

УДК 621.548

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**Аннотация**

В работе представлен анализ технологий ветровых турбин, включая их ключевые компоненты и перспективные направления развития. Проведено сравнительное исследование наземной и морской ветроэнергетики, выделены их преимущества и недостатки, а также проанализированы экономические и экологические аспекты каждого из подходов.

**Ключевые слова:** ветроэнергетика, возобновляемая энергия, ветровые турбины, энергоэффективность.

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**ABSTRACT**

The paper presents an analysis of wind turbine technologies, including their key components and promising areas of development. A comparative study of onshore and offshore wind power has been conducted, their advantages and disadvantages have been highlighted, and the economic and environmental aspects of each approach have been analyzed.

**Keywords:** wind power, renewable energy, wind turbines, energy efficiency.

Wind energy is currently one of the fastest growing and most promising areas of renewable energy. The global energy landscape is undergoing significant changes due to the need to reduce greenhouse gas emissions and reduce dependence on fossil fuels. In this regard, wind energy, with its huge potential and minimal environmental impact, is becoming a key element in achieving sustainable development goals [1]. In recent decades, there has been a significant increase in the installed capacity of wind farms around the world due to both technological advances and political incentives. However, despite significant advances, the industry continues to face a number of challenges, including issues of economic feasibility, reliability and integration into existing power systems. Wind energy development is key to achieving global climate goals such as reducing greenhouse gas emissions and achieving carbon neutrality. According to the International Renewable Energy Agency, wind power plays an increasingly important role in the global energy mix, demonstrating a steady increase in installed capacity and a reduction in the cost of electricity generation. This fact emphasises the need for comprehensive analysis and understanding of the industry's development prospects, including technical, economic and environmental aspects [2].

Modern wind turbines are complex engineering structures designed to convert the kinetic energy of the wind into electrical energy. The key components of any wind turbine are a rotor consisting of two or three blades, a nacelle placed on top of the tower, and a tower that provides the necessary height for the rotor to operate. Inside the nacelle are the generator, multiplier, braking system and other important components (Figure 1). The control system plays a key role in optimising the turbine's performance by adjusting the blade angle, the position of the nacelle in the wind direction and controlling the operation of the generator and braking system. The generator, in turn, converts the mechanical energy of rotor rotation into electrical energy. Current trends in wind turbine development include increasing the size of blades and towers, the use of direct drives, the use of intelligent control systems and the introduction of lighter and stronger composite materials [3]. Increasing the size of turbines allows capturing more wind energy, thereby increasing their efficiency. Direct drive turbines devoid of multiplier have higher reliability and lower energy losses. Intelligent control systems using machine learning algorithms allow turbines to be optimised in real time, adapting to changing wind conditions. The use of new composite materials such as carbon fibre reduces the weight of blades and other components, thereby increasing the overall efficiency of the turbines.

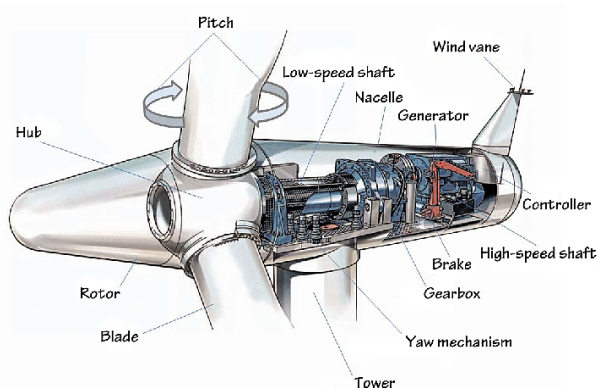


Figure 1. Main elements of a wind turbine

Source: <https://www.showme.com/sh/?h=4lFkOjQ>

Wind power can be realised both onshore and offshore, and each of these approaches has advantages and disadvantages (Table 1). Onshore wind farms are generally characterised by more variable wind conditions, which are landscape dependent, and lower wind speeds compared to offshore wind farms. However, onshore installations are characterised by lower costs and simpler infrastructure, making them more attractive for the initial stage of industry development. Offshore wind farms, on the other hand, utilise a stronger and more stable wind resource, which allows them to achieve higher efficiencies. Offshore installations, however, require higher capital costs, complex infrastructure, specialised vessels and equipment. The siting of offshore installations can also have an impact on marine fauna, and requires careful environmental planning. While onshore wind energy faces challenges related to land use, noise pollution and impacts on biodiversity, offshore wind energy has fewer siting constraints but is dependent on water depth. Onshore wind farms have a limited footprint, while offshore wind farms have great potential, especially in regions with long coastlines. The transport and installation of onshore turbines is usually easier, whereas offshore logistics are complex and expensive [4].

Table 1. Comparison of onshore and offshore wind energy.

Characteristic	Onshore	Offshore
Wind Resource	More variable, depends on location	Stronger and more stable, less turbulence
Wind Speed	Lower	Higher
Efficiency	Lower	Higher
Cost	Lower	Higher
Environmental Impact	Land use, noise, impact on biodiversity	Impact on marine fauna, visual impact
Infrastructure	Simpler and more accessible	More complex, requires specialized vessels and equipment
Transport and Installation	Relatively easier	Complex and expensive logistics
Siting Potential	More limitations due to terrain	Fewer siting limitations, but depends on depth
Potential	Limited area for deployment	Large potential

The potential for wind power is enormous and continues to grow due to technological advances and the decreasing cost of electricity generation. Wind power has the potential to meet a significant share of the world's electricity needs. However, there are certain limitations. A key limitation is the variability of the wind resource, which makes it necessary to utilise energy storage systems and backup sources to ensure the stability of electricity supply [5]. Infrastructural constraints are also an important issue as new transmission lines are required to connect wind farms. Environmental impacts including visual impact, noise and impact on birds and bats also require careful consideration and appropriate mitigation measures. High initial investment, particularly in offshore wind energy, represents a significant barrier to industry development. Social aspects such as protests from local communities due to visual impacts or noise can also slow down wind energy development. In addition, the wind resource is unevenly distributed and not all regions have sufficiently strong and consistent wind, which limits the possibility of installing wind farms. Nevertheless, cost reductions, technological innovations and political support will contribute to the expansion of wind energy utilisation and efficiency.

Wind energy plays a key role in the transition to a sustainable energy future. Continuous technological development, decreasing costs of power generation and political support make wind energy one of the most promising areas in the modern energy sector. Nevertheless, it is important to recognise that there are a number of problems and challenges that require further research and development. The impermanence of the wind resource remains one of the main obstacles to a more widespread deployment of wind power. Solutions related to the development of energy storage systems as well as the integration of wind farms with other types of renewable and conventional energy sources are essential to ensure the reliability and stability of energy supply. Infrastructural constraints related to the construction of new transmission lines and the adaptation of existing power systems to integrate large amounts of wind energy also require serious attention and significant investments. Further research and development, investment and policy support will help to increase the utilisation and efficiency of wind energy.

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