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STUDY OF PROSPECTS FOR THE DEVELOPMENT OF WIND ENERGY IN UKRAINE TO ENSURE THE SUSTAINABLE DEVELOPMENT OF THE ENERGY SYSTEM OF UKRAINE

ДОСЛІДЖЕННЯ ПЕРСПЕКТИВ РОЗВИТКУ ВІТРОВОЇ ЕНЕРГЕТИКИ В УКРАЇНІ ДЛЯ ЗАБЕЗПЕЧЕННЯ СТАЛОГО РОЗВИТКУ ЕНЕРГОСИСТЕМИ УКРАЇНИ

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Abstract. Purpose: The purpose of this article is to conduct a study of the prospects for the development of wind energy in Ukraine and its role in ensuring the sustainable development of the country's energy system.

Methodology: In this study it is used a comprehensive analysis, which includes an assessment of the resource base, technical capabilities and economic aspects of wind energy. The methodology includes collection and analysis of statistical data, modeling of economic scenarios, and takes into account current trends in the field of wind energy.

Results: The study shows that there are significant opportunities for the development of wind energy in Ukraine. Activation of this sector can help reduce greenhouse gas emissions and diversify the country's energy mix. The results of the analysis of resources and technical capabilities confirm the high potential of wind energy development in Ukraine.

Scientific novelty: The main contribution of this article is the actualization and in-depth study of the prospects of wind energy in the context of sustainable development of Ukraine. It is noted that this approach is relevant in connection with the challenges of climate change and the growth of demand for clean energy.

Practical significance: The results of the study can be useful for decision-making in the field of energy policy, development of wind energy and planning of investments in the energy sector in Ukraine. This article can serve as both a scientific basis and a source of information for authorities, businesses and the public interested in the sustainable development of Ukraine's energy system.

Formulation of the problem. Assessment of the current state of wind energy in Ukraine: the first task is to collect and analyze existing data on the development of wind energy in Ukraine at the current stage. This includes information on the number and size of wind farms, their location, electricity generation, investment and regulatory framework. Analysis of previous research and publications: Conducting a discussion and synthesis of the results of previous scientific research related to the development of wind energy in Ukraine. Establishing common points and unresolved aspects to which special attention should be paid. Identification of key success factors and inhibiting factors: Identification of key factors that contribute to the development of wind energy in Ukraine, including financial support, technological potential and legal framework. Also, an analysis of the inhibiting factors that can slow down or limit the development of this industry. Environmental Impact Assessment and Environmental Aspects: Carrying out an analysis of the impact of wind energy on the environment, in particular, the effectiveness in reducing emissions of CO₂ and other pollutants, as well as taking into account environmental aspects during the placement of wind power plants. Determination of prospects and recommendations for further development: formulation of specific prospects for the development of wind energy in Ukraine. Provision of practical recommendations on stimulating the development of this sector and maximizing its positive impact on the sustainable development of the energy system of Ukraine.

Key words: renewable energy; sustainable development; Ukrainian wind potential; efficiency of the wind systems.

Анотація. Метою даної статті є проведення дослідження перспектив розвитку вітрової енергетики в Україні і її роль у забезпеченні сталого розвитку енергосистеми країни.

У роботі використовується комплексний аналіз, що включає в себе оцінку ресурсної бази, технічних можливостей та економічних аспектів вітрової енергетики. Методологія включає збір та аналіз статистичних даних, моделювання економічних сценаріїв, і враховує поточні тенденції у сфері вітрової енергетики.

Дослідження показує, що в Україні існують значні можливості для розвитку вітрової енергетики. Активізація цього сектору може сприяти зменшенню викидів парникових газів та диверсифікації енергетичного міксу країни. Результати аналізу ресурсів та технічних можливостей підтверджують високий потенціал розвитку вітрової енергетики в Україні.

Основним внеском даної статті є актуалізація та поглиблене дослідження перспектив вітрової енергетики в контексті сталого розвитку України. Відзначається, що такий підхід є актуальним у зв'язку з викликами кліматичних змін та ростом попиту на чисту енергію.

Результати дослідження можуть бути корисними для прийняття рішень у сфері енергетичної політики, розвитку вітрової енергетики та планування інвестицій у секторі енергетики в Україні. Дана стаття може послужити як науковою основою, так і джерелом інформації для органів влади, бізнесу та громадськості, що цікавляться сталим розвитком енергосистеми України.

Оцінка поточного стану вітрової енергетики в Україні: першим завданням є збір та аналіз існуючих даних про розвиток вітрової енергетики в Україні на сучасному етапі. Це включає в себе інформацію про кількість та обсяги вітрових електростанцій, їх розташування, виробництво електроенергії, інвестиції та регулюючий фреймворк. Аналіз попередніх досліджень та публікацій: Проведення обговорення та синтезу результатів попередніх наукових досліджень, стосовно розвитку вітрової енергетики в Україні. Встановлення спільних точок і невирішених аспектів, на які слід звернути особливу увагу. Визначення ключових факторів успіху та гальмувальних факторів: Ідентифікація ключових чинників, які сприяють розвитку вітрової енергетики в Україні, включаючи фінансову підтримку, технологічний потенціал та правовий фреймворк. Також аналіз гальмувальних факторів, які можуть уповільнити або обмежити розвиток цієї галузі. Оцінка впливу на довкілля та екологічні аспекти: Проведення аналізу впливу вітрової енергетики на навколишнє середовище, зокрема, ефективність у зменшенні викидів CO₂ та інших забруднюючих речовин, а також врахування екологічних аспектів під час розміщення вітрових електростанцій. Визначення перспектив та рекомендацій для подальшого розвитку: формулювання конкретних перспектив розвитку вітрової енергетики в Україні. Надання практичних рекомендацій щодо стимулювання розвитку цього сектору та максимізації його позитивного впливу на сталий розвиток енергосистеми України.

Ключові слова: відновлювана енергетика; сталий розвиток; вітропотенціал України; ефективність вітрових систем.

ANALYSIS OF RECENT RESEARCH AND PUBLICATIONS

The issues of the current state, prospects for the development and classification of RES, in particular solar and wind energy, are considered in the works of such Ukrainian scientists as A.K. Shidlovskiy, S.O. Kudrya, O.I. Solovei, and foreign researchers such as M. Kaltschmitt, Streicher W., Weiss A. and Lund H. Economic competitiveness of aspects of solar energy was investigated by Hoffmann W., technological aspects of solar photovoltaic systems by Mohanty P., Muner T., Köhle M., resource and ecological, social and legal aspects of renewable energy – Bardacci R., Pasienza M.G., Tonini A. [5] and Bigerna S., Bolino K.A., Micheli S. The issue of RES development using energy storage technologies was studied by S.V. Shulzhenko and Radchenko O.L. Approbation of the system for evaluating modern technologies for obtaining electricity and the efficiency of renewable energy work was carried out by O. Havrysh and S. Narayevsky, proposals for the development of energy policy of Ukraine are presented in the work of F. Meissner and F. Ukerdt [6], the issues of regulation of renewable energy are highlighted by S. Voitko and O. Trofymenko.

SEPARATION OF PREVIOUSLY UNRESOLVED PARTS OF THE OVERALL PROBLEM

However, insufficient attention in the literature is given to the statistical assessment of the state and prospects of RES development, taking into account economic, social and environmental aspects in the context of the transition

to sustainable development and the development of state policy in the field of RES.

THE AIM OF THE STUDY

The purpose of this study is a systematic analysis and assessment of the prospects for the development of wind energy in Ukraine in order to ensure the sustainable development of the country's energy system. Conducting research consists in providing an informed basis for decision-making and formulating strategies for the development of wind energy in Ukraine, taking into account sustainable development and requirements for reducing the impact on the environment.

METHODS, OBJECT AND SUBJECT OF RESEARCH

The study of prospects for the development of wind energy in Ukraine will be based on the analysis of scientific articles, reports, technical literature and statistical data related to the development of wind energy in the country. This method will allow you to get an idea of the current state of the industry and its potential for future development.

OBJECT OF THE STUDY

The object of the study is wind energy in Ukraine in its full scope. This includes all aspects of the production, distribution and use of wind energy in Ukraine.

THE SUBJECT OF THE STUDY

The subject of the study is the prospects for the development of wind energy in Ukraine in view of its impact on the sustainable development of the country's energy system. This includes the analysis of

economic, ecological, technical and legal aspects of the development of wind energy, as well as the determination of opportunities for its integration into the energy system of Ukraine in order to ensure sustainable development.

BASIC MATERIAL

Wind power is one of the most efficient sources of electricity with a cost even lower than electricity generated from fossil fuels on average in the world. Technologies in the field of wind power are becoming more efficient every year, and their cost has been decreasing since 2009. Turbines differ in power, as a rule – from 1 to 5 MW, as well as in the type of suspension – with a horizontal or vertical axis. To build wind power plants, wind generators are combined in networks located on land (onshore) or on water (offshore) in the sea or ocean.

Wind and solar energy will play a leading role in the transformation of the global electricity sector. In the Global Energy Transformation Report 2022, IRENA provides possible scenarios for the development of global energy until 2050. An analysis of energy scenarios shows that there is a growing consensus regarding the growing weight of wind power in the energy balance over the coming decades. According to IRENA experts, onshore and offshore wind generation can provide more than one third (35%) of the total demand for electricity until 2050, which clearly emphasizes the importance of increasing the share of electricity generation from wind for the decarbonization of the energy system.

The President of Ukraine became one of the signatories of the Global Wind Energy Manifesto as part of COP26 and made an international commitment to completely stop domestic coal consumption by 2035 [3] and start gradually decommissioning thermal generation starting from 2022, then, on the other hand, the Government of Ukraine continued to direct all efforts to support the outdated nuclear energy infrastructure and adopted a state program for the development of the nuclear industrial complex until 2026.

Wind energy remained second, after solar energy, in the national RES sector, in terms of total installed capacity. However, it should be noted that it was the wind energy sector of Ukraine that added the largest number of new capacities to the country's "green" energy mix last year. The share of wind power capacities commissioned in 2021 was 30.6% or 358.8 MW, which is 2.5 times more than the volume of new wind power capacities commissioned in 2020 (144.2 MW). Thus, the total installed capacity of the wind energy sector at the end of 2021 was 1,672.9 MW. Before the beginning of the large-scale war, in Ukraine "green" electricity was generated by 34 wind power plants (WES) or 699 wind turbines, the average unit capacity of which is 3.5 MW.

The geography of the location of RES facilities differs according to the renewable source of energy that is natural and corresponds to the natural potential of RES of a

particular region. If wind power plants are located mainly in the southern and southeastern regions, primarily on the coast of the Black and Azov Seas — about 85%, then solar generation is much more widespread, but again, about 60% of industrial solar power plants are concentrated in the southern and southeastern eastern regions of Ukraine.

As of the beginning of 2022, Dnipropetrovsk (1,350.06 MW), Kherson (1,139.65 MW), and Mykolaiv (1,121.16 MW) regions are the leaders among all regions of Ukraine in terms of total installed renewable energy capacity. All these regions account for more than 37.3% of all RES capacities in Ukraine. As for the annual growth, the largest number of new RES facilities in 2021 were added in the Mykolaiv (168.7 MW), Odesa (149.1 MW), Kherson (145 MW) and Zaporizhzhia regions – 98.8 MW. It is interesting to note that these four regions, in particular, are the leaders in terms of installed wind energy capacity [2].

Small and medium-sized wind generation, which includes wind power plants with a capacity of up to 20 kW and a capacity of 20 to 500 kW, which have quite good prospects in Ukraine, developed quite slowly in the country before the war. Although there is no official information on the number of installed autonomous systems of small power generation, since the official statistics include only those solar and wind installations (WEU) of households that received a "green" tariff, but it is known for sure that before the beginning of the large-scale war in Ukraine there were 4 WEU and 8 combined solar + wind stations with a total installed capacity of 0.321 MW. It is known that 1,639 kWh were generated in 2021 by small wind turbines that receive a "green" tariff, and 163,148 kWh by combined plants.

Wind power plants. The cost of implementation of such projects compared to 2012. on average decreased by more than 30%. The largest concentration of implemented projects is characteristic of the coast of the Black and Azov seas, where it is possible to achieve the lowest present value of electricity due to the high coefficient of conversion of the wind flow. For such a region, the cost of projects has decreased by 40% over the last 7 years. At the same time, implemented projects in other regions of Ukraine demonstrate lower efficiency than the southern regions, and thus — a higher present value of electricity.

The reduction in costs for the construction of wind power plants has a slightly slower pace than in the field of solar energy. Power plants with a capacity of less than 5 MW have a higher tariff, it is 0.09 dollars. US per kWh. The average cost of electricity production in 2023 ranged from \$0.06 USD per kWh in China and Asia up to USD 0.09. USA per kWh in Africa. The average cost of electricity in North America was \$0.07. US per kWh. At the same time, the potential of wind energy in Ukraine is currently estimated at 16 to 24 GW.

Capital costs for the construction of wind power plants on land range from 1,287 USD/kW (China) to

3,024 USD/kW (Japan), in the sea and ocean – from 3,300 to 5,000 USD/kW. Of them, the share of costs for the main components of the stations for these options is as follows: turbine – 65–84% and 30–50%, connection to the network – 9–14% and 15–30%, construction – 4–16% and 15–25%, other expenses – 4–10% and 8–30%. The shares depend on the location and the technologies used. There is quite a wide range of prices for wind turbines, depending on the cost structure of the local market. In particular, in China, turbines are sold at a price of 644 dollars. US/kW, while in Japan their cost is 2100 dollars. US/kW.

The development of wind energy is based on modern technologies, which every year increase the efficiency of systems and increase the limits of their application. In the wind energy industry, these are technologies for building generators, blades and hangers. An important factor is also the construction of an optimal system for the transmission of electricity to the general network and the development of separate networks for RES. China, Germany, Japan and the USA are the leaders in the production of equipment for wind energy. Ukraine also has factories for the production of generators, there are potential opportunities for the production of equipment for wind energy.

The average wind speed in Ukraine is 3–6 m/s, which corresponds to a wind pressure of 400–600 Pa. In Europe, this indicator ranges from 3 to 11 m/s.

In Ukraine, the share of electricity production by solar and wind energy companies for 2023 (excluding temporarily occupied territories) is at a very low level compared to developed European countries and amounts to 0.92%, which in absolute terms equals 1560.9 million kWh.

An important factor in promoting the development of wind energy is the incentive system through the mechanisms of the "green" tariff, as well as the support of the industry with the help of financial incentive mechanisms (tax reductions, state and private programs at the national and local levels).

Wind energy in the modern world has become a symbol of the transition period in the energy industry. Rapid growth in consumer demand, environmental constraints, and rapid technological evolution make wind power an attractive and competitive source of sustainable electricity generation. Ukraine, which has a great potential in this field thanks to its natural favorability, has also become an active participant in this global movement. The study of prospects for the development of wind energy in Ukraine to ensure the sustainable development of the energy system is of great interest and requires a comprehensive analysis and assessment.

Ukraine has great potential for the development of wind energy due to its geographical location and natural conditions. Southern and Southeastern Ukraine, as well as the coasts of the Black and Azov Seas, have an excellent wind resource. Studies have found that these regions have significant potential for hosting wind farms.

This potential makes it possible to predict the growth of wind energy production and the reduction of greenhouse gas emissions, contributing to the preservation of the environment.

Wind energy is becoming more and more economically feasible thanks to the reduction in the cost of wind turbines and the increase in their productivity. The economic analysis includes the calculation of costs for the construction and operation of wind farms, as well as the assessment of costs compared to other sources of electricity. This takes into account financial incentives, including tariffs for renewable energy, which contribute to the attractiveness of investments in wind energy.

The use of wind energy is not accompanied by emissions of greenhouse gases and other negative effects on the environment. This makes wind energy one of the most environmentally friendly sources of energy. It contributes to the reduction of air and water pollution, improves the quality of the environment and contributes to the preservation of natural resources.

Technical aspects and integration into the energy system. The integration of wind farms into the energy system requires careful planning and coordination. The technical aspects include the selection of locations, the development of infrastructure for the collection and transmission of electricity, and the development of efficient control and forecasting systems for energy production. Legal and regulatory framework The legal and regulatory framework plays an important role in the development of wind energy. Favorable legislative conditions and stable tariffs for renewable energy are important incentives for investment in this sector. If the legal framework will promote innovation and development of wind energy, it will contribute to the sustainable development of Ukraine's energy system.

The dynamic development of wind energy is impossible without the stability of the energy system, since the efficiency of electricity generation from RES depends on weather conditions. Therefore, further development should take place together with the construction of energy storage systems, maneuvering capacities and hybrid RES power plants.

DISCUSSION OF THE OBTAINED RESULTS

The obtained results indicate important conclusions and implications for the development of this branch of energy in Ukraine. The discussion is divided into several key aspects: The potential of wind energy in Ukraine: One of the main topics of the discussion is the determination of the potential of wind energy in Ukraine. The results of the study indicate a large natural potential for the use of wind energy in various regions of the country. The discussion of this aspect includes an analysis of the regions with the greatest potential for the placement of wind farms. Economic feasibility: An important aspect of the discussion is the economic feasibility of wind energy

in Ukraine. The results of the study make it possible to determine the costs of construction and operation of wind power plants compared to other sources of electricity. The discussion includes an analysis of the cost of electricity generation using wind farms and their competitiveness in the market. Environmental impact: Environmental aspects of wind energy use are considered, in particular, its impact on reducing greenhouse gas emissions and other aspects of the environment. The discussion includes an analysis of the benefits of reducing environmental pollution due to the use of wind energy. Technical aspects and integration into the energy system: The results of the study allow to discuss the technical aspects of the implementation of wind energy, including the reliability of systems and infrastructure. The discussion also covers the issue of the integration of wind power plants into the general energy system of Ukraine. Legal and regulatory framework: The discussion also includes an analysis of the legal and regulatory framework governing wind energy in Ukraine. Possible changes and improvements in this framework are identified to facilitate the development of the industry. All these aspects of the discussion are jointly aimed at determining important steps and recommendations for the further development of wind energy in Ukraine and achieving maximum benefits for the sustainable development of the country's energy system.

CONCLUSIONS

As a result of the study of prospects for the development of wind energy in Ukraine with the aim of ensuring the sustainable development of the

country's energy system, the following conclusions can be drawn: wind energy has great potential in Ukraine. Research shows that Ukraine has favorable natural conditions for the development of wind energy. The abundance of usable wind resources makes this type of energy attractive for development. Sustainability of energy system development: The use of wind energy can contribute to the sustainable development of Ukraine's energy system, reducing dependence on traditional energy sources and reducing greenhouse gas emissions. Economic Feasibility: Economic analysis suggests that wind energy can be competitive in terms of the costs of building and operating wind farms. Environmental sustainability: The use of wind energy helps reduce greenhouse gas emissions and reduces the negative impact on the environment, which contributes to the conservation of natural resources. Technical capabilities: It is important to consider technical aspects in the development of wind energy, in particular the reliability of systems and infrastructure, as well as their integration into the energy system. Legal and regulatory framework: The development of wind energy in Ukraine requires the improvement of the legal and regulatory framework to facilitate investment and ensure the sustainable development of the industry.

The development of wind energy in Ukraine has great potential for ensuring the sustainable development of the country's energy system. To achieve this goal, it is necessary to consider all aspects, including economic, environmental, technical and legal issues, and develop the industry according to best practices and standards.

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