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The Ukrainian power grid: lessons for Europe

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Abstract:

The war in Ukraine has turned its electricity system into a strategic target. Russia has waged a sustained campaign of physical and cyber attacks aimed at destabilising the grid, but Ukraine has demonstrated remarkable resilience thanks to inherited structural factors, the high level of technical expertise of its personnel, and international support. Synchronisation with Europe in March 2022 reinforced its stability and paved the way for unprecedented energy cooperation. However, the war has exposed vulnerabilities inherited from the USSR and its excessive centralisation. Ukraine has responded with a strategy designed to optimise available resources, and this strategy is proving effective. The Ukrainian case offers valuable lessons for Europe, whose grids also exhibit structural vulnerabilities that need to be addressed to ensure a supply as critical as electricity.

Keywords:

Ukraine, Critical infrastructure, Hybrid warfare, Power grid, Energy security.

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Introduction

From its very outset, the war in Ukraine has brought about a shift in strategic paradigms that depart from prevailing theories. One such shift was the transformation of Ukraine's energy infrastructure into a priority target of Russian strategy, through the systematic carrying out of attacks on power stations, substations and transmission grids[1] , without regard for how this would affect a population that was supposedly to be liberated.

The prolonged nature of this strategy has tested the resilience of the Ukrainian electricity system, which, after four years of war, has managed to keep its infrastructure stable and operational thanks to pre-existing robustness, the technical expertise of the staff operating it and constant international support, particularly in the early years[2] .

In March 2022, almost from the very start of the war, the Ukrainian electricity grid was synchronised with the European grid[3] . This milestone strengthened energy interdependence on both sides of the border, enabling the European Union to collaborate with Ukraine to maintain the stability of its system.

Against this backdrop, the country under attack has become a testing ground for evaluating the effectiveness of various potential responses to the threats facing an electricity supply network, whether physical, cyber or logistical[4] . At the same time, the International Energy Agency (IEA) has been developing specific plans aimed at strengthening the resilience of the Ukrainian system against attacks.

Most importantly, the practical lessons arising from this situation are perfectly applicable to other European countries, demonstrating how they can adapt their grids to an increasingly uncertain geostrategic environment.

Despite the global attention focused on the war in Ukraine, little emphasis has been placed on studying how it is affecting the country's electricity infrastructure. Whilst some

[1] ALBRECHTSEN, Helen Bille; KHODOROVSKA, Yelyzaveta; MANDZII, Anna-Mariia. 'Resilience Under Fire: How Ukraine's Energy Sector is Adapting – and What It Means for Europe', Ramussen Global, 3 June 2025. Available at: https://rasmussenglobal.com/wp-content/uploads/2025/06/REPORT_Resilience-Under-Fire.pdf

[2] INTERNATIONAL ENERGY AGENCY (IEA). 'Energy System Resilience: Lessons learnt from Ukraine'. Paris, 2026. Available at: https://www.iea.org/reports/energy-system-resilience

[3] ENTSO-E. 'Synchronisation of the Continental Europe Power System with Ukraine and Moldova Successfully Completed', *ENTSO-E Press Release*. 16 March 2022. Available at: https://www.entsoe.eu/news/2022/03/16/continental-europe-successful-synchronisation-with-ukraine-and-moldova-power-systems/

[4] CENTRE FOR SECURITY STUDIES (ETH Zurich). 'Critical Infrastructure Resilience in Ukraine: Energy, Transport and Communication', *CSS Risk and Resilience Report. Zurich, 2024.* Available at: https://www.research-collection.ethz.ch/entities/publication/8a858a30-b01b-4d75-bb61-11c6b7d25885

reports, such as those by Rasmussen Global or the EUISS, focus on analysing specific aspects of Ukraine's energy resilience, none offer a perspective that links their analyses to the impact on European energy security.

This article aims to illustrate that there are many lessons to be learnt from the Ukrainian case regarding the relationship between energy supply networks and their influence on strategic considerations. To this end, the ideas this text seeks to clarify are, firstly, how the Ukrainian electricity grid has survived and evolved over four years of war; secondly, its current state, as well as its main strengths and vulnerabilities; and, finally, what we can learn from the Ukrainian case to apply to other European countries[5] .

The Ukrainian electricity system

Echoes of the Cold War

Although thirty-five years have passed, the Soviet legacy remains present throughout Ukrainian society, and its electricity system is no exception. Based on large-scale thermal and nuclear power stations, connected via very high-capacity transmission nodes, this system was designed to enable high efficiency and control, but at the cost of creating single points of failure that made it extremely vulnerable in the event of armed conflict[6] .

The main idea was to concentrate a large volume of generation, using large substations and a radial, highly hierarchical topology. This resulted in a heavy reliance on a limited number of transformers and trunk lines to guarantee supply.

The result of all this was that, at the outbreak of the 2022 war, its electricity grid exhibited significant structural vulnerability, which was further exacerbated by Russia's in-depth knowledge of the critical elements of the infrastructure[7] .

[5]. HOBHOUSE, Caspar. 'Keeping the lights on: How Ukraine can build a resilient energy system (and why this matters to the EU)', European Union Institute for Security Studies (EUISS), *28 March 2025*. Available at: https://www.iss.europa.eu/publications/commentary/keeping-lights-how-ukraine-can-build-resilient-energy-system-and-why

[6] CONGRESSIONAL RESEARCH SERVICE. 'Attacks on Ukraine's Electric Grid: Insights for U.S. Infrastructure Security and Resilience', *CRS Report R48067*, Washington D.C., 2023. Available at: https://www.congress.gov/crs_external_products/R/PDF/R47590/R47590.3.pdf

[7] COLLINS, Baker. 'Ukraine's Electricity Sector: Urgency and Resilience in a Time of War', *Rice University's Baker Institute for Public Policy*, 2024. Available at: https://www.bakerinstitute.org/sites/default/files/2024-08/20240814-Ukraine%20Electricity%20Sector-WP.pdf

These structural dependencies have profoundly affected the electricity grid's resilience to Russian attacks. On the one hand, it is heavily reliant on transmission nodes based on large power transformers, which are difficult to replace due to their size, cost or manufacturing lead times[8] .

Russia has demonstrated that it is aware of this vulnerability, as, since the start of the war, it has prioritised attacking these transmission facilities over power stations. The aim has always been to cause systemic instability in the grid, enabling them to isolate entire sections, cutting off the supply of this vital resource to whole regions of the country and, in doing so, undermining public morale and confidence in the government.

Furthermore, Ukraine's electricity mix was heavily concentrated in the east and centre of the country, with a critical reliance on nuclear power stations such as those at Zaporizhzhia[9] . This is compounded by a heavy dependence on highly concentrated extra-high-voltage (EHV) transmission lines, operating at between 330 and 750 kV. EHV lines act as energy motorways, but are highly vulnerable to precision strikes.

The final inherited characteristic is the scarcity of distributed generation sources (small-scale and located close to consumption points). This, , compounds all the above factors to exacerbate the structural fragility that was already endemic prior to February 2022.

The few existing renewable energy installations, mainly solar and wind, have been concentrated in the south of the country, with very little geographical dispersion[10] .

The connection with Europe

The synchronisation of Ukraine's electricity grid with the European Continental System (ENTSO-E) took place in March 2022, a few weeks after the start of the war, as an emergency operation designed to ensure the country's energy stability[11] . Despite the

[8] IEA – INTERNATIONAL ENERGY AGENCY. 'Ukraine's Energy Security and the Coming Winter. An energy action plan for Ukraine and its partners', *International Energy Agency*, September 2024. Available at: https://iea.blob.core.windows.net/assets/cec49dc2-7d04-442f-92aa-54c18e6f51d6/UkrainesEnergySecurityandtheComingWinter.pdf

[9] AMNESTY INTERNATIONAL. 'Ukraine: nuclear watchdog findings on Zaporizhzhia tally with information from local sources', *7 September 2022*. Available at: https://www.amnesty.org.uk/latest/ukraine-nuclear-watchdog-findings-zaporizhzhia-tally-information-local-sources/

[10] PIDDUBNYI, Igor; GORIUNOV, Dmytro. 'Assessment of Damages and Losses to Ukraine's Energy Sector Due to Russia's Full-Scale Invasion'. Kyiv School of Economics (KSE), May 2024. Available at: https://kse.ua/wp-content/uploads/2024/06/KSE_Impact-of-the-war-on-energy_ENG-1.pdf

[11] EUROPEAN COMMISSION. 'Statement by Commissioner for Energy Kadri Simson on Synchronisation of the Continental European Electricity Grid with Ukraine and Moldova', *European Commission, Brussels,*

urgent circumstances in which it took place, it represented a highly significant technical and political milestone, as it involved the integration of the Ukrainian grid into the European energy framework.

Since the European Commission took this step, synchronisation has remained an essential pillar of support for Ukraine. It demonstrates the determination of both parties to move towards future integration into the EU[12] .

From a technical and operational perspective, the interconnection enabled two-way electricity exchanges, provided support in the event of production or supply disruptions, and enhanced the internal stability of the Ukrainian grid[13] .

In this regard, it is important to note that Ukraine generates 53 TWh of electricity from nuclear sources[14] and that, in certain cases, it can contribute to the total of 649 TWh produced by the entire European nuclear energy network[15] .

Viewed from a geopolitical perspective, this milestone marked Ukraine's long-awaited decoupling from Russia's electricity grid, representing a further step away from the Kremlin and undermining its ability to use grid stability as a means of exerting pressure[16] . Furthermore, for Kyiv, it signalled progress towards full integration into Europe's energy architecture.

However, energy cooperation between the EU and Ukraine was not limited to grid synchronisation: another key form of support has been the supply of materials to make up for the shortfalls caused by the attacks (generators, spare parts, emergency equipment, etc.).

STATEMENT/22/1789. 16 March 2022. Available at: https://ec.europa.eu/commission/presscorner/api/files/document/print/es/statement_22_1789/STATEMENT_22_1789_EN.pdf

[12] DARVAS, Zsolt; DABROWSKI, Marek; GRABBE, Heather; MOFFAT, Luca Léry; SAPIR, André; ZACHMANN, Georg. 'Ukraine's path to European Union membership and its long-term implications', *Policy Brief 05/2024, Bruegel*, 7 March 2024. Available at: https://www.bruegel.org/policy-brief/ukraines-path-european-union-membership-and-its-long-term-implications

[13] ENERGY COMMUNITY SECRETARIAT. 'Enhancing imports of electricity from the European Union to Ukraine', *Ukraine Energy Market Observatory, 16/2024*. Available at: https://www.energy-community.org/dam/jcr:a1d21225-bd4c-43d8-b996-d1bdabdc05d7/UA_MO_16_2024_import%20to%20Ukraine.pdf

[14] WORLD NUCLEAR ASSOCIATION. 'Nuclear Power in Ukraine', *Country Profile*. Electricity generation data for 2023 included nuclear. 2026. Available at: https://www.world-nuclear.org/information-library/country-profiles/countries-t-z/ukraine

[15] IAEA, POWER REACTOR INFORMATION SYSTEM (PRIS). 'Country Nuclear Power Profiles – Europe', European Nuclear Production Database. Available at: https://cnpp.iaea.org

[16] SABADUS, Aura. 'Wartime Ukraine's European energy integration continues', *Atlantic Council Eurasia Centre Report*. Washington D.C., 19 December 2023. Available at: https://www.atlanticcouncil.org/blogs/ukrainealert/wartime-ukraines-european-energy-integration-continues/

Since the war began, this aid has flowed steadily, as an extension of Europe's energy security guarantees[17] .

The Russian attacks

The objective

Missile and drone attacks on thermal and hydroelectric power stations, transformers and substations have been a constant feature throughout the war, but intensified particularly from 2024 onwards[18] .

The tactical objectives of this strategy were simple: to disable power generation capacity and disrupt the transmission of electricity, whilst helping to overwhelm and geographically disperse Ukraine's air defences.

But the Russians have not limited themselves to physical attacks alone. It is important to consider the intense cyber campaign they are waging against the Ukrainian power grid, seeking to cause targeted outages, disrupt SCADA ([19]) systems and force operators to manage the grid manually.

The outcome Moscow is seeking with these attacks is to keep the electricity grid in a state of constant strain. This would force the Ukrainian authorities to prioritise repairs, manually redistribute loads and continuously adjust the system to prevent widespread disruption, thereby wearing down human resources, infrastructure and resources, until the grid is ultimately forced into collapse[20] .

[17] EU CIVIL PROTECTION & HUMANITARIAN AID (DG ECHO). 'EU deploys emergency generators as Russian strikes leave 1 million Ukrainians without power in -20°C', *Directorate-General for European Civil Protection and Humanitarian Aid Operations (ECHO)*, 23 January 2026. Available at: https://civil-protection-humanitarian-aid.ec.europa.eu/news-stories/news/eu-deploys-emergency-generators-russian-strikes-leave-1-million-ukrainians-without-power-20degc-2026-01-23_en

[18] UNITED NATIONS HUMAN RIGHTS MONITORING MISSION IN UKRAINE (OHCHR-HRMMU). 'Attacks on Ukraine's Energy Infrastructure: Harm to the Civilian Population', *OHCHR Report*. Geneva, September 2024. Available at: https://ukraine.ohchr.org/sites/default/files/2024-12/ENG_Attacks_on_Ukraine%E2%80%99s_Energy_Infrastructure_Harm_to_the_Civilian.pdf

[19] ESET CYBERSECURITY RESEARCH LAB. 'ESET Research: Russian APT groups, including Sandworm, continue their attacks against Ukraine with wipers and ransomware'. 2023. Available at: https://www.eset.com/gr-en/about/newsroom/press-releases-1/eset-research-russian-apt-groups-including-sandworm-continue-their-attacks-against-ukraine-with-wipers-and-ransomware1/

[20] . HIMMELFARB, Anne (Editor). "Ukraine. Third Rapid Damage and Needs Assessment. February 2022 – December 2023", World Bank, the Government of Ukraine, the European Union, the United Nations, *RDNA3*, February 2024. Available at: https://ukraine.un.org/sites/default/files/2024-02/UA%20RDNA3%20report%20EN.pdf

The consequences

Despite its efforts, Ukraine's energy infrastructure has been sustaining continuous damage for years, undermining both its capacity to generate and transmit electricity. By 2024, Ukraine had already lost around 80 per cent of its thermal power generation capacity[21] , to which must be added the attacks on hydroelectric plants and other related infrastructure[22] .

It should also be borne in mind that, prior to the war, production was concentrated in the east, meaning that many power stations have ended up in occupied territory, such as the Zaporizhzhia nuclear power station (the largest in Europe), the Dnieper hydroelectric plant and the large thermal power stations at Vuhlehirsk, Starobesheve and Zuyivska[23] .

This situation is compounded by targeted attacks on high-voltage substations and large power transformers, aimed at isolating entire regions of the country and creating a state of systemic instability in the grid. This is a tactic designed to accumulate damage until the infrastructure collapses at its critical points[24] .

This forces operators to implement power cuts to prevent overloads or, quite simply, to deny the population access to the energy supply[25] , which is critical in a country where access to electricity directly determines survival in the face of harsh winters.

The strategy aimed at causing the grid to collapse has a dual strategic objective. On the one hand, it fosters social fatigue and erodes collective morale in order to wear down the

[21] HOBHOUSE, Caspar. 'Keeping the lights on: How Ukraine can build a resilient energy system (and why this matters to the EU)', European Union Institute for Security Studies (EUISS), 28 March 2025. Available at: https://www.iss.europa.eu/publications/commentary/keeping-lights-how-ukraine-can-build-resilient-energy-system-and-why

[22] AMNESTY INTERNATIONAL. 'Russia/Ukraine: Russian attacks causing catastrophic damage to critical energy infrastructure in Ukraine', *news.* 12 April 2024. Available at: https://www.amnesty.org/en/latest/news/2024/04/russian-attacks-causing-catastrophic-damage-to-critical-energy-infrastructure-in-ukraine/

[23] INTERNATIONAL ATOMIC ENERGY AGENCY (IAEA). "Two years of the IAEA's continued presence at the Zaporizhzhya nuclear power plant. The IAEA's unwavering support for nuclear safety, security and safeguards in Ukraine". 3 September 2024. Available at: https://www.iaea.org/sites/default/files/documents/two-years-of-iaea-continued-presence-at-the-zaporizhzhaya-nuclear-power-plant.pdf

[24] HUMPHREYS, Brian E. 'Attacks on Ukraine's Electric Grid: Insights for U.S. Infrastructure Security and Resilience', CRS Report, US Government, 17 May 2024. Available at: https://www.congress.gov/crs_external_products/R/PDF/R48067/R48067.12.pdf

[25] UNITED NATIONS HUMAN RIGHTS MONITORING MISSION IN UKRAINE (OHCHR-HRMMU). 'Attacks on Ukraine's Energy Infrastructure: Harm to the Civilian Population', *OHCHR Report*. Geneva, September 2024. Available at: https://ukraine.ohchr.org/sites/default/files/2024-12/ENG_Attacks_on_Ukraine%E2%80%99s_Energy_Infrastructure_Harm_to_the_Civilian.pdf

Zelensky government. This is why Russia concentrates its attacks during cold spells, to maximise the psychological impact and the coercive dimension of the strategy[26] .

On the other hand, the synchronisation between Ukraine and the EU forces the latter to compensate for supply shortfalls, thereby extending the pressure on the grid to European allies. Let us not forget that they already had to redesign their entire energy dependency strategy in February 2022, with the consequent increases in energy costs[27] .

Weather conditions pose an additional vulnerability. In Ukraine, winter is the key factor shaping daily life (demand peaks, increased heating requirements and adverse weather conditions), acting as an amplifier of the Russian strategy to maximise the impact on the civilian population and on Ukraine's ability to ensure its well-being, and indeed its very survival.

Factors contributing to the resilience of the electricity grid

A solid foundation

To understand how the Ukrainian electricity grid operates, it is necessary to analyse such basic elements as its design basis and its condition prior to the war. The first thing that stands out is that it is an incredibly oversized grid, designed to handle up to 56 GW, but with an effective generation capacity of only 38 GW[28] .

This slight excess gave the grid exceptional resilience, enabling it to withstand the initial attacks without collapsing and allowing operators to reconfigure the grid in line with the circumstances.

Although the Soviet model was based on centralised grids, these were all linked to their hub in Moscow. The aim was to ensure the stability of the USSR as a whole in the event of a NATO attack, but this has led to the existence, in today's Ukraine, of numerous high-

[26] IEA – INTERNATIONAL ENERGY AGENCY. 'Ukraine's Energy Security and the Coming Winter. An energy action plan for Ukraine and its partners', *International Energy Agency*, September 2024. Available at: https://iea.blob.core.windows.net/assets/cec49dc2-7d04-442f-92aa-54c18e6f51d6/UkrainesEnergySecurityandtheComingWinter.pdf

[27] MCWILLIAMS, Ben; SGARAVATTI, Giovanni; TAGLIAPIETRA, Simone; ZACHMANN, Georg. 'The European Union-Russia energy divorce: state of play', *Analysis 05/2024, Bruegel*. 22 February 2024. Available at: https://www.bruegel.org/analysis/european-union-russia-energy-divorce-state-play

[28] HOBHOUSE, Caspar. 'Keeping the lights on: How Ukraine can build a resilient energy system (and why this matters to the EU)', European Union Institute for Security Studies (EUISS), *28 March 2025*. Available at: https://www.iss.europa.eu/publications/commentary/keeping-lights-how-ukraine-can-build-resilient-energy-system-and-why

power transmission corridors that provide redundancy for the transmission of electricity[29] , giving the grid sufficient room for manoeuvre in the event of simultaneous failures.

Although having an infrastructure in place is essential, it would be of no use without the excellent technical training of the staff who manage Ukraine's electricity grid, whether they are engineers or technicians.

These professionals are well-trained, accustomed to a complex and demanding system, and have demonstrated, throughout the years of war, a great ability to swiftly manage the massive and simultaneous power cuts resulting from Russian attacks[30] .

A purely technical strategy

This combination of structural capabilities and human capital forms the basis for the survival of the Ukrainian electricity grid, but it must be coordinated through the implementation of a well-defined strategy. The objective: to provide technical responses that are rapid, agile and adaptable to any reduction in transmission capacity[31] .

The rapid repair of damage is carried out by specialist teams capable of operating simultaneously at different locations across the country to restore power lines, substations and critical equipment within very short timeframes[32] . It may seem trivial, but this capacity for intervention has, on numerous occasions, prevented isolated incidents of damage from escalating into larger-scale cascading failures.

Another key element of the Ukrainian strategy has been the creation of improvised redundancies, by implementing temporary solutions (bypasses, provisional lines, mobile transformers, etc.) to compensate for, and even prevent, the loss of key network

[29] BÖTTCHER, Philipp C.; RYDIN GORJÃO, Leonardo; BECK, Christian; et al. 'Initial analysis of the impact of the Ukrainian power grid synchronisation with Continental Europe', Energy Adv., 2023, 2, 91. 2023. DOI: 10.1039/d2ya00150k

[30] INTERNATIONAL ENERGY AGENCY. 'Energy System Resilience. Lessons learnt from Ukraine', IEA, 11 February 2026. Available at: https://www.iea.org/reports/energy-system-resilience

[31] INTERNATIONAL ENERGY AGENCY. 'Energy System Resilience. Lessons learnt from Ukraine', IEA, 11 February 2026. Available at: https://www.iea.org/reports/energy-system-resilience

[32] UKRAINE WAR ANALYTICS. 'Infrastructure Repair Capacity: Ukraine's Ability to Restore Energy, Water, and Telecoms After Strikes', 19 February 2026. Available at: https://ukraine-war-analytics.com/comparisons/repair-capacity-infrastructure.html

components[33] . The aim is always to guarantee the supply to urban centres and critical facilities, whilst allowing time to carry out more complex repairs.

Furthermore, Kyiv has adopted a 'critical stock' approach that enables strategic management of spare parts. This involves identifying, prioritising and stockpiling spare parts and auxiliary equipment, ensuring the availability of those that are essential for sustaining the electricity grid.

The approach focuses on minimising logistics-related delays, with the aim of avoiding prolonged outages due to a lack of necessary spare parts[34] .

However, none of this would have been possible without the technical, material, financial and energy support from Europe and the US, which have provided everything necessary to underpin this strategy. This combination of internal capabilities and external support has been crucial in ensuring the success of Ukraine's strategy regarding its electricity grid[35] .

Human capital

The Ukrainian professionals maintaining the electricity grid have demonstrated not only unquestionable technical expertise but also organisational prowess[36] . They have managed to adapt their work to a wartime environment, characterised by extreme stress, a scarcity of resources and a lack of communication with decision-making bodies.

Particular mention must be made of the capacity they have developed to provide a decentralised response through the various regional units. They have been able to act autonomously even when communications or information were degraded or interrupted[37]

[33] UNITED NATIONS DEVELOPMENT PROGRAMME (UNDP), WORLD BANK, GOVERNMENT OF UKRAINE. 'Ukraine. Energy Damage Assessment', Executive Summary, 5 April 2023. Available at: https://www.undp.org/sites/g/files/zskgke326/files/2023-04/UNDP-UkraineEnergyDamageAssessmentEN_ExecutiveSummary%20%281%29.pdf

[34] DIXI GROUP NGO. 'Holding the Grid: Ukraine's Energy Resilience Playbook', International Renaissance Foundation, 11 March 2026. Available at: https://dixigroup.org/en/analytic/holding-the-grid-ukraines-energy-resilience-playbook

[35] SABADUS, Aura. 'Europe can do more to help Ukraine counter Russia's energy attacks', Atlantic Council, 1 August 2024. Available at: https://www.atlanticcouncil.org/blogs/ukrainealert/europe-can-do-more-to-help-ukraine-counter-russias-energy-attacks/

[36] CENTER FOR SECURITY STUDIES (ETH Zürich). 'Critical Infrastructure Resilience in Ukraine: Energy, Transportation, and Communication', *CSS Risk and Resilience Report. Zürich, 2024.* Available at: https://www.research-collection.ethz.ch/entities/publication/8a858a30-b01b-4d75-bb61-11c6b7d25885

[37] INTERNATIONAL ENERGY AGENCY. 'Energy System Resilience. Lessons learnt from Ukraine', IEA, 11 February 2026. Available at: https://www.iea.org/reports/energy-system-resilience

, which has been critical in carrying out the emergency repairs that have ensured continuity of service in partially isolated areas.

In addition, control operators effectively implemented manual procedures, reducing or eliminating reliance on SCADA systems in the face of recurring cyber-attacks[38] . Thanks to this, it was possible to prevent cascading failures, maintaining the flow of power despite the critical nature of the working conditions.

The professional ethos of Ukraine's electricity network technicians has proved to be one of the most valuable assets in sustaining the network. Having always been accustomed to operating with limited resources and in hostile environmental conditions, they have demonstrated a remarkable ability to adapt to circumstances[39] .

Foreign aid

However, for all of the above to be sustained over time, a flow of resources, capital and technical support is required – resources that Ukraine does not possess[40] . In this context, external support has been crucial to sustaining the Ukrainian electricity system.

Since 2022, the EU has not only guaranteed electricity interconnection capacity but has also supplied thousands of generators, equipment, spare parts and materials, as well as the technical support needed to repair damaged power stations and substations[41] .

Furthermore, the IEA has developed annual contingency plans aimed at guiding Ukraine in preparing its strategy[42] . The lessons learnt from the Ukrainian case will enable the IEA

[38] LEE, Robert M.; CONWAY, Tim. 'Ten Years After Ukraine's Power Grid Cyberattack: Lessons Learned and Questions Answered About CRASHOVERRIDE'. Dragos, Inc. 5 February 2026. Available at: https://www.dragos.com/blog/ukraine-power-grid-cyberattack-crashoverride-10-year-lessons

[39] ALBRECHTSEN, Helen Bille; KHODOROVSKA, Yelyzaveta; MANDZII, Anna-Mariia. 'Resilience Under Fire: How Ukraine's Energy Sector is Adapting – and What It Means for Europe', Ramussen Global, 3 June 2025. Available at: https://rasmussenglobal.com/wp-content/uploads/2025/06/REPORT_Resilience-Under-Fire.pdf

[40] WORLD BANK. 'The World Bank and Ukraine: Laying the Groundwork for Reconstruction in the Midst of War', Results Brief, World Bank Situation Report. 30 November 2023. Available at: https://www.worldbank.org/en/results/2023/11/30/the-world-bank-and-ukraine-laying-the-groundwork-for-reconstruction-in-the-midst-of-war

[41] EU CIVIL PROTECTION & HUMANITARIAN AID (DG ECHO). 'EU deploys emergency generators as Russian strikes leave 1 million Ukrainians without power in -20°C', *Directorate-General for European Civil Protection and Humanitarian Aid Operations (ECHO)*, 23 January 2026. Available at: https://civil-protection-humanitarian-aid.ec.europa.eu/news-stories/news/eu-deploys-emergency-generators-russian-strikes-leave-1-million-ukrainians-without-power-20degc-2026-01-23_en

[42] IEA – INTERNATIONAL ENERGY AGENCY. 'Ukraine's Energy Security and the Coming Winter. An energy action plan for Ukraine and its partners', *International Energy Agency*, September 2024. Available at: https://iea.blob.core.windows.net/assets/cec49dc2-7d04-442f-92aa-54c18e6f51d6/UkrainesEnergySecurityandtheComingWinter.pdf

to improve and extend these plans to other European countries and, in doing so, prevent grid instability even in times of peace.

Furthermore, it should not be forgotten that the US has also played a key role in ensuring the sustainability of the electricity grid, specifically through technical advice and cooperation on cyber defence[43] .

Surviving and evolving

The first lesson learnt by Ukraine was that the model of massive grids inherited from the USSR has ultimately proved to be a critical vulnerability[44] . The large nodes that concentrate electricity generation, transmission and transformation have proved easy for the Russians to identify and attack, especially as they have access to all the technical information regarding their design[45] .

It became clear that the grid's original architecture could not maintain a sustained supply over time, unless a shift was made towards a decentralised energy model[46] . This measure is not merely a technical improvement – by spreading the risks and minimising the infrastructure's exposure – but has also been a strategic necessity to anticipate threats and optimise Ukraine's response.

Interestingly, although this new approach has been forced by circumstances, it aligns perfectly with the standards sought by Europeans, which are based on more distributed and flexible networks[47] .

[43] RAYMOND, Nathaniel A.; HOWARTH, Caitlin. 'Russian Attacks Targeting Ukraine's Energy Infrastructure', FPC Briefing, US Department of State, Washington DC, 4 March 2024. Available at: https://2021-2025.state.gov/briefings-foreign-press-centers/russian-attacks-targeting-ukraine-energy-infrastructure

[44] COLLINS, Gabriel; MEDLOCK III, Kenneth B. 'Ukraine's Electricity Sector: Urgency and Resilience in a Time of War', Baker Institute for Public Policy, Centre for Energy Studies, Working Paper, 14 August 2024. Available at: https://www.bakerinstitute.org/research/ukraines-electricity-sector-urgency-and-resilience-time-war

[45] HUMPHREYS, Brian E. 'Attacks on Ukraine's Electric Grid: Insights for U.S. Infrastructure Security and Resilience', CRS Report, US Government, 17 May 2024. Available at: https://www.congress.gov/crs_external_products/R/PDF/R48067/R48067.12.pdf

[46] DREVES, Harrison; FALL, Sara; MCCAN, Isabel. 'Ukraine Fights To Build More Resilient, Renewable Energy System in Midst of War', *National Laboratory of the Rockies*, News & Feature Stories, 27 July 2023. Available at: https://www.nlr.gov/news/detail/features/2023/ukraine-fights-to-build-a-more-resilient-renewable-energy-system-in-the-midst-of-war

[47] INTERNATIONAL ENERGY AGENCY. 'Empowering Ukraine Through a Decentralised Electricity System'. IEA Publications, December 2024. Available at: https://iea.blob.core.windows.net/assets/1cb1324f-e145-41c3-b0c2-d78561b4f1fd/EmpoweringUkraineThroughaDecentralisedElectricitySystem.pdf

Emergency generation and the energy mix

Constant attacks and the loss of equipment at major hubs forced the adoption of measures aimed at developing distributed generation, leading to the proliferation of local microgrids and autonomous systems capable of operating in isolation[48] . In many cases, these are individuals seeking to meet their own needs by installing small diesel generators, but in others they involve entire communities or essential public services that have set up power generation centres using generator sets, thereby guaranteeing their supply.

Furthermore, the Ukrainian authorities have made extensive use of mobile and tactical solutions to guarantee the civilian power supply, temporarily replacing damaged substations or reinforcing those facing excess demand. Although these are only temporary measures, they succeed in alleviating dependence on major hubs and even reducing demand on an ad hoc basis[49] .

It is also important to consider how Ukraine's energy mix has evolved during the war. Nuclear power has retained its central role. Despite the loss of the large Zaporizhzhia power station, most of the nuclear fleet has remained undamaged during the war[50] .

Other sources, such as renewables – although not particularly widespread in Ukraine – have suffered substantial losses, though in areas not controlled by Russia they continue to generate power steadily[51] .

However, thermal power generation infrastructure has borne the brunt of the damage. In 2024, it was estimated that around 80 per cent of its capacity was out of service, necessitating an accelerated transition towards alternative and less centralised sources.

[48] INTERNATIONAL ENERGY AGENCY (IEA). 'Energy System Resilience: Lessons Learnt from Ukraine. International Energy Agency Report, 2026', IEA Publications. 16 February 2026. Available at: https://iea.blob.core.windows.net/assets/2c6f2378-31e8-442a-815a-18e693167915/EnergySystemResilience.pdf

[49] COUNCIL OF THE EUROPEAN UNION (CONSILIUM). 'EU assistance to Ukraine: energy security and infrastructure', *Official Council Report*. 2026. Available at: https://www.consilium.europa.eu/es/policies/ukraine-solidarity-energy-transport/

[50] INTERNATIONAL ATOMIC ENERGY AGENCY (IAEA). 'Nuclear Safety, Security and Safeguards in Ukraine'. Reports by the Director General, 2023–2025. Available at: https://www.iaea.org/

[51] ENERGY COMMUNITY SECRETARIAT. 'Secretariat releases report on post-war development of the renewable energy sector in Ukraine', 17 April 2024. Available at: https://www.energy-community.org/news/Energy-Community-News/2024/04/17.html

As a result, the Ukrainian system has been evolving towards decentralisation and greater flexibility in its energy sources to ensure continuity of supply. This is where interconnection with Europe becomes crucial.

A vulnerable Europe

Electricity grids are critical infrastructures that are highly vulnerable to hybrid threats of questionable origin (cyber-attacks, terrorism, sabotage, etc.), particularly because they do not usually constitute a clear *casus belli*[52] . Ukraine had already been suffering attacks of this kind since 2014, but their intensity has increased dramatically since 2022, manifesting primarily as physical and cyber-attacks[53] .

Europe must accept the possibility that similar scenarios could occur in its critical infrastructure (CI), if they are not already taking place. The protection of European CI cannot depend solely on implementing increasingly costly technical measures, but rather on structuring the response to attacks in such a way as to optimise the available resources, in a similar manner to how Ukraine is doing[54] .

The war has shown that reducing obstacles to emergency response (whether bureaucratic or regulatory) and the operational decentralisation of response teams are key to facilitating an effective response.

Despite greater decentralisation, the situation in Europe bears clear parallels to that in Ukraine. In terms of network design, they are overly focused on cost efficiency at the expense of redundancy[55] . Like Ukraine, Europe suffers from an excessive reliance on large substations and strategic corridors.

The failure of any one of these could lead to regional outages or cascading failures, with no alternative routes available to divert the supply. Take, for example, the 2025 blackout

[52]SANCHEZ HERRAEZ, Pedro. *The New Hybrid War: A Brief Strategic Analysis*. IEEE Analysis Paper 54/2014. Available at: https://www.ieee.es/Galerias/fichero/docs_analisis/2014/DIEEEA54-2014_NuevaGuerraHibrida_PSH.pdf

[53] MARTÍNEZ CORTÉS, José M. 'Conflict in Ukraine: when hybrid strategy fails', *Journal of International Security Studies*, vol. 10, no. 1. 2024, pp. 39–67. DOI: http://dx.doi.org/10.18847/1.19.4

[54] FUENTE COBO, Ignacio. 'Ukraine 2024. Is a good war better than a bad peace?' IEEE Analysis Paper 63/2024. Available at: https://www.defensa.gob.es/documents/2073105/2145603/ucrania_2024_mejor_una_buena_guerra_que_una_mala_paz.pdf/5742be41-32cc-41e7-b6bc-9384ff06f5dc?t=1729075532413

[55] FUENTE COBO, Ignacio 'The War in Ukraine (October 2024 – September 2025). Attrition, resistance and stalemate on the eve of its fourth winter'. IEEE, Analysis Paper, 20/2026. Available at: https://www.defensa.gob.es/ceseden/-/ieee-2026-guerra-ucrania-desgaste-resistencia-estancamiento-analisis20

on the Iberian Peninsula, when a confluence of factors (it has not yet been clarified whether these were accidental or not) led to a total blackout of the electricity system in Spain, Portugal and southern France[56] .

High-power transformers are particularly sensitive components of any grid. This equipment is essential in the Ukrainian conflict and is a priority target for Russian attacks, as replacing them requires lengthy manufacturing times and complex logistics, which limits their availability[57] .

In this regard, Europe has a critical weakness, as it lacks sufficient *stocks* of spare parts and is also dependent on external suppliers. If it were to face a situation of high demand, as is the case in Ukraine, it would find itself in serious difficulty.

It is therefore necessary to urgently rethink the design of Europe's electricity grids: increasing structural redundancy, geographically dispersing critical nodes and establishing strategic *stocks* of key components (such as power transformers) would be the first step.

The next step would be to organise, train and equip grid operators and maintenance staff so that they are capable of handling such situations in a variety of ways and independently of decision-making bodies. It is also prudent to maintain a certain capacity to operate using analogue systems, as SCADA systems tend to be excessively vulnerable to cyber-attacks that render them inoperable[58] .

In short, the aim is to replicate the Ukrainian strategy in Europe, step by step.

Lessons learnt

The first lesson is that Europe must begin to implement a structured and urgent response before the problem arises. The IEA's '10-Point Plan', drawn up following an exhaustive analysis of the behaviour of the Ukrainian electricity grid during the war, is the best guide

[56] DACOBA CERVIÑO, Francisco José. 'Ukraine: neither a blitzkrieg nor a lasting peace', IEEE Bulletin No. 27. IEEE, 2022. Available at: https://www.ieee.es/Galerias/fichero/BoletinesIEEE3/2022/BoletinIEEE27.pdf

[57] SANCHEZ HERRAEZ, Pedro. 'The New Hybrid War: A Brief Strategic Analysis'. IEEE Analysis Paper 54/2014. Available at: https://www.ieee.es/Galerias/fichero/docs_analisis/2014/DIEEEA54-2014_NuevaGuerraHibrida_PSH.pdf

[58] LEE, Robert M.; ASSANTE, Michael J.; CONWAY, Tim. 'Analysis of the Cyber Attack on the Ukrainian Power Grid. Defence Use Case'. E-ISAC, Electricity Information Sharing and Analysis Centre, 18 March 2016. Available at: https://nsarchive.gwu.edu/sites/default/files/documents/3891751/SANS-and-Electricity-Information-Sharing-and.pdf

for Europe: diversification, decentralisation, cybersecurity, risk assessment, strategic reserves of equipment… a corollary to the measures set out in this article[59] .

Furthermore, these lessons are clearly in line with the spirit of the REPowerEU framework programme. Although its initial aim is to reduce energy dependence on Russia, it also sets out to accelerate the transition towards more autonomous energy systems and to strengthen cross-border interconnections to sustain supply during prolonged crises[60] .

These measures are simple in concept, but their implementation is the responsibility of each individual EU country. After all, if one Member State suffers a cascading failure, it puts the entire EU at risk[61] .

The case of Spain

Like the other EU countries, Spain should also incorporate these measures into its national security strategy[62] . Our situation is unique, as the Spanish electricity grid is characterised by forming an 'energy island' on the Iberian Peninsula.

It is possible that this fact was the factor that prevented the 2025 cascading blackout from spreading to the rest of the European Union (and possibly to Ukraine), facilitating the disconnection from France in the Pyrenees[63] .

However, this event, as well as highlighting a whole series of structural deficiencies in our grid, served as an example of how regional autonomy can be an effective tool in the face of cascading failures[64] .

It is not that cutting off the entire peninsula from the power supply should be considered a success, but it illustrates how isolating one part of the grid can keep the rest operational.

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[59] INTERNATIONAL ENERGY AGENCY (IEA). 'Energy System Resilience: Lessons Learnt from Ukraine', *Report*. 2026. Available at: https://iea.blob.core.windows.net/assets/2c6f2378-31e8-442a-815a-18e693167915/EnergySystemResilience.pdf

[60] EUROPEAN COMMISSION. 'REPowerEU: Joint European Action for Affordable, Secure and Sustainable Energy', *Official Communication*. 2022. Available at: https://www.consilium.europa.eu/es/policies/ukraine-solidarity-energy-transport/

[61] HICKS, Marie-Laure; HOWARD, Ioli; OHRVIK-STOTT, Jacob; et al. 'Study on Clean Energy R&I Opportunities to Ensure European Energy Security by Targeting Challenges of Distinct Energy Value Chains for 2030 and Beyond'. RAND Europe, Publications Office of the European Union, 2024. DOI: 10.2777/906828

[62] ESCRIBANO, Gonzalo. 'Ten ways Spain can contribute to increasing European energy autonomy from Russia', Real Instituto Elcano, ARI 30/2022, 11 April 2022. Available at: https://media.realinstitutoelcano.org/wp-content/uploads/2022/04/ari30-2022-escribano-ten-ways-spain-can-contribute-to-increase-european-energy-autonomy-from-russia.pdf

[63] RED ELÉCTRICA DE ESPAÑA (REE). 'Report on the Spanish electricity system 2025'. REE, Madrid, 2026. Available at: https://www.ree.es

[64] RED ELÉCTRICA DE ESPAÑA (REE). 'Incident in the Spanish Mainland Electricity System on 28 April 2025'. Madrid, 2025. Available at: https://d1n1o4zeyfu21r.cloudfront.net/WEB_Incidente_SistemaElectricoPeninsularEspanol_18junio2025.pdf

Building on , it is then a matter of analysing to what extent this option is scalable to regional environments[65] .

Conclusions

Ukraine's electricity grid has demonstrated far greater resilience than expected, not only due to pre-existing structural factors, but also because of its human capital, international support and the restructuring of the system.

Ultimately, the war has forced a complete overhaul of its energy model to substantially improve the grid's resilience. This has provided us with a unique case study to analyse how critical infrastructure is affected by a hybrid warfare strategy aimed at its disruption.

Furthermore, it is interesting to note how Ukraine's vulnerabilities are analogous to those of the rest of the continent[66] .

European electricity grids also suffer from an excess of critical nodes and a reliance on digital systems, which not only poses a technical risk but is further exacerbated by the geopolitical tensions and growing strategic competition we are currently experiencing.

This article has outlined a series of measures (decentralisation, autonomy, availability of critical spare parts and redundancies) which are merely a rough outline of a solution to a problem of such magnitude that it could potentially affect the entire continent.

However, these are simple principles which, if properly adopted today, could make a significant difference in addressing tomorrow's challenges.

It is obvious that electricity grids with such a high degree of interoperability as those in Europe cannot operate in isolation, but redundancy mechanisms can be put in place to overcome isolated faults or failures.

Isolating damaged sections should not mean leaving them out of service for excessive periods; this is where the availability of critical equipment and the responsiveness of the teams come into play.

[65] ANG, Fei; GUO, Yuhan; WEI, Siaoqing; et al. 'An intentional controlled islanding strategy considering island frequency stability for power systems'. Frontiers in Energy Research, vol. 11, 2023. Available at: DOI: doi.org/10.3389/fenrg.2023.1247412

[66] INTERNATIONAL ENERGY AGENCY. 'Energy System Resilience. Lessons learnt from Ukraine', IEA, 11 February 2026. Available at: https://www.iea.org/reports/energy-system-resilience

These are measures that have been thoroughly studied by the relevant European authorities (IEA 10-Point Plan; REPowerEU), but which member states do not seem to be in any hurry to implement, perhaps due to the additional cost involved in such a disruptive shift in the energy paradigm at a time when the war effort is the priority.

The Iberian Peninsula's situation is somewhat unique due to the well-known 'energy island' effect. Whilst this is a disadvantage in many respects, in the context under consideration it may present a real opportunity: it constitutes an isolated environment.

It is the ideal testing ground for the European Union, where new protective measures, response protocols, materials and design approaches can be trialled. It represents an opportunity for Spain and Portugal.

Ukraine's cooperation with Europe is proving to be one of the key pillars for understanding the optimal strategies for dealing with attacks on electricity grids.

Continuing to support them financially, technically and in terms of energy is almost an obligation for European countries, whose own energy security may depend on being able to learn enough in good time to react.

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