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PROSPECTS FOR RENEWABLE ENERGY DEVELOPMENT IN THE POST-WAR RECONSTRUCTION OF UKRAINE

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ПЕРСПЕКТИВИ РОЗВИТКУ ВІДНОВЛЮВАНОЇ ЕНЕРГЕТИКИ В УМОВАХ ПОВОЄННОЇ ВІДБУДОВИ УКРАЇНИ

The purpose of this paper is to explore and analyse the opportunities and prospects for renewable energy sources in the post-war reconstruction of Ukraine, to examine different technologies such as combined hybrid systems and biogas plants, with a focus on their socio-economic and environmental impacts, and to propose sustainable solutions that will contribute to energy security, economic recovery and long-term development.

The article focuses on the importance of renewable energy sources in the current post-crisis environment in Ukraine and their role in the country's recovery and further development. The article provides detailed data on the state of the renewable energy sector in Ukraine both before the full-scale invasion of the Russian Federation and during active military operations. It describes in detail the widespread methods of generating electricity from solar power and wind kinetic energy, as well as innovative experimental hybrid co-generation plants.

The article focuses on the perspectives of using biogas plants as an alternative fuel source for thermal power plants (TPPs) and combined heat and power plants (CHPs), considering their real efficiency, productivity and economic feasibility. Additionally, the potential benefits of using biogas power plants as an important step in creating a sustainable and long-term energy solution in Ukraine after the difficult period of war and crisis are considered. The transition to renewable energy sources is not only a strategic decision to ensure energy security, but also an important component of economic recovery and socio-economic development.

The paradigm shift in energy consumption contributes not only to creating a sustainable energy plan for future generations, but also to reducing dependence on imports and traditional sources that are subject to fluctuations in global markets. Integral to this transition is the creation of new employment opportunities and the advancement of renewable energy technologies, envisaged as linchpins for the country's economic revitalization post-war. While acknowledging the substantial investment required for this transformative shift, the article underscores the immense socio-economic and environmental dividends that will accrue in the future. This visionary pivot towards renewable energy is poised to play a central role in Ukraine's sustainable development, affirming its resilience and charting a course towards a more prosperous and environmentally conscious future.

Мета даної статті – ретельне дослідження та аналіз перспектив та можливостей використання відновлюваних джерел енергії в Україні під час та

після війни. Висвітлено важливість відновлюваних джерел енергії в умовах сучасних посткризових реалій в Україні, підкреслено їхню роль у відновленні та подальшому розвитку країни. Представлено деталізовані дані про стан сектору відновлюваної енергетики в Україні перед та під час воєнних подій. Здійснено огляд різноманітних технологій, зокрема комбінованих гібридних систем та біогазових установок, з фокусом на їхньому соціально-економічному та екологічному впливі. Запропоновано стійкі рішення для сприяння енергетичній безпеці, економічному відновленню та довгостроковому розвитку. Сфокусовано на поширених методах генерації електроенергії з сонячної та вітрової енергії, а також інноваційних гібридних когенераційних установках. Основний акцент зроблено на перспективах використання біогазових установок як альтернативного палива для ТЕС і ТЕЦ, враховуючи їхню ефективність, продуктивність та економічну доцільність. Досліджено потенційні переваги використання біогазових електростанцій як ключового елементу сталого та довгострокового енергетичного рішення для України після складного періоду війни та кризи. Підкреслено, що перехід до відновлюваних джерел енергії не лише стратегічний крок для забезпечення енергетичної безпеки, а й важлива складова економічного та соціального відновлення. Зміна енергетичного споживання сприяє не лише створенню сталого плану для наступних поколінь, але й зменшенню залежності від імпорту та традиційних джерел, що піддаються коливанням на світових ринках. Розглянуто розвиток технологій відновлюваної енергетики як ключового фактору економічного відновлення після війни. Визначено потребу значних інвестицій, підкреслюючи, що вони принесуть великі соціально-економічні та екологічні вигоди у майбутньому. Обґрунтовано, що такий стратегічний поворот до відновлюваної енергетики грає ключову роль у сталому розвитку України, закладаючи фундамент для процвітання та екологічно свідомого майбутнього.

Keywords: *Renewable energy sources, power system, photovoltaic power plants, wind power plants, hybrid systems, combined systems, biogas, efficiency.*

Ключові слова: *Відновлювані джерела енергії, енергосистема, фотоелектричні електростанції, вітрові електростанції, гібридні системи, комбіновані системи, біогаз, ефективність.*

Statement of the problem in general and its connection with important scientific or practical tasks. The full-scale war has created serious problems for Ukraine's energy sector. The use of thermal power plants (TPPs), CHPs and nuclear power plants (NPPs) for electricity generation is becoming less and less promising, as it requires constant consumption of fuel resources. In addition, the above-mentioned types of plants are hazardous to the environment and people in particular. Renewable energy sources allow generating electricity without consuming fossil fuels and provide environmentally friendly energy. In turn, decarbonization of the energy sector helps to reduce economic costs of fuel and find new ways to generate energy, such as using ordinary waste to power biogas plants, etc. The efficiency of RES generation depends on many factors, such as wind speed, sun position, etc. To ensure a stable frequency, the system uses a combination of different generation means, which increases the "flexibility" of the power system. Thus, the use of hybrid and alternative systems allows replacing part of the traditional energy sector without significant losses in power and quality of power supply. Such conditions as increasing the capacity of the energy sector without losing product quality and stability are among the key ones in the post-war recovery and development of the country.

Analysis of latest research and publications. The following scholars have studied the development of renewable energy in Ukraine: O. Trofymenko, O. Shevchuk, V. Omelchenko, N. Kolkowska, N. Pryshliak, M. Mykolaichuk, T. Drozdova, D. Burdyga and others. At the same time, despite existing research and scientific contributions in the field of renewable energy, a significant number of issues related to the study and expansion of experience in the use of alternative energy in the context of post-war reconstruction of Ukraine remain unresolved. This includes aspects of adapting modern technologies in the context of a full-scale Russian invasion and implementing effective solutions to meet the energy needs of the population and industry, which requires further research and practical measures to ensure the sustainable and efficient use of renewable energy in the context of post-war reconstruction in Ukraine.

Formulation of the objectives of the article (task statement). The objective of the article is to propose an integrated approach to solving the problems of Ukraine's energy sector during and after the war, through the use of hybrid renewable energy systems and biogas plants as an effective way to achieve an ecological alternative and a strategic solution to overcome the energy crisis exacerbated by the full-scale Russian invasion in order to ensure energy independence and sustainable development of the country in the context of post-war reconstruction.

Summary of the main research material. In 2021, the year before the full-scale invasion, the renewable energy sector in Ukraine mainly developed in accordance with the provisions of the Memorandum of Understanding on the Settlement of Problematic Issues in the Renewable Energy Sector of Ukraine. In general, the period of 2019-2021 is characterized by a higher volume of investments in renewable energy sources than in traditional ones, which can be used to describe the course towards "greening" the electricity sector (Fig. 1).

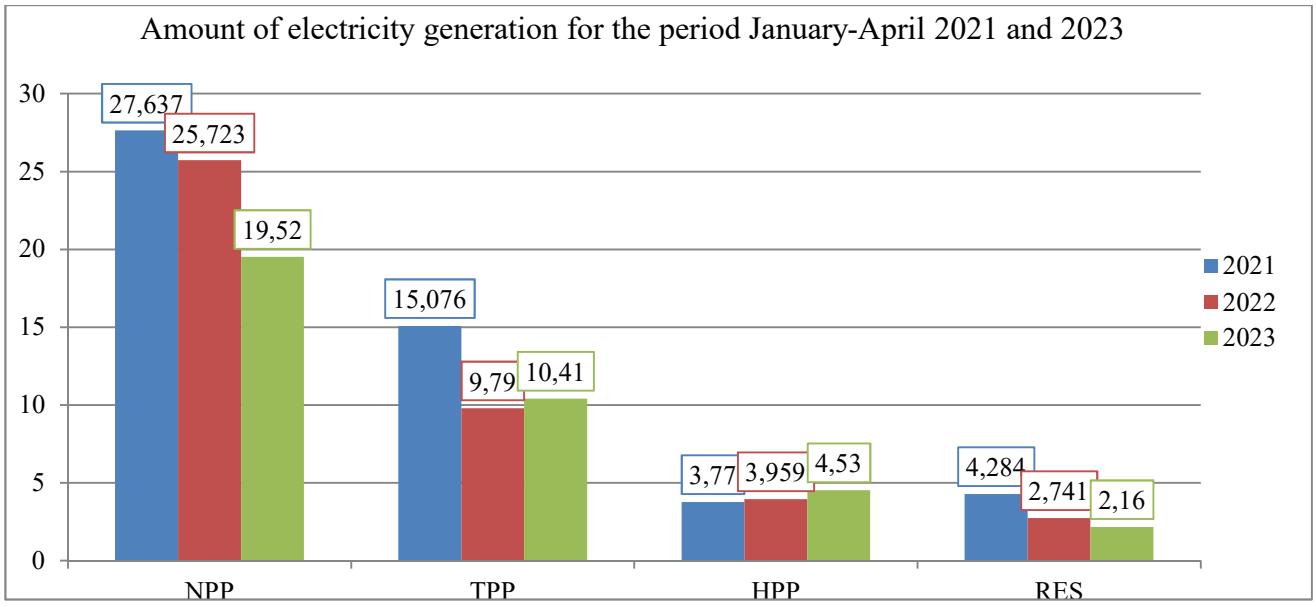

Fig. 1. Comparison of power generation capacities in January-April 2021–2023
Source: compiled by the authors based on [1]

Regarding the specific capacity of the country's power plants, 50.768 billion kW of electricity was generated in January-April 2021. Accordingly, the volume of electricity produced by alternative energy sources amounted to 4.284 billion kWh, which is 8.27% of the total consumption for the specified period. With the beginning

of the full-scale invasion, one of the first to suffer was the infrastructure, including the energy sector. Accordingly, the continued regular attacks, which targeted power plants, transformer substations, power lines and other facilities, negatively affected the system's performance and efficiency. Electricity generation by power plants in January-April 2021 was as follows: nuclear power plants (NPP) – 27.637 TW*h, thermal power plants and power centers (TPP) – 15.0765 TW*h, hydroelectric power plants (HPP) – 3.7705 TW*h, renewable energy sources (RES) – 4.284 TW*h. [1].

As can be seen from the diagram, after the military invasion, only thermal and hydroelectric power plants partially resumed generation, while the generation power of nuclear power plants decreased significantly due to the occupation of Zaporizhzhia NPP with a rated capacity of 6000 MW. Electricity generation from renewable sources also decreased, which was also caused by the occupation of significant amounts of generating facilities (Fig. 2).

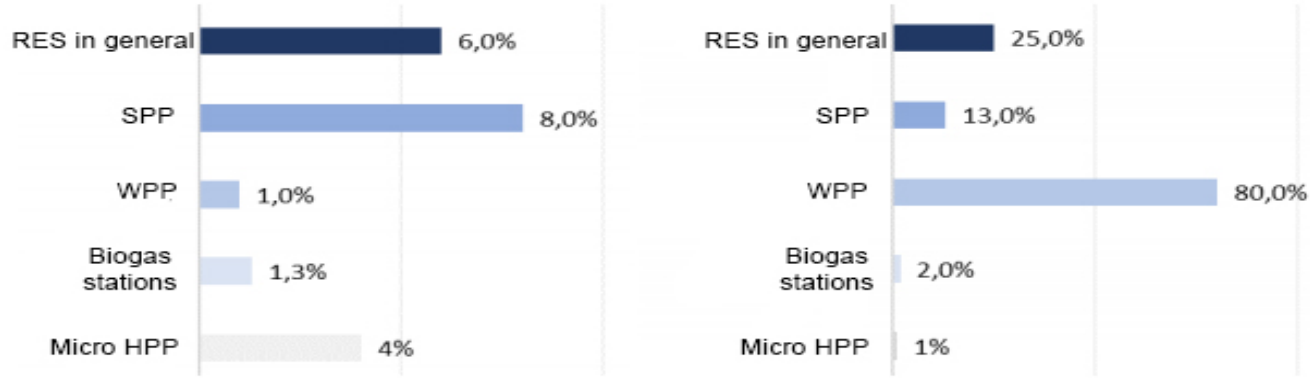

Fig. 2. Percentage losses of generating power in the electricity sector of Ukraine
Source: compiled by the authors based on [2]

The left part of the graph shows the percentage loss of generating potential of alternative energy sources due to their damage or destruction. The right graph shows the percentage loss of generating power due to their occupation. As you can see, wind power plants suffered the greatest losses, with more than 80% of their capacity lost due to occupation and damage. It is worth noting that the geographical location of RES has become perhaps their biggest problem, as the majority of them are located in the southern and eastern regions of Ukraine. Thus, from the beginning of the war to the end of 2022, more than 30% of the facilities were damaged in one way or another

by hostilities and attacks. The wind sector suffered the greatest losses. According to the Ukrainian Wind Energy Association, more than 75% of all capacities, or more than 1.4 GW, are currently shut down, and some of the capacities have been destroyed, such as the turbines of Myrnenska, Syvash and Novotroitska stations in Kherson region. As can be seen from Fig. 2, the majority of wind power generation capacities are currently under occupation, and those that have not been damaged or destroyed, unfortunately, produce electricity for the needs of the occupiers. Also, almost 600 MW of wind power generation power in Zaporizhzhia region is out of operation due to the damage to 330 kW of the power transmission line in Melitopol. It is worth mentioning that this damage figure may be higher, as the level of damage to those stations that are under occupation by Russian terrorists without physical access to them is currently impossible to determine. However, it is known for certain that there are renewable energy assets worth more than USD 5.6 billion in the area of active hostilities, and more than USD 3.6 billion in the regions neighboring the areas where active hostilities are taking place. 1.8 MW of bioenergy capacity in Chernihiv was damaged, while bioenergy plants with a total capacity of 2 MW were located in the occupied territories of Donetsk region, namely in Volnovakha and Mariupol, meaning that 3.8 MW of the 245 MW installed at the end of 2021 are currently not supplying electricity to the grid [3]. In general, wind and solar energy generation has decreased by more than half compared to its pre-war level. According to the UNDP, as of April 30, 2023, the generating capacity has more than halved from 37.6 GW to 18.3 GW. The maneuverable power of the system decreased by 68 percent, from 14.3 GW to 4.6 GW, primarily at thermal power plants. Available nuclear generation capacity decreased by 44 percent, from 13.8 GW to 7.7 GW [4].

This is mainly caused by two factors. First, as mentioned above, as a result of direct military attacks or to prevent damage to electrical equipment. Secondly, the growing problems associated with the destruction of demand and the high inflexibility of the generation subject to dispatch, especially solar generation, given that the cumulative capacity of solar generation has exceeded 6 GW.

That is why, in our opinion, to ensure constant power generation using renewable energy sources, it is necessary to use hybrid systems consisting of several generating devices, such as wind turbines, photovoltaic power plants, micro-hydroelectric power plants and/or other traditional generators operating on fossil fuels. Hybrid systems allow combining these energy sources to achieve the most efficient work and stable supply of electricity, especially when the time of day and weather conditions change. The advantages of a hybrid renewable energy system are as follows:

- two or more renewable energy sources can be integrated into one system based on the local renewable energy potential;
- the entire hybrid renewable energy system (e.g., photovoltaic, wind, and hydropower) produces no form of emissions;
- modular (photovoltaic and wind) systems are easy to install and, in most cases, do not require design for home use;
- small hybrid systems are cheaper than large and complex systems such as nuclear;
- a small hybrid system is best suited for autonomous electrification;
- the fuel for a hybrid renewable energy system is available, free and inexhaustible, so the electricity generated by these systems does not depend on the price of fuel;
- autonomous commercial photovoltaic or wind systems do not produce energy around the clock and throughout the year. the combination of PV and wind energy has advantages such as reduced battery capacity and diesel fuel requirements (if a conventional generator is used as a backup), among other benefits.

It should be noted that the only alternative source of electricity that has hardly suffered any negative consequences from Russian aggression is hybrid micro-hydroelectric power plants (MHPs), which are mostly located in the western part of Ukraine. It should also be noted that according to ANDRITZ, the technically possible national hydropower potential in Ukraine is about 21500 GWh per year [5]. The

operation of such a station is based on a hybrid charge controller used to connect two power sources: a photovoltaic panel and a wind turbine (Fig. 3).

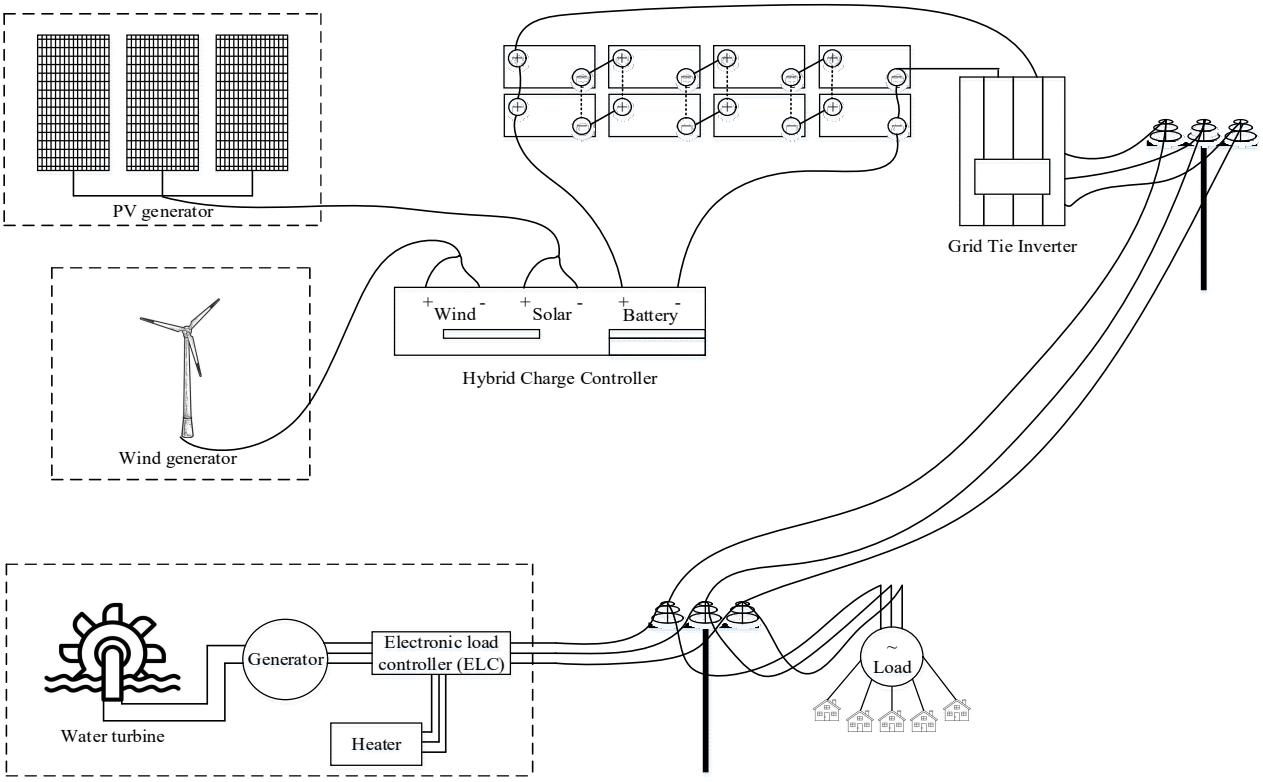

Fig. 3. Schematic diagram of a typical hybrid micro-hydroelectric power system (MHP) - photovoltaic-wind power system

Source: compiled by the authors based on [5]

Depending on the load, the excess power is used to charge the battery. The battery is used to store excess energy and provide power to the load in case of insufficient power generation from the hybrid system. A DC/AC inverter is required to change the DC voltage to AC voltage to meet the demand of the consumer load. The outputs of all the chargers, the battery and the input terminals of the DC/AC converter are connected in parallel. At the same time, instantaneous changes in solar radiation and wind speed greatly affect energy production, making this system limited in its application under different atmospheric conditions. Hybrid photovoltaic systems, which are best suited for reducing dependence on fossil fuels by utilizing available solar radiation in hot climates, can be another option for using combined power generation systems. These energy systems are considered to be one of the most cost-effective solutions for meeting the energy needs of remote areas.

At the same time, the combination of photovoltaic and wind energy in a hybrid energy system reduces the need for batteries and diesel fuel. It is worth noting that the feasibility of a hybrid photovoltaic/wind energy system strongly depends on the solar radiation and wind potential available at the site. It is believed that the ratio of photovoltaic and wind energy in a hybrid photovoltaic/wind energy system should be 70% in order to have the lowest cost [5]. According to the International Renewable Energy Agency (IRENA), Ukraine has a total wind energy potential of 16-24 GW, with 16 GW considered economically feasible [6].

In view of the above, hybrid photovoltaic and wind power systems are very promising in Ukraine in particular: In the Zaporizhzhia region, where the 200 MW Prymorska wind farm is located, and the integration of wind and solar energy can increase energy production power and grid stability in the region [4]; in Mykolaiv region, where DTEK has started construction of the first stage of the 500 MW Tiligul wind farm in the region. Given its proximity to the front line and the critical need for energy balance, Mykolaiv is the best location for a hybrid energy system [7]; in the Kherson and Kharkiv regions, where the combination of solar and wind energy resources can significantly contribute to energy rehabilitation and increase the sustainability of these areas [8].

At the same time, one of the problems associated with hybrid systems is maintaining a stable and reliable power supply with an increasing percentage of renewable energy, which is associated with the variability and intermittency of power supply in the system [9]. Solar and wind power generation can be weather-dependent, which leads to fluctuations in energy production. This problem can be solved by incorporating energy storage systems, such as batteries or pumped hydro, to store excess energy during periods of high generation and release it during periods of low generation [10]. An additional obstacle is the integration of hybrid systems into existing power grids, which may require modernization to accommodate fluctuations in renewable energy production. Another problem associated with hybrid systems is the monitoring of the status and management of electricity distribution, which requires sophisticated artificial intelligence solutions to ensure system reliability and

stability. In addition, the cost of implementing hybrid systems, including the installation of multiple energy sources and storage systems is very high [12].

In our opinion, the following problems should be added to the above:

- underdeveloped infrastructure for storing and transporting electricity from wind and solar power plants;
- insufficient development of electricity storage technologies, which can lead to energy losses and instability of the power grid;
- underdeveloped technologies for the production and installation of equipment for wind and solar power plants;
- insufficient development of technologies for monitoring and controlling the power grid to ensure the stability and security of energy supply.

That is why,in the context of a full-scale war with the Russian Federation, the provisions of the Ukraine Recovery Plan until 2032 [4], presented by the Government of Ukraine in July 2022 at the international donor conference in Lugano, have become a priority for the further development of renewable energy sources. (Table 1).

Table 1. Key areas of development included in the Recovery Plan of Ukraine

Document	Key areas of development envisaged by the documents
The National Council for the Recovery of Ukraine from the Consequences of the War (2022)	Construction: 5-7 GW of new solar and wind power plants to expand Ukraine's export capacity, 30+ GW of RES facilities for renewable hydrogen production, 3.5 GW of hydroelectric power plants and pumped hydroelectric power plants. Commissioning: 1.5-2 GW of peak capacity, 0.7-1 GW of batteries and 15 GW of electrolysis plant capacity, 0.7-1 GW of batteries; Development of the sector of small solar generation: Installation of photovoltaic systems on the roofs of buildings and in households The capacity of electrolysis plants: 15 GW; Estimated investment: 130 billion US dollars

Source: compiled by the authors based on [4]

By 2032, it is planned to expand the export capacity of Ukraine through the construction of new solar and wind power plants with a total capacity of 5-7 GW. Also in the plans is the development of renewable energy using 30+ GW of facilities from renewable sources for the production of hydrogen, as well as the construction of 3.5 GW of hydroelectric power plants and pumped hydroelectric power plants. In addition, 1.5-2 GW of peak power, 0.7-1 GW of batteries and 15 GW of electrolysis plant capacity are expected to be put into operation in the next 10 years. The total volume of future investments in the national program "Energy independence and green course" is currently estimated at 130 billion dollars. The outlined objectives within Ukraine's Renewal Plan until 2032 fail to encompass the complete potential offered by renewable energy sources. For instance, as indicated by the Ukrainian Wind Energy Association, the wind energy sector in Ukraine has the potential to incorporate a minimum of 7 GW of new wind farms into the existing installed capacity by 2030. This prospect stems from two main factors: Firstly, by the end of 2021, 4 GW of new wind energy projects had already obtained construction permits, with the majority expected to be operational between 2024 and 2026. Secondly, the proposed average unit capacity of wind turbines slated for operation in the new wind farms from 2021 onwards is 6 MW or higher [4].

Regarding the future progression of solar energy, considering the prevailing market conditions in Ukraine and aligning with the objectives established in the RePowerEU Plan, there will be an active focus on the growth of small-scale solar generation. This specifically pertains to the installation of photovoltaic systems on rooftops and in residential properties. Furthermore, Ukraine's Recovery Plan until 2032 does not establish precise objectives for the advancement of offshore wind energy, such as offshore wind farms. Nonetheless, it's important to highlight that, according to the World Bank, Ukraine boasts one of the most promising technical capacities for offshore wind energy development in the Black Sea among all the countries in the Black Sea region. The theoretical technical potential for offshore wind energy in the Black Sea and the shallow waters of Ukraine stands at an impressive 250 GW. This is notably higher when compared to the collective

theoretical potential of all Black Sea countries, which amounts to 435 GW. The growth of the offshore wind energy market is poised to notably bolster Ukraine's export potential. Offshore wind presents a considerable advantage over onshore wind due to its heightened and consistent power generation. Offshore wind turbines yield substantially larger quantities of environmentally friendly electricity. This surplus electricity holds the capacity to not only suffice for domestic consumption within the southern regions of Ukraine (illustrated by an example: a 1000 MW offshore wind farm can generate ample "green" hydrogen to heat approximately 250,000 households) but also enables surplus energy for export to the European Union [4].

Moreover, offshore wind farms possess the ability to operate efficiently without the necessity of grid connections. The majority of solar and wind power installations are concentrated in the southern region of Ukraine, which is currently facing technical limitations in integrating new power facilities into the grid. Overloading the grid with excess power could potentially result in grid failure. One significant advantage of offshore wind farms lies in their potential for autonomous operation. They can function as connectors between maritime region countries (such as Turkey, Romania, Bulgaria, Georgia, and Ukraine) or operate independently to produce electricity for the creation of renewable hydrogen.

This war has showed the whole world what the price of traditional energy is and can be. That is why the specialized associations for renewable energy sources in Europe and Ukraine, namely WindEurope, SolarPowerEurope, Ukrainian Wind Energy Association and Solar Energy Association of Ukraine, are convinced that the post-war reconstruction of Ukraine should be based on renewable energy sources and that Ukraine has sufficient technical and resource potential to achieve a 50% share of renewable energy in the total electricity balance of Ukraine by 2030. Ukraine needs this not only to ensure its energy security, but also to upgrade energy infrastructure and compensate for the electricity that will be lost due to the decommissioning of outdated fossil fuel generation.

The use of biogas plants to generate biomethane as an alternative to fossil fuels for traditional CHP and TPPs is a very promising area of development in the field of

alternative energy sources. The principle of functioning of a biogas plant is to produce gases such as methane and other by-products such as carbon dioxide, etc. by decomposing (breaking down complex substances into simple/basic ones) biomass (organic matter - natural substances derived from plants and animals, such as cow manure, vegetable waste) in the absence of air (anaerobic fermentation) and in the presence of water. In other words, biomass is mixed with water and then decomposed by anaerobic bacteria into gases (methane, hydrogen, carbon dioxide) and other by-products (manure, fertilizers).

Let us analyze the above diagram, going through the following stages of the biogas plant operation. The inlet of the biogas plant is the mixing tank. In this tank, the biomass is mixed with water to form a slurry. The slurry is a mixture of water and biomass. The mixing tank is also called the slurry compartment. This slurry then enters the biomass tank (digester). The biomass tank (sealed chamber) is an oxygen-free zone (anaerobic zone) and is inhabited by microorganisms (anaerobic bacteria). Therefore, these microorganisms in the tank decompose the biomass, which means they break down the complex substance into basic substances such as methane, hydrogen, carbon dioxide, and hydrogen sulfide. The resulting gases are stored in a gas tank and, if necessary, are discharged through a gas outlet. Other by-products, besides the gas produced during decomposition, are manure and fertilizers. The biogas produced in a biogas plant has many commercial and domestic applications, for example, it can be used as a fuel, even as a household gas, in gas engines. Biogas is used as a fuel for boilers and internal combustion engines as an alternative to natural gas in thermal power plants and CHP plants to generate heat and electricity. As expected, perhaps the most important issue in the use of biogas plants for the post-war restoration of Ukraine's energy sector is their efficiency and profitability in the relevant conditions.

Compared to thermal power plants, biogas power plants have many advantages, such as the fact that the operation of biogas plants has no impact on the environment, and the fact that the raw materials for biogas power plants are

renewable, so there will always be a resource to provide the required generation capacity.

After fermentation in biogas plants, high-quality organic fertilizer remains, which is used to replace mineral fertilizer. So ordinary plant and animal waste is already a fertilizer, but the efficiency is only 0.15 of the maximum possible, while processing into biogas, this ability improves, for example, a biogas plant processes 37 thousand tons of waste per year, which produces 35 thousand tons of fertilizer. Valuable fertilizers have 3.5 kg of nitrogen per 1 ton of fertilizer. Fertilizers that have been treated are much better than organic fertilizers such as peat, manure or litter [13].

Main advantages: conventional organic fertilizers, if not recycled, can harm the soil, while biofertilizers do not, as they are environmentally friendly; there is an active microflora that ensures plant growth, without pathogenic microflora; animal waste contains a lot of harmful weeds, which harms cultivated plants. biofertilizers usually do not have the kind of composition that ensures the growth of only the right plants; valuable bio-fertilizers immediately fulfill their main task without an adaptation period, which would take time.

The idea of reducing emissions of harmful gases is to replace non-renewable sources, where different types of fuel are burned in large quantities, emissions are released into the atmosphere, thus harming our planet, and by replacing power plants, the impact of greenhouse gases on the atmosphere is reduced while maintaining generating capacity. Also, when working on farms, animal waste is placed in anaerobic ponds, which causes methane to be released into the atmosphere, although this can be changed, namely, biogas is transferred to a cogeneration unit and then burned [8].

Therefore, given the above, we can state that the further development of biogas plants is determined by a number of promising areas in the context of sustainable development of the energy sector. In particular, the introduction of the latest technological solutions and optimization of anaerobic biomass conversion processes contribute to increasing the efficiency and production capacity of biogas plants.

Expanding the use of various types of feedstocks, including organic waste from agriculture and urban areas, is seen as a promising way to diversify the sources of biomass input. Additionally, improving the processes of biogas collection and transmission will contribute to more efficient use of the energy produced. The introduction of innovative methods of biogas purification and preparation for further use in energy systems will help to increase its energy value and meet modern environmental standards. Such a set of measures will help biogas plants to become an important tool for the production of sustainable and environmentally friendly energy, thereby contributing to the implementation of the concept of renewable energy sources and ensuring energy sustainability.

Conclusions and prospects for further research in this area. The hostilities in Ukraine are having a significant impact on the energy sector, creating challenges related to dependence on conventional power plants. The declining viability of thermal power plants, combined heat and power plants and nuclear power plants raises concerns about fuel consumption, environmental risks and economic costs. The development of renewable energy sources is becoming an important solution to address these issues by offering a sustainable and environmentally friendly alternative. Under these circumstances, a key challenge for Ukraine in its post-war recovery is to ensure an efficient and sustainable transition to renewable energy, taking into account factors such as the volatility of energy production and the need to increase capacity without compromising the quality and stability of energy supply.

The scientific novelty of the study is to identify specific ways to integrate renewable energy sources and use the latest technologies to create a resilient and efficient energy system in the context of post-war recovery, to justify the need to use methods of electricity production from solar energy and kinetic wind energy, as well as innovative experimental hybrid cogeneration units. This provides an opportunity to highlight the theoretical and practical recommendations of one of the options for achieving energy independence and sustainable development of Ukraine in the post-war period. The rationale for the use of solar and wind power generation methods in the context of post-war reconstruction creates fundamental approaches to ensuring

the sustainability and development of the energy sector. The emphasis on innovative hybrid cogeneration plants indicates the need to find and implement new technological solutions to optimize energy production and increase its efficiency in the context of post-war recovery. Such an integrated approach is essential for ensuring energy security and developing sustainable energy in the long term.

Based on the results of the study, it is clear that Ukraine has enormous potential to use alternative renewable energy production systems as a catalyst for post-war development and reconstruction. Among the most promising areas is the introduction of combined hybrid systems. These systems intelligently integrate various energy sources, including kinetic wind and solar energy, traditional fossil fuels, small river energy, and efficient energy storage systems. This versatility not only increases the stability of decentralized power supply, but also helps to maintain the quality of electricity and increase its production.

Another important aspect highlighted in the article is the use of anaerobic digestion biogas plants. This technology allows for the efficient conversion of organic waste into biogas, which can be used as a renewable energy source. Biogas can play a crucial role in diversifying Ukraine's energy mix and reducing its dependence on traditional fossil fuels.

The adoption of these integrated hybrid solutions offers a multifaceted set of benefits for Ukraine's energy landscape. First, they significantly increase the stability of the decentralized electricity supply, thereby reducing the susceptibility to disruptions and outages that could hamper post-war recovery efforts. This increased reliability of electricity distribution is complemented by improved quality of electricity supply, ensuring that it meets the needs of different industries and households. In addition, the introduction of these technologies has the potential to increase the total amount of electricity generated, a critical component for economic growth and development.

Furthermore, by implementing these innovative solutions, Ukraine can significantly enhance its energy security. Diversifying energy sources and

introducing renewable energy production systems reduces the country's vulnerability to supply disruptions and external energy dependence.

An important aspect of the transition to renewable energy sources is a significant reduction in environmental damage. Shifting from fossil fuels to cleaner alternative energy sources helps to mitigate environmental impacts, which is essential for a sustainable and resilient energy sector. This, in turn, aligns with global sustainable development goals and supports Ukraine's commitment to environmentally responsible energy practices. It is important to recognize that such a transformational shift from fossil fuels to renewables will indeed require significant financial investment.

However, the long-term economic, environmental and energy benefits and socio-economic gains that Ukraine can achieve from this strategic transition far outweigh the initial financial costs. This transition not only enhances energy security, but also acts as a catalyst for economic revival, green job creation, technological innovation and, ultimately, the holistic sustainable development of Ukraine in the post-war period.

The prospect of further research lies in exploring the socio-economic and environmental implications of integrating advanced renewable energy technologies into post-war reconstruction in Ukraine, as well as conducting in-depth cost-benefit analyses to optimize resource allocation and maximize the long-term benefits of sustainable energy solutions.

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