American University Kyiv

A Capstone Project

INTEGRATED GOVERNMENT MANAGEMENT FOR SUSTAINABLE ENERGY RESILIENCE IN HIGH-RISK REGION

ІНТЕГРОВАНЕ ДЕРЖАВНЕ УПРАВЛІННЯ ДЛЯ ЗАБЕЗПЕЧЕННЯ ЕНЕРГЕТИЧНОЇ СТІЙКОСТІ В РЕГІОНАХ З ПІДВИЩЕНИМ РИЗИКОМ

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ABSTRACT

The purpose of this study is to assess Ukraine's energy resilience posture and focuses on Ukraine's path toward energy resilience, specifically investigating the strategic choices between rebuilding the traditional centralized energy infrastructure and adopting a decentralized system in line with modern sustainable practices. The object of the study is Ukraine's energy infrastructure and its potential evolution in response to contemporary challenges, with an emphasis on resilience and sustainability. A central question of this study is whether Ukraine should rebuild its existing heavy centralized infrastructure or transition to a decentralized system that aligns with the European Union's Green Deal and the global Sustainable Development Goals. The study's data were derived from survey results obtained from professionals across energy industries.

This research investigates energy resilience through a structured four-chapter approach. The first chapter offers an extensive review of the literature, employing content analysis to establish a solid theoretical framework. The second chapter details the methodologies, outlining the research design and tools utilized. The third chapter presents findings on the current state of Ukraine's energy sector, its resilience goals, and an analysis of existing gaps. The final chapter delivers practical recommendations to bridge these gaps, including enhancing infrastructure, implementing energy storage solutions, enacting regulatory reforms, and allocating resources for modernizing the grid. By addressing these critical areas, the study provides valuable insights for developing a sustainable and resilient energy system in Ukraine, aligned with both global and regional sustainability goals.

Keywords: energy resilience, energy infrastructure, renewable energy generation, distributed generation

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LIST OF ABBREVIATIONS

CMU – Cabinet of Ministers of Ukraine;

CHPP – Combined Heat and Power Plants;

BESS – Battery Energy storage systems;

HPP – Hydroelectric Power Plant;

HSPP – Hydroelectric storage power plant;

IPS – Integrated Power System;

NEURC – National Energy and Utilities Regulatory Commission;

NPC «Ukrenergo» – National Power Company «Ukrenergo» (Grid Operator of Ukraine);

NPP – Nuclear Power Plant;

SDGs – Sustainable Development Goals;

SC – State Company;

SPP – Solar Power Plant;

TPP – Thermal Power Plant;

UAH – Ukrainian hryvnia (currency);

WPP – Wind Power Plant

INTRODUCTION

Energy resilience is a vital aspect of national security, particularly in the face of conflict and geopolitical tensions. In Ukraine, the war with Russia has brought unprecedented challenges to the country's energy infrastructure, leaving thermal power plants, hydropower facilities, and renewable energy sources heavily damaged.

According to the Kyiv School of Economics analytical report "On losses as a result of Russia's military aggression against Ukraine" (2024), the indirect revenue losses in infrastructure energy sector are $43.1 billion.

This research focuses on Ukraine's path toward energy resilience, specifically investigating the strategic choices between rebuilding the traditional centralized energy infrastructure and adopting a decentralized system in line with modern sustainable practices. A central question of this study is whether Ukraine should rebuild its existing heavy centralized infrastructure or transition to a decentralized system that aligns with the European Union's Green Deal and the global Sustainable Development Goals (SDGs). Ukraine's Eurointegration aspirations make this a timely and significant decision, as aligning with European energy policies will be crucial to its future stability, economic development, and sustainability.

Ukraine's commitment to the United Nations' SDGs is a key driver in this discussion. SDG 7, which calls for affordable and clean energy, directly ties into Ukraine's need to develop an energy system that is both resilient and environmentally sustainable. Rebuilding the energy infrastructure provides an opportunity not only to address the immediate post-war recovery but also to advance long-term sustainability goals, such as reducing carbon emissions, increasing renewable energy capacity, and ensuring energy access for all citizens. Additionally, SDG 9, focusing on industry, innovation, and infrastructure, emphasizes the importance of resilient infrastructure and sustainable industrialization—both of which are crucial as Ukraine reconstructs its energy sector.

In this context, Ukraine's National Strategy for the Development of Distributed Generation for the period until 2035 plays a pivotal role. This strategy aims to decentralize energy production by promoting smaller, more flexible, and locally managed energy sources, such as solar, wind, and bioenergy. Decentralization not only enhances energy security by reducing dependence on large, vulnerable power plants but also supports Ukraine's broader Eurointegration goals, aligning the country with European Union energy policies and market structures. Distributed generation fits well within the framework of the EU's Green Deal, which seeks to transition to a climate-neutral economy by 2050. For

Ukraine, embracing this decentralized approach could accelerate its integration into the European energy market, strengthening both its economic resilience and its environmental sustainability.

Despite extensive research on energy infrastructure vulnerabilities in conflict zones, there remains a gap in understanding the specific challenges faced by Ukraine as it balances post-war recovery, sustainability, and Eurointegration. This study aims to bridge that gap by conducting a comprehensive literature review, media analysis, and interviews with key stakeholders in the Ukrainian energy sector. The research will assess the current state of Ukraine's energy infrastructure, analyze the security and governance measures in place, and explore potential paths for aligning with the EU Green Deal and SDGs.

Ultimately, this research seeks to provide actionable recommendations for policymakers, energy professionals, and international stakeholders on how to best support Ukraine's transition to a more resilient and sustainable energy system. This includes addressing vulnerabilities, improving governance, and leveraging the latest technological innovations to build an energy sector that can withstand future geopolitical pressures while contributing to global sustainability goals.

CHAPTER 1. THEORETICAL FOUNDATIONS OF SUSTAINABLE ENERGY RESILIENCE

Ukraine's energy resilience has come under intense scrutiny as the nation grapples with war-induced pressures on its energy infrastructure. Significant damage to Ukraine's energy infrastructure has revealed both immediate vulnerabilities and potential pathways for improvement. By mid-2024, almost all of Ukraine’s thermal power plants, hydropower facilities, and renewable energy sources suffered damage, with the available capacity dropping from 37.6 GW in early 2022 to 18.3 GW in 2023.

1.1 Threats to Critical Infrastructure and Energy Security in Conflict Zones

Kane et al. (2024) provide an extensive analysis of the types of vulnerabilities faced by infrastructure during armed conflicts, including missile strikes, cyber threats, and sabotage, which disrupt essential services and cause widespread instability. Their study underscores the strategic need for adaptive protection and resilience measures in critical sectors like energy to prevent long-term systemic impacts. This framework is pertinent to Ukraine, where attacks have drastically reduced the operational capacity of energy facilities, disrupting power availability for civilians and military operations alike .

Another critical source, Jermalavičius et al. (2023), examines the broader context of energy security under wartime conditions. Their research, which includes Ukraine as a primary case study, highlights the cascading effects of infrastructure attacks on national and regional security. The authors argue that resilience in the energy sector requires not only physical protection but also a diversified and decentralized approach to energy generation, which can offer better resistance to concentrated attacks on centralized facilities. The report also suggests that resilience frameworks should integrate both conventional and renewable sources, improving adaptability and reducing dependency on a single source.

1.2 Established Vulnerabilities and Opportunities for Decentralization

Brekis (2024) highlights the critical need to strengthen energy independence, especially considering Ukraine's reliance on external sources and the current conflict. Brekis (2024) examines a range of autonomous and off-grid power generation technologies, such as decentralized renewable energy systems, energy storage innovations, smart grid applications, nuclear reactors, and other alternative solutions. These technologies are designed to align with the objectives of the EU Green Deal and NATO’s strategic vision, supporting the reconstruction and modernization of Ukraine’s energy

infrastructure in the post-conflict period. The proposed advancements are intended to serve both civilian and military needs, contributing to sustainable and resilient energy development.

European Business Association's survey "Development of Energy Autonomy of Businesses" (2024) revealed that since 2022, 87% of companies report that power supply disruptions have impacted their operations. Despite the challenges of war, Ukraine's energy system demonstrates significant potential for sustainable development and independence. 85% of Ukrainian businesses have invested in building energy independence, and 66% of the companies surveyed have their generation or alternative energy sources. According to survey, the energy situation could be improved by enhancing incentives for the development of renewable energy sources and distributed generation, protecting investments and investors, encouraging innovative solutions, and implementing market mechanisms.

Miyake and Teske (2024) identify Ukraine's substantial untapped potential for solar and wind energy and highlight that Ukraine has favorable geographic conditions for both types of renewable energy, which could help the country transition from reliance on fossil fuels. It suggests that solar and wind energy could play a transformative role in Ukraine's path toward sustainable energy independence and resilience in post-war reconstruction.

1.3 Gaps in Understanding Wartime Resilience and Recovery under full-scale war conditions

While studies on infrastructure protection provide essential insights, there remains a gap in literature specific to Ukraine's unique conditions. The rapid succession of attacks has left critical knowledge gaps regarding the adaptive resilience of Ukraine's energy infrastructure under prolonged duress. Current literature does not sufficiently address the layered effects of conflict, such as cascading failures within interconnected energy systems or the practicalities of rebuilding an energy grid under continuous threat. This study aims to fill this gap by examining how Ukraine's experience might inform strategies for enhancing critical infrastructure resilience, particularly through a decentralized system that can support both immediate recovery and long-term sustainability.

Sukhodolia (2017) analyzed the impact of Russian attacks on Ukraine's critical energy infrastructure (CEI) from 2014 to 2016, offering insights for enhancing CEI resilience. These attacks, including destruction, seizure, looting, cyberattacks, and exerting political, economic, and psychological pressure, revealed the effectiveness of CEI targeting as a non-military warfare strategy. The events in Ukraine underscore the critical importance of integrating CEI protection into national defense policies.

The Ukrainian experience during the "hybrid war" highlights the necessity of adopting proactive energy security measures to counteract aggressors' efforts to disrupt the energy sector.

The International Energy Agency's (IEA) 2024 report, outlines an energy action plan for Ukraine and its partners to address immediate energy challenges. The report identifies 10 critical energy actions to bolster energy security and mitigate risks during winter months. A key recommendation emphasizes increasing and decentralizing energy supply, as centralized energy systems are more vulnerable to attacks. While diesel generators have been widely deployed as backup power sources, the report stresses the urgent need to accelerate the adoption of smaller-scale gas-fired combined heat and power plants, solar PV, wind systems, and complementary battery storage technologies to enhance energy system resilience.

Lukash & Namoniuk (2024) examine Ukraine's energy policies and the war's impact on potential decarbonization pathways. Despite the ongoing conflict, Ukraine remains committed to its National Energy Strategy 2050, which targets a 65% reduction in emissions compared to 1990 levels. Their analysis reveals that the war exposed the vulnerabilities of centralized, carbon-intensive energy systems but may also act as a catalyst for rapid, structural transitions to low-carbon energy models. These transformations could create a more resilient and adaptable energy sector capable of addressing global changes and systemic interdependencies.

Ignatiev (2024) examines how distributed generation could strengthen Ukraine's energy system amid war. By decentralizing energy production—mainly through renewables like solar, wind, and biomass º distributed generation minimizes reliance on vulnerable infrastructure and focuses on local energy needs. Despite high levels of damage to solar and wind facilities in conflict zones, distributed generation remains crucial for resilience. The article discusses barriers to distribute generation expansion and the potential benefits of Ukraine's integration into the European energy system.

This literature review highlights both the established knowledge and existing gaps regarding energy resilience in conflict zones. Ukraine's challenges and the potential of decentralized energy models to enhance resilience present a compelling case for a targeted approach to rebuilding its energy infrastructure. The findings of this research are expected to provide actionable insights for Ukraine and other nations facing similar threats, offering frameworks to ensure energy security, support sustainable growth, and contribute to national resilience.

CHAPTER 2. METHODOLOGY OF THE INVESTIGATION

Methodology framework for researching energy resilience in Ukraine has an **Objective** to assess the resilience of Ukraine's energy infrastructure by examining generation losses, financial impacts, restoration needs, and strategic plans and investigate and identify specific condition challenges Ukrainian energy sector, particularly under war-time circumstances. **Approach** for this research: use a mixed-methods design combining qualitative data (e.g., expert interviews) and quantitative data (e.g., financial loss reports, equipment damage records). It allowed to identify gaps in resilience strategies, to develop specific recommendations for infrastructure decentralization, and to propose funding and policy recommendations based on findings.

The **study's research question** is “Whether to maintain/rebuild the existing heavy centralized energy infrastructure or build a new, decentralized one aligned with the EU Green Deal strategy?”

At first stage, it was collection of qualitative data and analysis of the open data and media publication on Ukrainian energy sector situation, losses and technological decisions to restore, maintain and develop sufficient level of Energy security for Ukrainian population and economy. It covered analyze reports from Ukrainian governmental and international organizations and agencies on network reform, Smart Grid, and BESS funding, latest legislative and regulatory acts.

This research also includes semi-structured face-to-face interviews with representatives from the Ukrainian government (Ministry of Energy), SC Ukrenergo, SC Naftogaz, SC Energatom, and the business. The focus of the interview questions will be on the actual situation in the sector. The **questions** were developed based on a conducted literature review, which outlines security challenges and were focused on:

- Infrastructure loss trends and investment needs,
- Restoration plans for centralized heating and electric networks, and
- Plans for gas-fired plants, emissions implications, and grid modernization.

The nine questions are presented in Appendix A.

This research collected qualitative data, specifically semi-structured face-to-face interviews with civil servants of within the Ministry of Energy of Ukraine, managers and advisers to leadership of SC Ukrenergo, SC Naftogaz, heads of structural units in oblast organizations.

Ten interviews were conducted from 9 October to 9 November 2024 on conditions of confidentiality and anonymity. No incentives were offered to participants. Interview's time usually last approximately 80 minutes.

A key condition of the interview was the exclusion of classified information, in strict accordance with Martial Law and ongoing hostilities in Ukraine, to ensure compliance with legal and security requirements. The interview process was carefully designed to balance the need for comprehensive data collection with the sensitivity of the ongoing conflict.

The questions were designed to elicit insights into decision-making processes, challenges, and strategies within the energy sector under the current socio-political and economic conditions. This approach facilitated an open-ended conversation, enabling respondents to provide detailed and nuanced answers while allowing the interviewer to probe further when necessary.

The participants were selected using purposive sampling to ensure the inclusion of key stakeholders from different levels of the energy sector hierarchy. The respondents represented both strategic and operational levels of the energy structure, including policy-making bodies, regulatory authorities, energy generation, distribution, and management units. This diversity provided a holistic understanding of the dynamics within the energy sector.

In total, 10 respondents participated in the interview. The criteria for participant selection included their role in decision-making processes, their tenure within the sector, and their expertise in managing energy-related challenges in Ukraine. Efforts were made to ensure a balanced representation of various branches of the energy sector, including renewable energy, traditional energy sources, and infrastructure management.

The social and demographic profile of the respondents, including variables such as age, gender, years of experience, and area of expertise, is presented in Table 1. This information helps contextualize their perspectives and contributions to the study.

Table 1. The social and demographic portrait of the respondents

Parameters	Numbers	Share, %
Age		
30-39 years	2	20%
40-49 years	5	50%
50-59 years	3	30%
Total	10	100%
Gender		
Male	9	90%
Female	1	10%
Prefer not to indicate	0	0
Total	10	100%
Job		
Ukrenergo	3	30%
Business	3	30%
Ministry of Energy	3	30%
Ministry of Defence	1	10%

Total	10	100%
Work experience in the energy sector or related fields		
Less 10 years	2	20%
11-20 years	4	40%
More than 20 years	4	40%
Total	**10**	**100%**

Source: developed by the author.

Gap analysis offers a structured way to pinpoint the specific areas where Ukraine's energy infrastructure falls short of resilience goals, enabling targeted interventions.

It can systematically identify weaknesses and areas for development by comparing the current state of Ukraine's energy infrastructure to its desired or required state. This framework can structure the research as follows:

1. Identify Current Conditions: Assess Ukraine's energy sector, focusing on losses, system reliability, security measures, and operational capacities amid conflict.

2. Define Desired Resilience State: Determine what Ukraine's energy infrastructure needs to achieve resilience, aligning with EU Green Deal and the National Distributed Generation Strategy until 2035.

3. Analyze Gaps: Compare findings in infrastructure, technology, governance, and funding needs against the resilience goals. This can include gaps in restoration plans, financial requirements, and technological capabilities for decentralized and renewable generation.

4. Develop Recommendations: Based on identified gaps, propose strategies to address vulnerabilities, such as infrastructure strengthening, energy storage implementation, regulatory reforms, and funding allocations for grid modernization.

This approach aligns with broader strategies, such as the EU Green Deal and Ukraine's Distributed Generation Strategy, by revealing critical gaps between current capacities and the strategic objectives for green, resilient infrastructure. These aspects underscore gap analysis as an adaptable, rigorous method for resilience planning in Ukraine's unique energy context.

The methodology adhered to ethical research principles, including informed consent, confidentiality, and the right to withdraw at any stage. These measures were particularly important given the sensitive context of the research and the potential risks associated with the ongoing hostilities.

CHAPTER 3. FINDINGS ON UKRAINE'S ENERGY SECTOR: CURRENT CONDITIONS, DESIRED RESILIENCE, AND EXISTING GAPS

The respondents presented often official (Governmental) version of Ukraine's energy infrastructure development but in some scope expressed their own opinions based on their personal experience and knowledge that in some points differ from official stance of their organizations. Some of these issues vary from one interlocutor to another.

The respondents were asked to independently, from their own experience, provide several problematic organizational issues regarding rebuilding Ukrainian energy sector and approaches to cover the losses of energy generating equipment and restoring the power plants.

Most respondents referenced government programs and plans as the foundation for describing the energy sector's situation and future direction. The most notable among these are:

- Ukraine's Resilience plan (not available for public);
- Energy Strategy of Ukraine until 2050 (April 2023) (not available for public);
- National Energy and Climate Plan (June 2024);
- National Distributed Generation Strategy until 2035 (July 2024);
- National Renewable Energy Action Plan until 2030 (August 2024).

3.1 Identify Current Conditions of the Ukraine's energy sector

Ukraine's Integrated Power System (IPS) was developed as part of the Unified Power System of the Soviet Union to support heavy, energy-intensive industries and to meet the needs for electricity exports and gas transit. The National Transmission Grid features robust high-voltage lines that transmit electricity from Ukraine's nuclear and large thermal power plants to Europe. As of January 1, 2014, before Russia occupied Crimea and Donbas, the Ukrainian IPS was a diverse network featuring 22969 km of Overhead Power Lines, the IPS of Ukraine boasted a substantial 137 substations of the National Transmission Grid, run by NPC "Ukrenergo".

The power system of Ukraine has always had an excess of essential capacities with a large installed capacity of power units and aggregates for the export of electricity and a shortage of maneuverable capacities (quick reserves), first of all, all power units of Ukraine's Nuclear Power Plants (NPP). In addition, the main generating capacities to produce electricity and heat in designated energy nodes (thermal power plants and combined heat and power plants) are designed to maintain the reliable

operation of Ukraine's IPS in normal, emergency, and post-emergency modes. Most consumers in large cities receive a centralized heat supply from large Thermal Power Plants (TPPs) and Combined Heat and Power Plants (CHPPs).

75% of the respondents admitted that the most of thermal power plants were morally and physically outdated, with equipment significantly degraded and just some of them had partial success in modernizing their equipment. It was need in deep modernization, replacement of the old equipment, and construction new modern thermal generation plants.

From 2014 to early 2022, the Ukrainian power system lost about 4 GW of capacity due to the occupation of parts of Crimea, the Donetsk and Luhansk regions.

Data on electricity generation for 2021, published by the Ukraine's Ministry of Energy in relative terms to the total electricity production in 2021 (156.575 billion kWh), the share of electricity generated by producers from renewable sources is 8%, and it was increase in renewable sources, compared to 2020, by 15.3% - to 12.519 billion kWh.

The share of each component in the overall structure of electricity generation in Ukraine in 2021 presented in Figure 1.

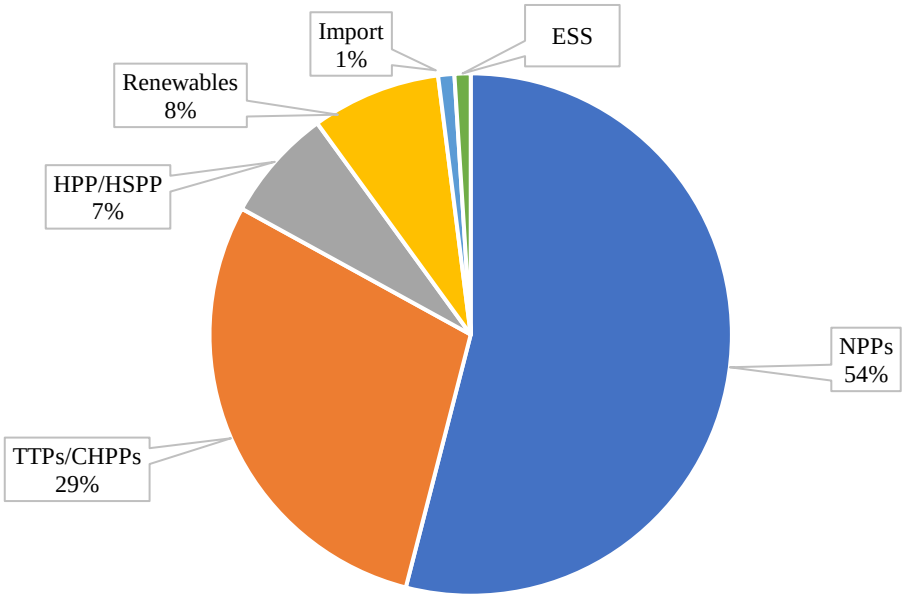

Figure 1. Structure of electricity generation in 2021 (pre-war condition).

Source: Data adapted from Expro Consulting (2021).

Nuclear power plants (NPPs) accounted for 54% of Ukraine's electricity production, operating on a consistent schedule to provide a stable energy base throughout the day. Due to their slow capacity

adjustment capabilities, NPPs are unsuitable for rapid changes in demand, such as increasing output during evening peaks or reducing it during the "night dip" when electricity consumption drops.

Thermal power plants (TPPs) and combined heat and power plants (CHPPs), contributing 29% of electricity generation, typically serve as maneuverable capacities capable of quickly responding to fluctuations in consumption. These facilities predominantly rely on coal, natural gas, or fuel oil for operation (Expro Consulting, 2021).

Hydroelectric power plants (HPPs) and hydroelectric storage power plants (HSPPs), producing 7% of electricity, are primarily used to meet peak consumption demands. HSPPs operate by pumping water during low-demand periods, such as nighttime, and discharging it during peak hours in the morning and evening. These plants also serve as a reserve to quickly offset sudden power shortages (Expro Consulting, 2021).

Renewable energy sources, including solar power plants (SPPs), wind power plants (WPPs), and biopower plants, accounted for 8% of electricity generation. While these environmentally friendly options harness solar, wind, and biological resources, their output is highly dependent on weather conditions and seasonal variations. In interviews, 80% of respondents identified electricity balance as a critical challenge for integrating renewable energy sources into Ukraine’s integrated power system (IPS). They highlighted the need for additional funding and tailored technical solutions for synchronization in specific cases (Expro Consulting, 2021).

Before the large-scale Russian invasion, Ukraine's electricity production infrastructure included 4 nuclear power plants, 15 thermal power plants (2 of which were in uncontrolled territories), and 43 CHPPs (10 of which were in uncontrolled areas). Hydropower was anchored by a cascade of 6 large hydroelectric power plants along the Dnieper River and the Tashlytskaya HSPPs on the Southern Bug River, totaling 8 operational hydroelectric power plants and 3 HSPPs (Expro Consulting, 2021).

By December 2022, approximately 50% of Ukraine's energy infrastructure had been damaged, resulting in a power shortage and the need for electricity imports from European energy systems.

As a result of missile attacks and hostilities during 2022, as of the end of January 2023, the IPS of Ukraine had a generation deficit of up to 5,000 MW during peak consumption hours (morning and evening), and at night the deficit amounted to about 3,000 MW. In the occupied territories, there are remaining generating capacities with a total volume of up to 10,000 MW.

During this period, a third of Ukrainian power plants were occupied, including the largest nuclear power plant in Europe - the Zaporizka NPP with an installed capacity of 6,000 MW, which provided the production of almost a quarter of Ukraine's electricity.

According to interview interlocators, up to 30% of Ukrainian solar power plants and about 80% of wind generation were located in the temporarily occupied territories.

Structure of electricity generation in 2022 change drastically from pre-war period due to hostilities, the decrease in total electricity production in Ukraine, reached 34%, compared to 2021 – to 113 393 billion kWh.

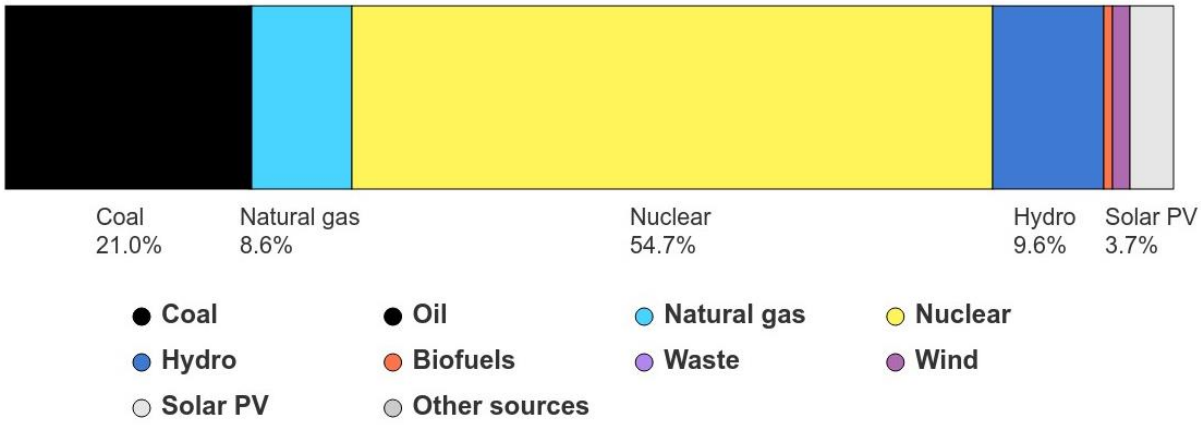

Figure 2. Structure of electricity generation in 2022

Source: Data adapted from International Energy Agency

Even in these circumstances, a sizable portion of energy comes from renewable sources; in 2023, solar and wind energy accounted for around 10% of all electricity produced. This share increased to 20.3% when the amount of electricity generated by big hydroelectric power plants is taken into consideration (higher than in the pre-war period). Over 650 MW of new renewable energy capacity were put into service in Ukraine overall in 2022–2023, including: 227 MW of wind power plants; 50 MW of bioenergy facilities (biogas and biomass); 1 MW of small hydroelectric power plants; and 371 MW of solar power plants (287 MW by private households).

According to Ukrainian Government, since March 22, 2024, new targeted attacks by Russian forces on critical energy infrastructure have resulted in additional damage and the loss of most thermal and hydropower generation. 50% respondents admitted that the currently available capacity of thermal power plants and combined heat and power plants is less than 20 percent of their capacity before the start of full-scale military aggression, and the share of available capacity of hydro and pumped storage power plants has decreased to 50 percent.

60 % interviewed experts and officials point out that the most common targets of missile strikes were large transformer substations which synchronize and connect the Ukrainian power system together.

In the wave of large-scale attacks at the Ukrainian energy sector from late March to May 2024 have severely damaged or destroyed around a half of generating capacity - over 9 GW. Several thermal (TPP) and hydroelectric power plants (HPP) in the oblasts of Kyiv, Kharkiv, and Zaporizhzhia were completely destroyed, with other TPPs and HPPs damaged that varying degrees.

The International Monetary Fund estimated the losses of the Ukrainian energy sector due to Russian shelling at USD 56.5 billion. For two and a half years, the Russian army occupied about 18 GW capacities, in particular the Zaporizhska nuclear power plant, which is considered the largest in Eastern Europe.

3.2 Define desired energy resilience of Ukraine

Ukraine’s Ministry of Energy declared in March 2023 that the nation will increase the proportion of renewable energy in its power generation to 50% by 2035, with nuclear power accounting for the remaining 50% of the power mix.

In order to achieve carbon neutrality in the energy sector by 2050, the Ukrainian Government has approved the country's Energy Strategy until 2050, which focuses on modernizing and automating transmission and distribution systems, as well as developing nuclear and renewable power generation capacity. Ukraine seeks to join the European network of electricity transmission system operators (ENTSO-E) to strengthen energy security and the sustainability of its energy system.

The National Energy and Climate Plan (NECP) for the period up to 2030 require the reducing of greenhouse gas emissions by 65% compared to 1990 levels and reaching a 27% share of renewable energy sources in total final energy consumption.

The Strategy for the Development of Distributed Generation for the period until 2035 as well as the Operational Plan of measures for the implementation of the Strategy in 2024-2026. The Ministry of Energy together with NPC "Ukrenergo" created a plan and approved locations for distributed generation. The Cabinet Ministers simplified the procedures for connecting to electric, gas and heat networks, simplified the allocation of land plots for the construction of cogeneration plants.

The development of distributed generation process will be carried out in 3 stages, 1 GW is expected to be built by the end of 2024 and another 4 GW by the end of 2026.

The primary advantage of distributed generation lies in its ability to establish and position new generating capacities across numerous sites connected to distribution networks and situated close to end-users. This decentralized approach significantly enhances the resilience of the energy system. Unlike centralized power plants, the destruction of a large number of smaller, lower-capacity power plants and

energy storage facilities presents a considerably more challenging task for potential aggressors. This decentralized infrastructure reduces the risk of widespread power outages and helps minimize energy losses within Ukraine's unified energy system, thereby improving its overall reliability and security.

The main types of electric power facilities, the use of which is expedient for the creation of distributed generation systems and solving the problem of insufficient generating capacity in the Integrated Power System of Ukraine are electrical installations that provide a guaranteed supply of available power and use natural gas as fuel, as well as renewable energy projects and energy storage facilities. It include gas turbine units, gas piston engines, cogeneration plants that provides guaranteed output of power according to command of dispatcher; flexible with big range of capacity reserves; has a quick start; has a short period of construction and commissioning; is focused on the natural gas of own production; the combined production of electricity and thermal energy, in the case of cogeneration, the overall efficiency of such an installation can reach 90 %.

The commissioning of the relevant projects will require the determination of a list of the most optimal sites in all regions of Ukraine with available connection points to the networks of electric energy distribution systems, gas transportation/gas distribution systems, centralized heat supply systems, taking into account the regional balance of generating capacities and demand for electric and thermal energy.

Achieving the goals of Strategy on the development of distributed generation will be carried out in three stages.

At the first stage (until the end of 2024), it is expected:

- construction and/or placement of installed capacity of distributed generation facilities and the achievement of up to 1 GW of additional generating capacity within the framework of the implementation of projects by business entities of private ownership and business entities of state and communal ownership in as a result of the support provided by international, foreign institutions, organizations that implement projects (programs) of international technical assistance, own funds, and other sources not prohibited by law;
- implementation of state support programs for the installation of solar and/or wind power plants together with energy storage facilities by the population in households, associations of co-owners of apartment buildings, and housing cooperatives;
- implementation of projects to install solar and/or wind power plants together with energy storage facilities in public and administrative buildings (health care facilities, educational institutions, etc.);
- development and creation of effective financial mechanisms for financing projects of distributed generation and energy storage facilities;

- carrying out the operational modernization of the network infrastructure within the framework of the connection of new distributed generation with an increase in the level of control over the operation modes of the distribution network, accounting, automation, and management in accordance with the purpose of the Strategy;
- creation of favorable conditions for the use of wastewater thermal energy.

In the second stage (until the end of 2026), it is planned to:

- construction and/or placement of distributed generation facilities and reaching up to 4 GW of additional generating capacity;
- continuation of the implementation and expansion of state support programs for the installation of solar and/or wind power plants together with energy storage installations by the population in households, associations of co-owners of apartment buildings, and housing and construction cooperatives;
- scaling up projects to install solar and/or wind power plants together with energy storage facilities in public and administrative buildings (health care facilities, educational institutions, etc.);
- accelerated renovation and automation of electrical distribution networks in the most priority areas, energy hubs, and districts; formation of highly automated, controlled, and predictable microgrids.

The steps outlined in the operational action plans for the implementation of this strategy will be implemented in order to carry out the third phase, which will begin in 2027.

Energy is one of the key areas within the Ukraine Resilience Plan presented by the President of Ukraine on November 19, 2024. The main focus is the development of nuclear generation as the foundation of energy security. Also, by the end of 2024, it is planned to create regional sustainability passports to assess the energy situation at a local level, and in 2025 – generation passports for efficient energy management. More detailed information is not yet available (…Energy – the most classified one (Annex) because of Russia's criminal intent to plunge Ukraine into a blackout).

In order to improve the energy resilience of the regions, "energy independence passports for regions" will enable central and local authorities to effectively coordinate their efforts toward the development of distributed generation on-site. Ministry of Energy is working on creating regional energy independence passports, considering local specifics for renewable energy development and distributed generation.

The passport makes it evident which vital infrastructure facilities require more capacity as well as the need for generation and consumption in each community, settlement, and metropolis, and to meet

local demands for heat and power, this permits high-quality decentralization. This will specifically address the decentralization of generation, as 75% respondents pointed out.

3.3 Analyze Gaps in infrastructure, technology, governance and funding

The Third Rapid Damage and Needs Assessment (February 2024) by the World Bank (2022), the Ukrainian government, the European Union, and the United Nations, estimates that the entire cost of recovery and reconstruction will be $47.1 billion over a ten-year period.

About US $40.4 billion is necessary to rebuild the power generation in Ukraine. At the same time, it is planned to use the principles based on green transition and following the agreements with the EU, once the war ends. The largest estimated needs are required by Zaporizka, Kharkivska, and Donetsk oblasts. US $1.73 billion from the total amount of the needs are already disbursed and US $3.19 billion are the commitments received.

Efforts have been focused on addressing critical energy infrastructure needs, including the repair and replacement of damaged transmission grid equipment and the development of protective measures to safeguard facilities against drone and missile threats. Additionally, new transmission connections have been established, and STATCOM devices have been installed to ensure effective voltage control, following the guidelines set by ENTSO-E. Hydropower plants have undergone necessary repairs, and distributed generation facilities have been installed to enhance energy decentralization. Furthermore, financial resources have been secured to support procurement activities for the heating season, contributing to the overall resilience and stability of the energy system (World Bank, 2022).

Given the extent of damage to existing generating capacities and the need to decentralize generation to enhance the stability of the power system, there is an urgent need for accelerated construction and/or placement of new distributed generation through the adoption of coordinated organizational, regulatory, legal and economic measures.

Purposeful destruction of the energy infrastructure by the aggressor state led to insufficient generating capacity and caused the need to revise plans for the development of the energy sector of Ukraine.

The Verkhovna Rada of Ukraine approved the State Budget for 2025, which provides for the allocation of UAH 115 billion (USD 2.8 billion) in state guarantees to restore critical infrastructure, including energy facilities. In addition, UAH 71.8 billion (USD 1.7 billion) will be raised as loans and grants from international financial organizations to finance projects in transport, industry, healthcare, education, and energy.

It is obvious that Government didn’t allocate enough money to rebuild the damaged infrastructure and highly rely on foreign aid.

Strategy for the Development of Distributed Generation for the period until 2035 assumes that the amount of financial, logistical, labor resources necessary for the implementation of the Strategy is carried out at the expense of international technical assistance and international organizations, other sources not prohibited by law. 30% of interlocuters expressed concerns that such approach could undermine the restoration of energy infrastructure and construction of new capacities.

The price of electricity in Ukraine significantly depend on the ways of solving technical problems in balancing the country's energy system which is inherent in inflexibility and lack of highly maneuverable and energy-accumulating capacities.

One of the ways to manage demand for electricity consumption is to switch to tariffs differentiated by time periods, specially, a night tariff. It will reduce the load on the network at the time of peak usage and provide the savings for consumers due to cheap "night" electricity.

The presence of large power plants (centralized generation) and large substations, which significantly affect both the output of power from these power plants and the stable energy supply of consumers, require additional measures aimed, on the one hand, at the development of distributed generation of small power (20-150 MW), on the other hand, for the development of effective means for the physical protection of energy equipment. It should be noted that distributed generation must guarantee stable production of electricity in accordance with the requirements of the power system and the demand for electricity from consumers.

As a priority, technologies using gas, biogas, wind energy, small modular reactors of nuclear power plants should be planned and implemented. Solar power plants should be considered only as an additional measure.

The Battery Energy Storage System (BESS) may be introduced, but given their current specific cost, existing energy poverty in Ukraine and significant debts in the country's electricity market, they are unlikely to become widespread in the nearest future. 2 respondents shared their experience of construction the Battery Energy Storage plant and pointed out the many technological and bureaucratic issues they are facing: staring from receiving land plot and providing all necessary commodities and transportation issue of equipment.

Most of respondents are pointed pot that what can be easily and affordably fixed must be fixed as soon as possible. Simultaneously, start new initiatives that will enable to restructure our energy sector in line with new "green" plans and improve its efficiency and sustainability (decentralized).

Gas generation should be given priority since it is a reasonably easy option that can be implemented rapidly. Because gas generation can balance unstable renewable energy sources in the future, it should be the foundation for Ukraine's energy system expansion in addition to nuclear, that confirmed 80% of respondents during interview. A the same time, 2 respondents pointed out that there is a risk of Russian attacks on gas-transportation and storage infrastructure and 5 respondents made comments that Government's proposal to triple price on gas transportation could jeopardize the efforts in switching to gas generation.

Given the scale of damage to existing generating capacities and the need to disperse generation to strengthen the sustainability of the power system, there is an urgent need for accelerated construction and/or placement of new distributed generation by, in particular, taking coordinated organizational, regulatory, legal and economic measures.

There is an urgent need for accelerated construction and/or placement of new distributed generation by, in particular, taking coordinated organizational, regulatory, legal, and economic measures, given the extent of damage to existing generating capacities and the necessity of dispersing generation to strengthen the sustainability of the power system.

More concentrated power generation eliminates the need for transformer stations and minimizes possible targets for enemy attacks by reducing reliance on lengthy transmission links from centralized sources, like hydro or nuclear power stations. Diverse energy sources should be developed in each location to guarantee resilience and lower vulnerability. Regional autonomy is strengthened by this decentralized strategy, which also shields energy infrastructure from significant interruption.

50% of respondents admitted one of the challenges is integrating new capacity into current electrical grids while maintaining their stability; in this case, innovations in technology such as "smart grids" are necessary. Distributed generation need advanced network balancing and management, which "smart grids" offer by monitoring and controlling energy output, distribution, and consumption through digital technology. New technologies also downsize the transformer stations' dimensions as a target for aerial attacks and increase survivability of stations.

Protection continues to be one of the critical requirements for restored and newly build power stations. As admitted 2 interlocuters, the Ukrainian government launched unprecedented program of energy system physical protection (so-called "Fortress Nation" concept) that require the engineering protection of objects critical infrastructure from enemy high-precision weapons, which is funded also by International partners. Due to high costs of construction, many project of highest-level protection (underground concrete structures) were put on pause.

As pointed out 5 respondents, Ukraine's ability to restore energy systems relied on emergency equipment reserves. To facilitate quick post-attack restoration, decentralized reserves of vital equipment, such as transformers and turbines, must be established. In order to prevent mishaps involving damage to energy equipment during missile strikes and unmanned aerial vehicle attacks, an emergency supply of equipment should be established.

CHAPTER 4. DISCUSSION AND RECOMMENDATIONS

The reliable operation of the Ukrainian IPS is essential for the stable functioning of all branches of the Ukrainian economy and for the uninterrupted supply of electricity to industrial and household consumers. It is especially important for defending a country against constant attacks of its territory.

A key area to explore is how Ukraine can balance its immediate needs for energy stability with its long-term vision of sustainability and Eurointegration. The trade-offs between centralized and decentralized energy systems should be analyzed through the lens of security, cost efficiency, environmental impact, and alignment with European directives like the Green Deal.

In the near term, Ukraine must restore large thermal power plants while transitioning pulverized coal units to gas turbines for balancing the grid. Large power plants and substations critical to energy generation and supply require strategic measures. Hydropower facilities need restoration, with new small hydro projects adhering to ecological standards.

Distributed generation, especially in war-affected regions, should expand with gas piston and turbine units for local resilience. Distributed generation (20–150 MW) must be prioritized alongside robust physical protection of infrastructure. Reliable sources like gas, biogas, wind, and small modular nuclear reactors are key, while solar should remain supplementary. Long-term energy security includes modular nuclear reactors, renewable projects (solar, wind), and 24/7 energy solutions to ensure grid balance and sustainable growth.

Battery storage, though promising, is hindered by high costs and energy sector debt. To address risks to major plants, Ukraine must develop cogeneration facilities that provide both electricity and heat, ensuring resilience and meeting consumer needs effectively.

The European Green Deal's instruments and processes can and ought to be incorporated into Ukraine's reconstruction, particularly in light of the "build back better" concept, which calls for a mix of renewable energy sources and decentralized generation to serve as the foundation for resilience and energy security.

Ukraine needs strategic roadmap for transforming its energy sector while addressing geopolitical and environmental challenges.

From the analysis of Ukraine's energy sector, several key managerial decisions can be taken to address challenges and improve resilience at National level:

1. Expanding decentralized generation is a crucial step toward modernizing Ukraine's energy sector and enhancing its resilience. Investing in distributed energy resources like microgrids, solar panels,

and energy storage systems can minimize dependence on centralized systems, reducing vulnerabilities to disruptions such as attacks or natural disasters. By diversifying energy production across regions, Ukraine can create a more balanced and reliable power supply while fostering energy independence and sustainability.

2. These investments also align with global trends and environmental goals, promoting the integration of renewable energy sources. Prioritizing decentralized generation empowers regions, strengthens energy security, and contributes to Ukraine's alignment with the European Green Deal and the Sustainable Development Goals.

3. Modernizing energy infrastructure is critical for ensuring the resilience and sustainability of Ukraine's power sector. Upgrading damaged and outdated power plants provides an opportunity to integrate renewable energy sources and flexible generation technologies into the electric grid. Replacing aging coal-fired power units with modern gas turbines or hybrid systems can improve efficiency, reduce emissions, and offer greater adaptability to fluctuating demand. Investments in smart grid technology, automation, and advanced monitoring systems will further enhance the reliability and management of the energy network.

Focusing on renewable energy in these modernization efforts aligns with global sustainability goals and Ukraine's commitments to the European Green Deal. It can diversify the energy mix while reducing dependency on fossil fuels. Infrastructure upgrades should also consider the development of distributed generation facilities to support regional energy needs, ensuring local communities have access to stable and clean energy even during disruptions.

Strengthening Ukraine's energy security requires a multi-pronged approach to safeguard the power system and ensure reliable energy access. Implementing regional "energy independence passports" can help assess local energy reliability and identify vulnerabilities in the energy network. These passports would serve as a strategic tool to guide investments in distributed generation and improve energy resilience at the community level, reducing dependence on centralized systems and minimizing risks from potential disruptions.

International collaboration is equally vital in addressing Ukraine's energy challenges. Partnerships with the EU, US, and global stakeholders can provide technical expertise, funding, and guidance for integrating Ukraine's energy systems with European networks. Such alliances are essential for modernizing infrastructure, enhancing regulatory frameworks, and adopting innovative technologies that align with global sustainability goals.

To prepare for crises, Ukraine must develop rapid-response mechanisms to rebuild and protect critical energy infrastructure against possible attacks. This includes hardening energy facilities,

expanding backup systems, and training personnel for emergency scenarios. Combining these efforts will ensure Ukraine's energy security while aligning with its long-term development and Eurointegration goals.

At the local community level, managerial decisions could include answers on the following questions worth examining:

- What role could distributed generation play in regional energy independence?
- How can renewable energy sources be scaled while ensuring grid stability?
- What incentives and partnerships are needed to attract investment for modernization efforts?

Promoting localized renewable energy sources offers a sustainable path for Ukraine to enhance energy security while reducing reliance on centralized systems vulnerable to disruptions. Installing solar panels, wind turbines, and small-scale hydropower projects in various regions can foster energy independence and resilience, particularly in areas most affected by war. Such localized systems could also support critical infrastructure during blackouts and empower communities to meet their energy needs sustainably.

To make this shift successful, Ukraine must establish supportive policies, including subsidies and tax incentives for renewable energy adoption. Collaboration with international partners and leveraging funding from the European Union's Green Deal initiatives could accelerate these efforts. Alongside technical support, Ukraine should focus on training local communities in operating and maintaining these systems, ensuring long-term viability and aligning with global Sustainable Development Goals (SDGs). This dual approach would strengthen energy independence while advancing Ukraine's environmental and economic priorities.

Investing in energy efficiency initiatives is critical for Ukraine to enhance energy resilience and reduce overall consumption. Retrofitting public buildings with better insulation and modernizing outdated heating systems can significantly cut energy wastage while improving comfort for citizens. Upgrades to infrastructure, such as introducing smart technologies for energy monitoring and management, would also ensure better resource utilization. These measures not only reduce dependency on external energy sources but also align with Ukraine's long-term goals for sustainable development.

Emergency preparedness is equally essential to address energy disruptions caused by ongoing hostilities. Developing localized resilience plans with robust backup power solutions for critical infrastructure, such as hospitals, water treatment plants, and emergency response centers, is paramount. Establishing microgrids and deploying mobile power units could provide immediate relief during outages, ensuring uninterrupted services for vital facilities.

APPENDIX A. INTERVIEW QUESTIONS

1. What are the trends in losses of power generation equipment within Ukraine's energy system from 2022 to 2024? Are there any comprehensive maps or diagrams that could illustrate these losses from 2014 to 2024 due to aggression?
2. What are the financial losses associated with damaged energy generation equipment? What is the required investment for rebuilding or constructing new generation and network infrastructure?
3. Will damaged thermal power plants (like Tripilska or Burshtynska TPPs) be restored in their original locations, or would it be more viable to develop equivalent distributed generation capacities elsewhere in Ukraine?
4. What is the plan for restoring centralized heating in Ukrainian cities and regional centers? Will increased gas-fired power plant construction lead to EU restrictions due to atmospheric emissions?
5. What are the plans for rebuilding Ukraine's electrical networks? Is USAID contributing a strategy for this network reform?
6. Are additional cross-border power transmission lines planned to enhance electricity import/export capacity with neighboring countries?
7. Are there any restrictions on the use of underground gas storage facilities following missile attacks in spring 2024?
8. What scale of Battery Energy Storage Systems (BESS) is being considered for future integration into Ukraine's power system?
9. What is the estimated funding needed to implement Smart Grid technologies in distribution networks, and is there a unified solution to manage distributed generation and maintain reliable operations in both distribution and transmission networks?

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