



Ensuring Energy Security in Ukraine: The Role of Cogeneration and Sustainable Funding for District Heating Systems

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Abstract: This article examines how to enhance energy security in Ukraine via increased efficiency and sustainability of district heating systems (DHS). It explores the role of combined heat and power (CHP) from a technical perspective and the sustainability of the funding from a financial standpoint, plays in securing energy security. Unlike specific technical/economic studies, this provides a comprehensive overview of technologies, funding, and policies for resilient Ukrainian DHS. The study highlights the critical impact of the ongoing conflict on Ukraine's thermal energy infrastructure and the need for modernization. Preventing system collapse is cheaper and faster than rebuilding. Moreover, small but strategic investments in DHS and CHP during critical periods ensure energy system survival, preventing irreversible damage and enabling long-term recovery. The article provides an *overview analysis* of existing heating technologies and assesses the feasibility of integrating modern solutions such as Power-to-Heat, Waste-to-Energy and explores distributed generation (biogas/biohydrogen and hydrogen fuel) for resilient energy production in Ukraine's DHS. It further explores funding mechanisms, highlighting the importance of international financing institutions (IFI), international partnerships, state support, non-governmental organizations (NGO), and humanitarian aid roles in advancing modernization efforts. Future research assesses cogeneration effectiveness under grant funding during crises and explores distributed generation for resilience. The study highlights the CHP's potential for increasing energy efficiency, reducing emissions, and enhancing energy security. It provides policy recommendations for market liberalization and infrastructure modernization, providing a framework for Ukraine's DHS transition toward renewable energy integration and energy system sustainability. The article concludes that a strategic approach – encompassing technological, economic, regulatory, and sustainable funding advancements – is essential for the long-term sustainability of energy systems in crisis.

Keywords: district heating, combined heat and power, cogeneration, power-to-heat, hydrogen, modernization of energy systems, district heating market, energy storage, resilience, grid stability

1. Introduction

The ongoing conflict in Ukraine has caused unprecedented destruction to the country's thermal energy infrastructure, affecting heat production, distribution, and end-use. Boiler houses, combined heat and power (CHP) plants, and extensive district heating (DH) network sections have suffered severe damage, leading to service disruptions and escalating recovery costs. Since early 2023, the estimated financial toll on Ukraine's thermal energy infrastructure has reached USD 1.2 billion, with the most devastating impacts recorded in Kharkiv, Kyiv, and Sumy regions due to bombings and occupation. By mid-2024, nearly 90% of Ukraine's heat generation capacity had been destroyed, including all Centrengo thermal power plants (TPPs) (REACH 2022). Aging infrastructure exacerbates this crisis. As of December 2024, over 92% of coal-fired TPPs have exceeded their design lifetime of 100,000 hours, with 84% surpassing their maximum operational limit of 200,000 hours. Many facilities require urgent refurbishment or a complete replacement, particularly in conflict-line cities and regions housing Ukraine's largest TPPs (Kessova et al. 2019).



Table 1. Characteristics of Ukrainian Thermal Power Plants (TPPs)

TPP Name	Installed Electric Capacity (MW)	Commissioning /Last Overhaul Years	Condition
Burshtynska	2,334	1965-1969/2010-2016	Damaged, partially operational
Vuhlehirsk	3,600	1972-1977/2008-2012	Damaged, 40%, occupied
Dobrotvirska	510	1960-1964/2010-2015	Severely damaged
Zaporizhska	3,600 (2,825; 800 – mothballed capacity)	1972-1977/1993-2014	Damaged, occupied
Zmiivska	2,200	1960-1969/2007-2012	Totally damaged
Zuyivska	1,270	1982-1988/2005-2010	Occupied
Kryvorizhska	2,820 (2,328; 2x282 – mothballed capacity)	1964-1973/1992-2005	Totally damaged
Kurakhivska	1,527	1972-1975/2007-2015	Totally damaged
Ladyzhinska	1,800	1970-1971/2001-2011	Damaged, temporarily out of service
Luganska	1,325 (1,220; 175 – mothballed capacity)	1956-1969/1996-2012	Occupied
Prydniprovsk	1,765 (1,195; 2x285 – mothballed capacity)	1959-1966/1993-2013	Totally damaged
Slovyanska	800	1955-1971/2015	Severely damaged
Starobeshivska	2,010	1961-1967/2003-2013	Occupied
Trypilska	1,800	1969-1972/2005-2011	Totally damaged

One of the most critical vulnerabilities of Ukraine's DH sector is its dependency on multiple interlinked resources—water, electricity, gas, and coal. A disruption in any of these supply chains could lead to a complete shutdown of heating services, especially in winter when freezing water in pipelines can cause irreversible damage, leaving thousands of residents without heat. Additionally, Ukraine's reliance on gas imports and the extinction of key coal-mining regions further worsen the situation, necessitating urgent energy diversification. However, existing research often lacks a comprehensive analysis of the effectiveness of cogeneration implementation, particularly under grant funding and within the context of Ukraine's energy crisis. This study addresses this gap by providing a comprehensive overview of technologies, funding mechanisms, and policies for building resilient Ukrainian DHS, considering technical, economic, and social aspects.

In response to the crisis, Ukraine has increasingly prioritized cogeneration (CHP) systems as a key component of its energy resilience strategy. Distributed gas generation technologies, specifically small-scale CHP units operating on natural gas, are now actively being implemented in Ukraine to support the energy system and potentially maintain critical infrastructure and heating systems. Gas cogeneration is proving more effective than the diesel generators installed in Ukraine in 2023. CHP technology enables the simultaneous production of heat and electricity, significantly improving fuel efficiency compared to conventional power generation. Given Ukraine's extensive district heating infrastructure, integrating CHP allows for optimized fuel utilization, reducing primary energy consumption by up to 30-40% and minimizing transmission losses. This is particularly critical in emergency and conflict conditions, where fuel shortages and supply chain disruptions necessitate more efficient energy use.

Moreover, deploying CHP enhances energy security by diversifying fuel sources and reducing dependence on centralized thermal power plants. Decentralized CHP units, especially those utilizing biomass, hydrogen, or waste heat recovery, provide greater operational flexibility and can maintain heating services even in regions experiencing grid instability or fuel supply constraints. Additionally, CHP plants can serve as backup power sources, ensuring continuous electricity supply for essential infrastructure such as hospitals, shelters, and industrial facilities during outages.

From an environmental perspective, CHP technology supports Ukraine's commitment to carbon emission reduction and EU energy integration. By utilizing cleaner fuels and improving combustion efficiency, CHP systems contribute to lower greenhouse gas (GHG) emissions, making them a viable solution for achieving Ukraine's National Energy and Climate Plan (NECP) targets. These systems are critical for maintaining a stable

energy supply, enhancing energy security, and aligning with Ukraine's climate commitments and European integration efforts (USAID 2020, Karpenko et al. 2024). Karpenko, Yevtukhova, and Novoseltsev (2024) highlight the benefits of market conditions in DHS, emphasizing that transitioning to market relations and integrating independent energy producers can lead to substantial system efficiency improvements, lower thermal energy prices, and enhanced sustainability in DHS. The alignment of CHP expansion with EU directives on energy efficiency further strengthens Ukraine's position in the European energy market, facilitating access to financial and technical support from international partners.

International partners such as USAID, UNICEF, UNDP, ICRC, and GIZ are actively supporting the transition to CHP-based heat supply to sustain DH operations under emergency and critical emergency situations. Mobile and modular boiler units have emerged as a viable short-term solution, given their mobility and ability to operate on solid fuels, which is essential in the event of gas grid failures. However, long-term resilience requires strategic investment in CHP systems, which offer higher efficiency, fuel flexibility, and decentralized heat production, reducing reliance on vulnerable infrastructure. Khodakivskyi and Karpenko (2024) identify that modernizing coal-fired thermal power plants using advanced combustion technologies and integrating steam, gas, and combined cycle generation is vital for improving maneuverability and reducing emissions. They also emphasize the potential of reconstructing existing CHP plants and converting municipal and industrial boilers into mini-cogeneration plants for integration into the European energy market. Mahnitko et al. (2019) also emphasize the role of autonomous generation in increasing the efficiency of the central heat supply. Moreover, this study emphasizes the potential of small-scale distributed generation, such as biogas and biohydrogen, to enhance system resilience and reduce reliance on natural gas, especially under conditions of limited accessibility. These decentralized sources can provide energy autonomy for individual regions and communities, contributing to a more robust and secure energy supply.

This review aims to identify the direction of the efficiency and resilience improvement of Ukraine's district heating systems (DHS) by examining cogeneration technologies and identifying viable funding mechanisms for ensuring their stable operation and rapid recovery in crisis conditions. The study also considers the role of energy management, heat metering, and Waste-to-Energy (WtE) solutions in enhancing the adaptability and sustainability of DHS. To achieve this, the following objectives are set: (i) Conduct a comparative review of existing heating technologies, including boilers, combined heat and power (CHP) systems, and mini-CHP units, evaluating their applicability to Ukraine's DHS in the context of energy system resilience. (ii) Examine technical and economic strategies for optimizing DHS performance, increasing energy efficiency, and reducing carbon emissions, focusing on integrating Power-to-Heat, hydrogen-based fuels, renewable energy sources, and Waste-to-Energy technologies to improve system flexibility and reliability. (iii) Analyze viable financing mechanisms to support the recovery and stabilization of DHS, considering the role of state support, international financial institutions, humanitarian aid, and public-private partnerships while emphasizing the significance of energy management and heat metering in ensuring cost-effective and adaptive operations. (iv) Summarize policy recommendations for strengthening the resilience of DHS, including strategies for market liberalization, fostering competition, promoting innovation, and ensuring long-term energy security through decentralized and diversified heat generation.

The research methodology follows a systematic five-step approach (Figure 1), providing a comprehensive framework for studying DHS resilience's technological, economic, and regulatory aspects. The findings of this review will serve as a foundation for future research, particularly in the development of mathematical models for assessing the economic feasibility of various strategies for maintaining, restoring, and adapting DHS under crisis conditions.

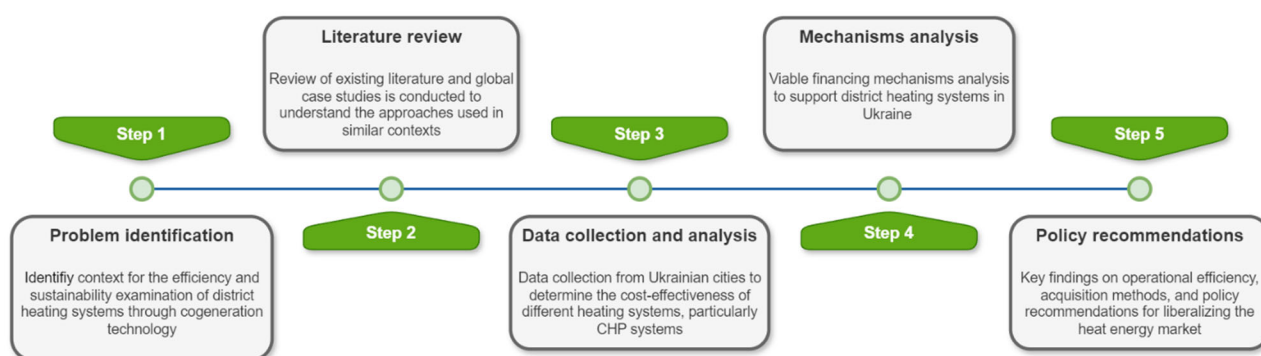


Fig. 1. Illustrates the research methodology, which follows a systematic five-step

This review identifies the critical problem of vulnerable and outdated district heating systems in Ukraine, synthesizes relevant literature, and formulates policy recommendations focused on maintaining system functionality and enhancing resilience during crisis periods. The review will inform the development of a detailed mathematical model and techno-economic evaluation for assessing the cost-effectiveness of different modernization scenarios. This will be presented in a subsequent publication. This approach aims to provide actionable insights for preserving district heating infrastructure and enabling long-term recovery.

2. Literature Review

Heating supply systems in Germany and China demonstrate different approaches to improving the efficiency of district heating (DH) networks. For instance, since 1997, the heating network in Dresden has operated without coal but remains heavily reliant on natural gas (NG). This highlights the potential to increase the share of renewable energy sources (RES) in the city's heating sector, a priority also relevant for Ukraine (Havrylenko & Derii 2024, Sun et al. 2024, Jin et al. 2021). Distributed gas generation technologies are considered a promising direction for enhancing Ukraine's energy security, particularly under crisis conditions. These systems can stabilize energy supply in small towns and rural areas, ensuring reliability and resilience (Kovalko et al. 2023, Schindler et al. 2023, DiXi Group ALERT 2023).

Hasung Song et al. (2019) explore integrating new technologies into traditional heating systems, including using renewable sources. This integration significantly reduces heat losses and CO₂ emissions. The topic's relevance is underscored by the fact that the United Kingdom lags behind European countries, such as Denmark and the Netherlands, in adopting innovative approaches. However, the study emphasizes the technical potential for improving these systems, positioning "smart" heating networks as a critical component of low-carbon energy infrastructure.

Woody biomass, accounting for 48% of Denmark's RES (Danish Energy Agency 2021), is central to DH but faces sustainability concerns due to high imports and excessive consumption (Danish Council on Climate Change 2022). Rising global demand exacerbates challenges. Public debates on BECCS highlight concerns over carbon neutrality and economic impacts, stressing the need for transparent dialogue to support energy transition (Savickas et al. 2012, Ugarte-Lucas & Jacobsen 2024).

Serbin et al. (2023) study explores hydrogen fuels as a solution for decarbonizing energy systems, focusing on gas turbine combustion chambers. Two configurations were analyzed: (a) premixed combustion with axial-radial swirlers and (b) sequential steam injection in an "Aquarius"-type system. Key outcomes include: (i) *optimal Hydrogen Mix*: Stable combustion without flashbacks was achieved with up to 20% hydrogen by volume in NG mixtures, producing NO emissions below 20 ppm and CO below 1 ppm; (ii) *Ppre Hydrogen Combustion*: The sequential steam injection approach prevented flashbacks and reduced NO emissions to ~38 ppm, demonstrating its feasibility for clean hydrogen combustion; (iii) *efficiency Considerations*: Advanced thermal and cooling strategies, such as turbine intake air cooling (TIAC) and waste heat recovery, are recommended for integration with gas turbines to enhance performance in combined heat, cooling, trigeneration and power systems. Future research should refine combustion stability, optimize steam distribution, and further develop green gas turbine technologies for broader applications.

The authors also discuss various methods for modeling and optimizing energy networks, including new models utilizing the concept of a "virtual power plant" to integrate heat and electricity production. Such a model can significantly improve the efficiency of energy systems by reducing thermal losses through optimized heat resource management, ultimately lowering emissions and costs. (Nikitin et al. 2024, Karpenko et al. 2024).

Fifth-generation district heating and cooling systems (5GDHC): Wirtz et al. (2022) emphasize the importance of implementing 5GDHC systems in Europe to decarbonize thermal networks. To date, only a small number of such networks have been deployed, primarily in Switzerland and Germany. This results in significant uncertainties and knowledge gaps regarding the planning and operation of 5GDHC systems. Data on 53 5GDHC systems in Germany, including technical, economic, and political indicators and design decisions, were collected from utilities and engineering offices. The results indicate that 5GDHC systems are typically designed for small new developments (fewer than 100 buildings). These systems are particularly effective in new, small neighborhoods with low energy losses, but their application in large urban areas and existing buildings requires further research.

Digital twins for thermal system management described in (Gao et al. 2024) offer enhanced balancing of supply and demand in urban heating systems. These tools optimize operational costs and environmental benefits by analyzing the overall system structure at the sensor, application, and network levels. They enable the creation of an informational service platform for smart heating networks. Data from the entire heating system, including heat sources, primary networks, substations, secondary networks, and consumers, are collected, analyzed, and diagnosed remotely. A statistical analysis of energy consumption by each heat source and station

ensures data exchange and analysis across different business systems. The study explored key technologies to optimize decision-making methods for system operation planning using simulation models and developed software solutions to support the intelligent modernization of heating systems. Pädam et al. (2019) examine the energy renovation of 343 apartment buildings in Sweden, integrating OPERA-MILP, IDA ICE, and MODEST tools to optimize heat load, life cycle costs (LCC), energy use, and CO₂ emissions. Results for code-compliant renovations showed a reduction in heat and electricity production (35.7 GWh/a and 6.5 GWh/a, respectively), primary energy use (-36.2 GWh/a), and marginal CO₂ emissions (-8.4 kton/a). However, emissions increased by 0.5 kton/a from electricity production, and financial deficits totaled €80.1M over 50 years for building owners, energy firms, and industries (Weinberger et al. 2021). That study highlights the complex interplay between energy efficiency, indoor environment, and DH. Energy savings during winter are valuable for utilities, but impacts vary depending on heat production profiles. Interviews reveal limited collaboration between property owners and energy utilities, leading to missed opportunities for optimizing outcomes. Heat meters can bridge this gap, enhancing transparency, cooperation, and efficiency for all stakeholders (Pädam et al. 2019).

According to Ukrainian legislation, DH companies were required to ensure heat energy metering on the consumer side by August 2018 (State Agency on Energy Efficiency and Energy Saving of Ukraine, n.d.). However, this deadline has been repeatedly postponed and is now set to occur within two years after the full-scale invasion concludes (Figure 2).

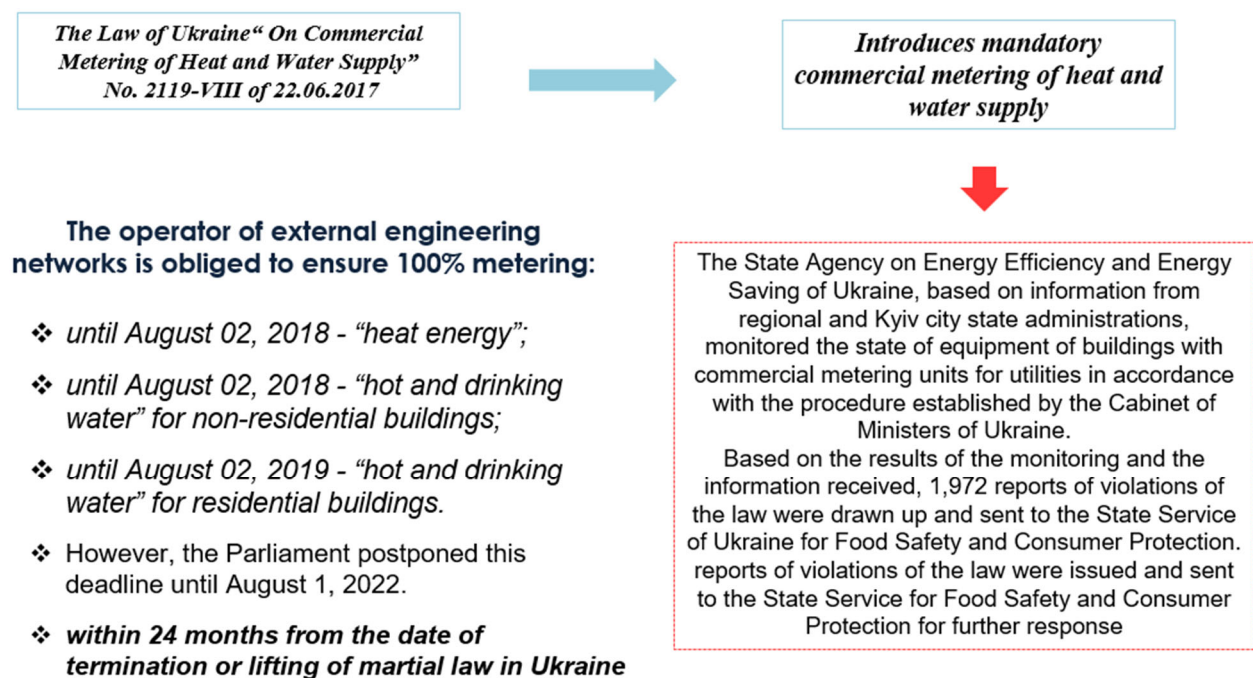


Fig. 2. Metering of heat energy on the consumer

Data collection and analysis were partially conducted in Ukrainian cities, such as Cherkasy, where heat, gas, and electricity meters of the local DH network are automatically queried every 6 hours. These processes require further optimization and nationwide implementation. The status of heat metering deployment in Ukraine as of November 2024 is illustrated in Figure 3. The lowest level of heat energy metering remained in Zakarpattia Oblast (0.0%), while the highest level shifted to Rivne Oblast (99%). (1) *Overall Progress*: Between 2021 and 2024, there has been significant progress in implementing commercial heat energy metering. (2) *Regional Disparities*: There are notable regional differences in metering levels. Certain regions like Rivne and Mykolaiv have achieved nearly complete coverage. In contrast, other regions, including Donetsk (57%), Ternopil (38%), and Zakarpattia (29%), lag significantly. (3) *Need for Improvement*: Continued efforts are essential to increase metering levels in regions with low coverage to ensure efficient resource utilization and reduce energy costs.

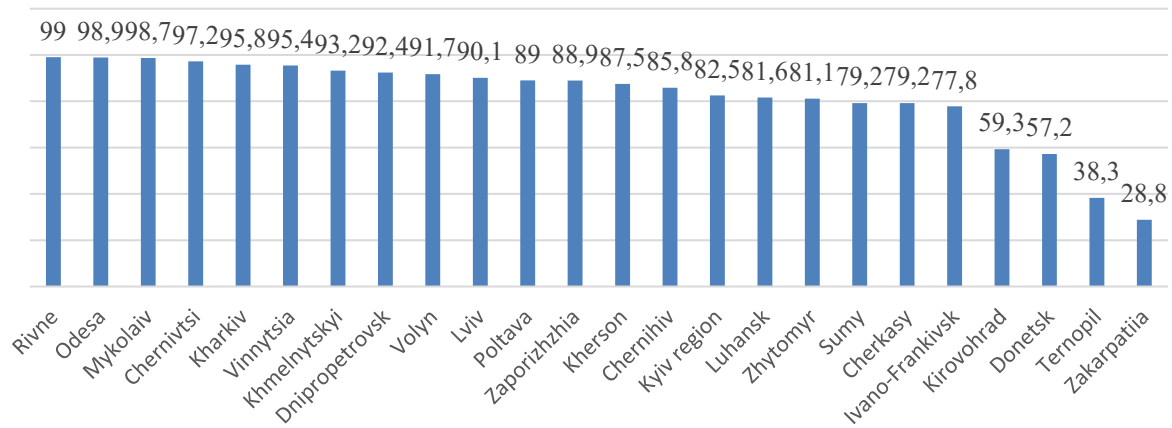


Fig. 3. The status of heat metering deployment in Ukraine (November 2024)

A commercial metering unit can be installed by both the operator of external engineering networks (heat supply company) and the co-owners of an apartment building themselves (Law of Ukraine "On Commercial Metering of Heat and Water Supply"). The equipment of buildings with commercial metering units and equipment of engineering systems to ensure such metering is carried out following the project documentation in compliance with building codes and regulations. (Article 3, part 1 of the Law of Ukraine "On Commercial Metering of Heat and Water Supply") Energy Efficiency Fund, n.d.).

For example, thanks to the fruitful cooperation of DH companies in Ivano-Frankivsk and loans from the European Bank for Reconstruction and Development (EBRD), the Nordic Environment Finance Corporation (NEFCO) and the Swedish International Development Cooperation Agency (SIDA), more than 100 block individual heating stations and heat metering units have been installed in our city in the area of Dovha-Karpatska, Fedkovycha, Pasichna and Gorbachevskoho streets (TKE, n.d.).

Installing metering equipment is one of the first steps before implementing energy efficiency measures. Metering allows you to analyze your energy consumption, optimize it to reduce utility bills, and pay only for what you use. The introduction of metering is important not only for consumers to save money but also for the DH company to understand the need for heat supply and implement measures to modernize networks and equipment. For example, the deterioration of heating networks in Burshtyn is 43.2%, leading to 18% of heat energy losses. The reconstruction of internal heating and hot water systems in multi-apartment buildings constructed during the Soviet period mostly before 1992 in Lithuania, and installing individual heat and hot water consumption meters for each final customer has the potential to decrease energy consumption for a final energy customer by about 25% (Savickas et al. 2015).

The transition to more efficient and sustainable energy systems is increasingly prioritized, with significant efforts to integrate heating, electricity, and mobility. For instance, the GreenSCIES project in London integrates these sectors, reducing CO₂ emissions by 5,000 tons annually (Revesz et al. 2022). This aligns with the European Green Deal, which aims for climate neutrality by 2050 (European Commission 2024, Mahnitko et al. 2019).

Electrification of heating is a key strategy for decarbonization. Thomaßen et al. (2021) highlight its potential to reduce greenhouse gas emissions by up to 17% when paired with expanding low-carbon energy sources. However, such electrification requires parallel development of distributed generation and cogeneration technologies to manage the increased demand on electricity grids.

The "Power-to-Heat" and Waste-to-Energy concepts represent key advancements in energy systems. Kovalko et al. (2023) emphasize their potential to integrate RES into heating systems, reducing fossil fuel dependence and potentially cutting emissions by up to 17%, dependent on further low-carbon generation development. Electrification of heating, particularly through distributed generation and CHP systems, helps reduce fossil fuel reliance, especially in winter. This integration improves system efficiency, as Schindler et al. (2023) noted, who also highlight the role of energy management systems in optimizing investments and operations. In Ukraine, electrification and modernization of thermal power generation are crucial for enhancing energy efficiency. Babak and Kulyk (2023) advocate for heating electrification to boost energy independence, while Deriya et al. (2023) demonstrate the economic viability of RES in district heating systems (DHS). Karpenko et al. (2024) stress the importance of reducing network losses in centralized heating systems to improve overall efficiency.

Kaposvár serves as a model for sustainable urban energy systems, integrating local resources and innovative technologies. The city transitioned from traditional district heating to gas engine cogeneration in the 1990s, added a sugarcane-based biogas plant in the 2000s, and implemented CNG-operated public buses supported by localized fueling infrastructure. These initiatives are complemented by a wood chip-fired heating plant, waste heat recovery, Waste-to-Energy, smart metering for over 60% of residential flats, and public EV charging stations, showcasing a holistic approach to energy efficiency, transportation, and environmental sustainability (Bánkuti & Zanatyné Uitz 2023, Kudri et al. 2024). Similarly, Wärtsilä's upcoming engine power plant in Finland demonstrates the potential of balancing capacity for electricity systems during disturbances, a strategy aligned with Ukraine's efforts to modernize its energy infrastructure (Wärtsilä 2024).

Ukraine is advancing toward energy-efficient district heating systems (DHS), transitioning from second-generation unregulated systems to automated third-generation systems and eventually to smart fourth-generation systems (4GDH). These 4GDH systems, integrating RES, cogeneration, smart metering, and energy dispatching, promise improved efficiency, reliability, and flexibility (Fialko et al. 2023). Modernizing CHP plants is also critical, as highlighted by Dunaevska (2023) and Basok et al. (2022), emphasizing advanced fuel processing technologies and the integration of cogeneration to reduce fossil fuel dependency. Case studies in Kamianets-Podilskyi, Chernihiv, and Zhytomyr demonstrate the economic feasibility and environmental benefits of small-scale biomass CHP in balancing the grid and lowering costs (Babak & Kulyk 2023, Mahnitko et al. 2019). These examples underline the global shift toward decentralized, efficient, and sustainable energy systems.

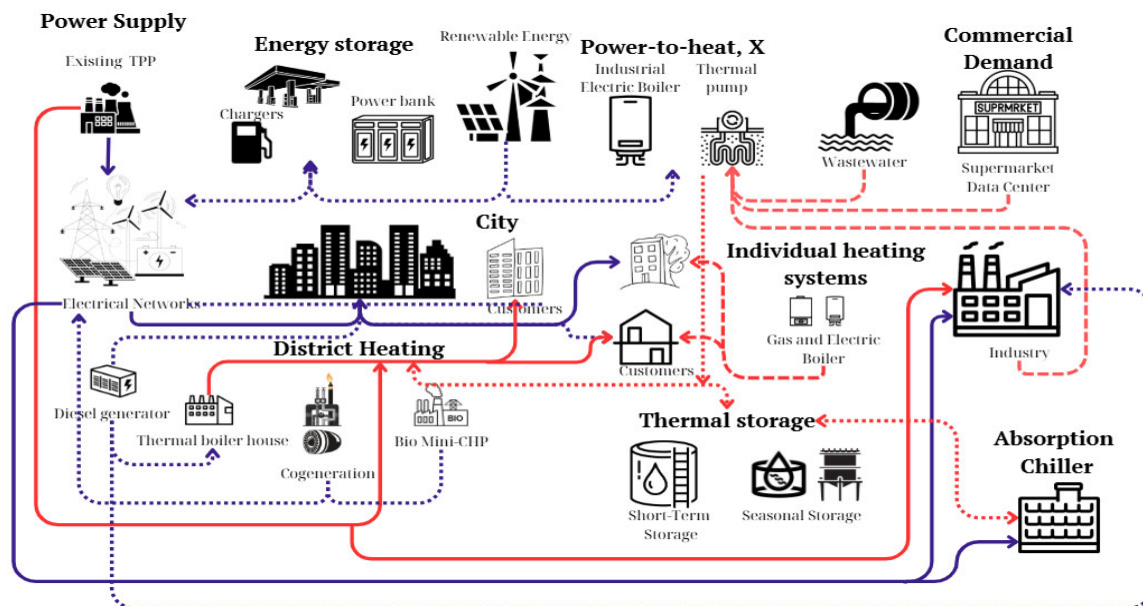


Fig. 4. The modern approach to upgrading centralized heating systems

In conclusion, integrating cogeneration, small-scale CHP based on the Organic Rankine Cycle (ORC), RES, energy management systems, "Power-to-Heat", Waste-to-Energy and hydrogen fuel source based solutions presents a sustainable pathway for reducing emissions and increasing the stability of DH, and electricity systems. These innovations are crucial for Ukraine's energy independence and rebuilding efforts. Adopting 4GDH systems, focusing on cogeneration, RES, and green hydrogen, aligns with global energy efficiency and sustainability trends, providing both environmental and economic benefits. Figure 4 illustrates the modern approach to upgrading centralized heating systems in Ukraine, emphasizing cogeneration technologies, Power-to-X from RES.

3. Materials and Results of the Study

The literature review underscores a multifaceted approach to transforming district heating systems into more efficient, sustainable, and resilient networks. Key innovations include the integration of RES, cogeneration and CHP systems, hydrogen fuels, fifth-generation district heating and cooling (5GDHC) systems, digital twins, smart metering, and energy-efficient building renovations. These advancements collectively address

critical challenges such as reducing CO₂ emissions, enhancing energy security, and optimizing resource management. For Ukraine, adopting fourth-generation district heating (4GDH) systems—integrating RES, cogeneration, smart technologies, and concepts like "Power-to-Heat" and Waste-to-Energy—offers a promising pathway toward energy independence and post-conflict rebuilding. Globally, examples like Dresden's shift from coal, Denmark's reliance on woody biomass, and the GreenSCIES project in London highlight these transitions' potential and complexities. However, challenges such as high implementation costs, technical complexities, regional disparities, and the need for supportive policies and infrastructure remain significant hurdles. Table 2 summarizes the primary technologies and approaches, their benefits, and associated challenges, providing a comprehensive overview of the strategies shaping the future of district heating.

Table 2. Primary technologies and approaches, their benefits, and associated challenges summarization of literature review

Technology/ Approach	Description	Benefits	Challenges/Considerations	Future Studies
Distributed gas generation	Small-scale gas-based power generation for localized energy supply.	Enhances energy security in small towns and rural areas (e.g., Ukraine).	Reliance on natural gas; requires infrastructure investment.	Optimization of placement, integration & environmental impact.
Renewable energy sources	Integration of solar, biomass, and other renewables into heating systems.	Reduces fossil fuel dependency and emissions (e.g., Dresden, Ukraine).	Sustainability issues (e.g., woody biomass imports in Denmark).	Local RES use, sustainable supply chains & climate adaptation.
Cogeneration and CHP	Combined heat and power systems for simultaneous electricity and heat production.	Improves efficiency; supports grid stability (e.g., Kamianets-Podilskyi).	High upfront costs; integration with existing infrastructure.	Operational optimization, flexibility, storage integration.
Hydrogen fuels	Use of hydrogen in gas turbines for cleaner combustion.	Low emissions (e.g., <20 ppm NO with 20% hydrogen mix); decarbonization potential.	Combustion stability; infrastructure and safety requirements.	Overcoming stability issues, infrastructure design & safety measures.
5GDHC systems	Advanced district heating and cooling networks for small developments.	Reduces energy losses; decarbonizes thermal networks (e.g., Germany).	Limited to small areas; needs research for large urban deployment.	Scalability for large cities.
Digital twins	Virtual models for real-time thermal system management.	Optimizes supply-demand balance; reduces costs (e.g., urban heating systems).	Data integration and scalability challenges.	Data integration, scalability & practical implementation
Smart metering	Installation of meters to monitor heat consumption.	Enhances transparency and efficiency (e.g., Cherkasy, Ukraine).	Regional disparities; implementation delays (e.g., Zakarpattia).	Overcoming disparities & accelerating implementation
Energy renovation of buildings	Upgrading building systems for energy efficiency.	Reduces heat and electricity use (e.g., Sweden's 343 apartments).	Financial deficits; coordination between stakeholders needed.	Innovative financing & stakeholder coordination.

Table 2. cont

Electrification of heating	Shifting heating to electricity-based systems.	Cuts emissions with low-carbon sources (e.g., up to 17% reduction).	Increases grid demand; requires distributed generation support.	Grid stability with RES, optimized control methods & sector-specific requirements
Power-to-Heat	Converting excess electricity into heat using RES.	Integrates renewables; reduces fossil fuel use (e.g., Ukraine's potential).	Dependent on low-carbon generation; economic viability concerns.	Technological advancement & optimized waste management
Waste-to-Energy	Converting waste materials into heat or power.	Reduces landfill use and emissions (e.g., Kaposvár model).	Technological maturity; requires waste management infrastructure.	Technological advancement & optimized waste management.

Based on an evaluation of various technologies and approaches for future district heating systems, the most promising options are those that excel in sustainability, efficiency, scalability, and alignment with global energy trends toward decarbonization and resilience. Below are the selected approaches, along with the reasoning for their potential:

- integrating renewable energy sources such as solar and biomass into district heating systems is highly promising. These sources significantly reduce reliance on fossil fuels and lower greenhouse gas emissions, making them a cornerstone of sustainable energy systems. While challenges like the sustainability of biomass imports exist, the overall potential of RES to support long-term decarbonization and energy security makes them a top priority;

- cogeneration systems, which produce heat and electricity simultaneously, offer exceptional energy efficiency and contribute to grid stability. Although they require substantial initial investment, their ability to maximize energy output and provide reliable heating and power solutions positions them as a critical technology for modern district heating infrastructures;

- smart metering enhances transparency and efficiency by providing detailed data on energy consumption. This technology is foundational for modern energy systems, enabling better demand management and cost savings. Despite regional implementation challenges, its role in creating responsive and efficient heating systems is essential.

While integrating renewable energy sources, cogeneration systems, and smart metering presents a forward-looking vision for district heating systems, their widespread adoption is not without hurdles. These technologies promise enhanced sustainability, efficiency, and responsiveness, yet their implementation often faces significant practical challenges. In many regions, including those striving to modernize their energy infrastructure, issues such as high upfront costs, technical complexities, and inconsistent policy support can impede progress. This tension between potential and practice highlights the need for tailored solutions that bridge the gap between innovative concepts and real-world application, paving the way for a deeper exploration of alternative approaches to meet both current demands and future goals.

The DH sector in Ukraine, after seeking support from the government and international organizations for CHP units, has encountered major implementation and maintenance challenges (Energy Club 2024, Kudri et al. 2024). This analysis emphasizes the need for modernizing DH systems, considering the integration of CHP and RES technologies, to increase efficiency, reduce dependency on fossil fuels, and improve environmental performance. The potential for decentralized heating systems and the use of local energy sources, such as biomass, can play a critical role in the country's energy transition.

Currently, two main types of gas-powered internal combustion engines are widely used in industry: spark-ignition gas engines and gas-diesel engines, where ignition of the air-fuel mixture occurs through the injection of liquid ignition fuel. Gas engines have become increasingly popular in the energy sector due to the rising demand for gas as an economically viable fuel (both natural and alternative) and their environmental benefits, such as reduced harmful emissions in exhaust gases. The comparison of engine types, fuel, power output, advantages, and disadvantages is summarized in Table 3.

Table 3. The comparison of engine types, fuel, power output, advantages

Company	Engine Type	Fuel	Power (kW)	Advantages	Disadvantages	LCOE (USD/MWh)
Guascor (Spain)	Gas piston power plants based on Guascor engines that operate on various types of gas	NG, associated gas, biogas, sewage gas	142.8-1,204	High reliability, electronic control systems, versatility, ability to run on various types of gas, low energy production costs, convenient maintenance.	Limited power range compared to other brands, less stringent gas composition requirements but not suitable for all conditions.	70-90
FG Wilson (United Kingdom)	Gas piston power plants based on Perkins, Scania, Isuzu, Ford, General Motors engines	NG and liquefied gas	11-276 (low power), 380-1,000 (medium power)	Wide model range, ease of connection to gas supply, high reliability.	Long delivery times (10–14 weeks), high likelihood of low-quality supplies from unreliable vendors, high cost for standard equipment.	65-85
MTU (Germany)	Gas piston power plants based on MTU engines	NG, biogas	116-1,948	High efficiency (up to 92%), proximity to consumers, automated remote control, 240,000-hour lifespan, and easy maintenance.	High installation cost.	75-95
Caterpillar (USA)	Gas piston power plants based on Caterpillar engines	NG, associated gas, biogas, sewage gas	10-3,860	High efficiency and fuel economy, CHP systems with up to 40% fuel savings, excellent operational and transient performance.	High installation cost, custom-order deliveries.	70-90
Elteco (Slovakia)	Gas piston power plants based on PERKINS, GUASKOR, MAN, DEUTZ engines	NG	3.8-3,916	High efficiency, cost-effectiveness, eco-friendliness, autonomy, and compatibility with other energy sources.	Long manufacturing, delivery, and equipment installation times (from 6 months).	70-85
Tedom (Czech Republic)	Gas piston power plants based on Tedom engines	NG, biogas	23-5,900	Reliability, compactness, easy network connection, modular design, and noise reduction with soundproof casing.	High installation cost.	65-85

Table 3 presents a comparative overview of gas piston power plants from various manufacturers, emphasizing critical characteristics for enhancing energy resilience, including engine types, fuels, power output, and operational advantages. Notably, the flexibility in fuel use (Guascor, Caterpillar) is vital for addressing fuel supply disruptions, while autonomous operation (Elteco) ensures continuity during grid outages. This comparison supports informed decision-making in selecting the most appropriate technology to bolster energy security and stability. LCOE (Levelized Cost of Energy) values are estimated and may vary based on specific project conditions and market factors, with an average range of 65-90 USD/MWh. The selection of a gas piston power

plant should be based on a comprehensive assessment of technical specifications, operational needs, and economic constraints. Ongoing advancements in research and technology are expected to further improve the efficiency and accessibility of these systems (LCOE 2024).

To provide a comprehensive overview, this article synthesizes information from various sources, including Statistical data on Ukraine's energy sector and district heating systems. Reports from international organizations (e.g., USAID, UNICEF, UNDP, ICRC, GIZ) on energy efficiency initiatives and humanitarian aid efforts. Research articles and publications on cogeneration technologies and energy market liberalization were selected based on their relevance to the Ukrainian context and methodological rigor.

It's important to acknowledge some limitations inherent in the data used. Statistical data may suffer from delays and incompleteness due to the ongoing conflict, while reports from international organizations often focus on specific projects or regions, potentially limiting their generalizability. Furthermore, publications may reflect the perspectives and biases of their authors. Various sources were consulted and cross-referenced to mitigate these limitations to ensure a balanced and comprehensive assessment. The review analyzes this data to identify key trends, challenges, and opportunities for enhancing the resilience and sustainability of Ukraine's district heating systems. Detailed calculations and modeling of different modernization scenarios will be presented in a subsequent publication. This review builds upon previous research by DiXi Group ALERT (2023), who highlight the importance of distributed gas generation for Ukraine's energy security; Energy Club (2024), who emphasize the need for stable heat supply during the heating season; Karpenko & Yevtukhova (2024), who discuss market features of heat producers' contribution to losses in district heating networks; Khodakivskyi & Karpenko (2024), who emphasize the potential of CHP plants and boiler houses for balancing Ukraine's energy system; USAID (n.d.), who provide guidelines for the development of heating supply schemes; and Ugarte-Lucas & Jacobsen (2024), who explore public perception of bioenergy with carbon capture and storage. By synthesizing these findings with the information described above, this review aims to provide a holistic perspective on the path towards preserving existing district heating infrastructure during the current crisis and enabling a more resilient energy future for Ukraine.

In a subsequent publication, we aim to build upon this review by (i) Analyzing total annual revenues and profitability metrics under various scenarios to provide insights into the economic feasibility of CHP and distributed generation for maintaining district heating services during crisis periods. (ii) Determining dependencies on operational hours, load levels, and the method of acquiring equipment. (iii) Assessing the impact of reduced load levels. (iii) Highlighting the importance of extended operational hours for revenue generation and profitability. (iv) Determining policy implications and recommendations for promoting efficient operational models and financing mechanisms prioritizing system preservation and resilience during crises.

4. Discussion

Given the review nature of this study, this article synthesizes key insights from the literature regarding the criticality of maintaining district heating system functionality during periods of crisis, the effectiveness of various support mechanisms, and viable strategies for enhancing overall system resilience.

This review contributes to the existing body of knowledge by synthesizing existing literature to highlight the critical need for enhancing the resilience of Ukraine's district heating systems during times of crisis. The forthcoming methodology will provide a framework for ensuring the stability and sustainability of these systems in all weather conditions and will open new possibilities for modernizing systems.

The schematic representation in Figure 5 illustrates a dynamic and competitive DHS characterized by the participation of multiple stakeholders across various stages of the energy cycle. The system is organized into four core functional groups: the energy production group, responsible for generating thermal energy from diverse sources; the energy transportation group, tasked with efficiently distributing energy through heat networks; the energy consumption group, encompassing end-users and their demand-side management; and the DHS operations group, overseeing system coordination, optimization, and management to ensure reliability and sustainability. This structure reflects an integrative approach to DHS operations, promoting collaboration and efficiency among its key participants.

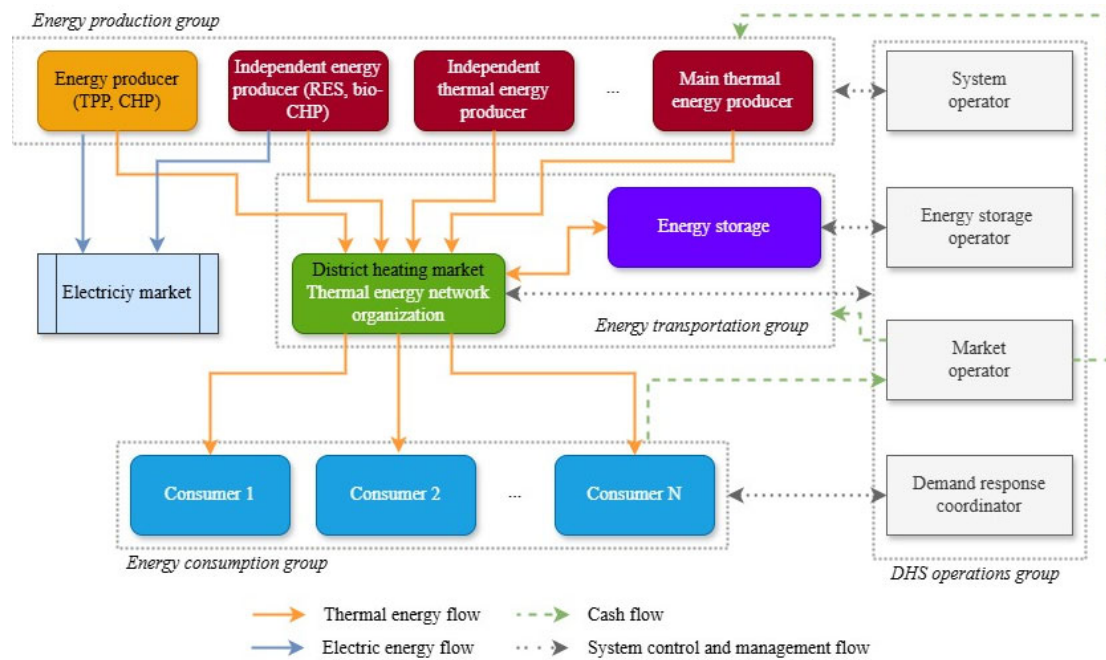


Fig. 5. Basic modernization of the structural scheme of the competitive DHS with ESD

Moreover, the results underscore the importance of support from the State and international partners. Free acquisition or subsidized equipment enables financially constrained enterprises to adopt modern technologies, such as CHP, RES, Power to Heat, green Hydrogen, Waste-to-Energy, and biogas, fostering energy independence and enhancing the resilience of energy systems. An essential consideration is the transition to market-driven conditions and the liberalization of the heat energy market by reducing artificial regulatory interventions in pricing and profitability processes. The operational experience of Ukrainian DH enterprises (DHEs) demonstrates that many companies have been unable to modernize their networks to meet contemporary requirements over 30 years of independence. Instead, most heating networks have become outdated and require substantial renovation, as exemplified by the city of Kryvyi Rih, which faced emergency operational modes and left some buildings without heating during the 2024-2025 heating season.

5. Future Research Directions

Building upon this review, future research will focus on developing a comprehensive methodology for assessing the effectiveness of cogeneration implementation under grant funding within the specific context of Ukraine's energy crisis. This methodology will address the existing gap in evaluating the potential of cogeneration in crises by integrating technical, economic, and regulatory factors. It will specifically examine the role of distributed generation, including biogas and biohydrogen, in enhancing system resilience and reducing reliance on natural gas, particularly under conditions of limited accessibility.

A key aspect of future studies will be the detailed economic assessment of cogeneration and distributed generation technologies. This will involve:

- evaluating total annual revenues and profitability metrics under various operational scenarios to determine the financial viability of CHP integration;
- analyzing the impact of load levels, operational hours, and equipment acquisition methods on system performance and economic returns;
- comparing profitability under full operational capacity versus reduced load levels, assessing the implications for revenue generation and cost-effectiveness;
- investigating different procurement strategies, including purchasing versus grant-funded equipment, to identify optimal financial models for DHS modernization;
- defining key profitability criteria and formulating policy guidelines to support efficient operational models and sustainable financing mechanisms.

The study will highlight the potential of CHP systems to improve energy efficiency, reduce emissions, and enhance energy security, reinforcing their critical role in the resilience of Ukraine's DHS. The findings will serve as a foundation for future policy development and investment strategies, ensuring the long-term sustainability and adaptability of the energy sector in crisis conditions.

6. Conclusions

This review synthesizes existing literature to highlight critical factors for enhancing the resilience and sustainability of DHS in Ukraine, particularly during periods of crisis. Further investigations will quantify the benefits of these strategies. Key findings from the reviewed literature and local data assessment include:

1. Ukraine's outdated thermal infrastructure, particularly older TPPs, demands urgent upgrades. With their higher efficiency and reliability, cogeneration units should play a central role in this modernization effort to ensure stable thermal energy delivery and decentralized electricity generation, increasing the resilience of the overall electricity grid.
2. The private and public sectors may fill missing capacity gaps through new business models. However, regulatory measures such as leasing models where at least 50% of DHS assets remain state-owned while private operators manage operations are vital to prevent monopolization.
3. First, the energy demand for heating must be reduced via buildings' energy performance increase, and only after investments into the DHS must be considered, allowing a dramatic decrease in the volume of investment for the same targeted energy increase level. Implementing energy management systems and heat metering at the final energy consumer level reduces energy consumption for the final energy consumers by up to 25%, reinforcing economic sustainability and affordability, providing pathways for accurate energy consumption and financial forecasting, improving operational efficiency, and allowing better infrastructure planning.
4. Transitioning to alternative fuels such as biofuel, biogas, and hydrogen enhances both environmental sustainability and energy security. A diversified fuel mix reduces dependency on single fuel sources and strengthens resilience in extreme conditions.
5. Small but essential investments in cogeneration and DHS keep systems operational during critical and emergency situations. Cogeneration also enhances resilience by providing decentralized, fuel-efficient, and independent energy generation, reducing vulnerability to supply disruptions. Immediate interventions to recover the system operation may be small in terms of investment Capex compared to rebuilding the overall system Capex. Therefore, timely support to DHS increases financial performance, preserves infrastructure, and prevents the overall system from collapsing.
6. A more detailed methodological framework is required to improve the assessment of DHS resilience and modernization strategies. Future studies should refine key assumptions, including investment costs, operational flexibility, and regulatory impacts, to enhance the applicability of research findings.
7. Regulatory constraints and policy incentives are crucial in DHS transformation. Further analysis of market-based mechanisms, investment support schemes, and legislative frameworks is needed to facilitate cogeneration development and attract sustainable financing.

These insights are a foundation for policymakers, industry stakeholders, and international partners to develop and implement robust district heating strategies that ensure resilience, efficiency, and sustainability. Further research on the potential models for assessing the effectiveness of cogeneration implementation under grant funding within the specific context of Ukraine's energy crisis will be explored and assessed in a more detailed way in future research activities and publications.

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