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# Ukraine's energy supply in the defense sector: The first lessons of war

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## Abstract

The terrible consequences of the Russian-Ukrainian war, which continues on the territory of the Ukrainian land, and the consequences of natural disasters indicate the need to create alternative (reserve or emergency) sources of energy supply for enterprises, institutions, and individual households, and objects of small forms of management, especially outside the points of permanent deployment. Ensuring an uninterrupted and stable electricity supply to all these forms is an extremely important problem for Ukraine as the country faced a large number of challenges regarding energy independence due to numerous missile strikes. The purpose of the study was to analyze the energy system and the level of damage to Ukraine after the Russian missile attacks, the impact on the state of energy supply of individual facilities and consumers of military camps, examine the possibilities of using emergency and backup energy sources and alternative energy, in particular, solar and wind. The study analyses the destruction of the energy system of Ukraine as a result of missile attacks and the possibilities of using emergency and backup energy sources and alternative energy, in particular, solar and wind, and the investigation of the potential and opportunities to attract investment in the field of alternative energy. Special attention is paid to small business facilities, including military camps. In the course of the study, it was determined that Ukraine has a geographical location that provides space for the installation of various alternative energy systems and the possibility of combining them to diversify and improve the stability and reliability of the Ukrainian energy system. The practical importance of the study lies in the ability to make more informed decisions regarding the implementation of programs aimed at switching to alternative and decentralized energy sources. This will make the country's energy infrastructure more stable and allow better meeting the energy needs of small forms of management, individual farms, military units, formations, and infrastructure facilities.



*Keywords*: Military formations, Military towns, Military infrastructure complexes, Reserve (emergency) sources, Alternative sources

## 1. Introduction

Destructive processes associated with the consequences of emergencies, and catastrophes, require the search for alternative sources of energy supply and analysis of the capabilities of known sources of electric energy, including “green” energy. The terrible consequences of the purposeful destruction of Ukrainian energy system facilities during Russia’s aggressive military operations on the territory of Ukraine add urgency to the problem. Sustainable provision of electric energy to enterprises, institutions, and organizations of various forms of ownership, all segments of the population, including military formations and provision of military camps during the Russian-Ukrainian war, becomes a cornerstone problem not only for Ukraine but also for many countries of the world that care about the proper life support of their population. Therefore, the issue of justification, search, and use of alternative sources of electric energy is an important task today.

There are several reasons to examine Ukraine’s energy supply problem during the war, particularly for small management forms (enterprises, farms, private farms, military towns, military infrastructure complexes) and military formations. First, energy supply is a critical aspect of the country’s national security and stability. Investigating this issue helps to understand the potential threats, risks, and vulnerabilities of the energy system, and develop strategies and measures to prevent them and provide electricity to the country’s population. Backup sources of electricity, in turn, can help in cases of emergency internet access or electricity supply to critical infrastructure facilities (military camps). Energy supply is an important component of economic development. Therefore, the study of this topic allows for assessing energy resources, the potential of energy, and energy efficiency, which will contribute to the development of the industry, attract investment, and support the energy sector for economic growth.

The problem of the current situation in the energy sector of Ukraine is the instability of the energy supply, dependence on the import of conventional energy resources, and negative impacts on the environment. One of the options for solving the problem of instability of the electric power system can be renewable energy sources (RES), because in this case, inexhaustible wind, solar, and other natural resources will be used, which are not limited in reserves and do not require additional mining activities.

As the importance of reliable electricity supply cannot be overstated, recent events have highlighted the critical role of energy infrastructure, especially in regions facing conflict and instability. The aggressive military operations carried out by Russia on Ukrainian territory have led to intentional destruction and disruption of Ukraine's energy system. Amid this conflict, the need for a sustainable and stable energy supply has become paramount. This study aims to assess the extent of damage to Ukraine's energy infrastructure, and its repercussions on various facilities and consumers, including military camps, and explores the potential of alternative energy sources as a crucial backup solution in these challenging conditions.

According to the assertions by [1], investigating the potential of using renewable energy sources will help to identify possible obstacles and challenges that may arise during their implementation. This process will include an analysis of legal, financial, and technological aspects, the need to create an energy infrastructure for energy storage and distribution, the modernization of power grids, and issues of social acceptance. [2] states that investigating the possibilities of using renewable energy sources will also help identify optimal technologies and solutions for different regions and conditions in Ukraine. For example, some areas may have substantial potential for solar power, while others may be more favorable for wind or hydropower. Understanding these options and their optimal use will help maximize renewable energy sources’ efficiency.

In the paper by [3], it is indicated that one of the advantages of using renewable energy is its independence from centralized networks. Solar and wind power is used with the necessary devices on site. For example, on the roof of a house or in the vicinity of a building, which makes them independent of the centralized electrical network and allows them to continue generating electricity even if the main power source is disconnected. According to [4], some RES can be equipped with battery systems to store excess energy. This allows the use of the stored energy during periods of power outages when the main power source is unavailable. Battery systems can provide energy for military camps and small farms for a certain period.

[5], in turn, noted that conventional energy sources can be exposed to various risks and emergencies, especially in conditions of war, continuous missile strikes, and price fluctuations. The use of renewable energy sources allows diversifying energy sources and reduces the risks of dependence on the main network. According to [6], the use of renewable energy sources as a backup energy source can provide economic benefits in the long term. Due to the lower cost of solar panels and wind turbines, the installation of renewable energy systems is becoming more affordable, and reducing energy consumption from the grid can lead to lower energy bills.

The purpose of this study is to examine the level of damage to the energy system of Ukraine and determine the impact on the state of energy supply of individual facilities and consumers of military camps, analyze the possibilities of using alternative energy in Ukraine in conditions of war, instability of the energy system and the urgent need for backup energy sources.

## 2. Research method

The main method used during the study was statistical analysis, which allowed for estimating the energy potential and economic feasibility of using renewable energy sources to provide military camps and assess opportunities for their development. All statistics collected during the operation were classified according to the types of energy sources, such as solar, and wind, which allowed determining the volume of each type and establishing their contribution to the total energy capacity. Analysis of data on the energy system of Ukraine allowed for analyzing the scale and level of damage to the country's electric power system. Using this method, it was also possible to assess the urgency of the problem related to the stability of the Ukrainian energy system. This allowed determining the possibility of using backup and alternative means of generating electricity as emergency ones, after which an assessment of the possibility of improving the state of the country's energy for military towns, military infrastructure complexes supply structure, and the potential for using renewable energy as a resource for this was conducted. Documents and reports on damaged and destroyed objects were also analyzed. A loss assessment method was used to determine the cost of losses, which was based on prices and costs for restoring or replacing damaged objects. The geographical distribution of damaged and destroyed objects was examined and analyzed to identify the regions that suffered the greatest and most substantial losses. All the information obtained was systematized and generalized to create a complete picture of the extent of damage and destruction of objects in various areas, in particular, administrative, and domestic.

The efficiency, stability, and economic feasibility of using renewable energy sources were determined using the analysis method. Its main purpose is to help determine how effective and viable the use of renewable energy in a military camp in a particular region or area can be. In the course of the study, a variety of information was collected about the potential of renewable energy sources, such as solar energy, wind, and hydropower. The data provided included the location of potential sources, resource intensity, and climate conditions. The technical feasibility and efficiency of various renewable energy technologies were evaluated and technical characteristics, scope of use, installation and maintenance cost, and prospects for improving technologies were considered. Further, the possibility and stability of integrating renewable energy sources into the existing electrical system were determined.

In the course of the study, it was determined how the use of renewable energy sources could help reduce the vulnerability of the Ukrainian energy system to provide military camps for blackouts. Energy storage, peak load balancing, transmission and distribution systems, and network planning were also considered. The study has helped identify which energy sources are more attractive and efficient from an environmental and economic standpoint. Based on the analysis, some features of the operation of systems based on renewable energy sources were identified, which can be used as a backup source of energy supply for the population, various small businesses, military camps, formations, and infrastructure complexes.

## 3. Results

Electricity is a necessary component of modern life, and almost all aspects of society depend on it. The population cannot live without electricity, as it is the basis for ensuring comfort, safety, health, and progress. Electric energy is necessary for lighting houses and streets, operating electrical appliances, providing heating, functioning of medical equipment, storing information on computers and servers, and providing military camps. In addition, electricity plays an important role in ensuring safety (operation of warning systems, access control, and fire safety systems). All this makes electricity an indispensable component of the modern way of life that plays an important role in meeting the needs and development of society.

Figure 1 presents a visual comparison of the Ukrainian territory from satellite images taken at two distinct points in time: before the outbreak of full-scale conflict and after the commencement of massive missile strikes. These images offer a poignant illustration of the dramatic impact that the conflict has had on Ukraine’s energy infrastructure and overall urban landscape. The image captured before the outbreak of war in October 2022, depicts a relatively peaceful and well-illuminated Ukrainian territory at night. The widespread presence of city lights signifies the normalcy of urban life and the functioning of energy systems. It serves as a reminder of the vitality of the region's energy infrastructure before the onset of hostilities.

The image taken after the initiation of massive missile strikes reveals a drastically altered landscape. The noticeable reduction in city lights and the prevalence of darkened areas are direct consequences of the deliberate targeting of energy infrastructure. These missile strikes have disrupted the electricity supply, plunging numerous regions into darkness and severely impacting the daily lives of Ukrainian civilians. Analyzing these satellite images underscores the critical importance of a stable energy supply, especially during times of conflict. The intentional destruction of energy facilities not only jeopardizes the well-being of civilians but also poses significant challenges to military operations, including the provision of electricity to military camps. Figure 1 serves as a visual testament to the urgent need for alternative energy sources and backup solutions in war-torn regions like Ukraine. They highlight the devastating consequences of energy system disruptions and emphasize the resilience and adaptability required to address such challenges.


Figure 1. Results of missile attacks on critical infrastructure of Ukraine [7]

In Figures 2-4, present a series of visual comparisons that vividly illustrate the dramatic changes in the urban landscape of individual Ukrainian cities before and after the Russian attacks. These images offer a poignant glimpse into the devastating impact of the conflict on these urban centers, emphasizing the importance of energy infrastructure resilience and the pressing need for alternative energy sources.

The image taken before the war, showcases Odesa, Mykolaiv, and Kherson in its peaceful state, characterized by well-lit streets, bustling urban life, and functioning energy systems. The presence of city lights signifies the vitality of the region’s energy infrastructure and the normalcy of everyday life. In stark contrast, the image on the right, captured after the Russian attacks, paints a starkly different picture. The reduction in city lights and the prevalence of darkened areas reflect the severe disruption of the energy supply caused by the attacks. The scars of destruction are visible, and the city's once-thriving streets now bear witness to the challenges faced by its residents (Figure 2).

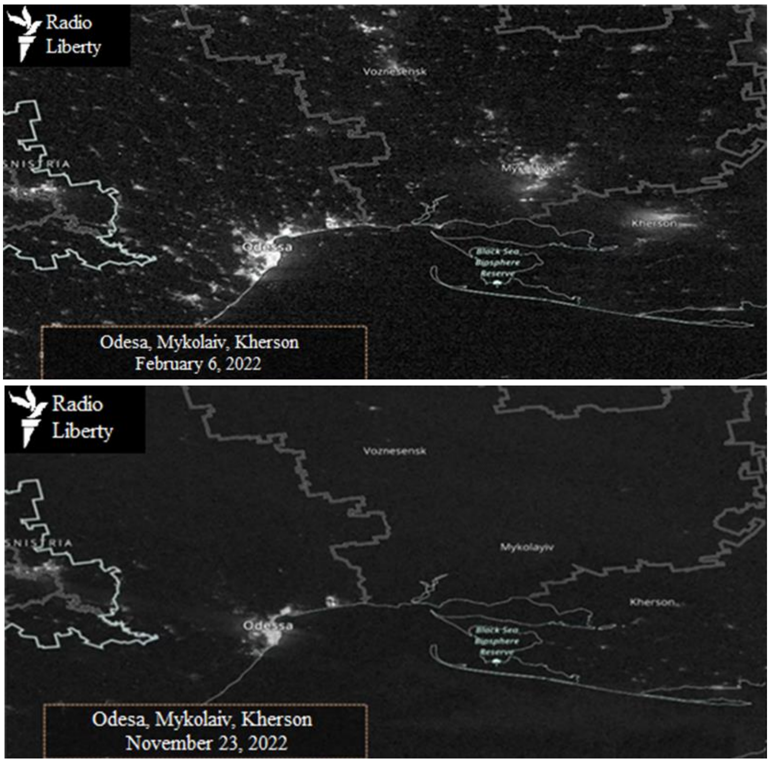
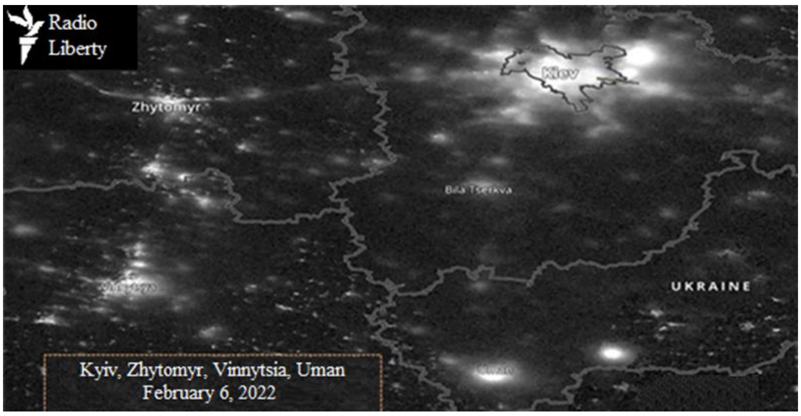


Figure 2. Results of attacks on Odesa, Mykolaiv, and Kherson [7]

Figure 3 provides another compelling visual comparison, this time featuring Kyiv, Zhytomyr, Vinnytsia, and Uman. The image from the pre-war period, showcases the city's vibrancy, with well-illuminated streets and a thriving urban landscape. The post-attack image paints a somber picture. The marked decrease in city lights and the emergence of darkened zones illustrate the devastating consequences of energy infrastructure disruption. The city’s resilience is put to the test as residents adapt to the new challenges posed by the conflict.



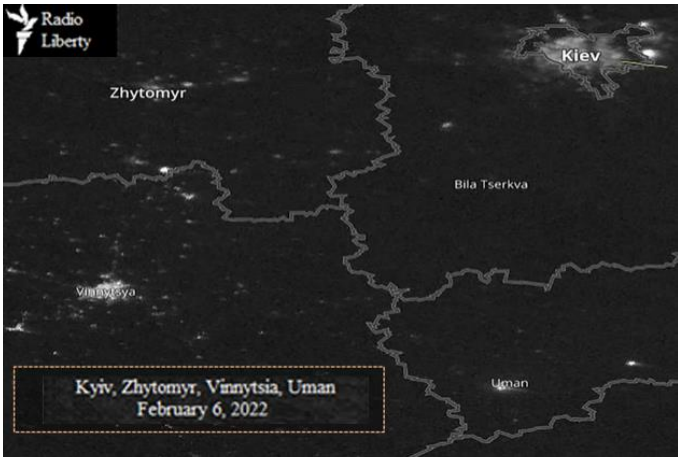



Figure 3. Results of attacks on Kyiv, Zhytomyr, Vinnytsia, and Uman [7]

Figure 4 presents a final comparison, this time featuring Lviv, Ivano-Frankivsk, Ternopil, and Chernivtsi. The image captured before the war, showcases the city’s nighttime vitality, with illuminated streets, buildings, and infrastructure. It stands as a testament to the importance of a stable energy supply in sustaining urban life. The image taken after the Russian attacks, reveals the city’s altered state in city lights and the prevalence of darkness reflects the impact of energy system disruptions. The city’s residents face the dual challenges of rebuilding their urban environment and adapting to life with limited access to electricity.

These visual comparisons serve as a powerful testament to the devastating consequences of energy infrastructure disruptions during the conflict. They underscore the urgency of exploring alternative energy sources and developing resilient energy systems that can withstand the challenges posed by warfare. As we delve into the study’s analysis, these images will provide valuable insights into the transformation of Ukrainian cities and the critical role that energy resilience plays in ensuring the well-being of urban populations.

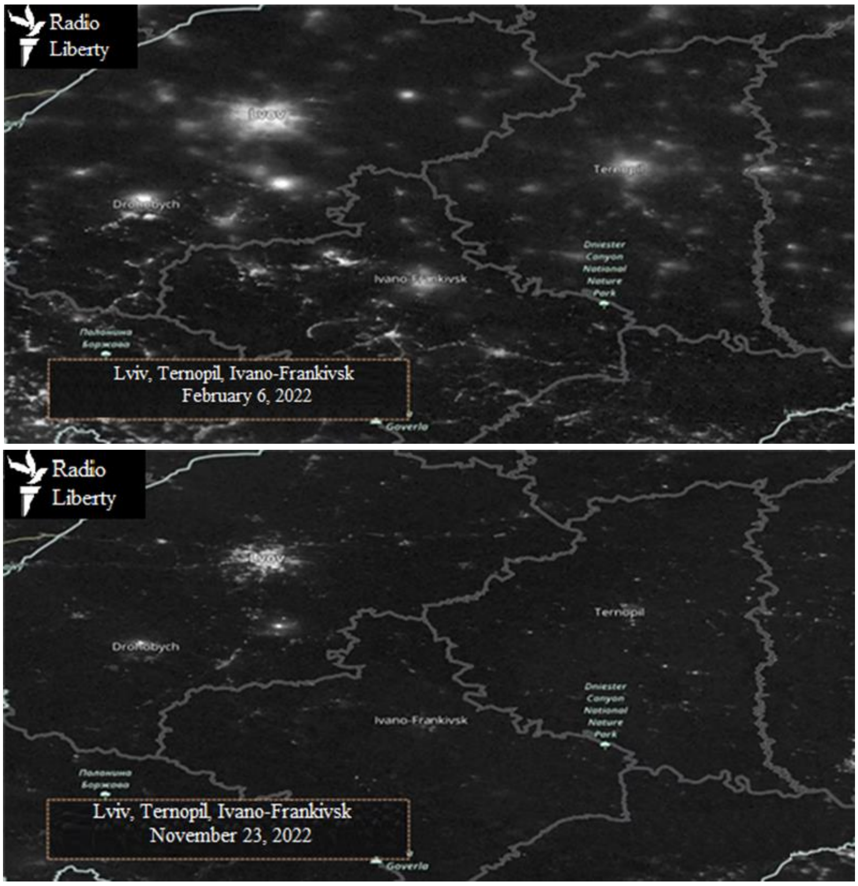



Figure 4. Results of attacks on Lviv, Ivano-Frankivsk, Ternopil, and Chernivtsi [7]

The press service of Ukrenergo reported that there was still a substantial shortage in the Ukrainian energy system in December 2022 after a massive rocket attack by the aggressor, which occurred on December 5. According to the Ministry of Energy, as of December 6, the most difficult situation with the energy sector has developed in the Kyiv, Vinnytsia, and Odesa regions. Volodymyr Omelchenko, director of the Razumkov Centre's energy program, stated that the energy system of Ukraine is under "great stress", and it is the energy infrastructure that has suffered the most [8]. On December 31, 2022, the city of Kyiv was the target of one of the largest missile attacks, as a result of which more than 20 people were injured and one person was killed (Figure 5).

Figure 5. Consequences of the missile strike on Kyiv on December 31 [9]

Figure 6 presents a visual representation of the extensive damage inflicted on Ukraine's energy infrastructure and housing as a result of the large-scale Russian attacks in January 2023. This information is crucial for understanding the severity of the situation and the urgent need for solutions in the aftermath of these devastating events. This includes data indicating that over 400 electricity and heat supply facilities were affected. This data underscores the widespread impact on critical energy infrastructure, which not only disrupts the daily lives of Ukrainian citizens but also hampers essential services such as heating during the harsh winter months [10].

Moreover, Figure 6 highlights that approximately 150 thousand houses were damaged or destroyed. This statistic reveals the immense toll these attacks have taken on civilian infrastructure, leaving a significant portion of the population without shelter and necessities. The combination of damage to energy supply facilities and housing reflects the complex and multifaceted challenges faced by Ukraine in the wake of these attacks. It underscores the urgency of finding effective and sustainable solutions to restore energy supply, rebuild housing, and ensure the well-being of affected communities.

Figure 6. Critical infrastructure damage [11]

According to the report on damage to infrastructure facilities covering the period from February 24, 2022, to February 24, 2023, the following facts can be distinguished [12]. The year after the start of the Russian military invasion, the total amount of direct damage documented is more than 143.8 billion USD. They are related to damage to residential, and non-residential real estate and other infrastructure facilities. According to information provided by the regional military administrations, as of February 24, 2023, the total number of destroyed or damaged housing facilities is estimated at approximately 153.86 thousand buildings. Of these, 136 thousand private houses, 17.5 thousand apartment buildings, and 0.3 thousand dormitories. This results in damage or destruction of housing for about 1.3 million households (approximately 3.2 million people) (Figures 7, 8).

Figure 7. Damage to civilian buildings [13]

Figure 8. Destruction of Lyman after missile attacks [14]

Figure 9 presents critical data regarding the extensive damage incurred during the fighting in Ukraine, particularly concerning the housing stock and administrative buildings. These figures shed light on the economic and infrastructural challenges facing the country in the aftermath of the conflict. This indicates that the estimated cost of direct damage to the housing stock stands at approximately 53.6 billion USD. This staggering amount underscores the devastating impact on residential areas, leaving a significant portion of the population without adequate housing. It is important to note that these figures are subject to additional verification, highlighting the need for comprehensive assessments to accurately quantify the damage.

Furthermore, the Figure 9 reports that 630 administrative buildings were either destroyed or damaged during the conflict. Among these facilities, 580 are state and local government buildings, while an additional 50 are centers for administrative services. This data underscores the disruption of government operations and services at various administrative levels, posing challenges to governance and public administration. Direct losses, according to preliminary data, amount to 0.54 billion USD. While this figure represents a smaller portion of the overall damage, it is still a significant financial burden for the country to address, particularly given the other substantial costs associated with the conflict.

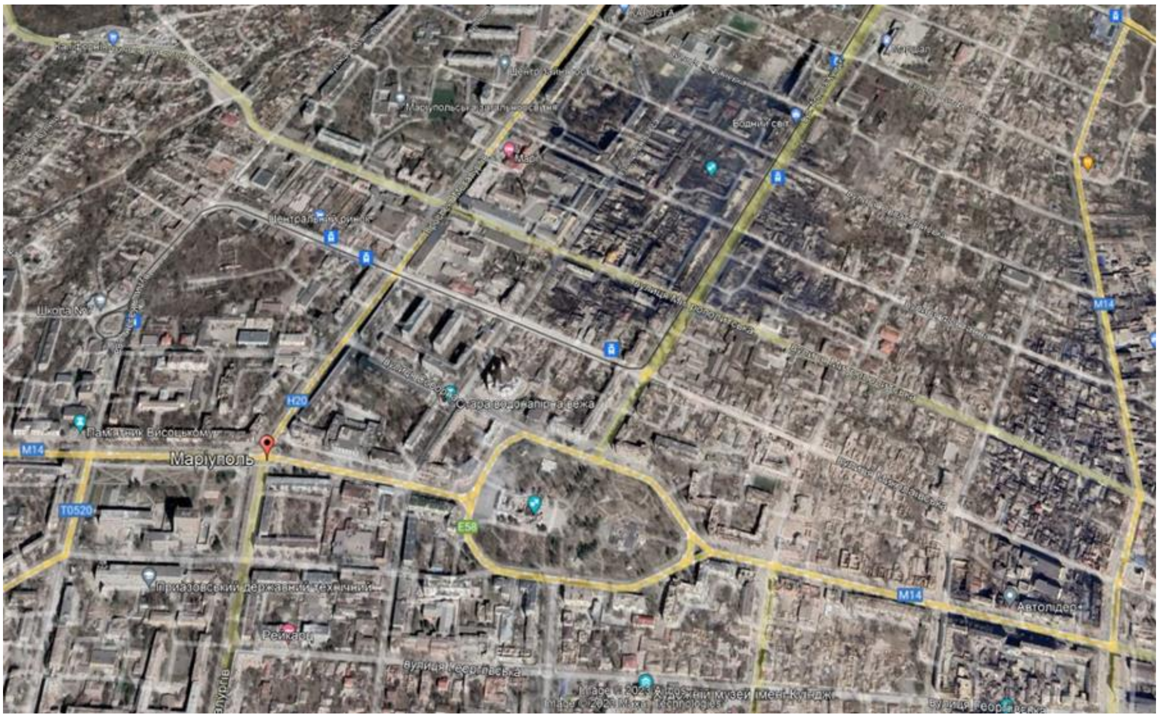



Figure 9. Destruction of Mariupol Central District

In the education sector, direct documented damage from destruction amounts to 8.94 billion USD. In total, at least 915 educational infrastructure facilities were destroyed, and 2165 facilities were damaged. Kharkiv, Donetsk, Chernihiv, Zaporizhzhia, and Kyiv regions suffered the greatest losses. Most damaged or destroyed educational facilities are schools (1497) and kindergartens (909). The scientific infrastructure also suffered substantial losses. Preliminary estimates indicate the destruction, damage, and seizure for the needs of the Armed Forces of Ukraine of 117 objects of movable and immovable property of 34 institutes and other institutions of the National Academy of Sciences of Ukraine. The estimated total losses associated with scientific institutions are approximately 7.8 million USD. A total of 348 religious sites, 703 houses or palaces of culture, 82 museums, 157 hotels or restaurants, and 8 sports stadiums have been damaged since the invasion began. These facilities are mainly located in 14 regions of Ukraine, in particular, in Dnipropetrovsk, Donetsk, Zhytomyr, Zaporizhzhia, Kyiv, Luhansk, Lviv, Mykolaiv, Odesa, Sumy, Kharkiv, Kherson, Chernihiv regions and in the city of Kyiv (Figures 10, 11).

Figure 10. St. George’s Skete before the missile strike

Figure 11. Destruction of St. George's Skete

Figure 12 provides significant insights into the extensive damage suffered in the fields of culture, religion, and tourism in Ukraine as a result of the conflict. The data underscores the profound impact of the war on these vital aspects of Ukrainian society and the challenges faced in their recovery and restoration. Figure 12 reports that, as of September 1, the total cost of direct losses in these sectors amounts to an estimated 2.2 billion USD. This substantial financial burden encompasses the costs associated with repairing and rebuilding cultural sites, religious buildings, sports facilities, and tourist destinations. It also reflects the potential long-term economic consequences of the damage, including reduced tourism revenue and cultural contributions to the economy.

Figure 12. Drama Theatre in Mariupol [15]

Since the beginning of the war, the total number of damaged airports and civilian airfields has reached 19, while at least 126 railway stations have been destroyed. Estimates show that total losses in the infrastructure sector in Ukraine reached 36.2 billion USD, considering the destruction and damage to facilities. The situation with more than 700 km of railway tracks located in the temporarily occupied after February 24 territory is also threatening. Preliminary estimates indicate damage to more than 5.5 thousand buildings belonging to Ukrzaliznytsia. Unfortunately, of the 35 airfields, 19 were damaged, including 12 civilian airfields and 7 dual-use airfields, not accounting for military airfields. Several airfields were the target of repeated attacks, which only worsened the situation. Direct losses in Ukraine's energy infrastructure, as of February 24, 2023, are estimated at 8.1 billion USD. The electricity production and transmission sectors have suffered the greatest damage from Russian aggression. The total damage estimate for these facilities is more than 6.5 billion USD. Some other energy facilities, such as Vugleghirsk, Zaporizhzhia, and Luhansk thermal power plants, are still in the occupied territory after February 24, 2022. In addition, the Kakhovka Hydroelectric Power Plant, which was destroyed as a result of attacks and explosions, is also under the control of the invaders.

Since the beginning of the full-scale invasion, 30 oil depots of various sizes and levels of modernization, including the fuel stored there, have been damaged or destroyed. The cost of direct losses in the fuel storage sector is estimated at almost 260 million USD. In addition, the existing capacities of the only major oil refineries that remained active were shelled by the aggressor. In particular, this applies to the Shebelinsky oil refinery in the Kharkiv region and the Kremenchuk oil refinery in the Poltava region. As of February 2023, the cost of direct damage caused to the heat supply sector (except for thermal power plants), water supply, sanitation, and household waste management is 1.4 billion USD. During the full-scale invasion, 5 thermal power plants were destroyed, and 8 were damaged. According to the State Emergency Service of Ukraine (SES), about 185 thousand square kilometers (approximately 30%) of the territory of Ukraine can potentially be contaminated with explosive objects that require inspection and neutralization [16].

According to the current results of Sapper activity, the density of neutralized explosive objects is 284 per 1 $km^2$ of cleared territory, while this indicator can substantially increase in areas of prolonged and active military operations [17]. Before the war, Ukraine’s energy system had a complex structure in which power plants that produced electricity supplied it to the common power grid. The power system itself consisted of two main components: state-owned main power transmission lines and generating capacities that could be either state-owned or privately owned [18]. On March 16, 2022, the integration of the Ukrainian energy system with the European Network of Transmission System Operators for Electricity (ENTSO-E) was completed, which led to its separation from the systems of Russia and Belarus and was a very important stage in ensuring Ukraine’s energy independence [19]. At that time, the following energy facilities were operating in Ukraine:

- 4 nuclear power plants with 15 power units;
- 15 thermal power plants;
- 21 thermal power plants with a capacity of more than 10 megawatts (MW), and several dozen low-power stations;
- 12 hydroelectric power plants/pumped storage power plants, seven of which were located on the Dnipro River;
- several dozen wind and solar power plants and facilities that worked using biogas, forming renewable energy (Figure 13).

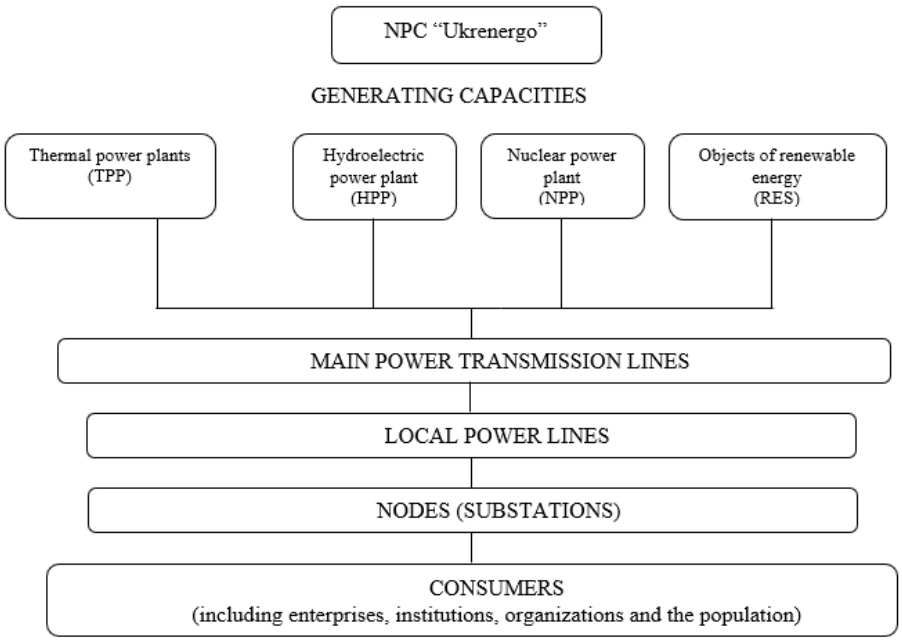



Figure 13. Structure of Ukrenergo

The harsh conditions of war and the instability of the central energy system jeopardize the country's reliable electricity supply. In such emergencies and in situations where there is a need for prompt provision of electricity, renewable energy sources can play an important role as an alternative source. Ukraine has demonstrated substantial progress in the development of renewable energy, which was noted by recognized international ratings. In 2019, the country took pride of place among the top 10 countries in the world in terms of renewable energy development rates [20].

In 2021, the energy sector of Ukraine was at a crossroads when the state was faced with an important choice regarding the further development of the energy industry. This uncertainty was also present in the renewable energy sector. On the one hand, the government began to gradually fulfill the obligations stipulated by the Memorandum of Understanding on the settlement of problematic issues in the field of renewable energy in Ukraine, which was concluded in June 2020 under the mediation of the energy community dispute resolution center between the government of Ukraine, the National Commission for State Regulation in the Fields of Energy and Utilities, the Ukrainian Wind Energy Association, and the European-Ukrainian Energy Agency. The government began to gradually pay off the accumulated debt to renewable energy producers, which had a positive impact on the market and created some positive signals. However, on the other hand, at the state level, there were attempts to recognize the "green" tariff as illegal state support or adopted unconstitutionally, initiated by the public association "League of Antitrust" [21]. Even though the President of Ukraine was one of the signatories of the global wind energy manifesto at COP-26 and made an international commitment to completely stop internal coal consumption by 2035 and begin the gradual decommissioning of thermal generation from 2022, the government continued to direct efforts to support the outdated nuclear energy infrastructure [22]. The state program for the development of the nuclear industrial complex until 2026 was adopted [23]. According to the National Energy Regulatory Commission, as of December 31, 2021, the installed capacity in the renewable energy sector of Ukraine reached 9655.9 MW. Figure 14 includes solar power plants for private households, without which the total capacity was about 8450 MW.

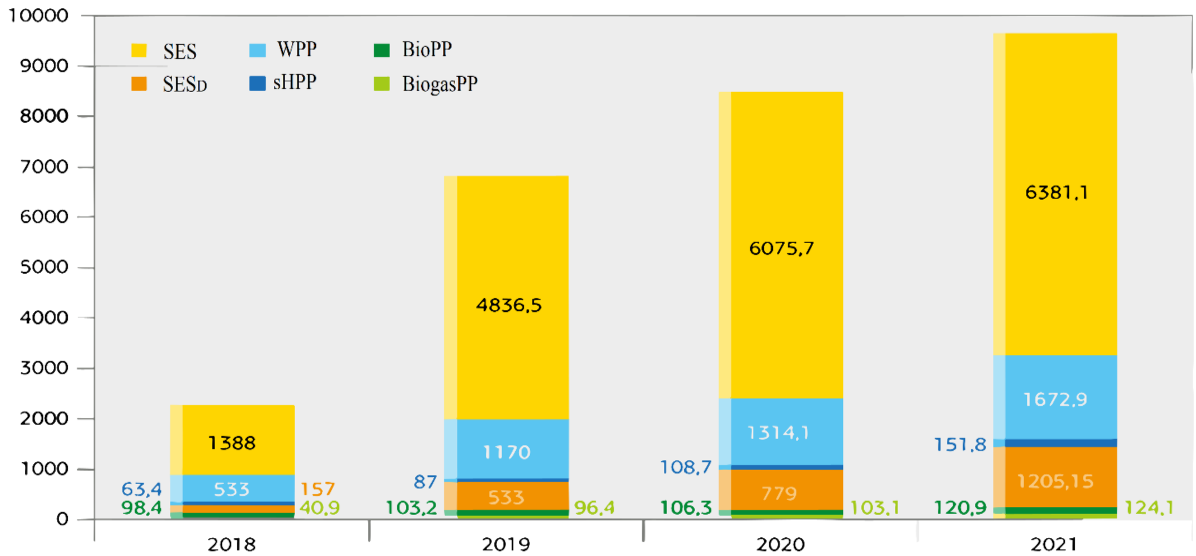



Figure 14. Dynamics of capacity growth of REF, MW [24]

Notably, during 2021, there was an active development in only one segment – private solar power systems (SPS), the capacity of which increased by 426.1 MW, which accounted for approximately 36.4% of the total volume of new renewable energy capacities put into operation. At the end of the year, the total installed capacity of solar systems in private households was 1205.1 MW, using approximately 45 thousand systems. In the industrial sector, on the contrary, there was a reduction in the pace of development of solar energy. During the year, the capacity of industrial solar generation increased by only 305.5 MW, which is 26.1% of the new renewable energy capacity introduced in 2021 and is worse than in 2020, when the capacity increased by 1123.6 MW (Figure 15).

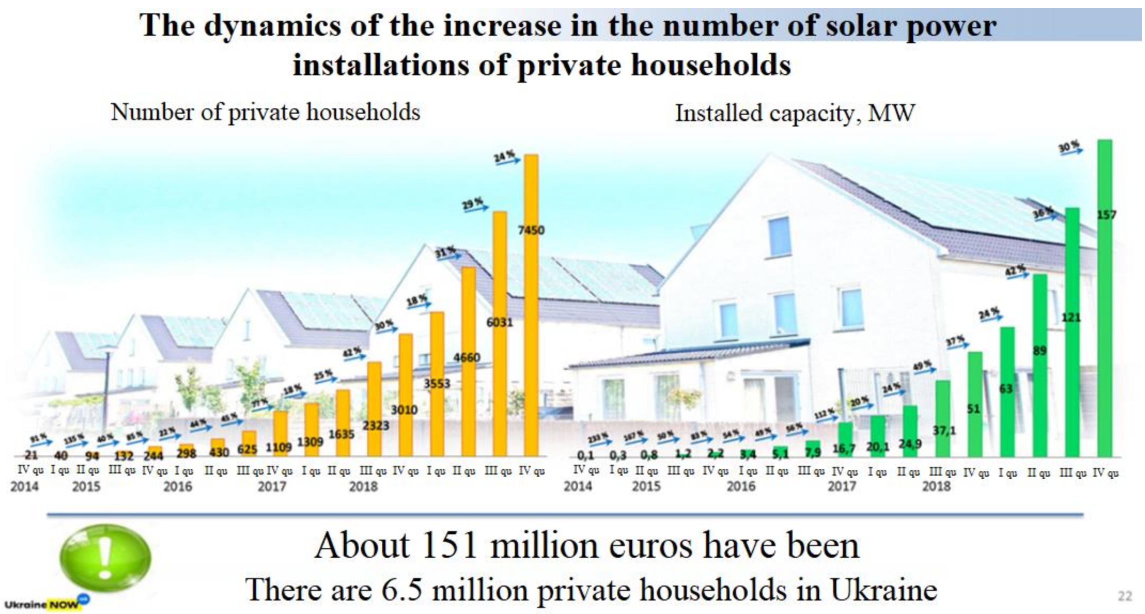



Figure 15. Dynamics of increasing the number of solar electrical installations of private facilities [24]

Overall, at the end of 2021, the country's total installed solar capacity was 7586.3 MW, which also included private solar systems. A substantial position in the country's renewable energy sector is also occupied by wind power, which can be used to generate electricity and other types of energy [25]. In contrast to the solar energy sector, wind energy added the most substantial amount of resources to the share of renewable energy sources in 2021. During the year, the share of wind power capacity put into operation was 30.6% or 358.8 MW. This is 2.5 times more than the volume of new wind power capacities that were launched in 2020 (144.2 MW). At the end of the year, the total installed capacity of the wind energy sector was 1672.9 MW. Ukraine had 34 wind power plants (WPPs), i.e., 699 wind turbines, the average capacity of one of which is 3.5 MW. Thus, wind power generated a substantial amount of renewable energy in Ukraine (Figure 16).

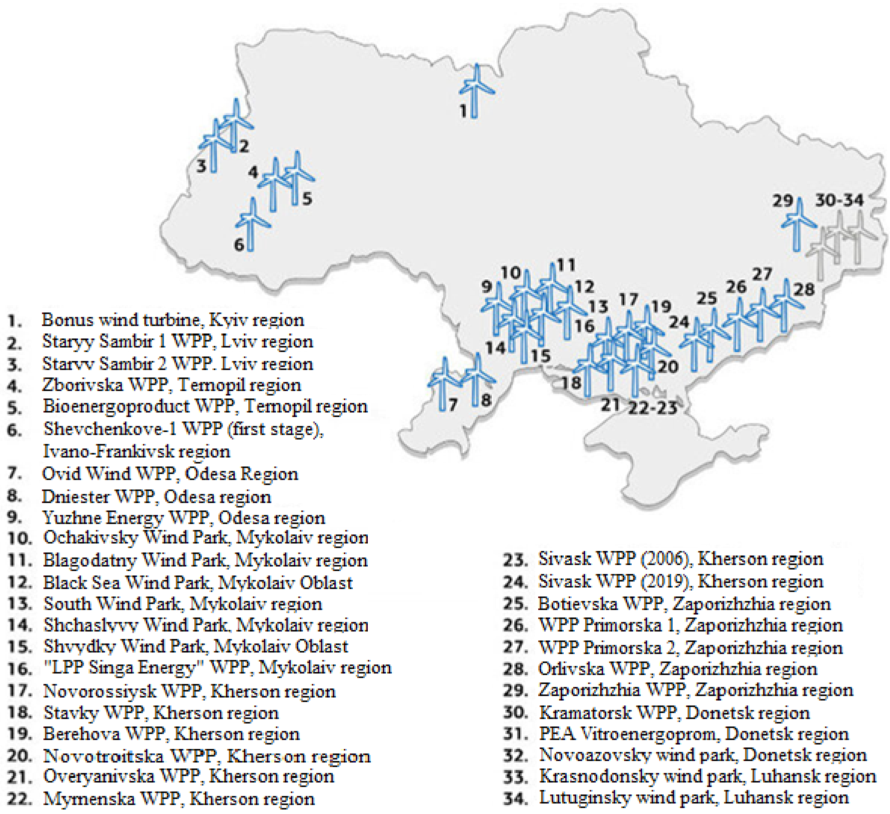



Figure 16. Active wind power plants in Ukraine at the end of 2021

The geographical location of renewable energy facilities in Ukraine differs depending on the type of renewable energy source and corresponds to the natural potential of these regions. For example, WPPs are mainly located in the southern and south-eastern regions, in particular, on the coast of the Black and Azov seas, which is approximately 85% of their total number. On the other hand, solar generation is more widespread, but it is also concentrated mainly in the southern and south-eastern regions of Ukraine, where about 60% of industrial solar power plants are located [26]. This distribution of renewable energy facilities corresponds to the natural potential of each region and contributes to the efficient use of renewable energy sources in accordance with their natural conditions. In general, as of 2021, before the start of a large-scale war, Ukraine has made substantial progress in the production of alternative electricity. According to 2021 figures, total electricity generation from renewable sources amounted to 12.804 million kWh, which exceeds the previous year's figures by 1941.9 million kWh or 17.8%. This indicates a substantial development of the renewable energy sector in the country [27].

2021 was particularly important for the National Renewable Energy sector, as a substantial event occurred on May 11 – daily electricity production from renewable energy sources exceeded production from thermal power plants, which highlights the substantial contribution of renewable energy sources to the overall energy system of the country. The development of small and medium-sized wind power in Ukraine has faced several challenges, but the potential of this sector remains extensive. Currently, the following power plants are located in the occupied territory: Zaporizhzhia Nuclear Power Plant (NPP), Zaporizhzhia Thermal Power Plants (TPP), destroyed Kakhovka Hydroelectric Power Plant (HPP), Vugleghirsk TPP, Luhansk TPP, Primorska WPP, and Botievska WPP. In addition, at least 12 thermal and gas power plants were damaged [28]. Russia's large-scale invasion in February 2022 substantially impacted progress in renewable energy and has irreparable consequences. A substantial part of Ukrainian WPPs, about 85%, ended up in the occupied territories, leaving only 372.5 MW of wind capacity in operation, mainly located in the Lviv and Odesa regions. In the regions affected by the Russian invasion, almost 30-40% of solar power plants were damaged [29].

A special event for Ukraine was the loss of generation at the Zaporizhzhia NPP, which previously provided the country with the largest amount of economically available electricity. As a result of the loss of generation at Zaporizhzhia NPP, Energoatom lost its ability to perform special duties, including the mechanism of preferential electricity supply for the population, which substantially affected the energy sector of Ukraine. As a result of active military operations and numerical destruction, in particular, damage to global and local electrical networks and distribution systems, a large number of enterprises and organizations were forced to pause or completely stop their activities. However, this is unacceptable for critical infrastructure facilities, such as hospitals, state and military facilities, and camps. The lack of a stable and constant power supply can have serious consequences because there is a high probability of automatic shutdown of some consumers in case of damage to generation facilities. The destruction of distribution centers is even more dangerous, as it can lead to a lack of electricity supply in entire regions. Considering this, the government is taking measures to restore infrastructure to ensure satisfactory conditions for military camps and the life of the population. Therefore, owners of small businesses or private homes can consider various backup energy sources that will help in emergencies.

One example of countries that also suffered the destruction of energy infrastructure during the war is Syria. The civil war, which lasted for many years, caused serious damage to the country's energy system. As a result of military operations, power plants, gas pipelines, and other energy facilities were often attacked and seriously damaged. This has created a humanitarian crisis, as many people are left without access to basic services such as lighting, heating, and communications. Due to damage to the energy infrastructure, the local population faced a shortage of electricity, which substantially complicated their daily living conditions. Ensuring a stable energy supply has become an extremely important task for the authorities and humanitarian organizations that have tried to provide the local population with energy to meet basic needs [30], [31], [32].

During the war in Syria, some emergency means and energy sources were used in the face of destruction and power outages. One example is the use of generators. In many areas with limited or lacking electricity, diesel, gasoline, and gas generators helped provide electricity for basic needs such as lighting and electrical appliances. In addition, the use of solar panels has become widespread in some areas of Syria where power supply has been limited. Solar panels collect solar energy and convert it into electrical energy that can be used for residential applications, lighting, and charging electronic devices. In addition, batteries were used as temporary energy sources to provide electrical power. They can be charged from various sources, such as generators or solar panels, and used during power outages. All of these facilities helped provide vital functions and reduce the impact of power outages on the local population.

President of Ukraine Volodymyr Zelenskyi personally appealed to investors with a proposal to actively join the process of restoring Ukraine and developing various projects, in particular, in the energy sector. Then the president said that Russia has already seriously damaged about 40% of the entire energy infrastructure of Ukraine, in particular, THP, combined heat and power plant (CHPP), and HPP. One of the potential projects, as a solution to the current difficult situation, is the creation of the so-called "Energo Rammstein". This project provides for attracting foreign investment and technologies for the development of new energy facilities and expanding capacities in Ukraine. It aims to ensure the stable and efficient functioning of the country's energy system, reduce dependence on energy imports, and promote the development of renewable energy sources.

According to expert political analyst Ihor Reiterovich, the Rammstein energy project for Ukraine will not face the same delays observed in the supply of military-technical assistance. He believes that Ukraine will receive the necessary supply of funds that will help power engineers quickly restore and repair damaged energy infrastructure. According to the minister of energy of Ukraine, Herman Halushchenko, as a result of constant and continuous Russian attacks on energy facilities, Ukraine has developed and implemented several technical solutions that ensure the effective operation of the energy system in the conditions of enemy shelling. The minister also noted that the industry is doing everything possible to ensure that the projected blackouts are conducted with minimal impact on the population, industry, and critical infrastructure facilities [33]. Critical infrastructure facilities (military camps, military infrastructure complexes) are strategically important enterprises and institutions necessary for the functioning of the country's society and economy. Their unplanned shutdown, failure, or destruction can pose a threat to state security, and the natural environment, cause deterioration of defense capabilities, material, and financial losses, or even human casualties [34].

In Ukraine, this type of asset includes various forms of ownership of enterprises and institutions operating in the following industries: energy, chemical, food, transport, military, financial, and banking, information technology and telecommunications, public utilities (water, heat, gas supply), and healthcare. The procedure for recognizing an object as a critical infrastructure is established by the Cabinet of Ministers of Ukraine and as of 2023, is regulated by Resolution No. 1109. However, the decision on such recognition is made by sectoral bodies responsible for protecting sectors or subsectors of critical infrastructure. Resolution No. 1109 divides such enterprises and institutions into four categories of criticality:

- Objects that are important for the state and can substantially affect other configuration item (CI) objects. If their work is disrupted, there will be a crisis of national scale;
- Vital objects, and the termination or disruption of their operation will lead to a crisis on a regional scale;
- Important objects, the disruption or termination of operation of which will lead to a crisis on a city scale.
- Necessary objects, the damage or termination of which will lead to a crisis on a local scale.

Thus, facilities that are critical for the functioning of society should not only have the main source of electricity from the local network but also be provided with backup power sources for emergencies. This is necessary to ensure the continuity of operation of these facilities even in the event of a shutdown of the main power source. Table 1 shows the results of collecting, analyzing, and comparing some backup power sources.

Table 1. Comparison of the main backup sources of electricity [35]

| No. | Name of the electricity source | Main advantages | Main disadvantages | Average cost of one kilowatt of energy | Notes |
|---|---|---|---|---|---|
| 1 | Gasoline generator | 1. Excellent solution in terms of compactness and convenience, due to its small size.<br>2. Can be used outdoors, no need for cooling.<br>3. Availability.<br>4. The cheapest fuel generators run on regular A92 or A95 gasoline. | 1. Requires regular work breaks.<br>2. Short service life. | High cost of 1 kW of energy. | It is the most common option among users due to its accessibility and ease of operation. |
| 2 | Diesel generator set | 1. High motor power.<br>2. Compact, small size, can be used with heavy loads.<br>3. Cost-effective compared to gasoline generators. | 1. Higher noise level, compared to gasoline options.<br>2. High price, lower availability.<br>3. Low frost resistance due to diesel fuel. | | |
| 3 | Gas generator | 1. Longer service life.<br>2. Higher level of heat exchange compared to fuel analogues.<br>3. Availability and lower cost of gas. | 1. High level of danger due to working with gas. | Lower cost of 1 kW. | It is not as popular as diesel or gasoline but is not inferior to them in technical characteristics. |
| 4 | Backup solar power plant | 1. Unlimited amount of solar energy.<br>2. Long service life (about 25 years or more).<br>3. Convenience and comfort for the user.<br>4. Ecological cleanliness of the energy source.<br>5. Safety of use due to the absence of hazardous substances. | 1. A system with batteries may be more expensive than buying a generator.<br>2. The need to replace the batteries. | | Due to the presence of battery systems, it provides autonomy and independence from electrical networks. |
| 5 | Windmills | 1. It is a renewable energy source.<br>2. Eco-friendly due to the absence of emissions.<br>3. The ability to effectively use the surrounding space for other household needs. | 1. High dependence on natural conditions.<br>2. Requires substantial material costs, especially at the initial stage. | The cost of installing 1 kW of wind turbine power can be approximately 1,000 USD. | Substantial potential for the development of the industry due to the large amount of wind resources. |

Energy sources such as generators, despite their advantages in the form of high portability, convenience, and accessibility, have disadvantages in the form of high fuel costs. In such a situation, renewable energy sources can create prospects for the development of mandatory backup sources of electric energy for critical infrastructure facilities (military camps, military infrastructure complexes). Ukraine, due to its geographical location, has a great potential for the use of alternative energy, in particular, solar and wind, because it is located in the temperate zone, where there is enough solar radiation throughout the year, which gives favorable conditions for the installation of solar power plants in many regions of the country (Figures 17, 18).


Figure 17. The level of insolation on the territory of Ukraine. Data from NASA satellites for the period from 1985 to 2005 [36]


Figure 18. Levels of solar radiation on the territory of Ukraine (according to data from NASA satellites) [37]

According to President Volodymyr Zelenskyi, the development and attraction of partners' investments in the field of renewable energy is now one of the most important issues that need to be worked on. Obtaining the status of a European Union (EU) candidate opens up new prospects for the development of renewable energy sources in Ukraine. This will help bring the legislation in line with the directives of the European Union and create new mechanisms to support the renewable energy industry. In addition, the financial aspect is also of great importance since the EU will not finance projects related to polluting technologies for the restoration of Ukraine [38], [39], [40], [41].

Considering the current situation in Ukraine with energy supply issues, solar energy could be a wise investment for the country. With its potential for state support and environmental benefits, it can contribute to the development of a sustainable and profitable energy system. Investing in solar energy can not only help grow the renewable energy industry but also contribute to the overall development of the country.

## 4. Discussion

The situation with damage to the country’s energy infrastructure is of serious concern because of the destruction of energy facilities and critical infrastructure, such as power plants, and substations. has serious consequences for the population and economy. These facilities are vital for providing electricity and other types of energy necessary for the normal functioning of society, so it is necessary to immediately take measures to restore the energy infrastructure and ensure a stable supply of electricity [42], [43].

After the full-scale invasion on February 24, 2022, and massive missile attacks on critical infrastructure, the country’s energy system suffered very large losses and damage, which requires a timely response and measures to restore it and the search for modern solutions to improve the situation. One of the ways to solve this problem can be the use of renewable energy because Ukraine has great potential for this. The country is located in a region with high solar activity and wind resources, which allows the use of them as backup sources in the conditions of rocket attacks and improving the situation with energy supply for military infrastructure complexes and providing military formations [44], [45], [46]. The use of renewable energy sources has its problems, one of which is high initial costs and dependence on weather conditions since, in this case, electricity production depends on the availability of sun and wind [47], [48]. However, the results show that despite the shortcomings, renewable energy sources, especially solar power plants, are an attractive solution for ensuring a stable and environmentally friendly energy supply. Proper deployment and development of renewable energy sources can ensure sustainability, economic benefits, and dependence on energy imports, contributing to the development of a modern and sustainable energy system in the country [49].

Despite the challenges, renewable energy sources offer prospects for sustainable development and the transition to a cleaner and more energy-efficient future energy. An important fact is the development of the research base and innovative projects in the field of alternative energy. This includes supporting scientific research and technological developments aimed at improving the efficiency and reliability of renewable energy systems. Cooperation with scientific institutions and partners can contribute to the introduction of new technologies in the energy sector of Ukraine. One of the main challenges is to attract the necessary resources and funding to restore the country’s infrastructure [50]. This requires substantial investment and planning. The country should attract foreign partners and investors and mobilize internal resources to restore damaged facilities effectively. In addition, when restoring the energy infrastructure, it is necessary to consider modern technologies and environmental aspects. Investing in renewable energy sources can be a smart solution, as it reduces dependence on conventional sources, improves the situation with the electric power industry in the country, and promotes sustainable development [51], [52], [53], [54]. However, the development and restoration of energy infrastructure is a complex and lengthy process that requires coordination of efforts by various sectors of society and government agencies [55].

[56], [57] prove that the use of solar power plants with backup power can be quite efficient due to the presence of additional electrical circuits and control devices that ensure switching power from the main source (solar power plant) to a backup source. For such switching, it is necessary to install additional electrical circuits and control devices that include automatic switches, relays, and monitoring systems that determine the state of the power grid and control the switching process. In addition, the use of such systems requires the development of a detailed backup power management plan, including regular maintenance, battery level monitoring (if used), and technical support [58], [59], [60]. Notably, this approach’s effectiveness will depend on each district’s unique characteristics and energy needs. It is important to consider factors such as geographical location, climatic conditions, available resources, and energy infrastructure. Before implementing a backup power supply system, it is necessary to perform detailed analysis and calculations to select the optimal system that meets specific needs and ensures reliable operation.

According to the studies by [61], [62], improving the efficiency of solar panels using new materials, in particular, mineral solar cells, opens up new opportunities for collecting solar energy even in low-light conditions. Oxide minerals are used in solar panels as an active layer that can convert solar radiation into electrical energy [63], [64]. They have a high absorption capacity and the ability to efficiently collect solar energy even in weak sunlight or on a cloudy day. Their ability to be applied to flexible substrates and used in compact sizes opens up ample opportunities for integration into a variety of devices and surfaces, including buildings, automobiles, and electronic devices. Despite the advantages of such solar cells, their use also accompanies some features that need to be considered. One of the main disadvantages of oxides is their instability during long-term use and exposure to external factors such as humidity, temperature, and light, which can decrease the efficiency of panels and shorten their service life [65], [66]. In addition, the use of mineral materials in solar panels is a relatively new technology, which can lead to high research, development, and production costs [67]. This can make these solar panels less affordable and more expensive for the consumer.

[68], in turn, showed that solar concentrators are one of the ways to use solar panels efficiently because they allow the concentrating of solar energy in a small area, which leads to an increase in its intensity and an increase in the energy output of panels. There are also point-focusing systems that use a small amount of material to focus solar energy over a small area. For example, lenses or optical systems can direct solar energy to a small photocell or high-efficiency thermal receiver, providing high energy concentration and increased system efficiency [69], [70], [71]. However, it should be considered that solar concentrators often require tracking the movement of the sun, which can be complex and require additional mechanisms. These systems are sensitive to weather conditions such as cloud cover, which can reduce their efficiency [72], [73]. It is also important to note that solar concentrators often require special equipment and professional installation, which can increase the cost of the system.

[74] state that local power grids are also an innovative energy solution that revolutionizes the way solar power plants operate independently from centralized networks. They allow providing a stable power supply for local consumers regardless of the main network. This is especially useful on a variety of scales, from individual homes and commercial complexes to large areas such as neighborhoods or even islands [75]. In addition to solar power plants and batteries, local power grids can integrate other renewable energy sources, such as wind turbines or biofuel generators. This integration allows for a stable power supply, even in the event of insufficient solar activity, fully meeting the energy needs of consumers [76], [77]. Still, despite their advantages, it is worth considering some disadvantages and features that require attention. Implementing local area networks can be a costly task, especially when creating infrastructure for apartment buildings or large commercial complexes. When planning and implementing a system, it is necessary to carefully evaluate the cost and benefits and consider financial accessibility for consumers. In addition, in the case of integration of various energy sources, such as solar power plants, wind turbines, or biofuel generators, it is necessary to ensure compatibility and coordination of their operation [78], [79]. It is important to consider synchronization, stability, and management requirements between different power sources to ensure efficient and reliable operation of the local network.

[80], [81] believe that the key factor for efficient use and increasing the power of wind turbines is the use of advanced technologies. For example, using a turbine design with larger rotors and high-performance materials can substantially increase the wind area captured and improve turbine efficiency. Optimal placement of wind turbines on wind farms also plays an important role in increasing their capacity. Investigating local wind conditions, such as speed, direction, and stability, is essential to determine the most favorable locations for installing turbines [82]. This will maximize the use of wind energy potential and ensure the optimal performance of wind turbines. Notably, increasing the capacity of wind turbines using advanced technologies may be limited by the physical limitations of placement. Having a sufficient spatial area to accommodate larger rotors and efficient use of the captured wind area are important factors for achieving increased power [83], [84].

As noted by [85], [86] increasing the height of the wind turbine installation contributes to an increase in stable and powerful wind. Using tall towers to install turbines can improve their power and efficiency. It is important to have effective control and regulation of systems that allow you to optimize the operation of wind turbines depending on wind conditions. For example, automatic orientation systems can help wind turbines adjust their position according to wind direction and strength, which helps improve their efficiency. [87], [88], [89] substantiated options for choosing heat-generating equipment for the modernization of heat supply systems in military camps. A combined system for the use of boilers and solar collectors is proposed. Notably, tall towers may be limited to installation in certain areas. The availability of a free and safe area for installing high towers may also be limited. In addition, effective regulatory and control systems require added attention and maintenance. Setting up automatic orientation systems and maintaining their effectiveness may require additional effort and qualified specialists.

In general, the use of modern and advanced technologies of renewable energy sources allows diversifying the energy sector of the country, that is, attracting a variety of energy sources to ensure the sustainability and independence of the electricity supply system, enabling their more efficient use. Each type of renewable energy has its unique characteristics and can operate in different environments, so combining their use reduces the risk of power outages and ensures system stability [90], [91]. According to the authors, a backup solar power plant can be considered a reasonable investment in critical infrastructure facilities: military camps and formations. Receiving free electricity allows budget funds to be saved and used for maintenance and development.

## 5. Conclusions

The conducted studies on the level of damage to the energy system of Ukraine have determined the impact on the state of energy supply of individual facilities and consumers, including military camps and infrastructure complexes. The authors analyzed the possibilities of using alternative energy in Ukraine in the context of war, instability of the energy system, and the urgent need for backup energy sources.

According to the authors, it is most appropriate to use solar panels since they have several advantages: compactness, absence of environmental problems, proper access to electric energy, which allows ensuring a high level of life for the population, military camps and infrastructure complexes, providing the operation of any household equipment which depends on electricity; proper operation of water supply and sanitation systems, ventilation systems of buildings and structures. Thus, Ukraine can solve three problems that are essential for its future: ensure the continuity of electricity supply for critical infrastructure facilities and owners of small-scale economic facilities, military camps, and their provision. Using alternative sources of electricity in the future will allow Ukraine to enter the electricity market, provide accessibility for the population, and clear the platform for the functioning of the electric energy market after the end of the war.

Furthermore, the adoption of alternative energy sources, especially solar panels, can address three fundamental challenges for Ukraine's future. Alternative energy sources can provide a dependable backup during power outages or disruptions caused by conflicts or other emergencies. This is essential for maintaining the operation of critical infrastructure facilities and sustaining small-scale economic activities. The use of renewable energy sources positions Ukraine to enter the electricity market, fostering competition, and ensuring accessibility to electricity for the general population. This is vital for the nation's post-war recovery and economic development. The adoption of clean and renewable energy sources contributes to environmental sustainability by reducing reliance on conventional energy resources and minimizing pollution.

Moving forward, several areas warrant further research and exploration. Research should focus on improving the efficiency, reliability, and stability of energy systems, particularly those utilizing renewable energy sources. Advancements in energy storage and grid integration technologies can enhance the resilience of these systems. Developing effective methods and technologies for seamlessly integrating renewable energy systems into the existing energy infrastructure is critical. This includes upgrading power grids, implementing smart grid solutions, and ensuring compatibility with conventional energy sources. Policymakers should consider the findings of these studies to develop strategies and policies that promote the widespread adoption of renewable energy sources. This may involve incentives, regulations, and initiatives to encourage investment in clean energy technologies. Research should also focus on enhancing the resilience of critical infrastructure facilities, including military camps, to withstand energy disruptions. This may involve the deployment of backup energy systems, microgrids, and energy-efficient technologies.

In conclusion, the practical significance of the research results is substantial, as they offer valuable insights into addressing Ukraine’s energy supply challenges amid instability. By prioritizing the development and integration of renewable energy sources, Ukraine can strengthen its energy infrastructure, improve the quality of life for its citizens, and pave the way for a sustainable energy future. These efforts are not only crucial during times of conflict but also have long-term benefits for the nation's energy security and economic prosperity.

**Declaration of competing interest**

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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**Author contribution**

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**Abbreviations and acronyms**

| | |
|---|---|
| SES | State Emergency Service |
| ENTSO-E | European Network of Transmission System Operators for Electricity |
| MW | Megawatts |
| SPS | Solar Power Systems |
| WPP | Wind Power Plant |
| NPP | Nuclear Power Plant |
| TPP | Thermal Power Plants |
| HPP | Hydroelectric Power Plant |
| CHPP | Combined Heat and Power Plant |
| CI | Configuration Item |
| EU | European Union |

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