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MANAGING ENERGY SECURITY IN TIME OF WAR – AN ANALYSIS OF THE UKRAINIAN EXPERIENCE

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Purpose. To examine, identifies key strategies and provides insights into how nations can build more resilient, sustainable energy systems in the face of modern warfare. This article based on the case study of the current situation in Ukraine.
Design/methodology/approach: The study is based on a systematic review of peer-reviewed literature, policy documents, and case studies. Comparative and thematic analyses are applied to identify key trends, challenges, and best practices in integrating energy strategies into local economic policies.
Findings. The results show that energy-saving measures stimulate the development of sustainable production, support the expansion of green technologies, and attract environmentally oriented investments, all of which positively influence public health and foster regional economic growth. According to the organization Vision of Humanity "in 2025 we have 56 armed conflicts in the world". The Global Peace Index 2024 reveals that "the world is at crossroads. Without a concerted effort, there is a risk of a surge in major conflicts". The invasion of Ukraine by Russia has made European countries realize that war in the heart of Europe intensify a serious security crisis in Europe. In addition, it is alarming that war not only results in loss of life but also causes widespread damage to essential systems such as transportation, communication, water supply and energy. In the present days wars have become more destructive by using weapons dedicated to destruction in a precise and targeted manner.
Research limitations/implications. The study's conclusions are formed within the confines of the previous studies' availability and scope because it only employs secondary sources. There is a need for additional empirical research in order to assess the direct impacts of conservation strategies on specific territorial communities. How dependent are modern societies on electrical power? Are we prepared for a blackout? Life without electricity in today's world would be challenging. Our daily lives – whether it's using the internet, phones, medical services, transport or schools – rely on access to electricity in nearly every aspect. Considering that European countries must employ strategic instruments supporting national energy security.
Originality/value. By combining knowledge from various sources, this study gives stakeholders and policymakers an extensive understanding of how to restore Ukraine's electrical infrastructure during martial law and ensure the implementation of innovative tools and alternative energy sources.

Keywords: critical infrastructure; decentralization; energy security, managing energy security.
Category of the paper: research paper.
JEL: Q41, Q42, Q48, Q54, H56, O44.

1. Introduction

Before Russia's aggression against Ukraine in 2022, the energy sector was a substantial contributor to the national economy, generating significant revenues, particularly from electricity exports to neighboring countries in Europe. For example, electricity exports to Poland, Hungary, and Slovakia provided critical foreign exchange inflows, particularly in the nuclear and hydropower sectors (Assessment of damages and losses to Ukraine's energy sector due to Russia's full-scale invasion, 26.06.2024).

The originality of the presented material lies in the fact that, despite the growing number of analytical reports assessing wartime damage to Ukraine's energy sector, there is still a lack of academic studies that systematically classify the mechanisms of infrastructure destruction, compare traditional and modern warfare tools, and analyse their cascading impacts on interconnected infrastructure systems. This article offers a novel and integrated analytical approach by combining these elements into a coherent framework and by proposing a structured typology of threats to energy infrastructure during contemporary armed conflicts. Unlike existing assessments that mainly quantify losses, this study focuses on identifying causal mechanisms, vulnerabilities, and technologically driven protective strategies, thus filling a significant research gap in the current literature.

However, the ongoing war has dramatically altered the energy landscape. Destruction of energy infrastructure in conflict zones, has led to a reduction in energy production and, consequently, financial losses, which consequently made life very difficult for Ukrainians. It's not just about lighting, cooking or heating, but also communication issues Internet and phones, also, for example, modern hospitals, schools, banks depend heavily on electricity.

Additionally, in modern societies, infrastructure systems are becoming increasingly interconnected and complex. Power grids, water supply systems, transportation networks and communications systems are often interdependent, meaning that damage to one system can have a cascading effect on others. For example, a power outage caused by the destruction of a substation can result in the shutdown of water pumps and the interruption of Internet and telephone services. These interconnections make infrastructure more vulnerable to widespread disruption during wartime.

The rise of air-launched precision guided munitions and drones has led to more targeted strikes on infrastructure. While this theoretically limits collateral damage, it also means that adversaries can focus their efforts on specific, high-value targets like power plants (Kunertova, 2023).

The drone strikes on Saudi Aramco oil facilities in 2019, which temporarily crippled the country's oil production, demonstrated the potential for precision strikes to inflict severe economic damage with relatively few resources (Hafner et al., 2023). The protection of civilian infrastructure during wartime is governed by international humanitarian law, particularly the Geneva Conventions which prohibit attacks on civilian objects unless they are being used for military purposes (Luigi, 2024). However, the distinction between civilian and military infrastructure is often blurred in modern conflicts. Dual-use infrastructures such as bridges, power plants, and telecommunications networks—can be used by both civilian and military forces, leading to ethical and legal dilemmas when such targets are attacked (Protecting the Environment during Armed Conflict, 16.10.2024).

This paper explores the mechanisms through which war destroys energy infrastructure, with a focus on both traditional and contemporary methods of warfare. It also examines strategies for safeguarding infrastructure during wars, including technological approaches that can mitigate the damage and ensure the continuity of essential services. By understanding the threats posed to infrastructure and how to protect it, governments, international organizations, and other stakeholders can better prepare for and respond to the challenges and consequences of modern warfare.

This article does not address the role of public and private entities. Also, this article does not address ethical or political issues. It is not intended to discuss the topic of managing the reconstruction of the energy infrastructure in Ukraine.

2. Materials and Methods

Data for this study were collected through a comprehensive review of governmental reports, policy papers, and official communications from Ukrainian authorities, including the Ministry of Energy of Ukraine (*Annual Report on the Operation of the Ukrainian Energy System*, 18.09.2024) and the State Emergency Service (*State Emergency Service Report*, 18.09.2024). Additional materials were drawn from international organizations such as the United Nations (UN, *Transforming Our World: The 2030 Agenda for Sustainable Development*, 10.09.2024), the World Bank (World Bank Group, 10.09.2024), and the International Energy Agency (IEA, 11.09.2024). These sources were complemented by analytical assessments and damage evaluation reports (*Brief Ukrainian Energy Sector Evaluation and Damage Assessment*, 10.10.2024), as well as academic and policy-oriented literature examining best practices in energy security, infrastructure resilience, and wartime energy system management.

The literature review provided the theoretical foundation for the research, identifying key variables, indicators, and structural characteristics relevant to assessing Ukraine's energy system performance before and during the war. It also enabled the formulation of analytical categories related to infrastructure resilience, diversification of energy sources, grid vulnerability, and the role of decentralised and renewable energy solutions in enhancing national energy security.

Despite the increasing number of descriptive and sectoral reports, the systematic review of academic sources revealed a clear research gap: existing studies tend to focus either on quantifying wartime damage or on proposing general policy recommendations, but they rarely analyse the mechanisms of infrastructure destruction, their cascading effects across interdependent systems, and the technological options for mitigating such impacts in an integrated manner. Current literature thus lacks a comprehensive analytical framework that links wartime threat typologies with infrastructure vulnerabilities and protective strategies.

This gap highlights the need for an analytical study that connects mechanisms of wartime infrastructure disruption with their systemic consequences. Therefore, the aim of this article is to systematize the mechanisms through which war affects energy infrastructure and to identify technological and organizational approaches that may enhance the resilience of energy systems under extreme conditions.

The following research questions arise from this gap:

1. What mechanisms of energy infrastructure destruction are characteristic of modern armed conflicts?
2. How do disruptions in one segment of the energy system generate cascading effects in other interconnected sectors?
3. Which technological and structural solutions can enhance the resilience of energy systems during wartime?
4. How can lessons learned from international cases inform Ukraine's strategy for protecting critical energy infrastructure?
5. To ensure methodological rigor, the study employed a mixed qualitative-analytical approach. First, a *documentary analysis* was conducted to extract quantitative and qualitative information from official statistics, technical reports, and policy documents. Second, a *comparative analytical method* was applied to evaluate Ukraine's energy infrastructure in relation to international benchmarks and established models of energy resilience and post-crisis recovery. Third, *triangulation* of data from multiple independent sources was used to validate findings and minimize potential bias arising from incomplete wartime reporting.
6. In addition, the study incorporated elements of *system analysis* to assess interdependencies between different segments of the energy sector—nuclear, thermal, hydropower, renewable energy, and transmission networks – and to determine how wartime disruptions affected overall system functionality. This approach made it possible to evaluate not only the physical condition of energy infrastructure but also the institutional, regulatory, and operational capacities shaping Ukraine's ability to maintain and restore electricity supply under extreme conditions.

7. Collectively, these methodological steps established a robust empirical and analytical basis for examining Ukraine's wartime energy challenges and identifying strategic directions for reconstruction, modernization, and long-term transformation of the national energy sector.

3. Literature Review

Energy security is one of the key strategic goals of any state, particularly in times of war when access to resources is restricted, and infrastructure is under threat. The Ukrainian experience in this context provides a unique case study of how energy resource management can be adapted during war.

In the study by (Adenso-Díaz et al., 2017), the focus is on resource management under dynamic pricing, which allows for revenue optimization and waste reduction. While the article primarily deals with the management of perishable goods, its principles can be adapted to energy resource management during wartime. For example, in situations where resources are limited, the use of dynamic models can help optimize electricity distribution among consumers. The adaptability of these models to resource constraints is highly relevant for Ukraine during wartime, where energy shortages may become critical. Bernow (Bernow et al., 2001) emphasizes mechanisms for clean development in the context of climate policy. They analyze how clean technologies and strategic planning in the energy sector can contribute to reducing environmental impact. In Ukraine's case, which is highly dependent on fossil fuels, these approaches could be valuable for the development of alternative energy sources during wartime. By reducing reliance on imported energy supplies, Ukraine could strengthen its energy independence and ensure a more resilient energy infrastructure under conflict conditions.

The energy policy of the European Union, as discussed in the European Commission's report (2024), plays a crucial role for Ukraine as it integrates into the European energy market. The policy focuses on increasing energy efficiency and developing renewable energy sources, which becomes especially relevant during military conflicts when traditional energy sources may be destroyed or disrupted. For Ukraine, aligning with EU energy goals can help build a more secure and sustainable energy future. The Polish National Action Plan for Renewable Energy Sources (Polish Ministry of Climate and Environment, 2020) presents an interesting model for Ukraine. Poland's proactive policies aimed at reducing dependence on imported energy could serve as a valuable lesson for Ukraine during its own energy crisis caused by war. By diversifying energy sources quickly, Ukraine can reduce its vulnerability to external disruptions.

Statistical data provided by Eurostat (2024) underline the importance of accurately tracking energy consumption and the import/export balance. For Ukraine, this could be critical in evaluating its capabilities during wartime, when energy supply channels are disrupted or threatened. Such monitoring helps policymakers make informed decisions on energy resource management, especially when external supply lines are compromised.

Some authors rightly highlight the challenges of fossil fuel dependency. For example, Liu (Liu et al., 2019) explore coal consumption in China and its impact on achieving carbon goals. For Ukraine, which also relies heavily on fossil fuels, China's experience could be useful in identifying pathways to energy independence during armed conflicts, particularly by reducing carbon emissions and transitioning to renewable energy sources. By shifting away from fossil fuels, Ukraine could also mitigate the environmental consequences of wartime energy usage. Many authors stress the importance of corporate responsibility and innovation in energy management. For instance, Porter & Kramer (2006) highlights the significance of Corporate Social Responsibility (CSR). In times of war, energy companies in Ukraine could utilize CSR approaches to enhance the resilience of their operations, particularly in ensuring the supply of energy to critical infrastructure.

The Ukrainian experience can also be enriched by the research of Yakymchuk et al. (2024), which focuses on the importance of developing alternative energy sources and using natural resources to support the economy during wartime. Specifically, they emphasize the need for Ukraine to advance its environmental policies and diversify energy sources to reduce the strain on conventional energy systems during and after the war. A further strand of contemporary research highlights the growing militarisation of critical energy systems and the increasing relevance of hybrid threats, including cyberattacks, drone warfare, and precision-guided strikes. Studies on critical infrastructure resilience (Kunertova, 2023; Hafner et al., 2023) emphasise that modern conflicts blur the boundary between military and civilian targets, creating complex interdependencies that magnify the effects of physical and digital disruptions. Although these works provide valuable insights into threat typologies, they rarely integrate these insights with the broader debates on energy transition, decentralisation, or wartime resource allocation. As a result, the literature remains fragmented, with security-focused analyses and energy-policy analyses developing in parallel rather than informing one another.

Another relevant body of scholarship concerns the role of decentralised and renewable energy systems in enhancing national security under conditions of instability. Research on microgrids, distributed generation, and adaptive repair capacities suggests that decentralisation not only reduces vulnerability to targeted attacks but also supports faster restoration of essential services during crises. Yet, while these studies offer promising technological solutions, they seldom include the Ukrainian case or consider the specific operational constraints of an active war zone. This reinforces the research gap identified in the present paper: there is a lack of integrated analyses that connect threat environments, systemic vulnerabilities, technological pathways, and emergency management strategies into a single conceptual model applicable to countries experiencing full-scale military aggression.

4. Energy infrastructure in Ukraine before the outbreak of war in 2022

Before the war in 2022, Ukraine had a diverse energy generation portfolio that included nuclear power plants (NPPs), thermal power plants (TPPs), renewable energy sources (RES), and hydroelectric power plants (HPPs). Below is an overview of the locations and capacities of these energy sources.

Nuclear power plants (NPPS). Ukraine is notable for its nuclear energy sector, which, before Russia's invasion of Ukraine the year 2022, accounted for **2.6%** of the world's nuclear energy capacity. With four major nuclear power plants, including the Zaporizhzhia Nuclear Power Plant (the largest in Europe), Ukraine has been an important player in both regional energy security and the global nuclear landscape. Ukraine had a significant reliance on nuclear energy, which accounted for more than half of its electricity production before the conflict in 2022. There were four active nuclear power plants, all located in the central and southeastern parts of the country, with a total installed capacity of about 13.8 gigawatts (GW).

Zaporizhzhia NPP: Located near the city of Enerhodar in southeastern Ukraine, Zaporizhzhia was the largest nuclear power plant in Europe and one of the ten largest in the world, with an installed capacity of 6000 megawatts (MW) (6 reactors, 1000 MW each).

Rivne NPP: Located in northwest Ukraine, near the city of Varash, this plant had a total capacity of 2835 MW (4 reactors: two 1000 MW reactors and two smaller reactors of 440 MW).

Khmelnytskyi NPP: Situated in western Ukraine near the town of Netishyn, Khmelnytskyi NPP had an installed capacity of 2000 MW (2 reactors of 1000 MW each). Plans for two additional reactors were in progress but were not completed by 2022. **South Ukraine NPP**: Located near Yuzhnoukrainsk in southern Ukraine, the South Ukraine NPP had an installed capacity of 3000 MW (3 reactors of 1000 MW each).

To further strengthen the methodological framework, the study also employed contextual and temporal analysis to track how Ukraine's energy system evolved under the pressure of wartime conditions. This included examining the sequence of attacks on critical energy infrastructure, the timing of system failures, and the government's emergency response measures. Such temporal mapping allowed for the identification of critical vulnerabilities and bottlenecks in the energy supply chain, including disruptions in fuel logistics, damage to high-voltage substations, and instability in regional power balancing.

Additionally, geospatial analysis was used to assess the territorial distribution of damage and the resilience of specific energy assets. By correlating regional attack patterns with the location of key generating facilities – such as thermal power plants, hydropower dams, and renewable energy clusters – the study identified areas of highest systemic risk and regions where decentralised energy solutions could offer the most strategic value. Although high-resolution satellite data were not used directly, the analysis relied on publicly available geospatial incident mapping from Ukrainian authorities and partner organizations.

Finally, the methodological design incorporated an expert-based interpretative component. Insights from energy professionals, policy analysts, and international partners – obtained through publicly available expert interviews, briefings, and think-tank publications – were used to contextualize the empirical findings and validate assumptions about system resilience, reconstruction priorities, and post-war energy policy directions. This interpretative layer ensured that the study accounts not only for technical indicators but also for strategic considerations shaping Ukraine's ongoing energy transition.

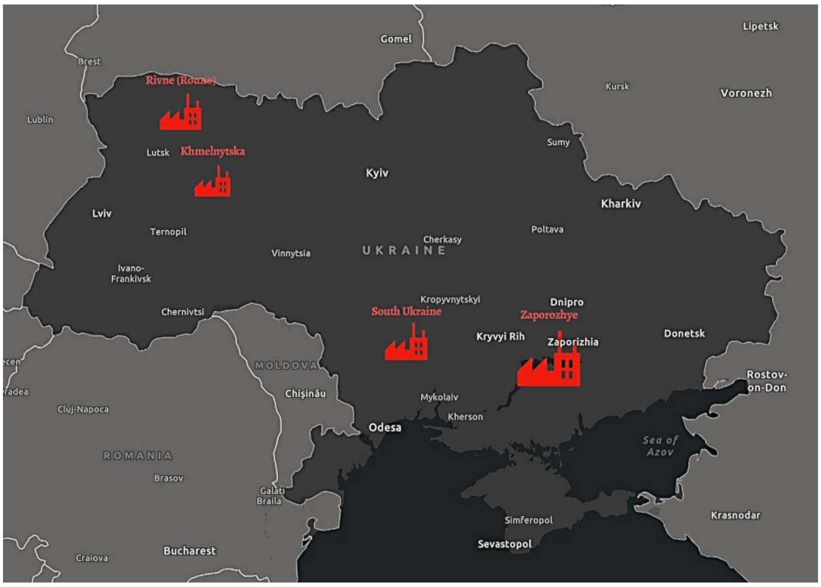

Figure 1. Nuclear Power Plants in Ukraine 2022.

Source: https://clemson.maps.arcgis.com/apps/dashboards/cd37c198d1b448aa95e8e59d033b03c0

Thermal power plants (TPPS). Ukraine also has thermal coal and gas-fired power plants. Although this accounts for only 0.6% of the global thermal power generation, it remains a vital component of Ukraine's energy mix and industrial output.

Thermal power plants, primarily fueled by coal and natural gas, played a major role in Ukraine's energy mix, providing around 30-35% of the country's electricity. The most significant plants were concentrated in the eastern and central parts of Ukraine, near coal deposits.

Burshtyn TPP: Located in western Ukraine, this plant had an installed capacity of **2335 MW** and was part of the "Burshtyn Energy Island," which was connected to the European grid, allowing for electricity exports to EU countries.

Zmiivska TPP: Situated in Kharkiv Oblast, northeastern Ukraine, Zmiivska TPP had a capacity of **2270 MW** and was one of the largest in the country.

Kryvyi Rih TPP: Located in Dnipropetrovsk Oblast, this plant had an installed capacity of **1600 MW** and was primarily coal-fired.

Vuhlehirska TPP: Located in Donetsk Oblast, Vuhlehirska had an installed capacity of **3600 MW**, but its operations were frequently disrupted due to the conflict in the Donbas region, which began in 2014.

Ladyzhyn TPP: Located in Vinnytsia Oblast, Ladyzhyn TPP had an installed capacity of **1800 MW**.

Trypilska TPP: Located near Kyiv, this power plant had a capacity of **1800 MW**.

In addition to these large plants, there were several other smaller TPPs spread across the country.

Thermal power plants (TPPs) constituted another essential pillar of Ukraine's pre-war energy architecture. Although Ukraine accounted for only 0.6% of global thermal power generation, thermal facilities – primarily coal – and natural gas-fired – remained a critical component of the national energy mix, supplying approximately 30-35% of total electricity production. Their strategic significance extended beyond electricity generation, as TPPs supported industrial output, district heating systems, and regional energy security, particularly in the eastern and central oblasts traditionally associated with coal mining and heavy industry.

Before the escalation of the war in 2022, Ukraine operated several large thermal power plants with substantial installed capacity. Among the most important was the Burshtyn TPP (2335 MW), located in western Ukraine, which formed the core of the "Burshtyn Energy Island" – a unique energy zone synchronised with the European grid, facilitating electricity exports to EU member states. Zmiivska TPP in Kharkiv Oblast (2270 MW) ranked among the country's largest facilities and played a key role in maintaining energy stability in northeastern Ukraine. Similarly, the Kryvyi Rih TPP (1600 MW) and Ladyzhyn TPP (1800 MW) provided essential baseload capacity for industrial regions in central Ukraine, relying predominantly on coal-fired units.

In eastern Ukraine, the Vuhlehirska TPP (3600 MW) was one of the most significant power stations prior to the full-scale invasion; however, its operations had already been repeatedly disrupted by conflict since 2014. The Trypilska TPP, located near Kyiv with an installed capacity of 1800 MW, served as a major source of electricity and district heating for the capital region. Beyond these major facilities, numerous smaller thermal power plants were distributed across the country, contributing to local grid balancing and providing reserve capacity.

Despite their importance, Ukraine's TPPs faced longstanding structural and environmental challenges, including aging infrastructure, dependence on fossil fuels, fluctuating coal supply chains, and relatively high emissions compared with other energy sources. The outbreak of full-scale war significantly exacerbated these vulnerabilities, as many thermal plants became primary targets of missile and drone attacks, resulting in severe physical damage, operational disruptions, and fuel shortages. As a consequence, the resilience of the thermal generation sector has emerged as a central issue in the broader discussion on Ukraine's post-war energy recovery, modernization, and transition to cleaner and more decentralized energy systems. The full-scale invasion dramatically intensified the systemic vulnerabilities inherent in Ukraine's thermal generation sector. Since early 2022, TPPs have been among the primary targets of Russian missile and drone attacks, resulting in large-scale destruction of generating units, transformer substations, and auxiliary infrastructure. Damage to coal mines, fuel depots, and railway logistics corridors further disrupted the supply chains essential for continuous TPP operation. In several regions, repeated strikes led not only to temporary shutdowns but also to the complete loss of generation capacity, significantly reducing the country's ability to maintain a stable baseload. As a result, the share of functional thermal generation sharply declined, placing increased pressure on nuclear, hydropower, and decentralized renewable systems to compensate for supply deficits.

At the same time, the war underscored the dual strategic value of thermal power plants. On the one hand, they are highly vulnerable, centralized assets that can be incapacitated by targeted attacks; on the other, they provide indispensable grid-balancing services, rapid ramp-up capabilities, and critical winter heating for densely populated and industrialized areas. This creates a challenging policy dilemma: while thermal generation must be preserved in the short term to ensure energy security under wartime conditions, it simultaneously requires long-term modernization, partial decarbonization, and technological diversification to align with Ukraine's commitments to EU energy standards.

Looking ahead, the modernization of Ukraine's thermal power sector is expected to follow several strategic directions. These include retrofitting selected TPPs with cleaner and more flexible technologies, such as high-efficiency gas turbines, biomass co-firing systems, and carbon-capture-ready infrastructure where feasible. Additionally, enhancing cyber-physical protection, decentralizing auxiliary systems, and integrating thermal units into smart-grid and energy-storage frameworks will be crucial for improving resilience. International support—from the EU, the World Bank, and bilateral energy partnerships—will also play a central role in financing reconstruction and accelerating the transition toward a more sustainable, adaptive, and less fossil-fuel-dependent thermal generation landscape in post-war Ukraine.

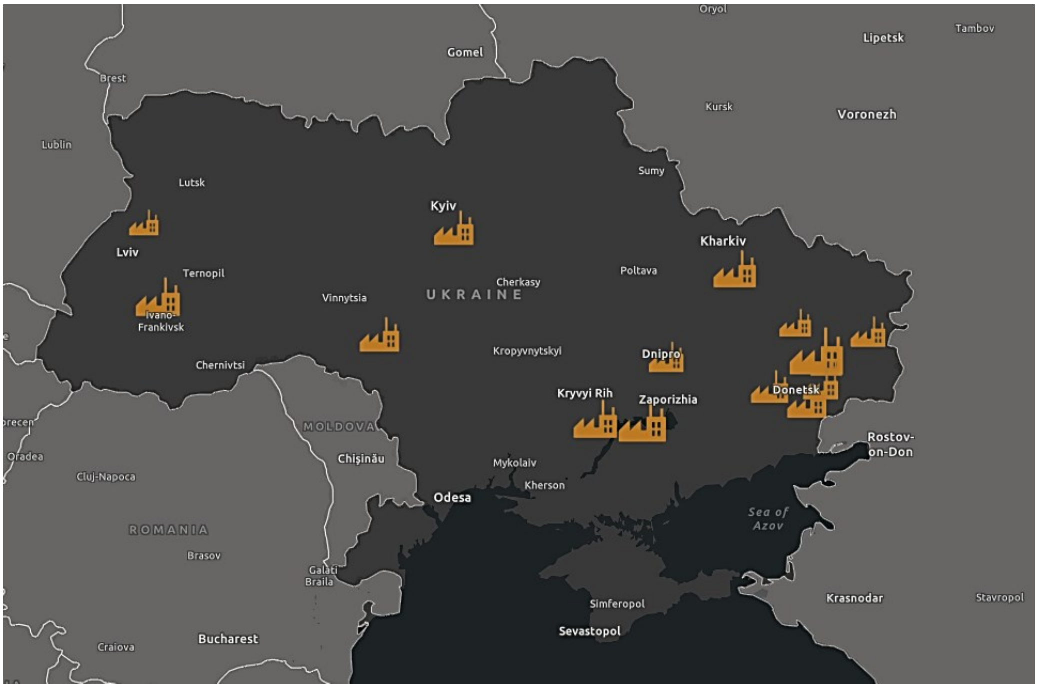

Figure 2. Thermal power plants in Ukraine 2022.

Source: https://clemson.maps.arcgis.com/apps/dashboards/cd37c198d1b448aa95e8e59d033b03c0

Renewable energy sources (RES). Renewable energy sources (RES) constituted an increasingly important component of Ukraine's pre-war energy landscape. Although the country's share in global renewable capacity remained modest compared to EU member states, Ukraine demonstrated notable progress, particularly in the solar sector, which accounted for approximately 1.2% of global photovoltaic capacity by 2022. Wind energy, while developing at a slower pace, represented 0.2% of global output, whereas hydropower contributed about 0.4% of global hydroelectric capacity. By 2022, renewable energy sources produced an estimated 7-8% of Ukraine's electricity, supported by more than 9 GW of installed capacity across solar, wind, biomass, biogas, and hydropower facilities. Despite this progress, the overall structure of the sector remained highly uneven and regionally concentrated, reflecting both geographical potential and infrastructural constraints.

Ukraine's solar power generation expanded particularly rapidly throughout the 2010s due to favorable climatic conditions and strong investment incentives. The majority of photovoltaic installations were located in the southern and central oblasts—regions characterized by high solar irradiation. Flagship projects included the Nikopol Solar Power Plant (246 MW) and the Pokrovska Solar Plant (approximately 240 MW), both situated in Dnipropetrovsk Oblast. By the beginning of 2022, Ukraine's total installed solar capacity reached nearly 7 GW, making solar energy the dominant component of the nation's renewable energy portfolio.

Wind energy development was concentrated primarily in the coastal regions of southern Ukraine, especially Zaporizhzhia, Kherson, and Mykolaiv Oblasts, where favorable wind conditions enabled the establishment of high-capacity installations. Among the largest facilities were the Primorsk Wind Farm (200 MW) and the Botievo Wind Farm (200 MW), both located in Zaporizhzhia Oblast. In aggregate, installed wind capacity reached around 1.6 GW by 2022, positioning wind power as the second-largest segment of the renewable energy sector.

Biomass and biogas projects, though significantly smaller in scale, played an increasingly important role in supporting rural and decentralized energy production. With around 250 MW of installed capacity, these technologies offered a valuable contribution to local energy resilience, particularly in agricultural regions with substantial biomass resources.

Hydropower remained a stable yet relatively modest contributor to Ukraine's energy system, generating roughly 5-7% of total electricity output. Hydropower facilities were predominantly located along the Dnieper River and its tributaries. Major installations included the Dnieper Hydroelectric Station (DniproHES) in Zaporizhzhia with a capacity of 1570 MW, the Kremenchuk HPP (625 MW), the Kyiv HPP (440 MW), the Kaniv HPP (444 MW), and the Dniester HPP in western Ukraine (702 MW). In addition to these large plants, numerous small hydroelectric stations complemented the generation mix, contributing to regional grid stability and balancing intermittent renewable sources.

Overall, Ukraine's renewable energy sector prior to the full-scale invasion exhibited strong growth dynamics but also remained vulnerable due to geographical concentration, limited storage capacity, and partial integration into the national grid. These structural characteristics became particularly significant during the war, when energy decentralization and resilience emerged as critical priorities for national security and post-war reconstruction planning.

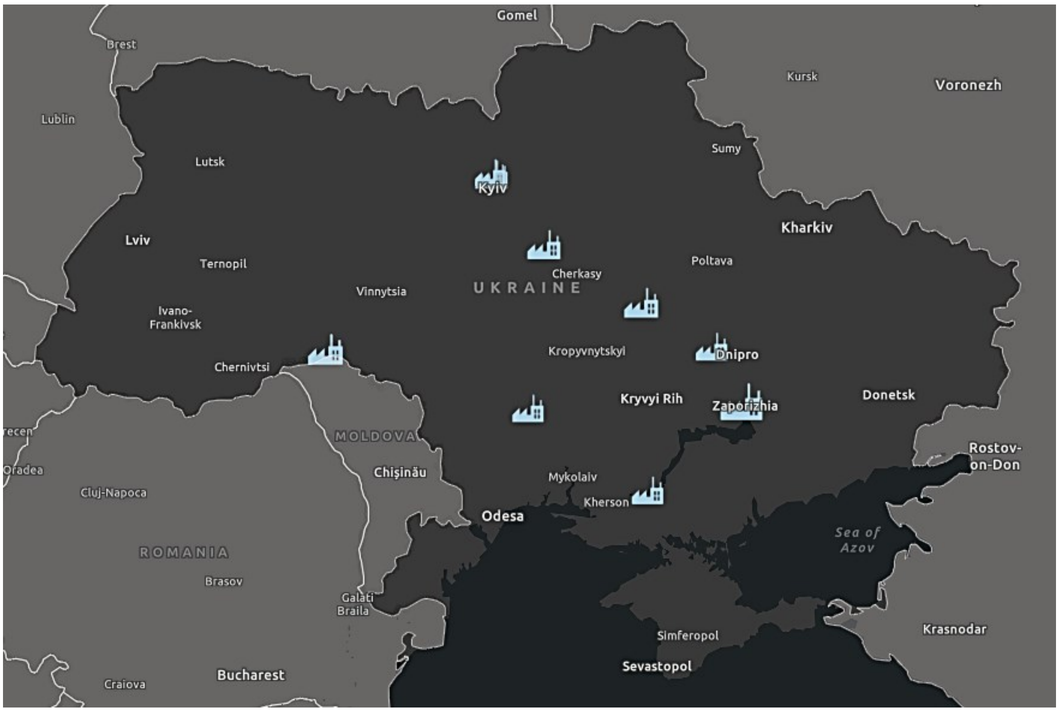

Figure 3. Hydroelectric Power Plants in Ukraine 2022.

Source: https://clemson.maps.arcgis.com/apps/dashboards/cd37c198d1b448aa95e8e59d033b03c0

The energy structure and economic efficiency of various energy sources in Ukraine before the outbreak of war in 2022 is provided in Table 1.

Table 1.
Power Capacities of Ukraine's Power Plants Before the War (up to 2022)

Type of Power Plant	Capacity, GW	Share in Total Energy Mix	Generation Cost, $/MWh (Ukraine)
Nuclear Power Plants (NPP)	13.8	51-55%	40-50
Thermal Power Plants (TPP)	21.0	30-35%	60-100 (depending on fuel)
Hydroelectric Power Plants (including PSPPs)	5.9	5-7%	30-40
Renewable Energy Sources (including solar and wind)	8.5	10-12%	100-120

Source: authors' work based on Eurostat (2024), World Nuclear Association (2020), Ministry of Energy of Ukraine (2021; 2024), Polish Ministry of Climate and Environment (2020), IEA (2021), British Petroleum (2021), SAEE (2024), WBA (2017) and European Commission (2024).

Nuclear Power Plants (NPPs) in Ukraine account for a significantly larger share of the energy mix (over 50%) with low generation costs in Ukraine. Thermal Power Plants (TPPs) share in Ukraine is around 30-35%. The generation costs are higher for TPPs due to fuel variability, especially fossil fuels. Hydroelectric Power Plants (HPPs) represent a smaller portion of the energy mix in Ukraine Renewable Energy Sources (RES) in Ukraine accounted for up to 12% of the market by 2022. However, the generation cost of renewables in Ukraine remains higher due to technological and infrastructure limitations. Before the full-scale invasion in 2022, Ukraine’s energy system demonstrated a relatively balanced but structurally vulnerable configuration dominated by nuclear and thermal generation. As shown in Table 1, nuclear power ensured more than half of total electricity production at comparatively low generation costs, while thermal power plants accounted for nearly one-third of the mix and remained highly sensitive to fluctuations in global fossil fuel prices. Hydropower and renewable energy sources held considerably smaller shares, though their strategic importance had been steadily increasing in the years prior to the war.

Despite the progress achieved in diversifying the energy portfolio, the pre-war energy architecture exhibited several systemic weaknesses, including limited grid flexibility, high dependence on aging thermal assets, and insufficient integration of distributed renewable generation. The onset of hostilities in 2022 further aggravated these structural challenges. Targeted attacks on critical infrastructure led to substantial damage to thermal power plants, substations, and transmission lines, significantly constraining the country’s generation and distribution capabilities.

The relatively high cost of renewable electricity compared with nuclear and hydropower also reflects pre-war technological and infrastructural constraints, such as limited domestic production of renewable equipment, challenges in grid balancing, and insufficient storage capacity. These limitations became even more pronounced during wartime, as the resilience and decentralization potential of renewables gained strategic relevance for sustaining electricity supply in affected regions.

Overall, understanding the pre-war energy structure is crucial for assessing Ukraine’s current needs and formulating effective recovery strategies. The war has demonstrated the urgent necessity of strengthening energy security through diversification, decentralization, and the deployment of innovative energy-saving technologies. Enhancing the share of resilient, low-cost, and decentralized energy systems – including small modular nuclear units, distributed renewables, and smart-grid solutions – represents a key pathway for rebuilding an energy system capable of functioning reliably under the conditions of prolonged military threat and post-war reconstruction.

5. Energy infrastructure in Ukraine in 2024

As of October 1, 2024, it is difficult to estimate the exact scale of the destruction of Ukraine's electrical infrastructure, as such data is not disclosed for strategic security reasons. Additionally, facilities occupied after 2022 can only undergo a comprehensive assessment once they are returned to Ukrainian control. In addition, Russian shelling continues therefore the scene of destruction is growing daily. Based on data reported in the media and reports the following conclusions can be reached. The Zaporizhzhia Nuclear Power Plant (ZNPP) remains occupied by Russian forces. A revised assessment can only be made after the de-occupation of the Zaporizhzhia (ZNPP). Pivdennoukrainska NPP was shelled. Khmelnytska NPP and Rivnenska NPP were also affected due to attacks on transmission system infrastructure.

In 2023 the Russian forces destroyed the Kakhovka Hydroelectric Power Plants (HPP). The destruction of the Kakhovka dam also caused increased nuclear safety risks due to the ZNPP's disrupted cooling supply from the Kakhovka reservoir. According to official reports, strikes were carried out on Dniprovska HPP, Dnistrovska HPP, and Kanivska HPP. As many as 73% of large Thermal Power Plants (TPP) are destroyed in Ukraine. According to official reports, strikes were carried out on the Burshtynska TPP, Dobrotvirska TPP, Ladyzhynska TPP, Zmiivska TPP, Trypilska TPP. According to the Energy Charter Secretariat, 13% of solar generation capacity is in temporarily occupied territories, and 8% have been damaged or destroyed.

About 80% of wind generation remains uncontrolled, with some facilities damaged by shelling. At least four biogas plants have been destroyed. Russian missile strikes targeted and destroyed power generation and transmission facilities in the Poltava, Kirovohrad, Lviv, and Ivano-Frankivsk regions. In September 2024, following another Russian attack, 490 settlements across Ukraine were left partially or completely without electricity, with the Dnipropetrovsk region suffering the most damage. A drone strike on a substation triggered a large-scale fire, leading to widespread power outages for both infrastructure and households. Additionally, shelling caused a ground fire that damaged an overhead line, resulting in voltage drops. As a result, Ukrainians are bracing for a harsh winter with frequent power outages and energy conservation measures in place.

The power networks were damaged, resulting in complete blackouts in almost all Ukrainian regions. The scale of the damage in millions of dollars is presented in Table 2.

Table 2.
Dameges to the electric power industry in Ukraine (up to May 2024)

Sector	Damage, $ million
Power distribution	801
Power transmission	2100
Power generation	8462
Nuclear Power Plants	843
Thermal Power Plants	3588
Combined heat and power plants	1433
Hydroelectric power plants	2378
Renewables	282

Source: Kyiv School of Economics.

Currently, 182 cogeneration plants have been installed, of which 83 are already working; the rest will be installed by the end of the year. Energy projects are being implemented in the country, currently, according to the National Bank of Ukraine, an application for 7.9 billion UAH has been approved. NB7 countries provide additional support. The European Commission allocates 3 million euros for the work of IAEA missions in Ukraine (Russian War Against Ukraine: Energy Dimension, 21.10.2024).

6. Results and Discussion

Despite the many challenges posed by modern warfare, there are several strategies that governments and organizations can implement to preserve infrastructure during conflicts.

Hardened and Resilient Infrastructure: One way to protect infrastructure from attacks is to design and build facilities that are more resistant to damage. In Ukraine, concrete blocks have been used to protect network infrastructure equipment. In preparation for the winter of 2023/2024, Ukrainians reinforced their existing facilities with concrete blocks or even sandbags. This approach would help safeguard equipment from basic threats like shrapnel, which can still cause significant damage to infrastructure. Installing redundant systems: that can take over if primary systems are disabled.

Decentralized energy systems, modernizing power grids to create more decentralized systems – such as microgrids – can enhance resilience in times of conflict. Smart grids, which use digital technology to monitor and manage electricity distribution, can also improve the grid's ability to adapt to disruptions and reroute power around damaged areas. Rapid Repair and Restoration Teams: In conflict zones, it is crucial to have specialized teams trained to quickly repair damaged infrastructure. These teams should have the necessary equipment and expertise to restore power services as quickly as possible after an attack. Prepositioning repair equipment and materials near critical infrastructure can significantly reduce the downtime of essential services.

Development of renewable resources according Saulius Rimutis "is important not only in thinking about the future of Ukraine but also in the current situation, and this must be supported by the Ukrainian government. RES resources can help the aforesaid decentralization of the grid, but at the same time, as noted by the United States NREL laboratory, solar power plants can significantly contribute to the longer operation of diesel generators. Managing energy security during wartime requires a comprehensive approach that integrates innovations, alternative energy sources, and flexible resource management methods. The Ukrainian experience demonstrates that success lies in aligning energy policies with international strategies and adapting to changes in the global energy system. By focusing on renewable energy, strategic planning, and corporate responsibility, Ukraine can strengthen its energy security even in the most challenging conditions of war.

7. Conclusions

Since October 2022, Ukrainian citizens have been living under conditions of emergency blackouts. The Ukrainian Government is working on the restoration of the energy sector – on starting as much generation as possible before winter. Work continues the protection of those capacities that have been preserved and those that energy workers are currently restoring. Ukraine is steadily increasing its import of electricity from the European Union: now the maximum possible import is 2.2 GW, but so far, the most that the EU can import politically is 1.7 GW. Therefore, they are currently negotiating with the European Commission to open imports. Ukraine has made progress in decentralizing electricity generation (Lessons of War: Ukraine's Energy Infrastructure Damage, Resilience and Future Opportunities, Eastern Europe Studie Centre, 22.10.2024). Thanks to international partners, Ukraine initiated the creation of a special fund to support the energy industry of Ukraine, where more than 500 million euros have already been collected (Only 27% of large TPPs are operating in Ukraine, 22.10.2024).

The war in Ukraine underscores the significant vulnerability of electricity transmission networks. The destruction of one or more key substations can lead to major disruptions in power supply, largely due to the centralized nature of the network, which relies on a few main substations and has limited backup options. Countries, especially those with electricity infrastructure exposed to artillery threats, such as the Baltic states, should consider expanding their networks not only to meet production and consumption demands but also to enhance resilience. This would ensure that even if a critical component is damaged, the stability of the power system can be maintained.

Moreover, the analysis conducted in this article highlights that the war-induced destruction of Ukraine's energy infrastructure is not only the result of traditional military actions but also a consequence of increasingly precise and technologically advanced methods of warfare. The presented synthesis demonstrates that the interconnectedness of modern infrastructure systems amplifies the scale of disruptions, creating cascading failures across essential public services. By integrating recent evidence from Ukraine and international cases of targeted strikes, the study offers an original perspective on the mechanisms of infrastructure vulnerability under wartime conditions. These insights underscore the urgent need for developing advanced protective technologies and resilience strategies that can ensure continuity of critical services even under high-intensity military threats.

Future research on this topic should be expanded to include Cyber Warfare. As digital and cyber systems become more integral to the operation of critical infrastructure, cyberattacks have become a powerful tool in modern warfare. Power grids, for instance, can be disrupted or disabled through these attacks. A notable example occurred in 2015 when a complex cyberattacks on Ukraine's power grid temporarily cut off electricity to 230,000 people. These types of attacks can immobilize key services without inflicting physical damage, posing a significant challenge for nations with highly digitized infrastructures.

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