvement in renewable energy projects. Proper information dissemination regarding economic and environmental benefits has been shown to significantly enhance local acceptance [75,83,88,93–95].

To increase social acceptance, implementing effective measures at various levels is crucial. Involving local communities in the planning process through early-stage public consultations can help dispel doubts and build trust. For example, in Denmark, residents have a say in selecting the locations of wind farms, which significantly increases their engagement and acceptance. The European Commission recommends early public consultations as part of the Wind Power Action Plan, highlighting that effective engagement methods, including public participation in site selection processes, are essential to achieving sustained local support [93,95–99].

Another essential step involves educational initiatives, such as information campaigns that highlight the environmental and economic benefits of wind farms. In Germany, open days organized at wind farms have gained popularity, allowing residents to learn about the technology and its impact on the surrounding environment.

Educational initiatives, such as open days at wind farms in Germany, play a critical role in social acceptance by enabling residents to directly observe the operation of wind turbines, thus significantly reducing public misconceptions about their environmental and technological impact [100–102].

A key element in supporting local communities is enabling them to share in the profits of wind farms through equity systems or compensation. In the United Kingdom, developers establish funds to support local initiatives, such as infrastructure development. Additionally, minimizing the impact on the landscape and environment—such as by using modern noise-reducing technologies and selecting locations distant from residential areas—can significantly influence acceptance. For instance, in The Netherlands, modern turbines with low noise levels are being utilized. The EU's Wind Power Action Plan further encourages economic benefit-sharing schemes, including financial compensation and local equity participation. Such measures have notably improved public acceptance in multiple European countries by creating direct economic benefits for affected communities [98,103].

Financial transparency also plays a critical role. Informing residents about planned investments and their impact on local economic development and infrastructure fosters trust and support for projects. According to the Wind Power Action Plan, transparency measures, such as public disclosure of financial data and project timelines via dedicated EU platforms, significantly increase local communities' trust in wind energy projects [102,104–106].

Practical successes in this area can be observed in Denmark, where local ownership of wind farms and profit-sharing with residents have yielded positive results. Similar solutions have been implemented in France, where educational and compensatory mechanisms were introduced. In Poland, good practices include municipalities where wind farms have funded the construction of roads and educational facilities, improving the image of wind energy among local communities. The EU's Net Zero Industry Act (NZIA) emphasizes legislative solutions, including the introduction of non-price criteria into renewable energy auctions, allowing projects to be evaluated based on environmental and community value. Such an approach further strengthens community acceptance by prioritizing projects beneficial to local economic development, employment, and environmental sustainability [75,107–109].

In summary, effective collaboration with residents, education, and financial transparency form the foundation for social acceptance of wind energy investments.

The Wind Power Action Plan, or the European Wind Power Action Plan, was developed in response to the challenges associated with accelerating the growth of the renewable energy sector. This document aims to streamline investment processes, increase transparency, and ensure the competitiveness of Europe's wind energy sector on the global market. The European Commission (EC) emphasizes the importance of an integrated approach that addresses technological, administrative, and regulatory aspects.

Table 2 outlines the key actions of the EC under the Wind Power Action Plan, which aim to support the sustainable development of wind energy, simplify procedures, and increase investments in innovative technologies [93,110–113].

Table 2. Key actions of the European Commission [25,114–116].

Action	Description
Proper auction design	New project qualification criteria: data security, environmental protection, delivery guarantees.
Contract indexing	Indexing of prices and auction tariffs by member states.
Investment financing	Funds for factories, infrastructure, and personnel related to wind energy.
Strengthening the role of the EIB	Risk mitigation tools, guarantees for the banking sector.
Information transparency	Publication of national auction plans on the EU platform.
Equal competition conditions	Monitoring of unfair trade practices, EC trade tools.
Acceleration of permits	Launching the EasyPermits tool for digitizing permit issuance processes.

Source: authors' own elaboration.

Wind energy constitutes a key pillar of the energy transition in Europe. Recognizing its importance, the European Commission introduced the Wind Power Action Plan—a comprehensive strategy designed to accelerate investments in wind farms. The plan focuses on streamlining administrative procedures, ensuring transparency of information, and implementing solutions to enhance the competitiveness of the European wind energy sector. A notable initiative under this plan is the EasyPermits 2023 tool, which digitizes permitting processes to reduce project implementation timelines. Additionally, contract indexing stabilizes the renewable energy investment market by providing price predictability.

Enhancing the competitiveness of Europe's wind energy sector is a crucial step toward achieving energy self-sufficiency and meeting climate goals. To achieve this, the Wind Power Action Plan outlines targeted actions addressing administrative, financial, and regulatory challenges, fostering a more efficient and sustainable energy transition.

The plan establishes proper auction design, introducing new qualification criteria for wind energy projects. These include requirements for data security, environmental protection, and delivery guarantees, ensuring high standards and reliable execution of projects. It also emphasizes indexing contracts, allowing EU member states to index prices and auction tariffs, which provides stability and predictability for investors.

Further, the investment financing action allocates funds for developing factories, infrastructure, and workforce training programs specific to the wind energy sector, driving innovation and economic growth. The Strengthening of the European Investment Bank (EIB) enhances this effort by introducing risk-reduction tools and guarantees for the banking sector, encouraging increased investments in wind energy projects.

The plan promotes transparency of information through the publication of national auction plans on an EU platform. This ensures stakeholders have access to clear and consistent information, fostering trust and broader participation in the sector. To ensure fair competition, a level playing field is maintained by monitoring unfair trade practices, with the European Commission providing tools to address these issues.

Finally, the acceleration of permits focuses on simplifying and expediting permitting processes through the launch of the EasyPermits tool. This digital solution significantly reduces delays in project implementation and facilitates faster deployment of wind energy infrastructure [84,117–119].

Collectively, these actions aim to enhance the efficiency, transparency, and competitiveness of the wind energy sector, contributing to Europe's broader goals of energy security, sustainability, and climate neutrality. By addressing critical barriers and fostering innovation, the Wind Power Action Plan ensures wind energy remains a cornerstone of Europe's energy transition (Table 3).

Table 3. Net-Zero Industry Act (NZIA).

Net-Zero Industry Act (NZIA)	Description
Goal	Increasing the production of net-zero emission technologies within the EU.
Key Actions	Simplifying regulations, improving the investment environment, and supporting green technologies.
Significance	Achieving climate neutrality and enhancing the EU's energy resilience.
Legislative Solutions	Allowing the inclusion of non-price criteria in renewable energy auctions (e.g., economic and environmental value).

Source: authors' own elaboration.

The introduction of the Net-Zero Industry Act (NZIA) by the European Union is a response to global challenges related to the decarbonization of industry. The key objective of this act is to increase the production of green technologies within the EU and to ensure a stable investment environment by simplifying regulations. The EU aims to accelerate the energy transformation while simultaneously supporting innovation and local supply chains, enhancing the EU's energy resilience by reducing dependence on imported fossil fuels and promoting self-sufficiency in energy through domestic green technologies.

Wind energy, a crucial element of the European Union's energy strategy, plays a significant role in these efforts. Achieving ambitious goals such as climate neutrality requires both international cooperation and the mobilization of resources at the national level. Strengthening the wind sector will not only contribute to achieving these climate goals but will also increase Europe's energy independence by reducing reliance on raw material imports. At the same time, investments in new technologies and infrastructure are expected to create numerous jobs, supporting economic development across the region.

The NZIA seeks to foster the development and production of net-zero emission technologies by implementing key actions such as improving the investment environment and allowing the inclusion of non-price criteria in renewable energy auctions, which means that decisions on winning bids can consider not just the cost but also the economic and environmental value they bring. This could prioritize projects that promise greater job creation locally, better environmental benefits like biodiversity conservation, or superior long-term sustainability.

These legislative solutions and actions underline the EU's commitment to a sustainable and environmentally friendly economy, positioning the NZIA as a robust framework designed to transition the EU toward a sustainable industrial base, supporting economic growth in a manner that aligns with environmental goals and global climate commitments.

6. Challenges and Needs of the Wind Energy Sector

The development of the wind energy sector faces several critical challenges that must be addressed to ensure its long-term sustainability and competitiveness. Key issues include supply chain bottlenecks, dependence on imported components, infrastructure shortages, and workforce deficits.

One of the most pressing concerns is the bottlenecks in supply chains, as Europe currently lacks sufficient production capacity for offshore wind foundations, cables, and steel towers. This limitation slows down the expansion of wind farms and increases reliance on non-European suppliers. Additionally, dependence on imports remains a significant challenge, with many key components such as cables, gearboxes, and steel towers being sourced from China. This reliance increases vulnerability to market fluctuations and geopolitical risks.

Another major obstacle is the shortage of infrastructure, including factories, ports, ships, and cranes necessary for the efficient development of both onshore and offshore wind energy projects. Without significant investments in industrial capacity and logistics, meeting Europe's ambitious wind energy targets will be difficult. Furthermore, the shortage of skilled workers highlights the need for greater investments in education and training programs to build a qualified workforce capable of supporting the growing wind sector.

To support the expansion of wind energy, it is essential to eliminate these key obstacles. Expanding infrastructure, increasing the number of local factories, and investing in workforce education are crucial steps toward meeting the rising demand for renewable energy. Strengthening Europe's domestic production capacity will enable the continent to position itself as a global leader in wind farm component manufacturing, enhancing its energy independence and economic resilience [120–123].

6.1. Ambitious Energy Targets of the European Union

The European Union has set bold targets to accelerate the deployment of wind energy as part of its broader strategy for energy transition and carbon neutrality. The primary objective is to increase the share of wind energy to 43% of Europe's electricity consumption by 2030, a significant leap from the current 17%. To achieve this, the EU plans to construct 35 GW of new wind farms annually by 2030.

Meeting these ambitious goals requires a substantial acceleration in renewable energy investments. Increasing the share of wind energy in Europe's power mix is essential for reducing CO_2 emissions and strengthening energy security. These efforts will not only contribute to environmental protection but also create thousands of new jobs and stimulate regional economic growth [124–127].

6.2. Future Prospects

Global projections indicate that installed wind power capacity could surge from 272 GW in 2023 to 3540 GW by 2030. Europe is expected to play a crucial role in achieving these targets, driven by regulatory support and technological innovation. The continent is planning a large-scale expansion of its transmission infrastructure and is actively supporting offshore wind projects, which are becoming an increasingly vital component of the region's electricity supply.

One of the most promising advancements in offshore wind technology is the development of floating wind turbines, which enable energy generation in deeper waters that were previously inaccessible to conventional turbines. Countries such as Germany, The Netherlands, and the United Kingdom are leading the way in offshore wind expansion while also implementing administrative reforms to streamline project approval processes. The goal is to reduce project implementation timelines from several years to just a few months, making wind energy deployment faster and more efficient.

On a global scale, the integration of renewable energy sources into existing power systems remains a key challenge. The successful implementation of advanced energy management systems and energy storage technologies will play a crucial role in stabilizing supply and ensuring the reliability of power grids.

Experts emphasize that the future growth of the wind energy sector depends on increased investment in research and development, particularly in next-generation turbine technologies that offer higher efficiency and lower operational costs. In developing countries, financial support mechanisms such as subsidies and low-interest loans will be essential for accelerating the adoption of wind energy.

By addressing these challenges and leveraging emerging opportunities, the wind energy sector can continue to expand, contributing to Europe's leadership in the global transition toward sustainable and resilient energy systems [128–131].

7. Results

7.1. Technological Analysis of Innovations in Wind Energy

7.1.1. New Technologies in Wind Energy

The development of technology in wind energy plays a key role in increasing turbine efficiency, improving energy supply stability, and integrating wind power into the electrical grid. Modern solutions not only enhance wind potential utilization but also minimize operational costs and reduce environmental impact. Innovations in this field focus on improving turbine design, advancing energy storage systems, implementing floating wind farms, and utilizing advanced predictive and grid management technologies.

Table 4 below presents key new technologies in wind energy, their applications, and their impact on the renewable energy sector.

The development of wind energy is closely linked to technological advancements that enhance turbine efficiency, optimize energy management, and reduce operational costs. Modern technological solutions are crucial for the further growth of this sector and its integration into the power grid.

One of the most significant trends in this field is the use of high-efficiency turbines with taller towers. Modern wind turbines feature larger rotors and longer blades, allowing for better utilization of wind potential, particularly in areas with lower wind speeds. The use of taller towers, reaching up to 200 m, enables access to more stable and stronger air currents. The introduction of new composite materials helps reduce the weight of turbines and their susceptibility to damage. Additionally, variable-speed technology optimizes energy production depending on atmospheric conditions.

A key challenge for wind energy is the variability of energy production due to changing weather conditions. Modern energy storage systems play a crucial role in stabilizing supply and integrating wind energy into the power grid. Various technologies are used for this purpose, including battery storage solutions such as lithium-ion, flow, and sodium/sulfur batteries, which allow excess energy to be stored and released during peak demand periods. Hydrogen systems are also gaining importance, enabling the conversion of surplus wind energy into hydrogen, which can be stored and used for power generation when needed. The development of artificial intelligence and predictive load management algorithms improves energy flow management and forecasts changes in production and consumption.

Table 4. New Technologies in Wind Energy.

Category	Description
High-efficiency turbines with taller towers	Modern wind turbines feature larger rotors and taller towers, optimizing wind energy potential. Key innovations include: - Taller towers (up to 200 m); - Longer rotor blades; - New composite materials reducing weight and damage susceptibility; - Variable speed technology optimizing energy production.
Energy storage systems and grid integration	Solutions for stabilizing wind energy generation fluctuations through energy storage. Key technologies include: - Battery storage (lithium-ion, flow, sodium/sulfur); - Hydrogen systems (Power-to-Gas); - AI and grid load prediction systems.
Floating wind farms as a new development direction	Floating wind farms enable wind energy utilization in deep-sea areas. Key aspects include: - Floating foundations instead of seabed-mounted structures; - Higher wind energy potential in deep waters; - Reduced spatial conflicts with fisheries and shipping, - Notable projects: Hywind Scotland, WindFloat Atlantic.
Advanced weather prediction and energy management systems	Advanced weather prediction and energy management technologies enhance wind farm efficiency include: - AI algorithms analyzing real-time meteorological data; - IoT-based monitoring systems for turbine diagnostics; - Satellite data and climate models for improved weather forecasts; - Smart grid management systems dynamically optimizing energy transmission.

Source: authors' own elaboration.

A new direction in wind energy development is floating wind farms, which allow for the utilization of strong and stable winds in deep-sea areas. Instead of traditional seabed-mounted foundations, turbines are installed on floating platforms, enabling deployment in locations with depths exceeding 50 m. In addition to increased efficiency, this solution minimizes spatial conflicts by reducing the impact on local ecosystems and other industries such as fisheries and maritime transport. The first successful implementations of this technology, such as Hywind Scotland and WindFloat Atlantic, demonstrate its effectiveness and open new investment opportunities (Figure 5).

Figure 5 provides a detailed illustration of a floating offshore wind turbine, highlighting its primary technological and structural components. At the top, a modern wind turbine is depicted, consisting of rotor blades designed to efficiently harness strong and consistent winds prevalent over open ocean waters. These blades drive a turbine, generating renewable electricity.

Below the turbine, a robust tower connects directly to a floating platform, engineered to maintain stability even under harsh maritime conditions such as strong winds, waves, and currents. The platform's design ensures minimal motion, which is crucial for both turbine operation and longevity.

Anchoring systems, clearly shown in the schematic, secure the platform to the seabed. These mooring lines ensure that the turbine maintains a consistent position, greatly reducing the risks associated with drifting. This anchoring mechanism typically consists of heavy-duty chains, cables, or synthetic ropes attached to anchors embedded in the ocean floor.

Moreover, the figure distinctly illustrates the undersea power cables, responsible for transferring the generated electricity from the floating platform to the shore. These subsea cables represent a critical infrastructure component, facilitating efficient energy delivery to the electrical grid on land.

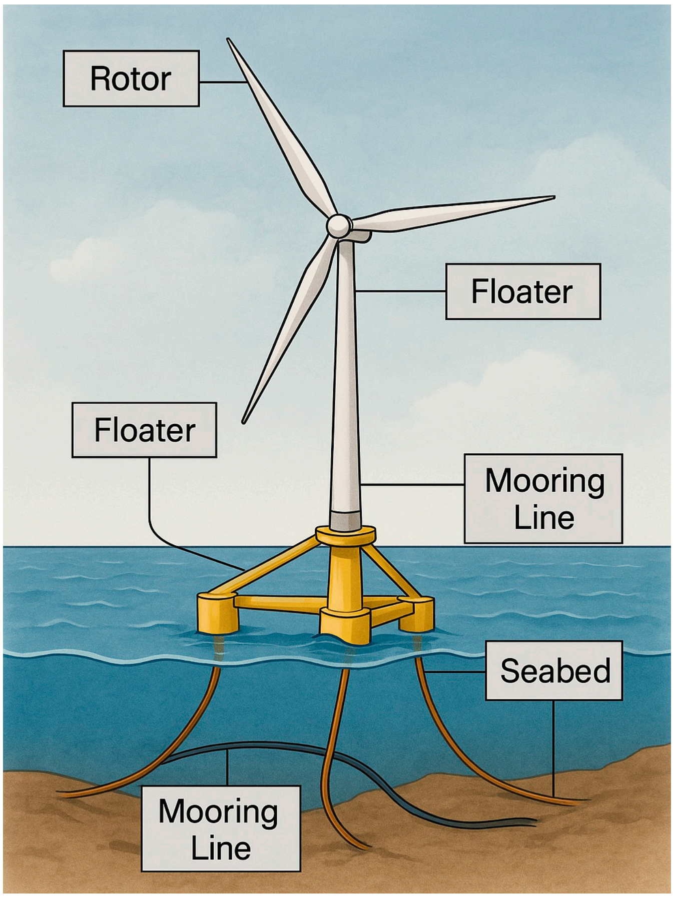

Figure 5. Enhanced Schematic of a Floating Offshore Wind Farm. Source: authors' own elaboration.

Floating wind turbine technology, exemplified by projects such as Hywind Scotland and WindFloat Atlantic, significantly expands possibilities for offshore wind deployment, particularly in deep-water locations (greater than 50 m), where fixed-bottom turbines are economically and technically unfeasible. Additionally, the floating turbine approach reduces environmental impacts, mitigates spatial conflicts with fishing and shipping industries, and opens substantial areas previously inaccessible for energy generation.

Overall, floating offshore wind farms represent a transformative step forward for renewable energy, enhancing the sustainability, flexibility, and economic viability of wind power generation in diverse maritime environments.

Another innovation in wind energy is the use of advanced weather prediction and energy management systems. Modern artificial intelligence algorithms analyze meteorological data in real-time, allowing turbines to adjust their operations according to current weather conditions. The development of IoT technology enables efficient monitoring of turbine technical conditions and predictive maintenance, minimizing the risk of failures and reducing operational costs. The use of satellite data and climate models improves the accuracy of weather forecasts, facilitating energy production planning and reducing energy losses. Smart grid management systems dynamically optimize energy transmission, adapting it to predicted changes in generation and demand.

Technological advancements in wind energy enable more efficient and stable use of this renewable energy source, contributing to the further decarbonization of the energy sector and increasing the share of renewable energy in the global energy mix.

7.1.2. Comparison of Wind Energy with Other Renewable Energy Sources

Wind energy is one of the most important renewable energy sources (RES), alongside solar and hydropower. Each of these technologies plays a crucial role in the energy transition, but their application depends on various factors such as geographical conditions, technological efficiency, investment costs, and environmental impact.

To better understand the position of wind energy within the renewable energy production structure, it is useful to compare it with other solutions based on key parameters such as energy production efficiency, supply stability, investment and operational costs, environmental impact, and integration with the power grid [132,133].

Table 5 below provides a comparison of the key aspects of wind, solar, and hydropower energy, allowing for an assessment of their advantages and limitations in the context of their application in Poland and Europe.

Table 5. Comparison of Key Aspects of Wind, Solar, and Hydropower Energy in the Context of Their Application in Poland and Europe.

Parameter	Wind Energy	Solar Energy	Hydropower
Investment Costs	Medium to high	Low to medium	High
Operational Costs	Medium	Low	Low to medium
Efficiency in Climate	High in windy areas	Dependent on sunlight	High, but requires a water reservoir
Development Potential in Poland	High on land and sea	High, especially in cities	Limited by water resources
Scalability	High, but requires large areas	High, with rooftop installation options	Limited by access to suitable rivers

Source: authors' own elaboration.

The comparative analysis of wind, solar, and hydropower energy highlights significant differences in costs, efficiency, and development potential for each technology. Solar energy stands out with the lowest investment and operational costs, making it particularly attractive for individual households. Wind energy, despite its moderate investment and operational costs, has the potential to generate substantial amounts of electricity, especially in areas with favorable wind conditions. Hydropower, while requiring high initial investments, offers stable and long-term energy production.

In terms of efficiency under different climatic conditions, wind energy performs best in regions with high average wind speeds, which in Poland primarily include coastal and central areas. Solar energy is most effective in locations with high sunlight exposure, but technological advancements now allow for its use even in less sunny regions. Hydropower provides a stable energy supply, but its efficiency is highly dependent on the availability of suitable rivers and water reservoirs.

The development potential of these technologies also varies based on geographic and technological factors. Wind energy, particularly offshore wind farms, has significant expansion potential and the capacity to deliver large amounts of electricity. Solar energy is highly scalable and can be utilized on both small scales, such as rooftop installations, and large-scale solar farms. Hydropower, though constrained by geographic limitations, still has development potential through the modernization of existing hydroelectric plants and the optimization of their efficiency [131,134].

7.1.3. Environmental Aspects and the Impact of Wind Energy on Ecosystems

Wind energy is one of the key sources of renewable energy, contributing to the reduction of greenhouse gas emissions and decreasing dependence on fossil fuels. Despite its many environmental benefits, the development of wind farms also presents certain environmental challenges that can impact both terrestrial and marine ecosystems.

One significant aspect is the effect of wind turbines on birds and other animal species, including the risk of collisions and habitat fragmentation. Migratory species are particularly vulnerable, as wind farms can obstruct their flight paths. In the case of offshore wind farms, seabed disturbances during construction and underwater noise generated during operation can disrupt marine ecosystems.

Another challenge is the noise produced by turbines, which can affect both humans and wildlife. However, technological advancements allow for the implementation of noise reduction solutions, such as sound-absorbing materials and optimized rotor blade design. Additionally, the issue of recycling wind turbine components, particularly rotor blades made from composite materials, remains a challenge due to the difficulty of processing these materials.

Table 6 below outlines the key environmental aspects of wind energy, its impact on ecosystems, and measures aimed at minimizing negative effects.

Table 6. Environmental Impact of Wind Farms and Mitigation Measures [89,127–130].

Category	Description	Mitigation Measures
Impact of Wind Farms on Birds and Other Animal Species	Wind turbines can pose a threat to birds and bats due to collisions with rotors and habitat fragmentation. Migratory species are particularly at risk. Wind farms can also influence animal behavior, deterring some species from nesting areas.	Conducting site assessments before construction to avoid migration areas. Using bird detection technology and automatic turbine shutdown systems. Painting turbine blades in contrasting colors to improve visibility for birds.
Effects of Offshore Wind Farms on Marine Ecosystems	Offshore wind farms disrupt the seabed during installation, potentially destroying habitats and altering sediment dynamics. Underwater noise generated by turbines may affect the behavior of marine mammals and fish.	Employing quieter installation methods for turbine foundations and creating artificial reefs around turbines to enhance biodiversity. Monitoring underwater noise levels and adjusting turbine operations during sensitive periods for marine wildlife.
Technologies for Noise Reduction and Other Negative Impacts	Noise from rotating turbine blades and internal mechanisms can impact both humans and terrestrial or marine animals. Various technologies help reduce noise emissions, such as the use of sound-absorbing materials and optimized blade design.	Using advanced noise-absorbing materials in turbine construction. Optimizing rotor blade shape based on owl wing structures to reduce noise emissions. Locating wind farms near natural sound barriers, such as forests.
Life Cycle Analysis of Wind Turbines and Component Recycling	Wind turbines have a lifespan of 20–30 years, after which the challenge of recycling components arises, particularly rotor blades made from fiber-reinforced composites. Recycling technologies are being developed, including repurposing materials for cement production and designing turbines with easier material recovery in mind.	Developing rotor blade recycling technology, e.g., repurposing them for cement production. Reusing mechanical and electrical components in new turbines or other industries. Designing turbines with recyclable materials to improve sustainability.

Wind energy plays a key role in the energy transition, contributing to the reduction of greenhouse gas emissions and decreasing dependence on fossil fuels. Despite its positive environmental impact, the development of wind farms presents certain ecological challenges that can affect both terrestrial and marine ecosystems.

One of the most significant environmental aspects is the impact of wind turbines on birds and other animal species. Their operation can lead to collisions with rotor blades and habitat fragmentation, posing a particular threat to migratory species for which wind farms may create obstacles along their flight paths. In offshore wind farms, seabed disturbances during turbine installation can result in habitat degradation for benthic organisms and alter sediment dynamics. Additionally, the noise generated by turbines during operation can disrupt the behavior of marine mammals and fish, interfering with their navigation and communication processes.

Noise pollution is also a concern on land, where it can affect both humans and wildlife. To address this issue, new technologies are being developed to reduce noise emissions, including the use of sound-absorbing materials and the optimization of rotor blade shapes. The placement of wind farms is also planned with consideration for natural sound barriers, such as forests, which can further reduce noise propagation.

Another important challenge is the recycling of wind turbine components, particularly rotor blades, which are made from fiber-reinforced composites that are difficult to process. In response, innovative recycling technologies are being developed, including repurposing blades for use in the cement industry and designing turbines with improved material recovery in mind. Additionally, mechanical and electrical components from decommissioned turbines can be reused in new installations or other industrial sectors.

Despite these challenges, the expansion of wind farms remains one of the most environmentally friendly directions in the energy sector. With modern solutions aimed at minimizing their environmental impact, it is possible to achieve a balance between producing clean energy and preserving ecosystems.

7.2. Analysis of Successful Wind Farm Projects in Poland and Selected European Union Countries

7.2.1. Examples of Successful Wind Farm Projects in Poland and Their Impact on Local Communities

The development of wind energy in Poland has brought numerous benefits to local communities, including economic growth, infrastructure improvements, and increased environmental awareness. Several large-scale wind farm projects have successfully integrated renewable energy production with regional development, fostering social acceptance through consultations and reinvestment in local economies. Below is an overview of selected wind farms in Poland, highlighting their capacity, benefits, and community engagement efforts (Table 7).

Table 7. Successful Wind Farm Projects in Poland and Their Impact on Local Communities.

Wind Farm Name	Location	Capacity	Benefits	Community Engagement
Potęgowo Wind Farm	Pomeranian Voivodeship, Poland	219 MW (largest wind farm in Poland)	New jobs, infrastructure development, revenue for the municipal budget	Local consultations and reinvestment of profits into regional development
Margonin Wind Farm	Greater Poland Voivodeship, Poland	120 MW, 60 wind turbines	Significant tax revenues enabled road modernization and public facility construction	Informational campaigns by local authorities to increase public acceptance
Jasna Wind Farm	Pomeranian Voivodeship, Poland	132 MW, developed following sustainable principles	New jobs, increased environmental awareness, active community consultations	Meetings with residents and environmental education initiatives

Source: authors' own elaboration.

Many successful wind farm projects have been developed in Poland, significantly contributing to the growth of local communities. One of the largest and most impressive projects is the Potęgowo wind farm in the Pomeranian Voivodeship, with a capacity of 219 MW, making it the largest wind farm in the country. This investment has led to the creation of new jobs, the development of local infrastructure, and substantial revenues for the municipal budget. Additionally, thanks to local consultations and the reinvestment of profits into regional development, the project has gained broad public acceptance. Another example is the Margonin wind farm in the Greater Poland Voivodeship, consisting of 60 turbines with a total capacity of 120 MW. The significant tax revenues generated by the farm have enabled road modernization and the construction of public facilities, significantly improving the quality of life for local residents. The community was actively engaged through informational campaigns aimed at increasing public acceptance of the project. Meanwhile, the Jasna wind farm, also located in the Pomeranian Voivodeship, is a 132 MW investment developed in accordance with the principles of sustainable development. In addition to benefits such as job creation and increased environmental awareness, this wind farm was established with active community involvement through informational meetings and educational initiatives. All these examples demonstrate that the development of wind energy in Poland not only contributes to the country's energy transition but also brings tangible economic and social benefits to the residents of the regions where these wind farms are located (Figure 5).

The map (Figure 6) presents the geographic locations of the largest and most significant wind energy projects in Poland: the Potęgowo, Margonin, and Jasna wind farms. These farms represent crucial centers for renewable energy development, substantially contributing to the increase of renewable energy in Poland's national energy mix. Their strategic positions in the northern and central-western regions of the country allow effective utilization of local wind conditions and existing energy infrastructure. Implementation of these projects is essential for achieving both national and European climate targets. Additionally, these developments provide considerable benefits to local communities, including job creation, infrastructure improvements, and increased municipal tax revenues.

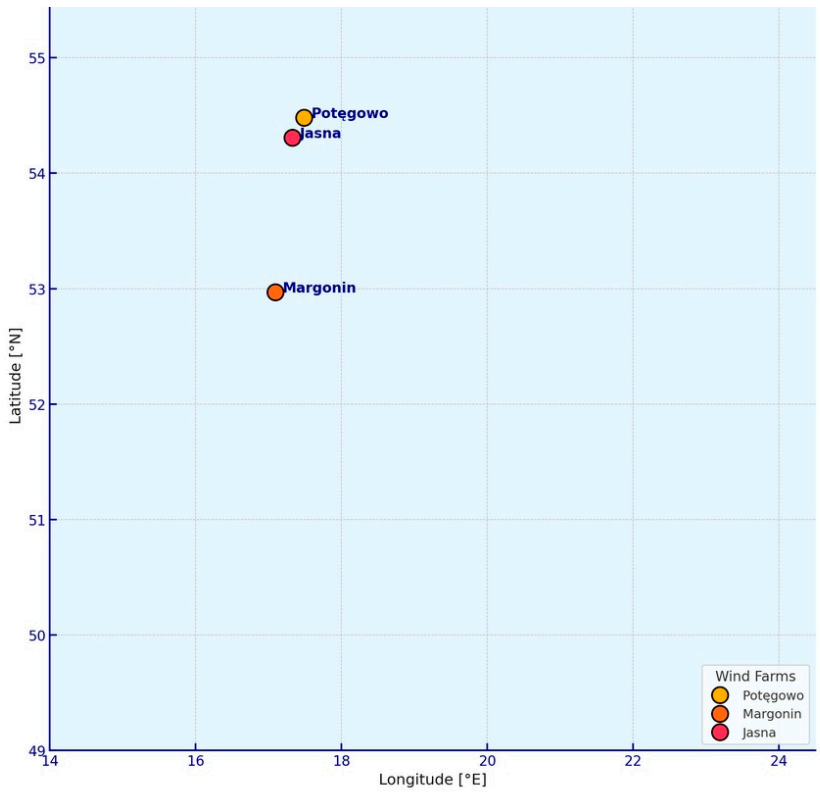

Figure 6. Geographic Location of Key Wind Energy Projects in Poland. Source: authors' own elaboration.

7.2.2. Selected Examples of Successful Wind Farm Projects in the European Union [135–137]

The European Union has been a global leader in wind energy development, with numerous large-scale projects that contribute to the transition toward renewable energy.

These wind farms not only provide clean electricity but also bring economic and social benefits to local communities. Investments in offshore and onshore wind farms have helped reduce carbon emissions, create jobs, and improve regional infrastructure. Many projects have also fostered public acceptance through community engagement initiatives, education programs, and participatory investment models. The table below presents selected examples of successful wind farms in the EU, highlighting their capacity, benefits, and community involvement (Table 8).

Table 8. Successful Wind Farm Projects in the European Union.

Wind Farm Name	Location	Capacity	Benefits	Community Engagement
Horns Rev 3	Denmark	407 MW (offshore in the North Sea)	Increased share of renewables in Denmark, CO_2 emission reduction	Government support for local fishing communities through economic compensation programs
Gode Wind	Germany	582 MW (offshore off the German coast)	Collaboration with the scientific sector to minimize environmental impact	Regional governments invested in environmental education and awareness programs
Whitelee	Scotland, United Kingdom	539 MW (largest onshore wind farm in Europe)	Local budget revenues supporting education and infrastructure	Open tourist trails, renewable energy education center
Middelgrunden	Denmark	40 MW (first citizen-financed wind farm)	Participatory model—Copenhagen residents could invest in turbines and earn profits	Strong public support due to the cooperative ownership model

Horns Rev 3 is a Danish wind farm with a capacity of 407 MW, located in the North Sea. Its construction significantly increased Denmark's share of renewable energy and contributed to reducing CO_2 emissions. To mitigate the impact of the investment on local communities, the Danish government introduced compensation programs supporting fishermen and related economic sectors. Another example is the German wind farm Gode Wind, with a capacity of 582 MW, situated off the German coast. This project was developed in collaboration with the scientific sector, allowing for the implementation of solutions that minimize the farm's impact on the marine environment. As part of community engagement efforts, German regional governments allocated funds for environmental education and information campaigns, raising public awareness of the benefits of renewable energy. Whitelee, located in Scotland, was the largest onshore wind farm in Europe before Brexit, with a total capacity of 539 MW. Its operation contributed to increased local budget revenues, which were used to finance education and infrastructure. In support of local communities, open tourist trails and an educational center promoting renewable energy were established. An innovative approach was also adopted by the Danish wind farm Middelgrunden, with a capacity of 40 MW, which was the world's first wind farm partially financed by citizens. Through a participatory model, Copenhagen residents had the opportunity to invest in turbines and earn profits from energy production, leading to widespread public support and greater acceptance of wind energy. Each of these projects demonstrates that the development of wind farms in the European Union not only supports the energy transition but also brings economic and social benefits to local communities.

8. Discussion

This review article has examined the development of wind energy specifically within the context of Poland and the European Union, identifying key regulatory, social, and technological barriers as well as economic opportunities. The analysis revealed that wind energy plays a pivotal role in Europe's energy transition strategy but faces significant region-specific challenges.

In Poland, restrictive zoning regulations, especially the "10H" rule requiring substantial distances between turbines and residential buildings, significantly limit investment opportunities. Adjusting regulations back to a 500-m minimum distance could substantially increase the available area for wind farm installations, boosting the country's renewable capacity by an estimated 60–70%. Furthermore, excessively lengthy administrative procedures—among the longest in Europe—require urgent digitization and simplification to expedite the implementation of wind projects in line with EU renewable energy directives.

Social acceptance emerged as another critical factor influencing wind energy deployment across Europe. Practical case studies, such as the Margonin and Potęgowo wind farms in Poland, highlighted effective approaches for increasing local acceptance, including community profit-sharing schemes, transparent communication, and targeted educational initiatives. The European Union's Wind Power Action Plan reinforces these strategies by advocating early-stage community involvement and financial transparency as essential for securing sustained local support.

Technologically, the review identified promising advancements such as floating offshore wind farms and integrated energy storage solutions, essential for managing the intermittent nature of wind-generated electricity. Case analyses from Denmark (Horns Rev 3) and Germany (Gode Wind) demonstrate that proactive management of environmental impacts and structured cooperation with affected sectors (e.g., fisheries) significantly enhance project feasibility and public acceptance.

Economically, wind energy investments were found to generate measurable local benefits, including increased employment, infrastructure improvements, and higher municipal revenues, making them attractive for regional development strategies. However, overcoming initial high investment costs requires stable financing mechanisms, such as Power Purchase Agreements (PPAs), and continued EU financial support.

To fully leverage wind energy's potential, policymakers in Poland and across the EU must prioritize regulatory reform, accelerated permitting, and robust community engagement models. Technological innovation should remain a central focus, particularly in enhancing turbine efficiency, expanding offshore capacity, and integrating renewable energy into existing power grids.

9. Conclusions

This review article has thoroughly analyzed the current state and future prospects of wind energy development, particularly in Poland and across the European Union. The findings underscore the pivotal role of wind energy in the global transition towards a low-carbon and sustainable energy system. While remarkable growth has been observed in total installed capacity, this metric alone does not adequately capture the effectiveness, efficiency, or equity of energy distribution.

The study highlights that per capita analysis offers a more nuanced understanding of wind energy deployment. Countries like Denmark and Germany, despite their smaller size, have succeeded in achieving significantly higher wind energy accessibility per citizen than larger economies such as China and India. This observation emphasizes the importance of integrating population-based metrics into national and regional energy assessments to ensure equitable access to clean energy.

Poland remains a promising but challenging environment for wind energy investments. Regulatory barriers, including restrictive zoning laws and prolonged permitting procedures, have historically constrained growth. However, the recent policy amendments—such as restoring the 500-m distance rule and initiating legislative reforms—indicate a positive shift towards unlocking the country's wind energy potential. Offshore wind development, with a projected capacity reaching 18 GW by 2040, also signals a significant step forward in aligning with EU climate goals.

Social acceptance has emerged as a central factor in the successful implementation of wind energy projects. Case studies from Poland, Germany, and Denmark demonstrate that community engagement, transparency, and economic benefit-sharing are vital to securing long-term support. Innovative approaches—such as energy cooperatives and local reinvestment initiatives—have proven effective in building trust and encouraging citizen participation.

Technological advancements such as floating offshore wind farms, improved turbine efficiency, and smart grid integration offer new opportunities to overcome environmental and technical challenges. These innovations, supported by targeted EU funding and regulatory frameworks like the Wind Power Action Plan and the Net Zero Industry Act (NZIA), are essential to accelerating the energy transition. Investments in research and development, workforce education, and domestic manufacturing capacity will further strengthen Europe's competitiveness in the renewable energy sector.

Economic analysis confirms that wind energy contributes significantly to local development, generating jobs, increasing municipal revenues, and enhancing energy security. However, initial capital intensity and supply chain vulnerabilities—particularly dependence on imported components—must be addressed through diversified financing mechanisms, industrial policy coordination, and robust infrastructure planning.

In summary, wind energy is no longer just an alternative but a strategic pillar of future energy systems. Realizing its full potential requires coordinated actions across policy, technology, economics, and society. The path forward lies in removing systemic barriers, leveraging innovation, and placing citizens at the heart of the energy transition. Only through this integrated approach can wind energy continue to grow sustainably and equitably, helping to meet the urgent climate objectives of the coming decades.

Author Contributions: Conceptualization, H.W., P.F.B. and I.M.; methodology, H.W., P.F.B., A.S., A.K. and I.M.; software, M.H., A.K., A.S. and F.C.; validation, A.B., S.O. and F.C.; formal analysis, H.W., M.H., A.B., S.O., I.M. and P.F.B.; investigation, H.W., I.M. and A.B.; resources, A.S., S.O., A.B. and M.H.; data curation, A.B., S.O., A.S. and A.K.; writing—original draft preparation, H.W., P.F.B., M.H. and I.M.; writing—review and editing, H.W., F.C., A.S. and I.M.; visualization, H.W., A.S. and A.B.; supervision, M.H. and P.F.B.; project administration, H.W., A.B. and I.M. All authors have read and agreed to the published version of the manuscript.

Funding: Co-financed by the Minister of Science under the "Regional Excellence Initiative".

Data Availability Statement: Data sharing is not applicable to this article.

Conflicts of Interest: Author Filip Czepło was employed by the Polish Photovoltaic Instalation. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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