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PROBLEMATIC ISSUES OF OPERATION AND UTILIZATION OF AIR TURBINE BLADES

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The gradual increase in the number of electricity producers predicts the further development of alternative energy.

Renewable energy is an environmentally friendly, inexhaustible source of energy, which makes it possible to reduce the burden on the resource base and reduce overall resource consumption.

In addition, the use of rene-wable energy sources contributes to the sustainable development of cities, which, thanks to solar, wind, biogas installations, can provide themselves with electricity, thereby reducing their costs and resource dependence.

The population can independently produce electricity and control its distribution, while also minimizing losses during transmission over long distances. Wind energy is one of the promising areas in the field of renewable energy sources. The article examines the problematic issues of using wind energy and disposing of wind turbine blades, which is the main goal of the work.

It is well known that certain conditions are required to generate electricity from wind turbines. As research has shown, the most promising places for the production of electrical energy are considered to be coastal sea areas, where powerful air currents are formed during the year. Research into the problem of disposal shows that this issue is very relevant and outweighs all the advantages of wind energy.

The typical lifespan of wind turbine blades is about 20-25 years. Among the modern recycling methods, the following options are being considered to solve this problem – using fiberglass as noise barriers, for example, on high-ways and pressing of blades, for example, into fibreboards for use as pallets in the construction industry, fencing and railway sleepers, etc.

To achieve the goal, the authors of the article applied the methods of analytical review of scientist's and specialist's works of scientists and experts, systematic analysis of theoretical materials and practical recommendations in world practice regarding the operation and disposal of wind turbine elements.

It was found that scientific analysis is mainly focused on researching the optimal and highest-quality disposal methods, which requires future, global research.

Keywords: *wind turbine, blades, ecological sources of energy, wind energy, recycling of wind turbine components.*

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ПРОБЛЕМНІ ПИТАННЯ ЕКСПЛУАТАЦІЇ ТА УТИЛІЗАЦІЇ ЛОПАТОК ПОВІТРЯНИХ ТУРБІН

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Поступове збільшення кількості виробників електричної енергії передбачає подальший розвиток альтернативної енергетики.

Відновлювана енергетика – це екологічно чисте невичерпне джерело енергії, що надає можливість зменшити навантаження на ресурсну базу та знизити загальну ресурсозатратність. Крім того, використання відновлюваних джерел енергії сприяє сталому розвитку міст, які завдяки сонячним, вітровим, біогазовим установкам можуть забезпечувати себе електроенергією, тим самим зменшуючи свої витрати та залежність від ресурсів.

Населення може самостійно виробляти електроенергію та контролювати її розподіл, а також мінімізувати втрати при передачі на великі відстані.

Вітроенергетика є одним із перспективних напрямків в області відновлюваних джерел енергії. В статті розглядаються проблемні питання використання енергії вітру та утилізації лопастей вітрогенераторів, що є основною метою роботи. Загальновідомо, що для виробництва електроенергії вітровими турбінами потрібні певні умови.

Як показали дослідження, найбільш перспективними місцями для виробництва електричної енергії вважаються прибережні морські райони, де протягом року утворюються потужні повітряні течії.

Дослідження проблеми утилізації показує, що це питання є дуже актуальним і переважує всі позитивні елементи вітроенергетики. Стандартний термін служби лопастей вітрових турбін становить близько 20-25 років.

Серед сучасних методів утилізації розглядаються наступні варіанти вирішення цієї проблеми – використання скловолокна в якості шумозахисних бар'єрів, наприклад, на магістралях, та пресування лопастей, наприклад, у ДВП для використання в якості піддонів у морській та будівельній промисловості, огорож та залізничних шпал тощо.

Для досягнення поставленої мети авторами статті застосовано методи аналітичного огляду наукових праць вчених і фахівців, системного аналізу теоретичних матеріалів і практичних рекомендацій світової практики щодо експлуатації та утилізації елементів вітрогенераторів.

Проведений науковий аналіз зосереджений переважно на пошуку оптимальних та найякісніших методів утилізації, що потребує майбутніх глобальних досліджень.

Ключові слова: *вітрогенератор, лопасті, екологічні джерела енергії, енергія вітру, переробка компонентів вітрогенератора/*

Introduction. Sustainable development of society means, first of all, a constant desire to further reduce the human impact on the environment. In the process of development of human civilization, cities have become the living environment of a growing population. Urbanization is an objective process determined by the needs of society, production, and the nature of the social system. However, urbanization is a powerful environmental factor, as a large city changes almost all components of the natural environment – atmo-sphere, vegetation, soil, relief, hydrographic network, groundwater, soil, and even climate. Wind energy is a green technology. Currently, 85-

90% of the total mass of a wind turbine can already be recycled, as it is known that the standard service life of an onshore wind power plant is about 20-25 years.

Most wind turbine components, including steel, cement, copper wire, electronics and gears, can be recycled. However, wind turbine blades are more difficult to recycle. They contain complex composite materials – a combination of reinforced fibers (usually glass or carbon fibers) and a polymer matrix. These composites improve the performance of wind turbines. They allow for lighter, longer blades with optimal aerodynamics. But their configuration also poses challenges for recycling. Therefore, the issue of their disposal is the most important scientific problem of our time, the well-being of the entire environment and humanity depends on the correct solution of which.

Formulation of the problem. Research into the problem of disposal shows that this issue is very relevant. Composites used in wind turbine blades are important materials in sectors such as *shipbuilding* and, in general, the *marine industry*, aviation, automotive, etc. The objectives of this study are an analytical review of scientific works by scientists and specialists, a systematic analysis of theoretical materials and practical recommendations from world practice regarding the operation and disposal of wind turbine elements.

Research results and their discussion. For several millennia, mankind has been using wind energy. The wind has filled the sails of ships and made windmills work. The kinetic energy of the wind has always been and remains available in almost every corner of the Earth. Wind energy is also attractive from an ecological point of view: when using it, there are no emissions into the atmosphere, no dangerous radioactive waste. Wind, as a primary source of energy, costs nothing. In addition, this source of energy can be used decentralized. However, we will emphasize some factors of negative impact of wind generators during operation.

One of the operational disadvantages is noise, which is generated due to the sharp collision of air with the surfaces of the wind turbine blades. Also, significant harm to the environment is caused by the transportation of components to the wind generator assembly site and the transportation of these same parts to disposal sites after the wind generators have reached the end of their service life.

This creates infrasound (frequency up to 20 Hz). This can cause harm to all living organisms over a long period of time, as it disrupts the functioning of some internal organs, especially the auditory organs. Environmentalists are greatly concerned about the injury and death of birds caught in the rotating blades of wind turbines. This problem was discovered when large groups of wind turbines began to operate. Birds flying at the level of rotating blades have virtually no way to anticipate a collision with rotating blades. Research shows that in the United States, the world's second-largest producer of wind power, approximately 150,000 birds die each year from collisions with wind turbines.

Energy development requires additional use of not only renewable resources: raw materials for fertilizers in the case of bioenergy, fossil natural gas for the production of hydrogen fuel, energy from fossil sources, so scientists and engineers are actively working on this [1; 4; 6,151-159; 7, 165-176; 9, 7-14; 10, 123-143, etc.].

As is known, early wind turbines appeared in the times of ancient civilizations such as Egypt, Persia and China. With the help of these installations, various grain crops were ground. Later, already in medieval Europe, they began to improve the design of windmills and their widespread use in various fields.

The Dutch introduced many different changes to the design of windmills, mainly wind wheels. In the United States, by the middle of the 20th century, several million small wind turbines with a unit capacity of up to 0,75 kW were installed.

The advantages of wind energy are well known: low cost – wind energy can compete with nuclear, coal and gas power; zero cost of fuel component, inexhaustible source of energy and available in unlimited quantities; environmentally acceptable energy – energy production is not accompanied by carbon dioxide emissions; wind energy has no risks associated with the volatility of fossil fuel prices; security of supply – wind energy avoids dependence on imported energy resources; modular design, quick installation; electricity supply in terms of volumes becomes comparable with traditional generation methods; wind energy does not interfere with agriculture and industrial activities near wind power plants. Several studies have been conducted around the world to assess wind energy resources, most in detail for Europe.

These studies confirm that wind resources are huge and evenly distributed across almost all regions and countries. Insufficient wind power is unlikely to be a limiting factor for wind energy development worldwide. Wind energy, being a derivative of solar energy, is formed due to uneven heating of the Earth's surface.

Wind speed is the most important factor affecting the amount of energy a wind turbine can convert into electricity. High wind speed increases the volume of air passing through. Therefore, as wind speed increases, so does the amount of electricity generated by a wind turbine.

Every hour the Earth receives 100,000,000,000,000 kWh of solar energy. About 1-2 % of solar energy is converted into wind energy. Here are some examples of wind turbine power compared to their size (Table).

Table

Wind generator capacities and size

Parameter	1MWt	2,3 MWt	Notes
Mast height	50-60 м	80 м	According to data for 2022
Blade length	26 м	40 м	
Rotor diameter	54 м	82,4 м	

The largest wind turbine was launched in China in 2023 – the giant is 152 meters high, and each blade is 123 meters long and weighs 54 tons. This means that when the blades rotate, their coverage area is 50,000 square meters. This is the first time that such a large turbine has been connected to a commercial grid.

Currently, some experts call wind turbines a modern achievement of environmentally friendly technologies and emphasize their widespread use in Europe [2; 3; 11, 152-172; 13; 15, 1-11; 17, etc.]. Other experts say wind turbines are too noisy, too big or dangerous for biodiversity [5, 88-94; 8, 168-188; 12, 237-246; 14, 357-366, 16, 128-134, 18, etc.]. But one thing is for sure: wind energy is currently facing difficulties in Europe. In the Ukrainian Energy Strategy, it is planned that by 2030, 2 TWh of electricity in Ukraine will be produced by wind turbines.

One of the most pressing problems is the problem with turbine blades, which are difficult to dispose of. They contain complex composite materials – a combination of reinforced fibers (usually glass or carbon fibers) and a polymer matrix. These composites improve the performance of wind turbines.

They allow for lighter, longer blades with optimal aerodynamics. But their configuration also poses challenges for recycling. Composite recycling technologies already exist, but these solutions are not yet mature, commercially available, and cost-competitive. Support from other composites users and the recycling industry will be needed to make these technologies commercially viable.

As a next step, the wind energy industry plans to develop a roadmap that will detail the technologies needed to reuse wind turbine blades. There is a need to work closely with the chemical industry as a supplier of innovative chemical recycling solutions, as well as with other composites-using industries where the issue of composite recycling and disposal is also acute.

Today, scientists are working on alternative technologies for processing composite blades, such as mechanical recycling, solvolysis and pyrolysis, high-voltage pulse fragmentation, and other methods. Successful research in these areas will make it possible to create waste-free wind turbines.

A huge number of wind turbines will be dismantled in Europe in the near future – first-generation turbines are becoming obsolete and need to be replaced with more modern and efficient ones. This process, called capacity upgrades, has begun at different rates around the world. Currently, most of the blades are reused. But the number of decommissioned blades will be so large in five to ten years that the entire system will have to be replaced. Blades that are not reused or incinerated end up in landfill. For example, in the vicinity of the American city of Casper, there is a landfill where wind turbine blades are disposed of.

The reason for the burial is the imperfection of utilization processes, which do not yet allow to fully recycle the blades. Almost 900 blades are stored on the territory of the «graveyard». Officially, they are buried in the ground to be stored until new recycling methods are invented that will allow the fiberglass to be recycled.

The materials the blade is made of are safe and do not harm living organisms, soil or water. But the organization of landfills for the burial of non-decomposable parts is becoming a real problem – there are more and more wind turbines being decommissioned, the area for recycling is getting smaller, and the organization of such places disrupts the ecological balance, turning green areas into wastelands. For example, just three 50-meter blades of a low-power wind turbine contain about 20 tons of fiber-reinforced polymers (FRP). They can't be burned or landfilled like regular garbage.

And if we don't come up with at least some acceptable way of recycling, by 2050, 40 million tons of composites will be waiting for recycling. Such data is given by the research project *Re-Wind*, which is actively engaged in search of solutions to the problems of recycling.

There are several successful examples of how to recycle wind turbines. General Electric's renewable energy division and cement manufacturer Holcim have struck a deal to recycle wind turbine blades. The company said in a statement that they are exploring «new ways to recycle the blades, including as a building material for the construction of new wind farms». In December 2021, *GE Renewable Energy* and *Veolia North America* signed a «multi-year agreement» to recycle blades removed from onshore wind turbines in the United States. *GE Renewable Energy* said the blades will be shredded at *VNA's* Missouri plant before being «used as a replacement for coal, sand and clay at cement manufacturing facilities in the United States».

Citing an analysis by Quantis US, *GE Renewable Energy* said that recycling the blades will reduce CO_2 emissions from cement production by 27 %. As for water consumption, the net reduction would be 13 %. *Wind Europe* expects about 25,000 tons of blades to reach the end of their useful life each year by 2027. Germany and Spain will have the most decommissioned blades, followed by Denmark. By the end of the decade, Italy, France and Portugal will also begin to largely decommission blades, and annual decommissioning could double to 52,000 tons by 2030.

Vestas will analyze all aspects of the life cycle of wind turbines with the aim of increasing the recycling rate of blades and nacelles. The recycling rate of blades will be increased from the current 44 % to 55 % by 2030. The company will launch several initiatives aimed at improving the efficiency of blade management after their decommissioning. These will include new recycling technologies that are optimal for composite waste.

In early September 2023, *Siemens Gamesa Renewable Energy* announced that it was able to develop the world's first recyclable blades for wind turbines, the Recyclable Blade. A trial batch of six 81-meter-long blades has already been produced at a plant in Denmark. This is a major breakthrough in green energy, as until recently, blades were the only part of wind turbines that could not be recycled.

Conclusions. The results of special studies conducted by scientists from different countries have shown that the processing of composite materials of wind turbine blades with the separation of the original components for reuse is a complex scientific and technological task that has not yet been finally solved.

Within the framework of the «Industry 4.0» concept, work is underway to create a computerized system of robots with artificial intelligence, supporting the flow of data exchange between themselves and optimizing and regulating production processes independently. According to the authors, the above factors of the negative impact of wind power generation on the environment need to be thoroughly studied and their scale assessed, which will lead to the development of effective technologies and solutions to minimize the harm from wind generation. At the same time, the environmental advantages of this type of generators in comparison with fuel energy seem indisputable.

Experts assume that in 10-15 years the problem of solar panel disposal will also rise to its full growth, because they will have an increasing impact on the economics of projects. Promising further research into the problem of solar panel disposal, from our point of view, will be in great demand, since waste prevention is the first priority in the waste management hierarchy.

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