CENTRAL ASIAN JOURNAL OF THEORETICAL AND APPLIED SCIENCE

https://cajotas.casjournal.org/index.php/cajotas

Volume: 05 Issue: 08 | December 2024 ISSN: 2660-5317

Article

Wind Power Enhancing Efficiency and Overcoming Grid Integration

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Abstract: Wind energy has emerged as a critical component of the global transition toward sustainable and low-carbon energy systems due to its environmental benefits and potential to reduce dependence on fossil fuels. This paper examines the efficiency of wind energy systems and the major challenges associated with integrating wind power into existing electricity grids. Key performance indicators such as installed capacity, capacity factor, and energy return on investment are discussed to evaluate the operational effectiveness of wind turbines. The study highlights how technological advancements, including larger turbine designs, advanced blade materials, artificial intelligence-based monitoring, predictive maintenance, and improved forecasting techniques, have significantly enhanced wind energy efficiency and reliability. Despite these improvements, wind power integration remains constrained by intermittency, grid instability, transmission limitations, energy storage requirements, and regulatory barriers. The paper reviews practical solutions such as geographic diversification of wind farms, smart grid technologies, battery and hydrogen-based storage systems, high-voltage transmission networks, and supportive policy frameworks to mitigate these challenges. Economic considerations, community engagement, and environmental sustainability are also identified as important factors influencing successful wind energy deployment. The findings suggest that continued technological innovation, grid modernization, policy support, and coordinated planning are essential for maximizing wind energy's contribution to reliable electricity generation and achieving a stable, sustainable, and resilient global renewable energy future.

Keywords: Wind Energy, Efficiency, Grid Integration, Energy Storage, Renewable Energy

Citation: Ullah, S. M. E & Ullah, M. S. Wind Power Enhancing Efficiency and Overcoming Grid Integration. Central Asian Journal of Theoretical and Applied Science 2024, 5(8), 744-755

Received: 10th Sep 2024
Revised: 21th Oct 2024
Accepted: 18th Nov 2024
Published: 02th Dec 2024

1. Introduction

The efficiency of wind turbines to transform wind kinetic power into electricity and the challenge of integrating this type of renewable energy into the existing power systems are some of the wind energy efficiency and grid integration issues [1]. With the current world enthusiasm on sustainable energy, these factors are coming into the limelight of increasing the contribution of wind energy on the world energy portfolio. The importance of wind energy as a means to cut greenhouse gas emissions is significant and reduce reliance on fossil energy. Meanwhile, the industry is experiencing a fast pace of technological advancements, such as increased and more efficient turbines, enhanced blade structures, and innovative data analysis and AI to streamline performance and maintenance. Installed capacity and capacity factor are often used as two main indicators used to assess the efficiency of wind energy systems [2].

Installed capacity is the highest amount of electricity that is theoretically possible to be generated by a wind turbine or wind farm, assuming ideal conditions. Conversely, the capacity factor is the proportion of the electricity that is produced in a given time to the total output that is possible had the turbo worked throughout the entire time at full load. This is a more realistic measure of wind energy technologies performance since it takes into consideration the differences in the availability of wind and operational characteristics. Wind energy capacity factors are determined by a number of factors including geographical location, design of turbine, and wind speed distribution, among other factors, and maintenance practices. Onshore wind farms normally have a rate of 25-40 in terms of capacity factors. Offshore wind farms, on the other hand, have the potential to run higher capacity factor, between 40 and 60 percent since the winds at the ocean are stronger and more predictable [3].

Technological progress in the turbines, such as taller towers and longer rotor blades enable turbines to harness more wind energy even in regions where there is a moderate wind speed. This has seen modern wind turbines being much more efficient as compared to previous designs and this has allowed more electricity to be generated using the same wind resource. Although these are the improvements, wind energy efficiency can be affected by a number of factors. The most important determinant is the local wind conditions. Stable areas with high wind velocities are good places to develop wind farms, and the one with high variation in wind patterns might have reduced productivity [4]. The location of turbines in a wind farm is also critical since close placement of turbines may bring about effects of the wake, where turbines downstream may have their output compromised by the air flow of the turbines in the first stage. Better spacing and consideration of wind farm design is therefore crucial in order to maximize overall energy production.

Operational and maintenance practices also impact efficiency. Digital monitoring systems and predictive maintenance technologies become more popular in modern wind farms in order to identify mechanical problems potentially causing a decrease in performance, or offline periods [5]. These systems examine the data about the operations in real time that enables the operators to enhance the reliability of turbines and increase the life of equipment. In sum, to enhance the efficiency of wind energy, a combination of best site selection, modern turbine technology, appropriate wind farm, and smart operation management is necessary. With ongoing research and innovation, the efficiency with which wind energy systems are run is likely to go even higher, so wind power is likely to become even a more important source of sustainable electricity generation in the global context.

2. Materials and Method

Technological Advancements and Grid Integration Challenges in Wind Energy

The use of technology can be at the center stage of ensuring that wind power systems are more efficient and reliable. The last 20 years have seen tremendous advances in the design of turbines, materials science, and computer technologies. The wind turbines today are much bigger and efficient as compared to the previous ones. By increasing height, taller towers enable the turbines to acquire stronger and more regular wind currents at a greater height. Meanwhile, increased rotor lengths mean that turbines have a larger area to receive kinetic energy of the wind [6]. These design advancements directly increase the electricity generation and overall turbine performance. Improvement in materials engineering has led to efficiency of turbines as well. Lightweight but high-strength materials, like carbon fiber composites, enable manufacturers to make longer, more lasting blades without a lot of structure weight. These materials prolong the lifespan of turbines and minimize their maintenance needs.

Furthermore, a new trend that researchers follow is biomimicry-based designs that mimic nature-based aerodynamic structures [7]. Indicatively, the use of the blade designs inspired by the humpback whale fins could demonstrate the ability to enhance the aerodynamic performance, decrease drag, and lower the operational noise. These innovations are not only effective in improving efficiency but also improving on issues of wind noise in the environment and to the communities. The other tech-packed event that deserves to be mentioned is the involvement of artificial intelligence and machine learning in the management of the wind farms. Wind turbines can produce huge amounts of operational information, such as the speed of wind, the rotation speed of turbine, temperature, vibrations, and power generation. This data is processed with the help of artificial intelligence systems and patterns are identified; this allows predictions of possible mechanical problems, before the system breaks down.

This predictive maintenance strategy minimizes downtime and makes sure that the turbines operate in optimum efficiency. It can also predict the wind patterns and predict the placement of turbines to be used in the wind farm more effectively through machine learning models [8]. Such technologies eventually lead to a more stable energy production and improved integration with electricity grids. The concept of Energy Return on Investment (EROI) is often used to determine the sustainability of wind energy systems. This ratio is used to measure the energy output produced by a wind energy system in relation to the total energy used to make, install, run and maintain that energy system. High EROI means that the system generates much more energy than energy used during its lifecycle. In most cases, wind power also has a relatively good EROI relative to most of the traditional energy sources, which strengthens its classification as one of the most well-suited and effective renewable energy technologies [9].

Challenges to grid integration include infrastructure of a nature. A majority of wind farms are in remote or offshore areas where wind energy is at its peak, yet in those areas they are not close to large population hubs. Consequently, thousands of dollars are needed to build transmission lines that can carry electricity produced in wind farms to cities. Other energy storage mechanisms like batteries and pumped hydro storage are also in demand to store the excess energy produced during times of high wind and release the power when wind winds become low. One of the viable options in the variability issue is geographic diversification of wind farms (Figure 1) [10]. With the wind installations spread over various areas, changes in the local wind patterns can be compensated.

In a case when the wind is slow in one region, it might be faster in other regions creating a more balanced total power output. Research has demonstrated that clusters of geographically spaced wind farms could be very beneficial in enhancing grid stability and decreasing electricity supply variability. There are also regulatory and policy impediments to the integration of wind energy. Developers can find it cumbersome and time wasting to endure permitting procedures, zoning rules and grid connection requirements. These administrative requirements cause delays in project implementation, and raise development costs in certain areas [11].

Proper policy frameworks are thus needed to aid the growth of renewable energy. Further simplification of interconnection processes and enhancing regulatory transparency and stakeholder cooperation can hasten the process of wind energy deployment without compromising grid reliability. With efficient technological improvement, wind energy systems have been greatly efficient and sustainable. Energy production and control of operations have been improved by innovations in the field of turbine design, materials science, and artificial intelligence [12]. Nevertheless, grid integration, infrastructure development challenges, and regulatory systems are some of the critical problems that have to be tackled. Technological innovation, enhanced grid infrastructure, and favorable policies are some of the painkillers necessary to overcome these obstacles to enable wind energy to maximize its value in the globalization of clean and sustainable energy systems.

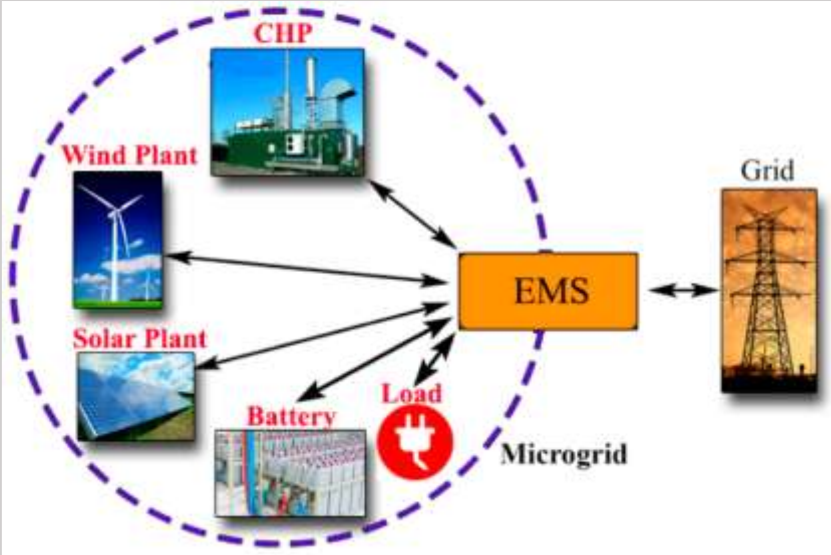

Figure 1. Addressing Intermittency and Grid Integration [13].

Economic Considerations and Solutions for Wind Energy Integration

Economics is also significant in defining the potential to successfully introduce wind energy into the system of national electric power. Although wind energy is increasingly competitive as compared to other forms of energy, there is still a limit of administrative complexities and regulation which can still add expensive costs and inadequate development in a project. To investors and energy developers, a lack of predictability in regulatory policies may deter investment and hinder the growth of renewable energy infrastructure [14]. Positive and supportive policies are thus necessary to promote the development of wind energy projects.

Policymakers and governments need to develop regulatory frameworks offering clear cut laws on how to permit, connect to the grids, and set the prices of power. The cost of project development can be reduced significantly by simplifying approval processes and by cutting bureaucracy delays. Besides this, there are financial incentives like tax benefits, renewable energy credit and feed-in tariffs that can establish the best market signs, motivating the use of the private capital to invest in wind energy technology. The existence of regulatory frameworks that are stable and predictable creates more willingness amongst developers to extend capital in the long term in renewable energy projects, thereby accelerating the establishment of wind farms and other associated infrastructure [15].

The electric cars are also becoming a new facet of incorporation in the eco-friendly waves of energy. With the growing population of electric cars all over the world, their batteries can serve as distributed storage devices in the power grid. Cars may be charged at the time when a lot of wind energy is produced and when there is a little demand of electricity. Vehicle-to-grid technologies could even enable electricity stored in vehicle batteries to be fed back into the grid at times of peak-demand in future, making the overall system more flexible. Besides the advances of storage technology, grid infrastructure enhancement is critical when it comes to effectively distributing the grid based on wind generated power. Numerous wind farms are situated in areas with good wind potential yet a small population density. This implies that electricity has to be transmitted long distances frequently to supply key centers of demand. Bottlenecks can be decreased by upgrading existing transmission networks and building new transmission lines that will guarantee efficiency in energy delivery to consumers (wind energy) (Table 1) [16].

Direct current transmission systems of high voltage are especially useful in long-distance electricity transmission. Compared to the conventional lines of alternating current, these systems incur less energy loss and they are able to couple renewable sources, which are located far away to national power grids. HVDC systems also aid in balancing variations in wind generation to a greater geographical area by connecting various areas to each other. The other critical measure towards making wind energy integration more effective is more precise forecasting techniques. The wind is unpredictable and varies at a quick rate such that grid operators find it hard to forecast the level of electricity production. The development of meteorological modeling and forecasting software has given operators an opportunity to predict the wind patterns several hours or days prior to its occurrence [17].

These projections assist in the electricity markets to plan how to generate power more effectively, eliminating the necessity to use expensive back-up sources of power. All in all, economic and technological advancement issues, as well as improvement in infrastructure, have a close interdependence in effective incorporation of wind energy in modern power arrangements. Favorable regulatory measures can spur investment and progress in energy storage, transmission systems and prediction technologies can be used to tackle the technical issues of wind power variability. Combined, these strategies offer a way forward to a more stable and sustainable renewable energy system where wind energy will have significant contribution.

Table 1. Wind Energy Efficiency Factors and Performance Indicators.

Aspect	Description	Key Findings	Reference
Installed Capacity	Maximum theoretical electricity output under ideal conditions	Does not reflect real-world variability of wind	[18]
Capacity Factor	Ratio of actual output to maximum possible output	More realistic performance indicator; varies by location	[3]
Onshore Wind Efficiency	Land-based wind farms	Typically achieve 25–40% capacity factor	[4]
Offshore Wind Efficiency	Ocean-based wind farms	Higher efficiency (40–60%) due to consistent wind	[3]
Turbine Design	Taller towers and longer blades	Increase energy capture and improve efficiency	[6]
Material Innovation	Use of carbon fiber and composites	Enhances durability and reduces maintenance	[7]
AI & Predictive Maintenance	Data-driven monitoring systems	Reduces downtime and improves operational efficiency	[8]
Energy Return on Investment (EROI)	Energy output vs lifecycle input	Wind energy shows high sustainability performance	[9]

Community Engagement, Site Assessment, and Case Studies in Wind Energy Integration

The elements integral to the development of wind energy are community participation and site evaluation. Wind farms can also take a lot of land and can have an impact on the local community, ecosystem and landscape. Consultation with the residents, the owners of the lands, and local governance in the initial phases of project planning assists developers in overcoming issues concerning the land use, environmental impacts, and visual or noise effects ([19]. Open communication will lead to a better acceptance of wind energy projects by the people and there will be less conflicts that could slow down or stop development. The case studies in the real world offer a great help in terms of understanding issues and solutions of wind energy integration. A number of large-scale studies have been made in the United States to get to know how the use of wind power can be incorporated in the current power stations. In 2008- 2015 national energy research projects carried out large-scale studies nationally on wind power integration. These studies were concentrated on large electricity networks, both on western grid interconnections and eastern grid interconnections, to enhance grid reliability and augment the portion of wind-generated electricity [20].

The results of these studies revealed that on large scale integration of wind energy is technically viable, but it must be coordinated at a number of sectors. The variability of the wind production should be under control by grid operators who need to always keep the balance of electricity production and demand at the required level. This has to be done using enhanced forecasting tools, variable power generation systems, and enhanced transmission networks that can accommodate varied energy sources. A challenge of technical barriers is also one of the biggest challenges. The production of wind energy is also largely seasonal, meaning that there can be a great difference in the output of the electricity in the short-term. It is such intermittency that causes it to be hard to rely exclusively on wind power, without other backup systems like energy storage or reserve generation. The use of these fluctuations needs various skills in different fields, such as meteorology, electrical engineering, data science, and energy economics. Another significant factor in the development of wind energy is the economic issues. The cost of wind technology has dropped sharply during the last ten years, but to start with the creation of wind farms initial capital expenditure is great [21].

Building of turbines, setting up of transmission lines and grid infrastructure all demand huge initial capital expenditures. These economic challenges may be especially challenging to financial small- and medium-sized enterprises that are aiming to gain entry into the renewable energy industry. Also, certain financial institutions can be reluctant to fund renewable energy programs because of the uncertainty about the returns after a few years or lack of skill to analyse such investments. Another significant challenge is regulatory and permitting processes (Table 2). In most wind energy projects, the consent of various government bodies dealing with environmental maintenance, land use planning, and power regulating general environmental policies is usually necessary. Antiquated or complicated regulatory structures may take months, or even years to approve any project, which aggravates the cost of development and deters potential investors [22]. The processes can be streamlined by enhancing interconnection standards that can expedite the renewable energy infrastructure deployment.

The role of regulatory clarity in the development of wind energy has also been brought to the fore by legal precedents. Cases that have been adjudged in courts on wind energy projects have underscored the importance of ensuring that the processes by government in its review is undertaken in a timely manner without compromising the environmental management. Such instances demonstrate the fragility between encouraging the development of renewable energy and responsible project appraisal [23]. All in all, experience of the previous wind energy projects has illustrated that the crucial conditions to effective integration is a combination of technological innovation, favorable policy frameworks and community involvement. Through moving towards coordinated action on technical, economic, and regulatory issues, nations will be able to increase wind power and still have reliable and sustainable electricity systems.

Table 2. Grid Integration Challenges and Solutions in Wind Energy.

Challenge Category	**Issue Description**	**Proposed Solutions**	**Reference**
Intermittency	Variable wind leads to unstable power generation	Energy storage systems (batteries, hydrogen)	[23]

Grid Infrastructure	Remote wind farms far from demand centers	Expansion of transmission networks (HVDC systems)	[16]
Forecasting Limitations	Difficulty predicting wind patterns	Advanced meteorological and AI-based forecasting	[17]
Regulatory Barriers	Complex permitting and policy delays	Simplified approval processes and clear policies	[11]
Economic Constraints	High upfront investment costs	Financial incentives and stable regulatory frameworks	[14]
Energy Storage Needs	Excess energy during high wind periods	Battery storage and vehicle-to-grid systems	[15]
Geographic Variability	Uneven wind distribution across regions	Geographic diversification of wind farms	[10]
Grid Stability	Fluctuations affect frequency and voltage	Smart grids and demand response systems	[24]

Future Perspectives of Wind Energy Efficiency and Grid Integration

The future of wind power is both bright and challenging with the world energy system being transformed to low-carbon and sustainable energy generation. It is projected that wind energy will become a greater source of energy in addressing the increasing electricity needs and curbing emission of greenhouse gases. Nevertheless, it needs to be constantly advanced in terms of technology, policy development, and social acceptance in order to fully utilize its potential. The success of wind energy systems in the next several decades will rely on the success of the development of these spheres and their communication with each other [25]. The use of technology will continue to be a significant source of wind energy efficiency and grid integration. The smart grid technologies are one of the most significant developments. Smart grids are digitalized and employ automated control systems and real-time data monitoring to have better control over electricity flows.

In contrast to the conventional power systems, which are based on centralized generation and minimal communication among the elements, smart grids provide two-way communication between the electricity producers and consumers. Such an ability will enable grid operators to smootherly control variations in renewable energy production and ensure stability in the system. Another important element of smart grid development is the demand response programs [24]. The programs motivate consumers to modify their consumption of electricity during peak hours. As an illustration, households or companies can be financially encouraged to minimize their energy consumption or move some operations to periods when production of renewable energy is at an increased rate. The demand response systems would reduce the load on the electricity grid as the demand peaks during times of good wind generation, which would enhance energy efficiency. The future integration of wind energy will also be very dependent on energy storage technologies.

Since the amount of electricity that is generated by the wind is determined by the weather conditions, it is important to store surplus electricity that is generated when the wind is strong to create a steady power supply. Improvements in battery technologies, especially large-scale lithium-ion battery systems are already enhancing the possibility of storing renewable energy in short durations [26]. Such systems will be able to stabilize grid operations by supplying electricity during the time when the wind speeds are reduced. Clear guidelines on how to connect renewable energy facilities to national power grids should also be a part of effective policy frameworks (Figure 2). The standards of grid integration need to be developed to enable the growing proportion of renewable energy sources. To sustain a stable supply of electricity, it will be necessary to update grid codes and make sure that they have transmission networks capable of accommodating variable power inputs. The future of wind energy development will also be influenced by social and environmental issues. The successful implementation of wind energy projects largely depends on the acceptance of the projects by the population. Land use, visual impact and noise issues can be addressed through community engagement initiatives. Support to increase wind energy can be enhanced through educating the masses about the environmental advantages of renewable energy, such as less air pollution and less carbon emission [27]. Wind energy planning should also focus on environmental sustainability.

Ecological impacts can be diminished by means of careful selection of sites, monitoring of wildlife, and enhanced tower design. As an example, new types of turbines are being designed that have features that reduce the risk of harm to birds and bats without sacrificing the effective generation of power. In general, the efficiency and integration of wind energy in the future will be determined by a mix of technology, favorable government policies, and effective community involvement. Wind power is projected to be an even more significant and reliable part of the global renewable energy system alongside the further development of innovations in smart grids, energy storage, and forecasting technologies [28]. Wind energy can be a key to creating a more sustainable and cleaner energy future, through coordinated action in the technological, political and social fields.

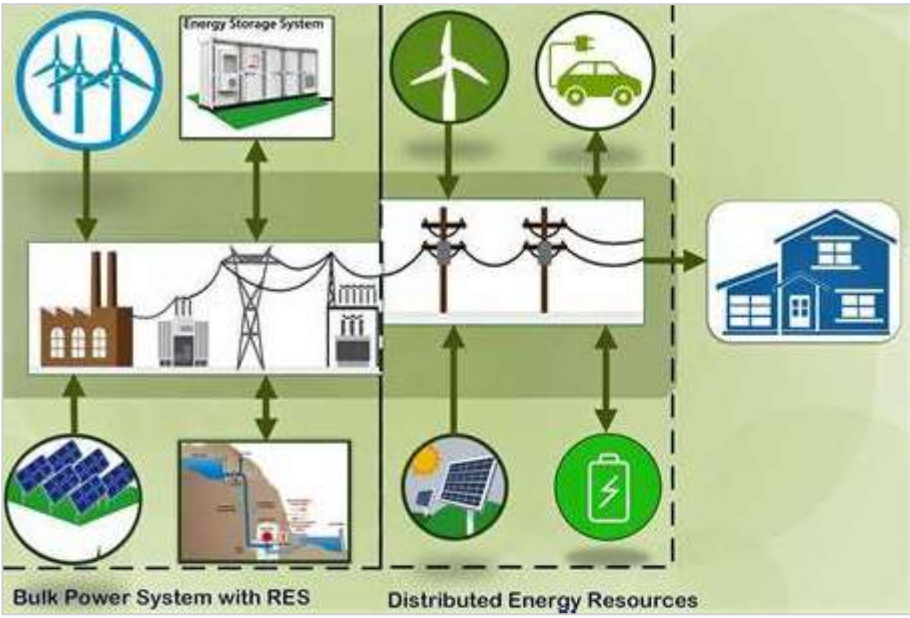

Figure 2. Addressing barriers to efficient renewable integration [29].

3. Results and Discussion

Wind energy has become a key in the global shift towards sustainable and low-carbon energy systems by being one of the most significant renewable energy sources. With the increasing concerns on climate change, environmental degradation, and energy security, nations are increasingly investing in renewable energy technologies in order to lessen their reliance on fossil fuels. Among them, wind power has been seen to experience incredible growth because it does not produce greenhouse gases in the process of producing electricity [30]. Nevertheless, despite the great environmental and economic advantages of wind energy, its effectiveness and implementation into the already existing power grids are complicated issues that demand constant technological, regulatory, and infrastructural advancements. Among various issues in the wind energy performance, the efficiency can be defined as the effectiveness of wind turbines in terms of their ability to transform kinetic energy of wind into electrical energy. This efficiency is normally measured in terms of installed capacity and capacity factor.

Installed capacity is a measure of the maximum theoretical power that the wind turbine or wind farm can generate under ideal conditions [31]. The capacity factor, on the other hand, is the amount of electricity produced (in a given time frame) compared to this maximum potential generation. Capacity factors offer a more realistic view of the performance of the system since the wind speed varies and not all turbines can work at full capacity at all times. Onshore wind farms normally have a capacity factor of between 25 and 40 percent. By contrast, offshore wind farms can go as high as 40 percent to 60 percent since the winds are much stronger and more stable over the oceans [32]. These differences highlight the importance of geographic location and resource assessment in determining wind energy productivity. The effectiveness of the wind energy systems has been significantly enhanced by technological innovation [33].

The current wind turbines are much bigger and sophisticated in comparison to the previous ones. Taller towers allow turbines to reach stronger winds in higher altitudes and longer rotor blades increase the area covered by the rotor that captures the wind energy. The advantages of these structural enhancements are that turbines can produce more electricity even in areas where wind is moderate. The materials science has also improved the performance of the turbines. Lightweight, but strong materials like carbon fiber composites enable manufacturers to create longer blades without reducing structural stability [18]. These materials minimize mechanical stress, increase the life of turbines and decrease maintenance needs. Biomimicry-based turbine designs are another new sphere of technological advances. To improve the design of blades to enhance the effectiveness of airflow and minimize turbulence, researchers have focused on aerodynamic structures in nature (including the fins of humpback whales). Not only do these innovations improve the efficiency of power generation, but also minimize noise levels, which is important in managing the community concerns about wind farm operations. These systems are able to anticipate mechanical failures, optimize the performance of turbines and assist in predictive maintenance plans.

The AI-based systems can minimize downtime and maximize energy production by detecting possible problems before they cause equipment failure [34]. Weather patterns and wind forecasts can also be analysed with the help of machine learning algorithm to optimise the work of turbines and enhance strategies concerning grid integration. Energy Return on Investment is another significant concept to consider when assessing wind energy sustainability and is a ratio of energy generated by a system to the energy needed to build, operate and maintain it. When the energy returning is high, it is a sign that the system is producing a lot more energy than it is using over its lifecycle. Wind energy has the tendency to have a high energy payoff compared to most traditional energy sources, further supporting its usefulness as a long-term sustainable energy source [30].

The integration and development of wind energy projects is also affected by economic factors. Despite the fact that the cost of wind technology has been reduced tremendously in the last 10 years, the initial capital cost of constructing wind farms is still very high. The financial investment in turbine construction, installation, connection to the grid and development of infrastructure is huge. Such initial expenses may deter small scale investors and restrict entry into the renewable energy markets. Moreover, not all financial institutions have adequate experience to analyze the renewable energy projects, which results in the conservative approach to lending [35]. A regulatory framework is important in surmounting these financial difficulties. Governments need to come up with conducive and transparent policies that can foster investment in renewable energy technologies. Development costs and the time spent on project implementation can be minimized and timelines shortened by simplifying permitting procedures, giving financial incentives, and making grid connection standards transparent. Good regulatory policies also offer stability in the long run that spurs investment in the private sector.

The other factors that will be significant in the successful growth of wind energy are community involvement and the environment. Wind farms may impact the local scenery, animal habitats and the community living around the wind farms. The involvement of residents in the planning phase will enable the developers to deal with issues of noise, land use, and visual impact. The involvement of the people contributes to the development of trust and the enhancement of the acceptance of renewable energy projects [36]. It also requires environmental protection strategies in order to have sustainable development of wind energy. Impact on birds and bats can be minimized by careful site selection, wildlife monitoring schemes and enhanced turbine designs. The growth of geographic information systems, land-mapping technologies allows developers to perform in-depth environmental analysis prior to the onset of construction, and reduce environmental disruptions.

4. Conclusion

Wind energy represents a crucial pillar in the transition toward sustainable and low-carbon power systems. This study demonstrated that improving turbine efficiency through advanced designs, AI-driven maintenance, and material innovation significantly enhances energy output. However, challenges such as intermittency, grid integration constraints, infrastructure limitations, and high initial costs remain key barriers. Addressing these issues requires coordinated efforts in policy reform, investment in energy storage, and modernization of transmission networks. With continued technological advancement and regulatory frameworks, wind power can become a reliable, scalable, dominant contributor to global clean energy systems.

Author Contributions

S.M.E.U.: Conceptualization, methodology development, data analysis, and preparation of the original manuscript draft. M.S.U.: Supervision, critical review, editing, and validation of the manuscript. Both authors contributed to the discussion of results and approved the final version of the manuscript.

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