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Review Paper

# Advances in Wind Turbine Technology: Efficiency and Application in Renewable Energy

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**Abstract:** Electricity is a crucial element in daily life as it supports various human activities. However, many remote areas remain unconnected to the national power grid due to long distances from PLN's network, resulting in high electricity provision costs. This study employs a qualitative approach by identifying and analyzing literature related to advancements in wind turbine technology, its efficiency, and its application in renewable energy. The review is based on sources from scientific journals, books, research reports, and conference proceedings. Wind energy holds great potential as an environmentally friendly renewable energy solution, particularly in remote areas with low wind speeds, such as Indonesia. Modern wind turbine technology continues to evolve, incorporating aerodynamic design, pitch control systems, and variable speed mechanisms to enhance energy conversion efficiency. Innovations such as the Darrieus turbine, vertical axis wind turbine (VAWT), and the "Antasena" turbine provide effective solutions for low-wind conditions, making them suitable for 3T (Frontier, Outermost, and Disadvantaged) regions. The integration of wind turbines with other renewable energy sources, such as solar panels or micro-hydro systems, along with the use of storage batteries, enhances electricity supply stability in remote areas. Despite challenges such as high investment costs and environmental impacts, proper mitigation strategies can minimize these negative effects. A holistic approach that involves local communities in wind energy projects also contributes to social and economic sustainability.

**Keywords:** Wind turbine; Electricity; Energy.

## 1. Introduction

Electricity is an essential element in everyday life as it facilitates various human activities. However, there are still many remote areas that have not been reached by the national electricity grid, so access to electricity in these areas is very limited. Various factors can cause difficulties in obtaining electricity, one of which is the long distance from the PLN network, which results in high costs for electricity provision. Some areas overcome this problem by using diesel generators, which are not only expensive but also potentially polluting the environment. As an anticipatory step to prevent an energy crisis, a solution that can be applied is the utilization of new renewable energy (EBT) [1].

Wind energy is a promising renewable energy source in the face of energy and environmental crises. The main advantage of wind energy is that it is environmentally friendly and free of carbon emissions, making it a sustainable alternative to fossil fuels. In addition, wind is an abundant and inexhaustible resource, which can increase energy independence and reduce dependence on fossil fuel imports. Technological developments such as aerodynamic design, blade angle control and variable speed have improved the efficiency of wind turbines, allowing for more optimized operation across a wide range of wind conditions [2].

Indonesia, as an archipelago with a vast coastline, has great potential in wind energy development, especially in coastal areas. However, its utilization is still limited as most areas only have low to moderate wind speeds, ranging from 1.5 to 6.5 m/s. This condition hinders the optimal performance of conventional wind turbines, thereby reducing the efficiency of wind power generation. With innovations in modern turbine design, it is expected that wind energy conversion in Indonesia can increase and contribute more to national energy needs [3]. An archipelagic country like Indonesia faces great challenges in ensuring equitable access to electricity for the entire population. Although the electrification ratio has steadily increased in recent decades, there are still many remote areas that do not receive adequate electricity supply, especially in areas with difficult geographical access, such as small islands and mountainous regions.

Wind turbines are one of the key technologies in the utilization of renewable energy in many parts of the world. In recent decades, wind energy has played a significant role in the global shift towards more environmentally friendly and sustainable energy sources. Developed countries such as the United States, Germany and China are pioneering the development of large-scale wind power plants that contribute greatly to their national energy supply. Whether onshore or offshore, wind turbines are designed to convert the kinetic energy of the wind into usable electrical energy [3].

Wind turbines are a key device in the conversion of wind energy into electricity, with innovations constantly evolving to improve efficiency. There are two main types: horizontal-axis turbines, which are commonly used on a large scale, and vertical-axis turbines, which are increasingly in demand due to their advantages in variable wind conditions. The main factors affecting turbine efficiency include blade design, wind speed, and system configuration such as transmission and blade angle settings. Savonius-type vertical-axis turbines have proven effective in low-speed winds due to their ability to generate large torque. An optimal wind speed is essential, as beyond a certain limit, efficiency may decrease or even cause damage. Proper integration between the turbine, generator and other components determines how well mechanical energy is converted into electricity [4].

Wind turbine designs are constantly evolving to improve efficiency, robustness and adaptation to various environmental conditions. Aerodynamic innovations enable more optimal wind energy capture, while advanced pitch control dynamically adjusts the blade angle. Variable speed technology is also applied to optimize energy conversion and reduce mechanical loads [2].

Based on the above description, the purpose of this journal review is to explore advances in wind turbine technology in understanding technological developments in wind turbine design, such as aerodynamic turbine blades and variable speed technology that contribute to increasing wind energy efficiency. Can evaluate the environmental impact of operating wind turbines.

## 2. Research and Methodology

### 2.1 Materials

The literature materials used in making journal reviews are journals, books, research reports and conference articles that are relevant to the desired topic, namely regarding advances in wind turbine technology in efficiency and its application in renewable energy. The research also highlights the literature on various wind turbine designs, especially vertical axis turbines (VAWT) and Turbines that are considered the most suitable for low wind speeds and these turbines are very suitable for developing countries such as Indonesia which has many islands and regional conditions that are difficult to reach for the construction of electric energy centers, therefore developed energy that is easy to build and renewable.

### 2.2 Experiments

This journal review uses a qualitative approach to identify and analyze literature related to advances in wind turbine technology with its efficiency and application in renewable energy. The selection of literature is based on research that focuses on small-scale wind turbines, low wind speeds, renewable energy and the application of technology in remote areas. In the final stage, the authors summarize the findings of the literature review with an emphasis on optimizing modern wind turbine designs to improve efficiency and performance in various wind conditions. These conclusions include recommendations regarding the most effective technologies or design approaches and suitable wind speeds to generate the most efficiency as well as challenges that still need to be addressed in future research.

Through this approach, the authors seek to contribute to the development of wind turbines that are more efficient and suitable for future renewable energy needs. Within the context of the literature review, this research applies analytical descriptive methods to understand and explain wind turbine efficiency improvements. Descriptive methods are used to describe existing design concepts, while analysis is conducted to evaluate the effectiveness of various innovations in improving performance.

This approach provides a comprehensive insight into the development of wind turbine technology and its relevance to future renewable energy challenges. As such, this work is expected to be a useful guide for researchers and practitioners in the development of more efficient and sustainable wind turbines.

## 3. Results and Discussion

### 3.1 Development of Modern Wind Turbine Technology

Wind turbines are a key technology in renewable energy solutions, but their development still faces many challenges, especially in terms of efficiency and performance. In recent decades, efforts have been made to optimize this technology to operate more effectively. In Indonesia, the development of small-scale wind turbines as a renewable energy source in remote areas faces many obstacles both in terms of technical and non-technical aspects. Although it has great potential in providing sustainable and environmentally friendly energy, its application is still limited by many factors such as low wind speed, inadequate infrastructure, and high investment and maintenance costs [5]. Therefore, innovations in design and technology are needed so that wind turbines can function optimally and become an effective solution for energy needs in remote areas of Indonesia.

Developments in wind turbine design have led to a variety of configurations that are more efficient and adaptive to environmental conditions. Modern wind turbines have progressed significantly from early models, with innovations that improve energy conversion efficiency, structural robustness and performance in various wind conditions. Aerodynamic design improvements allow for more optimal capture of wind energy, while more sophisticated pitch control helps to dynamically adjust the blade angle to maximize energy production as well as protect the turbine from high-speed winds [3]. Research shows significant performance differences between wind turbine types. In a comparative study, a conventional Savonius turbine was able to achieve a maximum rotation speed of 229.2 Rpm in a 5.9 m/s wind but could not operate in a 2 m/s wind speed. In contrast, the Savonius Helius turbine with a blade angle of 22.5° performed better in low winds, rotating at 47.8 Rpm in a 2.0 m/s wind [6]. This ability opens up opportunities for the utilization of wind energy in areas of Indonesia that are remote or difficult to reach by state electricity and areas that have wind speeds that were previously considered less potential or low.

One important innovation in wind turbine development is the contra-rotating system, which uses two rotors rotating in opposite directions to improve the efficiency of extracting energy from the wind stream. Experimental studies show that at a blade angle of 10° with a wind speed of 4.03 m/s, horizontal-shaft wind turbines with this system can achieve a maximum efficiency of up to 71.8%. This figure far exceeds the ideal power coefficient of a single-rotor turbine of only 59%, proving that the contra-rotating design is more efficient in converting wind energy than conventional single-rotor systems [7]. These advantages make the contra-rotating system a potential solution for the future, especially in improving energy conversion efficiency.

### 3.2 Design Innovation for Low Wind Speed Conditions

Indonesia, as an archipelago with one of the longest coastlines in the world, has great potential to develop alternative energy. Easily accessible renewable energy sources include wind and water, but wind is easier to harness. According to the Manager of the Wind Hybrid Power Generation Project (WhyPGen), Indonesia has abundant wind resources that are strong enough to drive turbine blades without relying on specific wind directions. This potential is expected to be a solution in reducing dependence on fossil energy and reducing global warming, along with the development of other renewable energy such as biomass and geothermal. One of the main challenges in the development of wind power plants is improving turbine performance in regions with low wind speeds. In Indonesia, this is a particular concern as most of the region has low to moderate wind speeds [8]. To overcome this obstacle, researchers from the Department of Mechanical and Industrial Engineering, Faculty of Engineering, Universitas Gadjah Mada, in collaboration with Puslitbang PLN, developed the "Antasena," a turbine specifically designed to operate in low wind conditions. This turbine has a cut-in wind speed or minimum wind speed to start spinning of 2.5 meters per second, making it ideal for use in 3T (Frontier, Outermost, Disadvantaged) areas in Indonesia.

There are two main types of wind turbines that are most commonly used: Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (VAWT) [5]. Horizontal axis wind turbines (HAWTs) are the most widely used type of turbine in the wind energy industry today. These turbines have a main rotor shaft positioned horizontally and parallel to the wind direction, with the turbine blades rotating with the wind flow. HAWTs are known to have higher efficiency than vertical-axis turbines (VAWTs), but require additional mechanisms to ensure the blades are always facing perpendicular to the wind direction. In contrast, vertical axis wind turbines (VAWTs) have a rotor shaft that is positioned vertically and perpendicular to the wind direction. The blades rotate by harnessing the wind from different directions without the need for a directional control system. The main advantage of VAWTs is their ability to capture wind from any direction without the need for additional mechanisms, but their efficiency is generally lower than that of HAWTs [9].

Because of this, VAWTs are more suitable for regions with low and unstable wind speeds, such as in some remote areas. Their design allows for installation closer to the ground, which can reduce installation and maintenance costs. In the context of small-scale wind turbines, this technology is designed to generate less power than the large turbines used in commercial wind farms. Despite their smaller capacity, small-scale wind turbines have the distinct advantage of being more suitable for meeting the electricity needs of remote areas. Areas such as rural or coastal areas often experience lower wind speeds, so turbines must be designed to still function optimally under these conditions [5]. In addition, the implementation of small-scale wind turbines can help communities in remote areas gain access to electricity without relying on the main power grid. Innovations in turbine blade design play an important role in improving wind turbine efficiency at low speeds. Blade angle variation was shown to affect the maximum efficiency of the turbine. Research shows that increasing the blade angle from 0° to 5° to 10° gradually increases the efficiency at various wind speeds, with the greatest increase occurring at an angle of 10°. These findings have a significant impact on the development of wind turbines, particularly for applications in regions with diverse wind characteristics [10][11].

### 3.3 Wind Turbine Performance Data and Analysis

The data obtained is through relevant literature in accordance with the journal title.

1. Comparison of Power Efficiency of Different Types of Wind Turbines

Various types of wind turbines have varying performance characteristics, especially in terms of the coefficient of performance (Cp). Based on research results cited from various literatures, the following is a comparison of Cp values for several types of wind turbines.

**Table 1.** Comparison of Coefficient of Performance (Cp) Values in Various Types of Wind Turbines

| No. | Wind Turbine Technology | Cp Value |
|---|---|---|
| 1. | LAPAN 10 kW Wind Turbine | 0,19 |
| 2. | LAGG 300 W Wind Turbine | 0,20 |
| 3. | LAGG 1 kW Wind Turbine | 0,40 |
| 4. | LAGG 2,5 kW Wind Turbine | 0,35 |
| 5. | Darrieus Wind Turbine (4 Blades) | 0,50 |

Based on the table above, it can be seen that the Darrieus vertical wind turbine with 4 blades has the highest coefficient of performance (Cp) of 0.50, while the 10 kW LAPAN wind turbine has a Cp value of 0.19 [12]. These differences in Cp values are influenced by various factors, such as blade design, aerodynamic characteristics, and turbine operational conditions. Although vertical Darrieus turbines show high performance under certain test conditions, it is worth remembering that horizontal axis turbines are generally more efficient for large-scale applications and higher wind speeds [13][14][15].

Darrieus wind turbines have blades arranged symmetrically with an adjusted angle with respect to their axis. This configuration allows the turbine to capture wind from various directions effectively. Unlike the Savonius turbine, the Darrieus utilizes the lift that arises when the wind blows. The blades of a Darrieus turbine rotate around its axis during operation [11].

2. Analysis of Number of Blades on Turbine Performance

Research on the impact of the number of blades on the performance of the H-type Darrieus vertical wind turbine with NACA 2410 profile shows a significant relationship between the number of blades and the output power and efficiency of the turbine. The following is the power and efficiency data for various blade count configurations [16].

**Table 2.** Variation of Number of Blades on Power and Efficiency of Darrieus Vertical Wind Turbine

| Turbine Quantity | Wind Power (Watt) | Turbine Power (Watt) | Efficiency (%) |
|---|---|---|---|
| 1 | 20,09 | 8,105 | 40,32 |
| 2 | 42,36 | 15,655 | 36,95 |
| 3 | 56,86 | 24,751 | 43,52 |
| 4 | 125,75 | 63,220 | 50,27 |

The data in the table shows that the Darrieus vertical wind turbine with a 4-blade configuration is capable of producing the highest output power, which is 63,220 watts, as well as achieving a maximum efficiency of 50.27% under the test conditions conducted [16].

Increasing the number of blades from 1 to 4 generally shows a significant trend of increasing output power. However, although the power generated increases, the efficiency of the turbine does not always increase linearly [14][17].

This phenomenon can be caused by various factors, including the complex interaction between the number of blades and the airflow characteristics around the turbine. In addition, increasing the number of blades also affects the distribution of aerodynamic forces acting on each blade, which can have an impact on overall performance. Another contributing factor is the change in air resistance as well as the structural loads generated by varying the number of blades. Therefore, while increasing the blades can increase the output power, further analysis is required to understand the optimal balance between turbine efficiency and performance [13][18].

The impact of the wind gate on turbine performance was analyzed, with the results indicating that turbine performance varies according to wind conditions. The following graph compares the turbine power with and without the wind gate.

Table 3. Wind Speed Relationship with Turbine Power Using Wind Gate and Not Using Wind Gate

| Wind Speed | 3 | 3,5 | 4,5 | 5,5 | 6,5 | 7,5 |
|---|---|---|---|---|---|---|
| Turbine Power with Wind Gate (watt) | 12,94 | 34,04 | 58,06 | 60,65 | 75,94 | 106,74 |
| Turbine Power without Wind Gate (watt) | 71,36 | 72,34 | 73,63 | 77,55 | 84,92 | 85,52 |

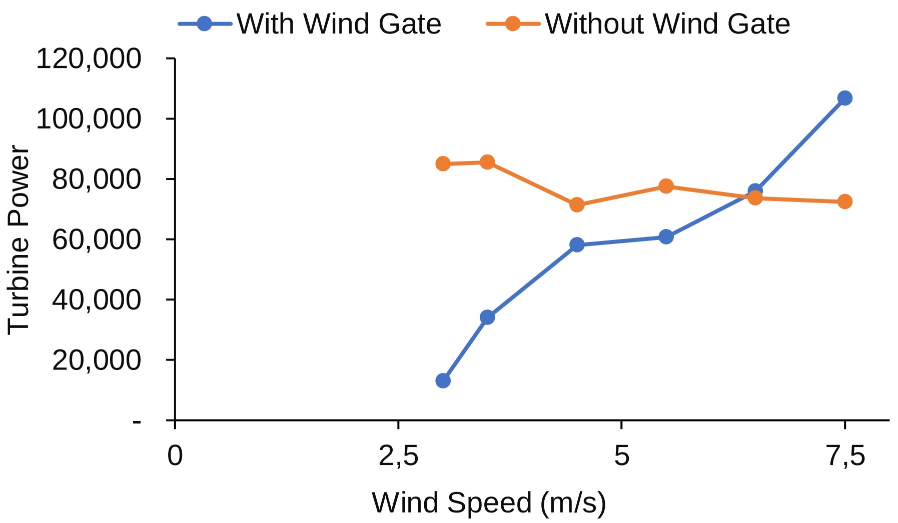


**Figure 1.** Graph of the Relationship Between Wind Speed and Turbine Power Using Wind Gate and Not Using Wind Gate

The graph above illustrates that at certain wind speeds, the use of a wind gate on the turbine can significantly increase the output power. The turbine equipped with a wind gate is able to reach a peak power of 106.74 watts at a wind speed of 7.5 m/s, while the turbine without a wind gate is only able to produce a maximum power of 85.52 watts at a wind speed of 3.5 m/s. This difference shows that the wind gate contributes to optimizing the conversion of wind energy into greater electrical power [19]. However, in terms of efficiency, the turbine with the wind gate had the highest efficiency of 50.73%, which occurred at a wind speed of 5.5 m/s. Meanwhile, the turbine without a wind gate showed a maximum efficiency of 45.42% at a wind speed of 3 m/s. Although the turbine with wind gate produced higher power, its efficiency was not always superior in all wind speed conditions. This indicates that there are other factors that affect turbine performance, such as blade design, air turbulence, and wind speed distribution around the turbine [18][8].

Overall, the use of a wind gate has a positive impact on increasing the power generated by the turbine, especially at higher wind speeds. However, optimization of wind gate design and configuration still needs to be considered to achieve a balance between output power and overall turbine efficiency.

3. Relationship between Wind Speed and Output Power

Wind turbine output power has a direct relationship with the cubic of the wind speed, so small increases in wind speed can result in significant increases in output power. This relationship is evident in the data from a study conducted on a vertical Darrieus wind turbine with a 4-blade configuration.

Table 4. Relationship between Wind Speed and Output Power for 4-bladed Turbine

| Wind Speed (m/s) | Wind Power (watt) | Turbine Power (watt) | Efficiency (%) |
|---|---|---|---|
| 3,5 | 53,98 | 14,832 | 27,47 |
| 4,2 | 79,88 | 28,267 | 35,38 |
| 4,5 | 95,47 | 34,483 | 36,11 |
| 4,8 | 112,97 | 56,475 | 49,98 |
| 5,0 | 125,75 | 63,220 | 50,27 |

The data in the table shows that there is a significant increase in output power as the wind speed increases. For example, when the wind speed increases from 3.5 m/s to 5.0 m/s which is an increase of about 43% the turbine output power experiences a drastic jump from 14,832 watts to 63,220 watts, or an increase of about 326% [18][20]. This confirms that the output power of the wind turbine has an exponential relationship to the wind speed, as explained in theory that the power generated by the wind turbine is directly proportional to the third power of the wind speed [11].

In addition, the efficiency of the turbine also shows an increasing trend as the wind speed increases until it reaches a certain limit. This indicates that there is an optimal wind speed range where the turbine can operate with maximum efficiency [21]. However, after passing that point, the efficiency may start to decrease or stagnate due to factors such as increased aerodynamic drag and structural limitations of the turbine. Therefore, understanding the relationship between wind speed and output power is crucial in designing wind turbines that are capable of operating optimally in a wide range of wind conditions [22].

### 3.4 Applications and Integration of Wind Turbines in Energy Systems

As an archipelago, Indonesia has considerable wind energy potential, although the level varies in each region. Based on the results of wind energy potential mapping conducted using data from 32 BMKG stations spread across all provinces, an overview of the distribution of average wind speed in Indonesia was obtained. The map shows differences in wind speed in various regions, where some areas such as East Nusa Tenggara, South Sulawesi, and some coastal areas have higher wind energy potential compared to other regions [15][23].

Integrating wind power generation into the national grid requires careful planning and adequate infrastructure to ensure optimal energy distribution. In addition, while wind energy is known to be environmentally friendly, its impact on ecosystems and landscapes needs to be minimized through careful planning and effective mitigation measures [2].

The application of wind turbines in 3T areas not only helps increase the national renewable energy mix, but also supports the provision of electricity in remote areas that have not been reached by conventional power grids. In this case, the ability of the Antasena turbine to operate at low wind speeds is strategic advantage that enables wider utilization of wind energy in various regions in Indonesia [9]. The development of hybrid systems that integrate wind turbines with other renewable energy sources such as solar panels or micro-hydro plants, is ongoing to overcome the intermittency of each energy source. This approach improves the stability and reliability of electricity supply, especially for off-grid systems in remote areas. In addition, the combination of wind turbines with storage batteries is gaining popularity as a solution to overcome fluctuations in energy production and ensure continuous availability of electricity [2][24].

### 3.5 Sustainable Aspects and Environmental Impacts

While the operating costs of wind farms are low, the high initial investment for the installation of wind turbines, transmission lines and supporting infrastructure often constrains their development in some areas. In addition, environmental challenges such as noise, visual impact and risk to wildlife also need to be considered. However, with good planning and the application of appropriate technologies, these impacts can be minimized. On the other hand, wind energy offers various opportunities, including as an environmentally friendly renewable energy source and contributing to climate change mitigation. The development of the wind energy industry can also boost local economic growth and create new jobs. In addition, the potential utilization of wind energy in remote areas and small islands that are difficult to reach by conventional power grids makes small-scale wind farms an effective solution to meet electricity needs in these areas [9]. This holistic approach ensures that wind energy development does not only focus on the energy production aspect but also pays attention to long-term sustainability both ecologically and socially.

Recycling of wind turbine components is an important aspect considering their limited operational life, around 20-25 years, as well as the amount of materials used in their production. The wind turbine industry continues to develop recycling methods, especially for turbine blades made from composite materials that have been difficult to reprocess. Advances in recycling technology and the application of circular economy concepts in wind turbine design have the potential to increase the sustainability of this technology in the future [2].

Community participation plays an important role in the success of wind turbine projects. Approaches that involve local communities in the planning, implementation and ownership stages of a project can increase social acceptance and ensure that the benefits are shared equally. Innovative business models, such as shared ownership or energy cooperatives, are being developed to encourage community involvement in the transition to renewable energy [5].

### 3.6 Future Prospects and Challenges

Despite rapid progress, wind turbine technology still faces challenges that require continuous innovation. Efforts to increase efficiency at low wind speeds, reduce costs, resist extreme weather, and develop more effective energy storage systems continue. Collaboration between government, industry, academia, and society is key to the sustainable optimization of wind energy, supporting the reduction of carbon emissions, and accelerating the transition to a more environmentally friendly energy system [9].

Digitization and the application of artificial intelligence in wind turbine management are growing. Technologies such as sensor-based monitoring systems, predictive maintenance, and operation optimization based on weather forecasts can improve efficiency and extend the operational life of turbines. The integration of these digital technologies also has the potential to increase the competitiveness of wind energy compared to conventional energy sources.

Although wind energy is considered an environmentally friendly energy source, the construction and operation of wind farms still have ecological and social impacts that need to be considered. One of the main issues often discussed is the risk to bird and bat populations, both through direct collisions with turbine blades and the barotrauma effects that can affect bats. Research shows that mortality rates vary significantly depending on factors such as location, the type of turbine used, as well as the species present in the area, with some species being more vulnerable than others [25]. To reduce these impacts, various mitigation strategies have been developed, including more selective site selection to avoid key migration pathways, the implementation of radar detection systems that allow turbines to be shut down when birds are detected approaching, and the use of blade designs with more visually striking patterns to be more easily recognized by birds [26].

## 4. Conclusion

Wind energy has great potential as an environmentally friendly renewable energy solution, especially for remote areas and regions with low wind speeds such as Indonesia. The development of modern wind turbine technology continues to progress, including aerodynamic design, pitch control, and variable speed systems, which improve energy conversion efficiency. Innovations such as the vertical axis turbine (VAWT) and the "Antasena" turbine provide effective solutions for low wind conditions, making them suitable for the 3T (Frontier, Outermost, Disadvantaged) regions of Indonesia. In addition, the integration of wind turbines with other renewable energy sources, such as solar panels or micro-hydro, as well as the use of storage batteries, increases the stability of electricity supply in remote areas. Despite facing challenges such as high investment costs and environmental impacts, proper mitigation measures can minimize these negative effects. A holistic approach that involves local communities in the development of wind energy projects also contributes to social and economic sustainability. Studies on the performance of different types of wind turbines reveal that turbine design and configuration play a crucial role in determining their output power and efficiency. For example, a four-bladed Darrieus vertical wind turbine can achieve a maximum efficiency of up to 50.27% under certain test conditions. In addition, the coefficient of performance (Cp) values of the different types of wind turbines analyzed show a variation range between 0.19 to 0.50, reflecting the differences in the effectiveness of wind energy conversion into electrical power. In addition to turbine design factors, the application of wind gates also affects the performance of wind turbines. The results show that under some conditions, turbines without wind gates can actually achieve higher efficiencies than turbines with wind gates. This finding indicates that while wind gates can increase output power, their effectiveness in improving efficiency still depends on other factors such as wind speed, turbulence, and the aerodynamic characteristics of the turbine itself.The sustainability of this technology is further supported by innovations in the recycling of turbine components and the application of circular economy concepts. The future outlook for wind energy includes digitization through the application of artificial intelligence to improve operational efficiency, predictive maintenance, and competitiveness. With collaboration between various parties, wind energy can become a key pillar in the transition to a more sustainable and low-carbon energy system.

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