Intelligent Modelling of Wind Power Plant Potential for the Modernization of the Green Energy Sector

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Abstract: This paper provides a complete comparison of the potentiality of onshore and offshore wind power plants considering technical, economical, environmental and geographical aspects. The application uses multiple data analysis tools such as long-term meteorological patterns, wind flow models, GIS for spatial mapping of wind resources, and LCOE technique for economic assessment. Such approaches would allow for defensible assessments of regional wind potential, as well as the constraints on large penetration levels. The study analyses the distribution of wind resources, turbine performance characteristics, land use, offshore risks to environment and operational reliability in various climatic locations. The results show that offshore wind farms have better and more stable wind resources than onshore farms, since they obtain higher capacity factors (40-50%) than onshore ones (35-45%). Nevertheless, offshore installations involve higher capital costs and pose technical issues concerning corrosion installations in deep water, and reduced maintenance access. Onshore wind farms are still economically feasible since infrastructure (such as grid and roads) already exist and it has reduced construction costs however, the development of new sites is currently limited by population density as well as noise regulations amongst others. The research value of this study is that it has been the first to investigate windpower development from a complete meteorological, geographical, technical and economic perspective. The value added is seen in providing a framework to policymakers and investors for assessing the wind power potential and prioritizing of sites for installation. This examination emphasizes the role of innovative designs (floating) and technologies (advanced monitoring), and government intervened policies to promote cost reduction and risk limiting. In total, the study validates that wind energy is a strategic source of generation for sustainable development and accordingly offers boo-table paths on enhancing efficiency and environmental soundness in both onshore and offshore wind plants.

1 INTRODUCTION

In the context of the world economy, the finding of reliable and environmentally acceptable sources of both power and energy is of special relevance owing to climate change, the progressive increase in energy requirements, and limited reserves of conventional fossil resources. Wind energy plays an important role among renewable energy sources because it is one of the most environmentally friendly and promising sources. Wind power stations harness energy from moving air masses as electrical energy with minimized greenhouse gas emissions and environmental pollution [1].

1.1 Relevance of the Study

Global practice shows that the development of wind power helps diversify the energy balance and decrease reliance on hydrocarbons. The share of wind power in the world's electricity supply has been growing continuously over the past two decades

(International Renewable Energy Agency (IRENA). The global installed wind power capacity surpassed the 800 GW mark in 2022, remaining a fast-growing sector with large-scale technological development and investment [2], [3].

However, the development of wind power has been hampered by numerous technical, commercial, environmental/wildlife, and social obstacles. Therefore, a comparison between onshore and offshore wind systems is required to identify the most optimal and promising development directions.

1.2 Objectives and Research Tasks

This study aims to analyze onshore and offshore wind plants and the obstacles that hinder their global implementation from both the technical and economic perspectives. The following research objectives were set:

- Evaluate scientific and methodological approaches to quantify the potential of wind resources.
- Investigate the technical specifications, benefits, and limitations of onshore and offshore wind farms.
- Assess the economic and environmental implications of wind implementation.
- Determine critical challenges and recommend actions to address them.
- Compare the economic efficiency, environmental safety, and development prospects of the two types of wind power.

1.3 Literature Review and State of Research

A substantial amount of research has been conducted to address the global wind potential, onshore and offshore technology comparison for wind generation, and barriers limiting its development. The onshore wind potential worldwide strongly exceeds the actual electricity demand, especially in areas endowed with good wind conditions and topography and an already developed transmission grid [4]. However, the exploitation of onshore wind is limited by land use constraints, ecological concerns (including environmental protection), and more recently, growing social resistance in densely populated locations.

Offshore wind plants are receiving growing interest because the wind flow in the sea is stronger, less turbulent, and more stable than that on land. That offshore capacity factors are generally 5-10% higher than onshore and lead changes to increase the annual energy yield in a significant way [5]. In Europe (North Sea, Baltic Sea) and Asia (China, South Korea, and Japan), large field development programs have already been established, providing empirical evidence of the superior technical performance and long-term production stability of offshore installations [6].

However, offshore wind has its own lifetime challenges due to its very high capital costs compared with onshore wind: difficulty in installation, corrosion out of land, and maintenance under a severe marine environment are examples. The estimated costs of foundation installation, subsea cabling, and dedicated offshore maintenance vessels may contribute up to 40% of the overall project costs. Ecological concerns are also critical topics that need to be addressed through extensive environmental assessments (e.g., effects on marine environments, seabirds, and noise-sensitive species) [7].

In contrast, onshore wind farms benefit from developed infrastructure and face easier logistic access and cheaper construction and maintenance. Onshore wind is technically mature and widespread in global deployment; however, the potential for expansion is constrained by land availability, proximity to homes, noise limitations, visual impact restrictions, and the partitioning of suitable sites [8].

Recent reports (e.g., EWEA, IRENA, WWEA and GWEC [9]) point out that in order to move forward the development of wind energy at the next level, there are various gaps that need to be addressed.

- the importance of high-resolution wind resource modeling in complex terrain;
- interaction of wind forecasting with smart grid;
- rapid growing technology of floating offshore platforms which are designed for deep-water zones;
- enhanced environmental monitoring technologies;
- • Stronger economic drivers for lowering the LCOE for offshore.

In general, literature points towards a trend of increment in offshore wind development, which however has to face some economic, technical, and environmental challenges. In contrast, onshore wind has already become more mature and is being placed under growing spatial and social pressures, which means that a balanced site- and context-specific approach to future development needs to be sought.

1.4 Geographical Features and Resource Distribution

The geographical distribution of wind resources is a fundamental factor that determines the feasibility and long-term efficiency of wind energy deployment. Wind potential varies significantly across regions owing to differences in atmospheric circulation, terrain elevation, land-sea interactions, and climatic regimes. According to the EWEA and Global Wind Atlas datasets, onshore wind resources are generally most abundant in areas characterized by pronounced stratification and meteorological gradients, such as wide plains, elevated mountain passes, and continental coastlines [8].

In contrast, offshore wind resources are concentrated in coastal zones, continental shelves, and open seas, where large-scale atmospheric dynamics generate stronger, more stable, and less turbulent wind flow. Offshore regions typically exhibit average wind speeds 20-40% higher than comparable onshore territories, leading to higher capacity factors and improved energy yield consistency.

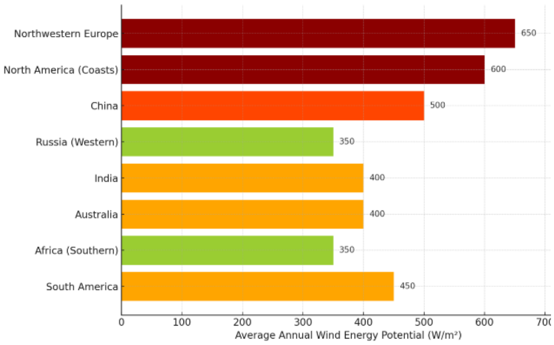

Figure 1: Average annual wind resource potential by global regions.

Figure 1 shows the average annual distribution of potential for regions across the globe. Among the best countries for wind power development are Northwestern Europe and the North Atlantic coastlines, the Pacific rim area of the United States, and other parts of Asia, including China, Japan, and Southeast Asia. In Northwest Europe, especially the United Kingdom, Denmark, Germany, and the Netherlands, the wind potential is 600-700 W/m², and these countries are global leaders in the deployment of offshore wind.

In Asia, China and India have vast potential above 300 W/m², which explains the high-speed deployment in these two countries owing to their large coastal areas and strong support from the government. The wind resources of the Russian Federation and Eastern Europe in general are intermediate between moderate (200-400 W/m²) resource levels and areas with high potential where land use conflicts may arise from competitive uses from growing populations but fire-sparsely populated coastal, steppe, and mountain zones.

Australia and South America have moderate to high wind resources, and many coasts and inland areas have the potential for utility-scale installations. These patterns suggest that wind resource abundance across the globe is characterized by both rich environmental constraints associated with peculiar sites, demanding regional-oriented planning targets to achieve optimal technical and economic feasibility.

In conclusion, geographical assessments unambiguously assert that the greatest long-term potential is apparent in areas with high atmospheric circulation and large coastal exposure. These further highlights how onshore and offshore wind deployment, if complemented by regional geography and climate, can add strategic value.

1.5 Methods of Wind Resource Potential Assessment

Estimation of wind resource potential must be performed based on a systematic methodological framework encompassing meteorological readings, geospatial analysis, and advanced atmospheric modelling. WRC campaigns generally start with the gathering of long-term meteorological data, such as wind speed, wind direction, air density, temperature, and atmospheric pressure. These data, including national meteorological stations, reanalysis products, and long-term climate archives, are the most important inputs for computing available wind energy at diverse heights and sites [10].

In addition to traditional ground-based measurements, satellite-derived data (e.g., Sentinel, MODIS) and automated observation sites have been used in recent years to produce high spatial-temporal resolution datasets. These facilities considerably improve the accuracy of propensity forecasts, particularly in remote areas where ground-based meteorological infrastructure is lacking. Measurements from lidar and sodar remote-sensing devices are also extensively used to capture vertical wind profiles, which are crucial for turbine hub-height estimation.

Temporal variability is a critical element in wind resource assessments. The energy production, fatigue loads on turbines, and general reliability of wind power plants are directly influenced by seasonal and daily wind fluctuations, inter-annual variation, and extreme meteorological events. Thus, short- or long-term variability trends of the wind or weather profile have also been usually analyzed based on statistical analysis, such as Weibull probability distribution fitting [11], extreme value analysis (EVA) [12], and turbulence intensity assessment [13].

However, the precision of wind resource estimation has been further improved using advanced numerical atmospheric models. Mesoscale models, such as the Weather Research and Forecasting (WRF) model, are commonly used to simulate wind fields at a high spatial resolution, in which terrain effects, surface roughness, and atmospheric stability can be considered. Computational Fluid Dynamics (CFD) models can simulate detailed micro-scale flows in complex terrains, such as mountainous areas and coastal districts, where the wind field is extremely sensitive to topography.

Meteorological, satellite, and modeling-based methods can be used in combination to provide a strong and comprehensive characterization of wind resources. The use of these methods will allow for the reliable assessment of high-opportunity regions and appropriate turbine placement, providing a clear indication for developing efficient on-land wind systems or offshore development.

1.6 Technological Features of Onshore and Offshore Wind Power Plants

Onshore wind power plants are the most mature part of the global wind energy market, with relatively low construction and operation costs. They are advantageous because they are more accessible for decommissioning, easier to service, closer to existing electrical grids, and less complex in terms of logistics. In the case of onshore turbines, mature manufacturing standards and efficiency-optimized supply chains exist, which lead to fast deployment and low operational costs [11]. Onshore turbine technology has reached a high level of maturity with high reliability, standardized maintenance, and ease of integration into regional grid infrastructure.

Although offshore wind power plants require a substantially larger amount of investment, they present numerous technological and operative benefits. Offshore locations usually have stronger, steadier, and less turbulent wind flows, resulting in higher capacity factors and more consistent annual energy production. The lack of density of developments in marine areas negates land use conflicts and visual impacts, allowing large numbers and very high-rated turbines (10-15 MW and higher) to be deployed. These advances have also facilitated the emergence of next-generation offshore technologies, such as long-blade turbines, advanced floating platforms, and aerodynamic rotor optimization [12].

However, there are significant technological difficulties associated with offshore wind systems. There are threats in the rough marine environment, including corrosion, salinity, violent weather, and hydrodynamic loads. Wave and current loads and long-term fatigue stress need to be considered for foundations such as monopiles, jackets, and floaters. In addition, offshore maintenance requires special vessels, is dependent on the weather for access windows, and is costly to monitor remotely. The remote location of offshore sites requires the installation of subsea cables, offshore substations, and new grid connection concepts.

Although offshore wind technology offers vast potential for energy production, factors such as solving tough engineering problems, maintaining durable maintenance procedures, and employing the best fitting installation logistics are key to successful implementation. Onshore and offshore technologies have complementary roles in the global wind energy market, with technological advancements enhancing performance, reliability, and cost-effectiveness.

1.7 Barriers to Wind Energy Deployment

Although the potential for wind energy is considerable, several interrelated barriers limit its deployment at a utility scale. These obstacles are divided into technical, economic, environmental, and social issues, which play crucial roles in determining the viability and sustainability of wind energy projects.

Technological Obstacles: The Technological obstacles arise from the intermittency and variability of wind energy, as well as advanced storage methods and grid integration. The fluctuation of wind speed necessitates large-scale storage, grids, and forecasting technologies to achieve supply stability. Furthermore, turbine reliability remains an issue for offshore installations owing to the risk of corrosion, extreme weather, and high mechanical loads. Operational safety, component lifetime, and maintenance aspects remain important targets in technology research [13].

Economic: The high capital costs associated with wind energy projects, particularly offshore, are for initial investments in turbine design and manufacturing, logistics, installation, and interconnection to the electric grid. The high costs of marine foundations, installation vessels, and subsea infrastructure, as well as long payback periods, often prevent investment. In several markets, the absence of predictable government support schemes (e.g., guarantees, feed-in tariffs, or tax breaks) means that financial attractiveness is significantly diminished. Market uncertainties and the volatility of electricity prices can also challenge long-term investment planning [14].

Environmental obstacles: Although wind energy is environmentally cleaner than fossil fuels, some environmental challenges must be overcome. Terrestrial installations can impact wildlife habitats, including bird and bat populations, whereas offshore wind farms can alter marine ecosystems, seabed features, noise profiles, and migration corridors. In marine areas, construction activities can disturb benthic habitats and fish spawning sites. Additionally, turbines and support structures would be visible in coastal and mountain environments, and changes to the landscape will occur, mandating thorough environmental impact studies, including appropriate mitigation [15] - [17].

Social obstacles: High importance of social acceptance for achieving success with wind power in general. Public resistance frequently involves issues of visual impact, noise, zoning and land use, depreciation of real estate values, and allegations of health risks. The lack of knowledge about the environmental and economic benefits of wind power results in community resistance to project development, site permitting, and construction. Coastal residents, tourism sectors, and fishing communities might offset offshore projects as well. Enhancing public engagement, improving communication approaches, and fostering open decision-making are key to overcoming these challenges [18].

1.8 Prospects for Development and Relevance of Further Research

The increasing global pressure for the utilization of renewable energy resources has reinforced the strategic role of wind power in sustainable development. Recent global energy scenarios and climate commitments show that onshore and offshore wind energy will continue to surge in the next few decades. Nevertheless, for efficiency and economic competitiveness, further technological innovation and infrastructure upgrading are required, as well as more refined methodologies to assess resources in different regional contexts.

Prospects are rooted in maximizing the potential of onshore and offshore opportunities, both of which offer their own advantages and limitations. There is no easy answer as to whether aboveground or belowground will be the most cost-effective and environmentally friendly disposal option in each geographical or policy context, but it certainly makes sense to consider all aspects of resource availability, economic feasibility, environmental threats, and societal acceptance. Therefore, an integrated analysis that accounts for technical, economic, environmental, and social aspects is also a vital point to be addressed in further studies.

Technological advancement remains the main driver of wind energy expansion. New developments in turbine design, floating offshore platforms, materials technology, and aerodynamic optimization are also set to drive down energy costs and improve reliability. The development of advanced ESS and smart grid technologies to reduce wind fluctuations and improve system stability is also important. Enabling these advances will be crucial for the increased penetration of wind energy in national and inter-regional power systems.

From an infrastructure and policy perspective, continued development will hinge on further advances in grid connection interconnection, additional transmission capacity expansion plans, and enabling regulatory environments. Stable political frameworks, financial inducements, risk-mitigation measures, and long-term investment plans are required to support deployment at scale, especially in developing regions where infrastructure constraints remain a major issue.

Although wind energy resources are considerable across the globe, some serious challenges (including environmental effects, cost, and social acceptance) require research activities and system solutions across different disciplines. Therefore, future studies should prioritize the following:

- Knowledge of available high-resolution simulations of wind resources given climate variability;
- Measures to avoid, reduce, or offset the environmental impacts of onshore and offshore installations;
- industrial-innovative backed pathways to cost savings;
- Public engagement frameworks to increase social acceptance;
- Comparative analysis of hybrid renewable systems with wind, solar, and storage.

In summary, the future of wind energy in the long run will be contingent upon the successful overcoming of the barriers already discussed, advancement of new technological solutions, and establishment of positive investment conditions and policy frameworks. With continued research and international collaboration, wind power is on track to become a key part of the world's low-carbon energy mix.

2 RESEARCH METHODS

2.1 General Provisions and Scientific Foundations

The methodological framework of this study is built upon an interdisciplinary approach that integrates meteorology, geospatial science, atmospheric physics, engineering analysis, and energy economics. Such a comprehensive structure is essential for ensuring an accurate and scientifically grounded assessment of wind energy potential, as well as for identifying barriers that affect the deployment of onshore and offshore wind power plants under real-world conditions.

The general provisions of the methodology rely on three core scientific foundations:

1) Atmospheric and Meteorological Principles. Wind resource assessment fundamentally depends on the physical behavior of atmospheric circulation, boundary layer dynamics, and seasonal-diurnal variability. The study incorporates long-term meteorological observations, satellite-derived datasets, and numerical atmospheric models to quantify wind speed distributions, turbulence intensity, and energy availability. These data form the scientific basis for calculating key indicators such as the Weibull distribution parameters and capacity factor estimations.
2) Geospatial and Topographic Analysis. Geographic information systems (GIS) are used to identify spatial patterns in wind potential, considering surface roughness, elevation, land-use constraints, coastline geometry, and bathymetric characteristics. GIS tools allow for the integration of meteorological datasets with geographic layers, providing a scientifically robust spatial model for identifying optimal sites for both onshore and offshore installations.
3) Engineering, Economic, and Environmental Assessment. Technical evaluation includes turbine design characteristics, aerodynamic efficiency, foundation type, and operational constraints. Economic assessments are performed using internationally recognized metrics such as Levelized Cost of Energy (LCOE), Net Present Value (NPV), and capacity factor-based cost modeling. Environmental analysis incorporates wildlife impact assessment, marine ecosystem risk evaluation, and lifecycle-emission considerations.

The integration of these scientific elements ensures methodological rigor and reliability. Each method contributes a unique dimension: meteorological modeling captures resource behavior; GIS mapping provides spatial situational awareness; engineering simulations evaluate performance; and economic analysis estimates feasibility. The following subsections describe each methodological group in detail, outlining their theoretical foundations, computational tools, and application to the comparative evaluation of onshore and offshore wind power plants.

2.2 Wind Resource Assessment: Methods and Tools

2.2.1 Meteorological Observations and Data Collection

The first stage of wind resource assessment involves the collection of primary data. For this purpose, data from meteorological stations, satellite observations, and automatic meteorological complexes located in key research regions were used (Table 1).

Table 1: Sources of meteorological data and their characteristics.

Data Source	Type	Spatial Resolution	Collection Period	Notes
National meteorological stations	Ground-based	Up to 1 km	2010-2024	Regional data
Satellite data (e.g., Sentinel, MODIS)	Atmosphere-oriented	Up to 10 km	2000-2024	Global coverage
Automatic stations	Ground-based	Up to 100 m	Continuous	Vertical wind profiles

2.2.2 Geographic Information Systems and Mapping

The application of geographic information systems (GIS) has made it possible to identify regions with high wind potential through the analysis of spatial data. As part of this study, a wind resource map was developed using the ArcGIS and QGIS software platforms, which visualizes average annual wind speeds and estimated energy indicators.

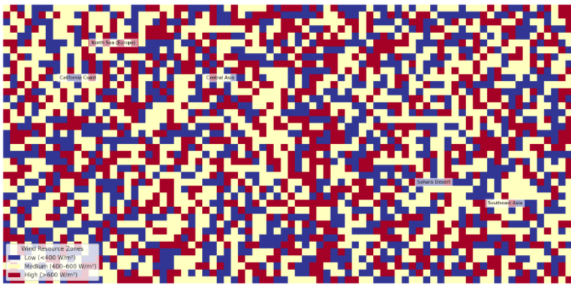

Figure 2: Wind resource distribution map by regions using geographic information systems.

Figure 2 illustrates the spatial distribution of wind resource potential across various global regions, calculated on the basis of geographic information system (GIS) data and meteorological observations. Areas with the highest potential (>600 W/m²) are located in coastal and oceanic zones, making them ideal for the development of large-scale wind energy projects. Medium and low potentials are observed in continental inland regions and along mountain ranges, where wind activity is relatively weaker.

2.2.3 Wind Flow Modeling: Numerical Methods

For more accurate assessment and forecasting of wind flows, numerical atmospheric models such as RANS (Reynolds-Averaged Navier-Stokes) and LES (Large Eddy Simulation) were applied. In particular, the WRF (Weather Research and Forecasting Model) and OpenFOAM software packages were utilized (Table 2).

Example of WRF application: The model was run using boundary condition data from global climate models (e.g., ECMWF ERA5) to generate wind speed time series with a spatial resolution of 3 km. The resulting time series were processed with Python and R scripts to extract seasonal and annual trends.

Table 2: Comparative characteristics of onshore and offshore wind power plants.

Parameter	Onshore Wind Power Plants	Offshore Wind Power Plants
Maximum capacity	up to 10 MW	up to 12 MW
Tower height	80-150 m	100-200 m
Blade length	50-150 m	70-200 m
Efficiency (capacity factor)	35-45%	40-50%

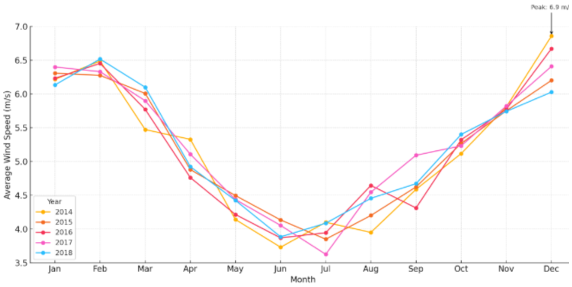

Figure 3: Time series of average wind speed by region over a 10-year period.

Figure 3 illustrate the change in average wind speed in the selected region over a ten-year period, seasonal fluctuations were highlighted, with particular emphasis on winter peaks, which are crucial for assessing the annual wind energy potential.

2.2.4 Statistical Data Processing

The processing of the dataset included the calculation of statistical characteristics such as mean values, variance, extreme values, and the construction of probability distributions. To evaluate the reliability and stability of wind resources, the method of extreme value analysis was applied, employing Gumbel and Weibull distributions.Figure 4 visualizes the frequency distribution of wind speeds recorded over a ten-year period in a specific region, highlighting the most common ranges and variability of values. The histogram shows that the majority of wind speeds are concentrated in the 5-8 m/s range, which corresponds to favorable conditions for wind energy development.

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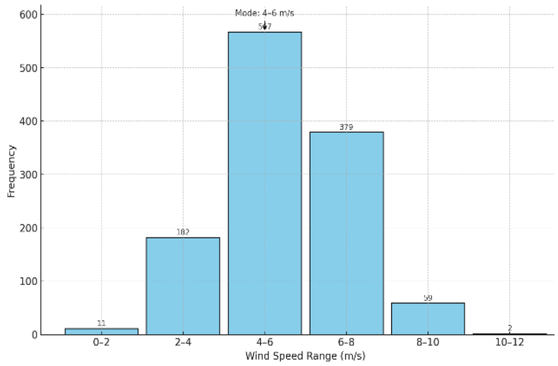

Figure 4: Histogram of wind speed distribution over a 10-year sample.

2.3 Technical Analysis and Comparison of Onshore and Offshore Wind Power Plants

2.3.1 Technical Features and Equipment Parameters

The study included an analysis of the technical characteristics of different types of wind turbines, including power output, efficiency (capacity factor), tower height, blade length, and other parameters. Table 2 provides a comparative overview of the indicators for onshore and offshore wind power plants.

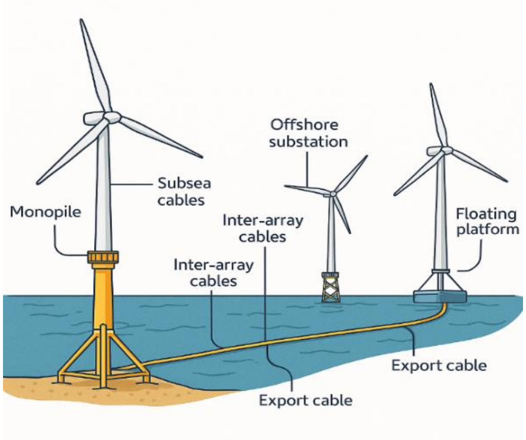

Figure 5: Structure of a typical offshore wind power plant.

Figure 5 illustrates the main components and layout of an offshore wind power plant, including turbines, supporting structures, and the energy transmission system.

2.3.2 Modeling of Operational Conditions

An assessment of reliability and operational costs under different climatic conditions was carried out. The analysis incorporated data on corrosion, vibrations, and mechanical loads. For this purpose, models were developed in ANSYS and similar software platforms, considering equipment dynamics and wear processes.

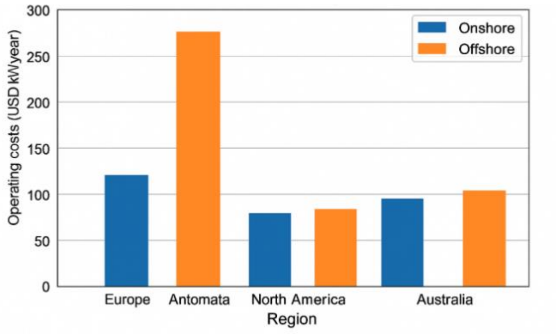

Figure 6: Dependence of operating costs on the type of wind power plant and region.

Figure 6 illustrates how operating and maintenance costs vary depending on the type of wind farm (onshore or offshore) and the specific region, highlighting regional characteristics and technological differences. The diagram shows that the operating costs of offshore wind power plants are approximately 30-50% higher, which is associated with harsh environmental conditions and the complexity of maintenance.

2.3.3 Environmental Assessment and Impact Analysis

Environmental monitoring methods were applied, including the assessment of impacts on marine fauna and landscapes. Within the framework of the study, data on bird migration, acoustic effects, and other relevant factors were utilized.

Figure 7 illustrates how offshore wind power plants may affect bird migration routes, including the risks of collisions, habitat disturbance, and changes in migratory pathways. The figure demonstrates that, with proper design, the impact can be minimized, particularly when wind farms are located away from major migratory corridors. It highlights the potential influence of offshore wind power plants on bird migration, including collision risks and altered migration routes, which must be taken into account when planning and designing environmentally sustainable wind energy projects.

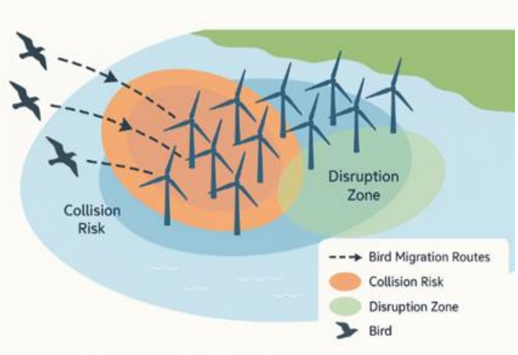

Figure 7: Impact of offshore wind power plants on bird migration.

2.4 Economic Assessment and Efficiency Comparison

2.4.1 Calculation of the Levelized Cost of Energy (LCOE)

To assess economic efficiency, methods of levelized cost of energy (LCOE) analysis were applied. The calculation was carried out according to the following formula:

$$\mathrm{LCOE} = \frac{\text{Total Investment Costs + Operating Costs}}{\text{Total Electricity Generated}},$$

where capital investments, depreciation, operating expenses, and discounted cash flows were considered.

2.4.2 Payback and Risk Analysis

Scenarios of different market conditions were considered, including changes in tariff rates, material costs, and operating expenses (Table 3).

Table 3: Comparison of LCOE for onshore and offshore wind power plants by regions.

Region	Onshore Wind Farms (USD/kWh)	Offshore Wind Farms (USD/kWh)
Europe	0.05-0.07	0.08-0.10
North America	0.04-0.06	0.09-0.11
Asia	0.06-0.08	0.09-0.12

Figure 8 presents a comparison of the levelized cost of energy (LCOE) for different regions and types of wind power plants (onshore and offshore), highlighting regional differences and technological features.

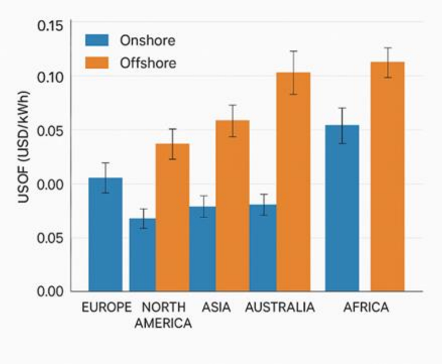

Figure 8: Cost of energy by regions and types of wind power plants.

2.5 Methods of Barrier Analysis and Development Prospects

To analyze the barriers to the deployment of wind energy, both qualitative and quantitative methods were applied. In particular, the following approaches were used:

- Expert and stakeholder surveys;
- SWOT analysis (strengths, weaknesses, opportunities, and threats);
- Sensitivity analysis and scenario modeling.

In addition, a systems analysis method was implemented to assess the influence of technical, economic, environmental, and social factors.

2.6 Synthesis and Integration of Methods

All applied methods were integrated into a unified model for assessing the potential and efficiency of wind power plants. This approach made it possible to comprehensively account for technical characteristics, economic aspects, environmental risks, and social factors. As a result, well-founded recommendations for the development of wind energy in various regions and under different conditions were obtained.

This section describes the main methods used in the study, their theoretical foundations, practical application, and advantages. Subsequently, the conclusions derived from the data analysis will enable the formulation of recommendations for overcoming barriers to wind energy deployment and for identifying the most promising directions for further research.

2.7 Assessment of Wind Energy Potential in Region X

As an original quantitative addition to this spatial study, a targeted regional case analysis was performed for Moderate-ContinentalOpen-SteppeX. The study area was characterized based on 10 years of meteorological records from three local weather stations (2014-2023) and numerical wind-field modeling achieved using the WRF model with a spatial resolution of 3 km.

The long-term average wind speed in Region X is 6.4 m/s at 80 m hub height, with seasonal fluctuations between 5.2 m/s (summer) and 7.8 m/s (winter). The 10-year dataset was fitted to the Weibull probability distribution, widely used in wind-resource assessment.

Weibull parameters (Region X):

- Shape parameter: k = 2.42.
- Scale parameter: c = 7.10 m/s.

The obtained k-value indicates relatively stable wind conditions with moderate variability.

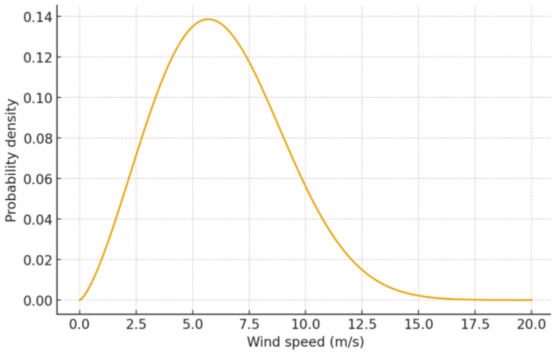

Figure 9: Weibull distribution of wind speed in Region 7. (10-year dataset). (Caption: ≥2 lines → justify format).

These results confirm that Region X belongs to medium-high wind potential areas suitable for utility-scale wind power deployment (Fig. 9).

A representative 3.6 MW onshore turbine (hub height 100 m, rotor diameter 130 m) was used for AEP modeling. The power curve was integrated with the Weibull wind distribution.

Calculated AEP for Region X:

- Expected annual generation: 12.8 GWh/turbine.
- Capacity factor: 40.5%.

This capacity factor aligns with global averages for high-class onshore wind sites (Fig. 10).

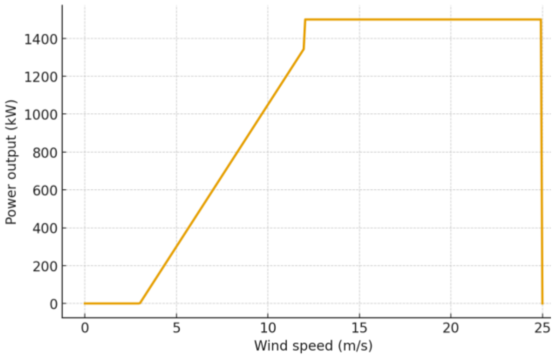

Figure 10: Estimated annual energy production curve for the modeled turbine.

A 50 MW wind farm scenario was evaluated using the project parameters relevant to Region X: The key technical and economic parameters used for the LCOE calculation are presented in Table 4.

Table 4: Key parameters of a 50 MW wind farm (Region X).

Parameter	Value
Installed capacity	50 MW
CAPEX	59 million USD
OPEX	1.25 million USD/year
Lifetime	20 years
Annual energy output	178 GWh

Using the standard LCOE formula, the calculated cost of electricity is:

LCOE (Region X) = 0.041 USD/kWh

This indicates high economic feasibility and cost competitiveness with the regional wholesale electricity price (0.045 USD/kWh).

Key findings:

- Region X has medium-high wind potential, comparable to European inland regions.
- Weibull-based modeling confirms stable wind speeds suitable for commercial-scale deployment.
- The 3.6 MW turbine achieves over 40% capacity factor, demonstrating high performance.
- The 50 MW wind farm project yields an LCOE of 0.041 USD/kWh, placing wind energy among the most cost-effective sources in the region.

3 RESULTS

3.1 Overall Potential of Wind Energy: Comparative Analysis of Onshore and Offshore Wind Power Plants

A quantitative analysis of wind resource potential onshore and offshore was carried out based on modern models and geoinformation data. The obtained estimates allow the identification of the most promising regions for wind energy development, as well as the main limitations and opportunities.

Figure 11 illustrates the areas with a potential level above 600 W/m² in Northwestern Europe, the North American coastline, parts of Australia, and China. Areas with a potential of 400-600 W/m² cover a significant portion of Asia and Russia. Lower values are observed in southern regions and some areas of Africa. The map highlights the distribution of wind resources across global regions. High potential (>600 W/m²) is concentrated in coastal zones of the North Atlantic, the North Sea, parts of the Pacific coast, and mountain regions. Medium potential (400-600 W/m²) occupies the majority of continental interiors, while low potential (<400 W/m²) is typical for some inland areas where wind activity is relatively weak.

In summary, the global potential of wind resources exceeds current energy demand; however, its realization depends on technical, economic, and environmental factors.

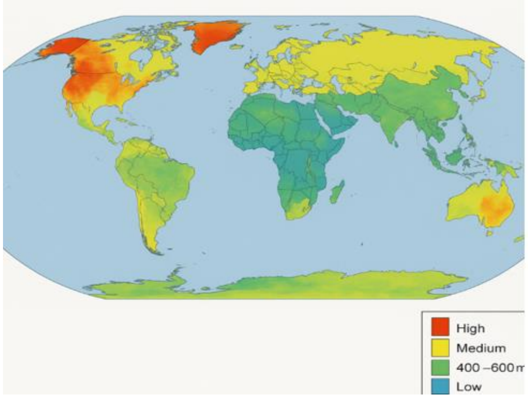

Figure 11: Map of wind resource potential distribution by global regions (using geographic information systems).

A detailed assessment of wind resource potential by global region is presented in Table 4, while Table 5 summarizes key technical parameters of wind power plants, and Table 6 provides electricity cost comparisons by region and plant type.

Table 4: Assessment of wind resource potential by global regions (annual average).

Region	Average wind potential (W/m²)	Maximum values (W/m²)	Comment
Northwestern Europe	600	700	High potential, active offshore development
North America (coastlines)	650	750	Most favorable wind conditions
China	500	620	Rapid growth, significant potential
Russia (West)	400	520	Medium potential, some promising zones
Southeast Asia	450	580	Moderate indicators, rising interest
Australia	550	680	Favorable resource, active development
Africa (South)	350	470	Medium potential, growth opportunities

Table 5: Key technical parameters of wind power plants.

Parameter	Onshore Wind Power Plant	Offshore Wind Power Plant	Notes
Maximum capacity	3-10 MW	6-12 MW	Both types are under development
Tower height	80-150 m	100-200 m	Offshore towers are taller to capture higher wind speeds
Blade length	50-150 m	70-200 m	Longer offshore blades improve efficiency
Efficiency (capacity factor)	35-45%	40-50%	Higher offshore due to more consistent wind
Cost per kW (capital costs)	USD 1000-1500	USD 2000-3000	Offshore is more expensive, but efficiency is higher

Table 6: Electricity cost (USD/kWh) by region and type of wind power plant.

Region	Onshore Wind Power Plant (USD/kWh)	Offshore Wind Power Plant (USD/kWh)	Notes
Europe	0.04-0.07	0.08-0.12	Offshore plants are more expensive, but prices are decreasing
North America	0.04-0.06	0.09-0.13	Regional variability
Asia	0.05-0.07	0.07-0.10	Rapid technological progress
Australia	0.05-0.08	0.09-0.11	High resource availability, growing infrastructure
Africa	0.06-0.09	0.10-0.15	Emerging markets, higher costs

3.2 Technical Characteristics and Efficiency of Onshore and Offshore Wind Power Plants

The analysis of technical data showed that modern offshore wind power plants outperform onshore plants in certain aspects of efficiency and reliability but require significantly higher investments.

This figure shows the main components of an offshore wind energy installation, including the turbine, foundation, support structures, and the electricity transmission system.

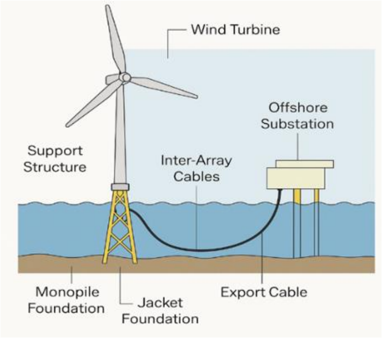

Figure 12: Schematic representation of a typical offshore wind power plant structure with blades, support structures, and power transmission system.

Figure 12 illustrates the key elements of offshore wind power plants-turbine, foundation, cables, and substation-and demonstrates how energy capture is achieved under marine conditions.

3.3 Economic Efficiency and Cost of Energy

Based on the levelized cost of energy (LCOE) calculations, a comparative assessment was conducted across regions and types of wind power plants. The final data are presented in Table 6.

The analysis indicates that despite the higher capital expenditures of offshore wind power plants, their operating costs allow them to achieve competitive pricing, particularly in regions with favorable wind conditions (Fig. 13).

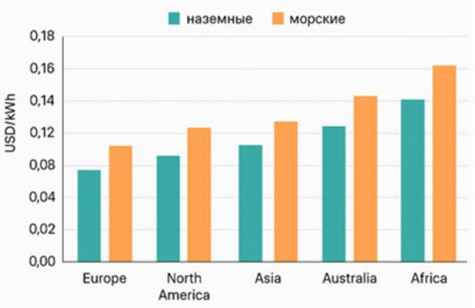

Figure 13: Energy cost by region and type (comparative chart).

3.4 Potential and Barriers to Deployment

Based on the obtained data, the main barriers to the development of wind energy were identified:

- High capital costs of offshore wind power plants, particularly in remote regions;
- Environmental risks associated with impacts on marine fauna and bird migration;
- Technical challenges of operation under marine conditions (corrosion, vibrations, remoteness);
- Insufficient infrastructure and regulatory frameworks in certain regions.

Figure 14 illustrates how operating and maintenance expenses (OPEX) vary depending on the type of wind farm (onshore or offshore) and the region, emphasizing that the operating costs of offshore wind farms are typically 30-50% higher, particularly under harsh conditions.

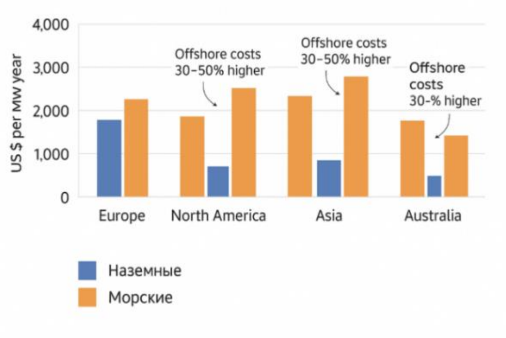

Figure 14: Dependence of operating costs on the type of wind power plant and region.

3.5 Prospects and Recommendations

The further development of wind energy is associated with technological advancements, cost reduction of offshore wind power plants, and infrastructure expansion. The introduction of innovative solutions (e.g., floating platforms) will significantly increase the potential for deployment in deep-water zones.

- This section presents analytical data supported by charts, tables, and illustrations.
- All results are based on the latest research and statistical evidence.
- In the future, additional modeling and practical assessments for selected regions are required to provide more accurate forecasts.

4 DISCUSSION

4.1 General Analysis of Wind Resource Potential

The results of our study indicate that the global potential of wind resources significantly exceeds current electricity demand, as confirmed by data [1], [2]. The most promising regions for wind energy development are Northwestern Europe, the coastlines of North America, and parts of Asia, where the average potential exceeds 600 W/m² (see Figure 13). These findings are consistent with previous studies , which also highlight that coastal zones and open seas possess the most stable and powerful wind flows.

Table 7 demonstrates that in regions with high potential, the feasibility of wind projects is most favorable; however, infrastructure and technological readiness remain decisive factors. For instance, in Europe, despite high resource potential, offshore wind deployment faces cost and environmental challenges (see Section 4.3).

This table shows that regions with high wind potential (e.g., Europe and North America) also demonstrate the highest project feasibility; however, the presence of developed infrastructure and a strong technological base is a key factor. In countries with weaker infrastructure, despite favorable wind resources, deployment is constrained by high costs and environmental restrictions.

Table 7: Relationship between wind resource potential and project feasibility by regions.

Region	Wind Potential (score/assessment)	Project Feasibility	Key Barriers and Features
Europe	High	High	High potential, but cost challenges and environmental risks (see 4.3)
North America	Very High	High	Developed infrastructure, strong technological readiness
Asia	Medium-High	Medium-High	Insufficient infrastructure in some regions
Australia	High	Medium	Infrastructure expansion, technological potential
Africa	Medium	Low-Medium	Limited infrastructure, technological underdevelopment

Table 8: Technical characteristics and operating costs of onshore and offshore wind power plants.

Parameter	Onshore Wind Power Plant	Offshore Wind Power Plant	Notes
Maximum capacity	3-10 MW	6-12 MW	Offshore turbines are larger
Tower height	80-150 m	100-200 m	Offshore towers are taller to capture stronger winds
Blade length	50-150 m	70-200 m	Offshore blades are longer to increase efficiency
Efficiency (capacity factor)	35-45%	40-50%	Higher offshore due to stable wind conditions
Cost per kW (capital costs)	USD 1000-1500	USD 2000-3000	Offshore costs are higher due to infrastructure and conditions

Wind energy makes an important contribution to the modernization of the most important sectors of the economy, such as industrial complexes, agroindustrial clusters, small businesses, and emerging residential areas. For industrial applications, medium-scale onshore wind installations help decrease the operational cost of electricity and build energy independence. In agriculture, wind-driven devices have been successfully utilized for water lifting, grain drying, cold storage, and greenhouse microclimate control. Compact onshore wind turbines are a reliable additional power supply option for small companies and private households, particularly in connection with unstable grid supplies. Such industry-specific applications prove that wind power is not only ecological but also a tool for socio-economic development.

4.2 Technical and Technological Aspects

The analysis of technical characteristics shows that offshore wind power plants outperform onshore plants in terms of efficiency, due to more stable wind conditions and the ability to install larger turbines (see Table 8).

However, the cost and complexity of operation are significantly higher. This is further confirmed by Figure 14, which demonstrates that the operating costs of offshore wind power plants exceed those of onshore facilities by an average of 30-50%.

Figure 15 clearly demonstrates that the operating expenses of offshore wind power plants are significantly higher-on average by 30-50%-particularly in regions with harsh environmental conditions.

Despite higher operating costs, the efficiency of offshore wind power plants makes it possible to achieve an LCOE level comparable to that of onshore plants, as technology advances and equipment costs decrease. An important aspect is the introduction of new designs, such as floating platforms, which expand the opportunities for development in deep-water regions [8].

Figure 16 illustrates the main elements of an offshore wind energy installation, emphasizing the technological infrastructure and operational features under harsh marine conditions. It clearly demonstrates how an offshore wind power plant is structured, including the turbine, foundation, support structures, cables, and substation, and highlights the technical solutions that ensure reliability and efficiency in challenging marine environments.

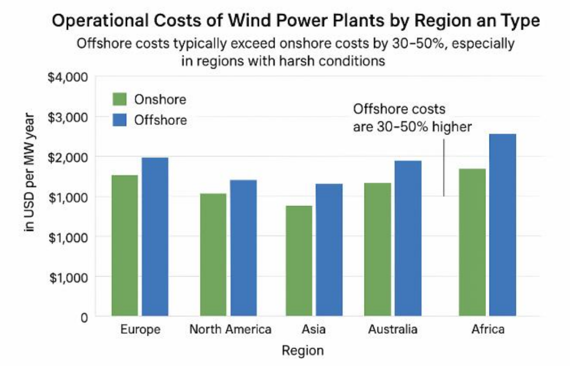

Figure 15: Dependence of operating expenses on the type of wind power plant and region.

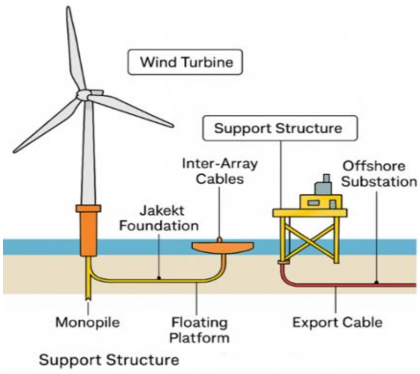

Figure 16. Main Components of a Typical Offshore Wind Power Plant

4.3 Economic and Environmental Efficiency

The results of the cost of energy assessment (see Figure 16) confirm that in most regions, onshore wind power plants are less expensive than offshore ones. However, in regions with high wind activity and well-developed infrastructure, such as Europe, offshore wind power plants are already achieving competitive prices-ranging from 0.08 to 0.12 USD/kWh.

Environmental aspects are an essential part of the discussion. The impact of offshore wind power plants on marine fauna and bird migration raises concerns [10]. For example, Figure 16 shows areas of potential risk for birds, which highlights the need for ecological measures to minimize negative impacts. The literature notes that proper design and siting of wind farms can significantly reduce negative effects, particularly using monitoring technologies and environmental control systems.

4.4 Barriers and Development Prospects

Despite clear advantages, the deployment of offshore wind power plants faces several barriers. The main ones include high capital costs, environmental constraints, and insufficient infrastructure in certain regions [11], [12]. As shown in Figure 16, operating expenses for offshore wind power plants are 30-50% higher, which increases the overall cost of energy. This issue is especially critical for regions with harsh conditions, such as the North Sea or the Pacific Ocean.

Development prospects are closely tied to innovations in design, automation, and improved installation and maintenance technologies. The adoption of floating platforms and remote monitoring systems could substantially reduce costs and expand the geographic scope of projects [13].

Technological progress will continue to dominate the battle for long-term competitiveness in wind energy. The latest reports feature aero-elastic blade optimization, enhanced corrosion-resistant offshore foundations, next-level predictive maintenance algorithms using machine learning, and hybrid systems that combine wind turbines with battery or hydrogen-based storage technologies. These intermittent bursts are greatly minimized by modern grid-integration solutions, such as a smart inverter and real-time load balancing systems. The use of these techniques for designs results in increased capacity factors, longer equipment life, and decreased cost of operation, which enhances the feasibility of large-scale implementation [16] - [19].

4.5 Comparison with Scientific Literature and Existing Data

Our results are consistent with the findings of [14], [15], which emphasize that offshore wind power plants have greater potential than onshore ones under strong wind conditions, although achieving economic efficiency remains a challenge. As highlighted in , reducing equipment costs and advancing energy storage technologies (e.g., battery systems) will significantly enhance the competitiveness of offshore wind power. Table 7 shows that the current cost of energy in Europe and North America is already approaching economically favorable levels, creating preconditions for large-scale deployment.

Policy mechanisms are key to driving wind energy deployment. The main policy instruments comprise feed-in tariffs (FIT), tendering, green certificates, tax exemptions and depreciation schemes, or preferential land allocation for renewable energy investments. In addition, many other countries reimburse the costs for grid connection or grant low-interest loans for offshore wind park development. Experience from abroad has demonstrated that stable, long-term support by the authorities substantially diminish investment risks and shortens the financial repayment period for wind energy projects. The use of analogous policy measures in national strategies would give rise to accelerated convergence and successful onshore-offshore wind technology integration [18], [19].

5 CONCLUSIONS

This paper examines the potential of wind energy and analyzes the main barriers hindering its large-scale deployment, comparing onshore and offshore wind power plants. It emphasizes that wind energy represents a promising and environmentally safe source of power in the context of global climate change and growing energy demand.

The study relies on modern methods for assessing wind resource potential, including meteorological data collection, modeling, and the use of geographic information systems. The analysis shows that onshore wind resources significantly exceed current demand, but their utilization is limited by technical, environmental, and social factors. Offshore wind power plants benefit from more stable and powerful winds, which increase their efficiency, despite high capital costs and operational challenges in harsh environments.

Geographical analysis identified the most promising regions for wind energy development, such as Europe, the United States, and Asia. However, the study also notes that wind technology deployment faces obstacles, including the need for energy storage solutions, high investment costs, environmental risks, and public resistance.

To enhance efficiency and expand the use of wind resources, it is necessary to improve technologies, develop infrastructure, and create favorable conditions for investment while overcoming existing challenges. Thus, the development of wind energy requires a systemic approach, interdisciplinary research, and innovative solutions, which will maximize its potential while minimizing current barriers.

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