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LOW-CARBON ENERGY MODERNIZATION OF CRITICAL INFRASTRUCTURE IN THE DIGITAL ECONOMY: TRANSITIONING WATER UTILITIES TO INDUSTRY 4.0/5.0 IN WARTIME[1]

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Summary. The article substantiates strategic priorities, organizational-economic, and financial mechanisms for the low-carbon energy modernization of water utilities as critical infrastructure assets in Ukraine. It is demonstrated that, under wartime conditions, power grid capacity shortages, and persistent blackout risks, improving internal energy efficiency and enhancing utility autonomy are key drivers of national security, community viability, and achieving national decarbonization targets. Based on an analysis of cost structures and load profiles, it is identified that the primary share of energy consumption in water utilities is concentrated at the water intake and distribution stages, justifying prioritizing investment in the energy modernization of these operational steps. Key technical-economic inefficiencies and energy-related economic risks facing water utilities during wartime are systematized. It is identified that legacy Industry 3.0 operational approaches (relying on mechanical valve throttling) lead to excessive electricity expenditures, whereas the deployment of Industry 4.0 and 5.0 digital tools (VSDs, SCADA systems, and IoT sensors) yields a 15–30% reduction in operating costs. A roadmap for deploying solar photovoltaic power plants at water utility sites integrated into internal energy management systems is proposed. Relying exclusively on municipal budgets for funding such projects is shown to be impractical; instead, financial models are formulated that combine municipal co-financing (10–15% of CAPEX), green loans from international financial institutions (EBRD, EIB, NEFCO), non-repayable grants, and PPAs with private investors. A conceptual framework for the organizational-economic support mechanism for energy modernization is developed to optimize capital costs and build green resilience within the municipal sector. It is proven that decarbonization, energy security, and operational resilience of water utilities represent mutually reinforcing objectives. The practical value of the findings lies in establishing a decision-support system for municipalities. Future research may

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focus on leveraging Industry 5.0 tools, artificial intelligence, and industrial energy storage systems to further support the energy modernization of water utilities.

Keywords: critical infrastructure, water utility, low-carbon energy modernization, digital economy, Industry 4.0/5.0, solar photovoltaic power plant, martial law, sustainable development.

Relevance of the issue. The current stage of global economic development is characterized by increasingly stringent requirements to minimize anthropogenic impacts on the climate and by the rapid transition toward a low-carbon economy. Global decarbonization challenges, the dynamic evolution of international and national regulatory frameworks, rapid technological innovation, and changing societal expectations are compelling organizations to fundamentally reconsider traditional approaches to energy production, procurement, and consumption. Across many sectors, the ability to effectively manage the energy transition has become not only a matter of compliance with environmental standards but also a prerequisite for maintaining long-term competitiveness, operational viability, and resilience to external shocks. This issue is particularly significant for critical infrastructure operators, especially in the municipal sector and water supply and wastewater (WSW) utilities. For these companies, energy modernization is directly linked to national and regional security, as the reliable energy supply of technological processes determines the uninterrupted provision of essential public services (IEA, 2021; Capodaglio, 2025).

The specific challenges faced by Ukrainian municipal utilities in the context of the low-carbon transition and wartime economic conditions lie in the need to address several interconnected tasks simultaneously: substantially improving internal energy efficiency through the adoption of digital technologies, strengthening the resilience of energy supply systems by integrating distributed energy generation, and optimizing the economic costs of these measures under severe financial constraints imposed by the ongoing war (Sotnyk et al., 2023, 2024, 2025). The development of the digital economy requires a fundamental transformation of municipal asset management, replacing conventional engineering solutions with cyber-physical systems that can adapt to stochastic operating conditions and frequent power outages (Bhandari et al., 2023). Against this background, providing a scientific basis for strategic priorities and developing practical organizational, economic, and financial mechanisms for the energy modernization of critical water supply and wastewater infrastructure constitutes an important scientific and practical challenge.

Analysis of recent research and publications. Strategic energy transition management and the implementation of low-carbon technologies in critical infrastructure have attracted increasing attention from international organizations and leading researchers. In contemporary research, water supply and wastewater utilities are increasingly analyzed through the Water-Energy-Carbon nexus, which examines the interdependencies between the technical and economic performance of water utilities and greenhouse gas emission reduction (e.g., Abe et al., 2019; Han et al., 2023). International experience demonstrates that the decarbonization of municipal water utilities is driven by three major strategic directions: substantial improvements in the energy efficiency of pumping systems, extensive digitalization of operational management, and the integration of distributed renewable energy generation directly into utility infrastructure, accompanied by the economic optimization of these measures (Rani et al., 2022; Sapkota et al., 2020; Capodaglio, 2025).

Studies on the structure of energy consumption and operating costs in water utilities, including those by Hamawand (2023), Abe et al. (2019) and reports published by international financial institutions (International Financial Institutions, 2020), provide a scientific basis for allocating operational expenditures across the major technological stages of water supply and wastewater systems. At the macroeconomic level, these studies consistently identify pumping systems as the dominant contributors to operating costs in municipal utilities (Jocanovic et al., 2019). Techno-economic modeling of hydraulic regimes and the identification of inefficiencies in pumping systems have been further developed in the works of Vieira et al. (2019) and in analytical reports prepared by the European water regulators' association (WAREG, 2025).

Within the broader context of the low-carbon transition, a growing body of research focuses on environmental inefficiencies in water distribution systems. Previous studies indicate a strong relationship between the technical condition of water distribution networks and the level of indirect greenhouse gas emissions (Collet et al., 2023; Mazzolani et al., 2023). Methodological approaches to monitoring and standardizing operational water losses have been discussed in reports published by sectoral organizations (WAREG, 2025). At the same time, assessments of decentralized energy solutions suggest that water utilities are technically and economically well suited for integrating local renewable energy sources, particularly solar photovoltaic generation (Cabrera et al., 2021; Liu et al., 2020).

The challenges posed by wartime conditions and prolonged economic instability in Ukraine require adapting conventional theoretical approaches to the realities of critical infrastructure security. As noted by Sotnyk et al. (2025; 2025a), for Ukrainian water utilities, the deployment of distributed energy gen-

eration, particularly hybrid solar photovoltaic power plants (SPPs), represents not merely an environmental component of the low-carbon transition but also a fundamental instrument for strengthening energy autonomy, infrastructure resilience, and the uninterrupted provision of water services under conditions of repeated damage to the centralized power system. The destruction of electricity generation facilities caused by Russian attacks, combined with generation shortages and prolonged power outages, has fundamentally altered the risk profile of municipal utilities. Under these circumstances, the traditional reliance on diesel generators for emergency backup power is constrained by fuel supply disruptions, high operating costs, and increased local air pollutant emissions. These challenges have reinforced the concept of green resilience, which emphasizes the development of local microgrids based on Industry 4.0 and Industry 5.0 technologies through the integration of SPPs and energy storage systems (ESSs) to maintain critical water utility operations in autonomous mode (OECD, 2022).

Despite the growing body of literature, a significant research gap remains regarding the organizational, economic, and financial mechanisms required to manage such modernization processes under wartime conditions. This gap provides the rationale for the present study.

The purpose of the article. Unlike previous papers, which typically examine energy efficiency, renewable energy deployment, or the digitalization of water utilities as separate research areas, this study proposes an integrated framework that combines Industry 4.0 and Industry 5.0 technologies, distributed solar power generation, and organizational, economic, and financial mechanisms to enhance the resilience and decarbonization of water supply and wastewater utilities as critical infrastructure under wartime conditions in Ukraine. To achieve this objective, the research addresses the following research tasks:

– to conduct a comprehensive assessment of the energy consumption structure of water utilities and identify the key techno-economic inefficiencies limiting their low-carbon transition;

– to identify priority directions for the energy modernization of water supply and wastewater systems based on Industry 4.0 and Industry 5.0 technologies and to develop a strategic roadmap for implementing distributed SPPs at critical infrastructure facilities under wartime conditions;

– to substantiate the conceptual framework for organizational, economic, and financial mechanisms to integrate energy autonomy and decarbonization into the operation of municipal water utilities.

Research methodology. The study's methodology is based on a systems approach to the analysis of water supply and wastewater utilities. Techno-economic inefficiencies within the sector were identified, and available empirical evidence was synthesized through descriptive and structural-comparative analyses. The development of the roadmap for deploying distributed energy generation and the identification of the conceptual framework for appropriate organizational, economic, and financial support mechanisms under wartime economic conditions were based on logical generalization, cause-and-effect analysis, and functional component analysis.

Research results. Developing strategic priorities for the energy modernization of water supply and wastewater utilities as critical infrastructure within the transition to the digital economy requires a comprehensive understanding of the sector's current energy performance. To identify the principal drivers of energy consumption, empirical data from municipal utilities reported by international financial institutions, the European water regulators' association (WAREG), and recent sector-specific studies were analyzed (Abe et al., 2019; International Financial Institutions, 2020; Hamawand, 2023; H2O Global News, 2025a; Naser & Abdulrazzaq, 2021; Vieira et al., 2019; WAREG, 2025).

The analysis revealed a highly uneven distribution of electricity consumption across the main technological stages of water supply and wastewater operations (Fig. 1). Water transmission and distribution account for the largest share of total energy use due to the continuous energy demand required to maintain network pressure and overcome elevation differences across extensive distribution systems. A substantial proportion of electricity is also consumed during water abstraction and primary pumping, particularly in systems reliant on groundwater. In contrast, water treatment and conditioning generally account for a smaller share of total electricity consumption, though their energy intensity may increase with the adoption of advanced treatment and disinfection technologies. Administrative and auxiliary operations constitute only a minor, relatively stable component of overall energy demand.

A comparison of the technological components demonstrates that water abstraction, together with water transmission and distribution, accounts for approximately 60–95% of the total electricity consumption of water supply and wastewater utilities. This distribution provides a clear rationale for prioritizing investment in these processes. Isolated investments aimed solely at improving the energy efficiency of auxiliary operations or water treatment facilities are unlikely to generate substantial improvements in the overall technical, economic, or financial performance of utilities. Instead, the greatest potential for low-carbon transformation lies in modernizing primary and secondary pumping systems and optimizing water distribution networks.

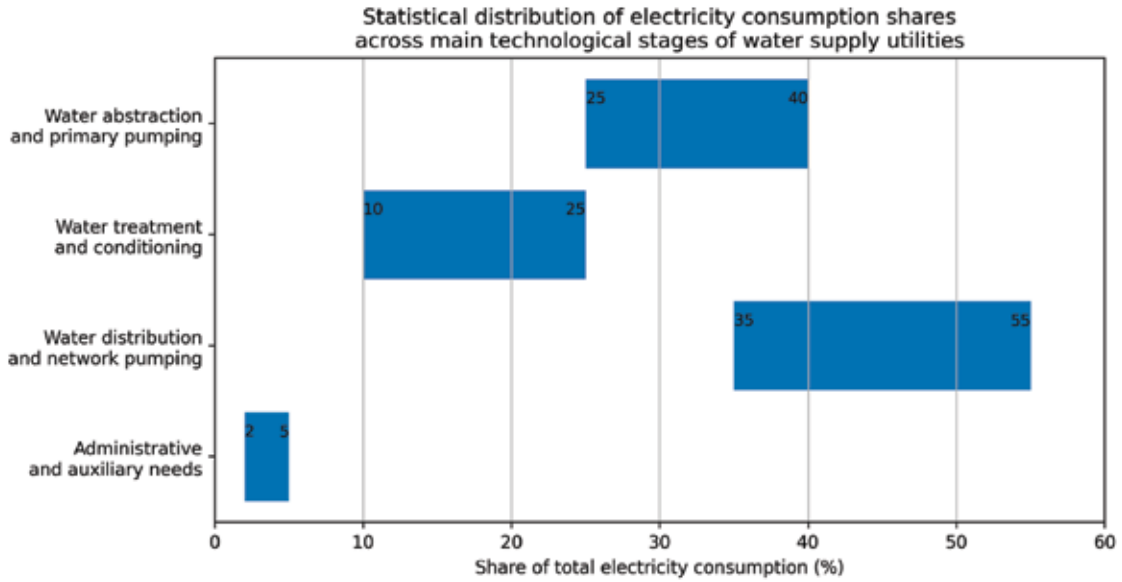


Figure 1 – Interval distribution of electricity consumption shares across technological stages of water supply and wastewater utilities, %

Source: developed by the authors

From both economic and energy management perspectives, these processes offer the highest return on investment, as even relatively modest improvements in pumping efficiency can significantly reduce operating costs, electricity consumption, and associated greenhouse gas emissions. Under wartime conditions, when investment resources are severely constrained, concentrating modernization efforts on the most energy-intensive stages becomes particularly important for maximizing both economic efficiency and infrastructure resilience. Table 1 summarizes the principal techno-economic energy-related inefficiencies that constrain the low-carbon transition and operational resilience of water supply and wastewater utilities across the main technological stages, while increasing the cost of providing essential water and wastewater services.

Analysis of sectoral evidence confirms a strong negative relationship between the level of non-revenue water and the energy performance of water utilities [20; 18]. Under wartime conditions, this relationship becomes even more critical. Dynamic ground vibrations from shelling, together with repeated hydraulic transients caused by frequent power outages and system restarts, have significantly increased the occurrence of hidden leaks in Ukraine's

Table 1 – Classification of techno-economic energy-related inefficiencies in water supply and wastewater utilities by technological stage

Stage of water supply	Category of inefficiency	Technical and economic characteristics
1	2	3
Raw water abstraction	Oversized pumps	Oversized pumps designed for historical water demand that currently operate far from their best efficiency point, resulting in excessive electricity consumption and higher operating costs.
	Aging infrastructure	Severe wear and aging of electric motors and mechanical components, reducing both electrical and mechanical efficiency and increasing specific energy consumption.
	Hydraulic losses	High friction losses, hydraulic resistance, and turbulence in suction and discharge pipelines caused by corrosion, scaling, and sediment accumulation, leading to increased pumping energy requirements.
Water treatment	Outdated aeration and mixing systems	Use of energy-intensive mechanical mixers instead of modern automated chemical dosing systems and fine-bubble aeration technologies.
	Schedule-based filter regeneration	Excessive filter backwashing performed according to fixed time schedules rather than actual water quality indicators (e.g., turbidity), resulting in unnecessary energy and water consumption.

Продовження таблиці 1

1	2	3
Water distribution	Excessive network pressure	Maintaining artificially high operating pressure to supply distant consumers, causing excessive electricity use, increased leakage rates, and higher maintenance costs.
	Suboptimal pumping schedules	Operation of pumping equipment during peak electricity tariff periods without optimizing reservoir storage and pumping schedules.
	Non-revenue water losses	Hidden water losses in deteriorated distribution networks, requiring additional abstraction, treatment, and pumping of water that never reaches consumers, thereby increasing the unit cost of water supply.
	Absence of variable-speed control	Fixed-speed pump operation in which flow regulation is achieved through throttling control valves instead of variable speed control, resulting in substantial energy losses.

Source: developed by the authors based on the synthesis of data from [34; 12]

water distribution networks [35; 30]. Consequently, water losses act as a negative multiplier of energy consumption: utilities expend electricity to abstract, treat, and pump water that never reaches consumers, requiring additional pumping to compensate for network losses and maintain service continuity. This results in a disproportionate increase in specific electricity consumption and operating costs per cubic meter of delivered water.

Energy-related challenges are not limited to water supply systems. Wastewater utilities are likewise highly energy-intensive due to the continuous pumping, aeration, and treatment processes required for wastewater management. Under wartime conditions, power outages and physical damage to wastewater infrastructure not only increase operational expenditures but also substantially elevate environmental and public health risks through the potential discharge of untreated wastewater and failures of treatment facilities. Consequently, strengthening the energy resilience of both water supply and wastewater systems has become a strategic priority for maintaining essential municipal services during prolonged disruptions. The principal energy-related risks affecting Ukrainian water supply and wastewater utilities under wartime conditions are summarized in Table 2.

Table 2 – Key energy-related risks and their consequences for the Ukrainian water supply and wastewater utilities during wartime

Risk	Technical consequence	Economic implication	Environmental implication
Power outages	Interruption of water supply and wastewater pumping	Higher operating costs due to emergency response, backup power use and service disruptions	Untreated wastewater discharges; deterioration of water quality
Missile attacks	Damage to water supply, sewer networks and treatment facilities	High reconstruction costs, asset losses and service interruptions	Soil and water contamination from damaged infrastructure
Fuel shortages	Limited operation of backup generators	Increased operating costs and reduced service reliability	Higher emissions from diesel generators and emergency fuel use
Budget constraints	Delayed rehabilitation and modernization of infrastructure	Rising maintenance costs, lower energy efficiency and growing investment gap	Slower implementation of environmentally efficient technologies
High non-revenue water	Increased pumping and water treatment requirements	Higher electricity costs and reduced financial performance	Overexploitation of water resources and unnecessary energy use
Damage to sewer networks	Infiltration/inflow and increased pumping demand	Higher energy consumption and repair costs	Groundwater contamination and uncontrolled wastewater leakage
Frequent start-stop operation of pumps	Accelerated equipment wear and reduced operational efficiency	Increased maintenance and replacement costs	Lower overall energy efficiency and increased indirect emissions

Source: developed by the authors

The identified systemic inefficiencies and risks affecting water supply and wastewater utilities demonstrate that conventional modernization approaches, based solely on replacing physically worn equipment with functionally equivalent assets, are no longer sufficient. Within the context of the digital economy, the transformation of utility energy systems should be based on the convergence of energy-efficient engineering solutions with the digital technologies of Industry 4.0 and Industry 5.0. This transformation requires the development of cyber-physical systems that integrate the Internet of Things (IoT), Supervisory Control and Data Acquisition (SCADA) platforms, and intelligent monitoring and control technologies capable of converting conventional infrastructure into adaptive, resilient systems that can respond effectively to dynamic operating conditions and external disruptions [3; 19].

To operationalize these strategic priorities for the low-carbon transformation of the municipal sector, we developed a matrix of organizational, technological, and digital modernization measures, structured according to the principal components of water supply and wastewater infrastructure (Table 3). The proposed framework links specific technological interventions with their expected energy, economic, and environmental benefits, thereby providing practical guidance for planning modernization projects under conditions of financial constraints and elevated infrastructure risks.

A central element of the Industry 4.0 architecture is the integration of variable speed drives (VSDs) with SCADA systems. In conventional pumping systems without variable speed control, water flow is regulated by throttling control valves rather than by adjusting pump speed. This traditional engineering approach, characteristic of Industry 3.0, causes electric motors to continue operating close to their rated power while excess energy is dissipated as hydraulic losses. In addition to increasing electricity consumption, throttling accelerates pipeline wear, raises pressure fluctuations, and contributes to higher leakage rates and maintenance costs.

The integration of VSDs with SCADA platforms, using real-time data collected from IoT pressure sensors installed throughout the distribution network, enables continuous adjustment of pump operating conditions to actual water demand. By reducing motor speed during periods of lower consumption, utilities can substantially decrease electricity use while maintaining the required service pressure. According to the affinity laws for centrifugal pumps, a 20% reduction in rotational speed can reduce electricity consumption by approximately 50%, illustrating the significant energy-saving potential of intelligent pump control. Beyond direct electricity savings, digital pump control also improves hydraulic stability,

Table 3 – Matrix of organizational, technical, and digital measures for the energy modernization of water supply and wastewater systems

Source of energy modernization	Organizational and technical measures
Pumps and motors	• replacement with high-efficiency units (IE3 or IE4 motors, optimized impeller design); • installation of variable speed drives to match pump output with demand; • hydraulic redesign to reduce static lift and pipe friction losses; • condition-based maintenance to ensure equipment operates at peak efficiency.
Treatment processes	• upgrading mixing and aeration systems to fine-bubble diffusers or high-efficiency mixers; • automating chemical dosing to avoid overuse of pumps and mixers; • process optimization to align treatment intensity with actual water quality requirements.
Distribution network	• pressure management systems to maintain optimal pressure profiles and reduce leakage; • zoning and district metered areas for targeted leak detection; • optimized pump scheduling to shift load to off-peak tariff periods; • network rehabilitation to reduce friction losses and leakage rates.
Control and automation	• SCADA upgrades to integrate energy performance data into operational decision-making; • demand forecasting tools to adjust pumping schedules proactively.
Auxiliary energy systems	• replacement of lighting with light-emitting diodes and installation of occupancy sensors; • efficient heating, ventilation, and air conditioning systems with programmable controls; • on-site renewable generation (solar photovoltaic on treatment plant roofs, small-scale wind where feasible) to offset grid electricity.

Source: developed and structured by the authors based on [34]

reduces physical water losses, extends equipment lifetime, and lowers operating and maintenance costs. Consequently, the combined implementation of VSDs, SCADA, and IoT technologies represents one of the most cost-effective pathways toward improving both the energy efficiency and operational resilience of water supply and wastewater utilities. The estimated electricity savings, along with the associated organizational, environmental, and economic benefits of implementing these modernization measures, are summarized in Table 4.

Reducing electricity consumption from Ukraine's interconnected power system, which has become increasingly unstable due to the extensive destruction of flexible generation capacity during the war, directly lowers the indirect greenhouse gas emissions associated with water utility operations. However, under conditions of persistent generation shortages and the high vulnerability of centralized electricity infrastructure, improvements in energy efficiency and intelligent pump control alone cannot ensure the operational resilience of critical municipal services. Consequently, enhancing energy efficiency should be complemented by the deployment of local autonomous power systems based on distributed energy resources that are fully integrated into the operational management of water supply and wastewater utilities.

Among the available technological options, the deployment of SPPs represents the most economically viable and technologically mature solution for municipal water utilities. The extensive roof areas, treatment facilities, reservoirs, and other utility-owned sites provide significant opportunities for on-site photovoltaic installations capable of supplying a substantial share of daytime electricity demand. Beyond reducing electricity costs and carbon emissions, on-site solar generation strengthens energy security by decreasing dependence on the centralized power system and improving the continuity of essential public services during power disruptions.

To support the systematic implementation of such projects, we propose a strategic roadmap for deploying SPPs at water supply and wastewater utilities under wartime conditions. The roadmap comprises the following sequential stages [24; 4; 5]:

1. Defining the strategic objectives for integrating renewable energy generation.

At the initial stage, the utility's management defines the SPP project's strategic objectives, taking into account the specific challenges posed by wartime conditions. The main objectives include: environmental (reducing the carbon footprint), security-related (enhancing the energy autonomy of pumping stations and water/wastewater treatment facilities during power outages and potential infrastructure damage), economic (reducing expenditures on expensive grid electricity or electricity generated by diesel generators), and regulatory (complying with national renewable energy targets and policies).

2. Assessing spatial constraints and resource potential. This stage involves analyzing meteorological data to assess the solar irradiation potential of the project location. At the same time, a technical audit of the utility's existing infrastructure is conducted, including an assessment of the load-bearing capacity of building roofs, the availability of vacant land or water reservoir areas suitable for photovoltaic panel installation, and the condition of the internal electrical network for connecting the SPP.

3. System design and equipment selection. At this stage, the optimal installed capacity of the SPP is determined based on the utility's actual daily and seasonal electricity demand profiles, while also considering wartime risks that may disrupt normal operations. The primary objective is to maximize on-site consumption of generated electricity while minimizing surplus electricity exported to the external grid and ensuring the highest possible degree of energy autonomy during power outages. This stage also includes selecting photovoltaic modules, inverters, mounting structures, and determining the required capacity and technical specifications of the ESSs to ensure stable operation during critical periods.

4. Economic evaluation and financing strategy. A long-term financial model is developed that covers both capital expenditures (equipment procurement and installation) and future operating and mainte-

Table 4 – Estimated energy-saving potential and associated benefits of modernization measures in water supply and wastewater utilities

Measure	Average energy savings (%)	Additional organizational, financial and environmental benefits
Pump replacement	10–25	Reduced maintenance and operating costs
VSD installation	15–30	Reduced pressure surges and improved operational flexibility
Pressure management	10–20	Reduced leakage rates and extended asset lifetime
Aeration system upgrade	20–40	Improved treatment efficiency and process performance
Distribution network rehabilitation	5–15	Improved water quality and reduced water losses

Source: developed and structured by the authors based on [13; 6; 32; 34]

nance costs. The economic feasibility of the investment is evaluated using conventional financial indicators, including Net Present Value (NPV), Internal Rate of Return (IRR), Profitability Index (PI), and Discounted Payback Period (DPP). At the same stage, the optimal financing structure is determined by balancing municipal funding, loans, grants, and private-sector participation.

5. Construction and commissioning. This stage includes preparing detailed engineering documentation, obtaining required permits and regulatory approvals, conducting procurement, and selecting contractors. Construction and installation activities are followed by commissioning tests, comprehensive verification of protection and control systems, and synchronization of the SPP with the utility's internal power supply system.

6. Integration into the utility's energy management system. To maximize operational and economic benefits, the SPP is integrated into the utility's SCADA platform via smart metering and IoT technologies. This enables real-time monitoring of electricity generation and the automatic optimization of energy-intensive operations, such as shifting reservoir filling cycles or filter backwashing to coincide with periods of peak solar production. As a result, electricity consumption is optimized while reducing dependence on the external power grid. An equally important function of the integrated energy management system is maintaining reliable operation during blackouts, emergency situations, and infrastructure disruptions caused by military attacks. In addition to monitoring technical parameters, the system can also integrate economic indicators, allowing real-time tracking of energy expenditures by cost centers and supporting more effective operational and financial decision-making.

The proposed roadmap enables water supply and wastewater utilities to minimize organizational, economic, environmental, and technological risks throughout every stage of project implementation. A hybrid energy supply system developed according to these principles substantially reduces dependence on vulnerable external energy sources while providing a reliable foundation for long-term sustainable development. Nevertheless, the practical implementation of such projects in the Ukrainian municipal sector remains constrained by severe financial limitations and the specific characteristics of the wartime investment environment.

The financing strategy for Ukrainian water utilities should account for several major external constraints, including limited internal financial resources resulting from socially regulated water tariffs, elevated macroeconomic risks, restricted municipal capital expenditures under martial law, and the need to achieve national decarbonization targets. Under these conditions, the traditional self-financing model is no longer viable, necessitating a diversified financial architecture that combines multiple sources of investment capital. Within this framework, three principal financing mechanisms can support the low-carbon transformation of municipal water infrastructure:

- partial co-financing by utilities. Despite limited financial capacity, municipal utilities should provide an initial capital contribution of approximately 10–15% of total capital investment (CAPEX). This contribution serves as an important signal of local commitment to the project and reduces the overall investment risk perceived by external lenders and donors, thereby improving access to additional financing;
- long-term concessional financing through green lending instruments. The primary source of funding for large-scale technological modernization and investment in renewable energy infrastructure should be concessional financing from international financial institutions to support decarbonization and energy efficiency projects. For example, the European Bank for Reconstruction and Development (EBRD) provides long-term financing through dedicated programs, such as FINTECC, specifically designed to reduce greenhouse gas emissions [9]. Similar low-interest municipal lending instruments with extended repayment periods are available from the European Investment Bank (EIB) and the Nordic Environment Finance Corporation (NEFCO) [8; 22]. Beyond financial resources, these institutions also provide technical assistance, including support in preparing feasibility studies, business plans, and international procurement procedures. Such assistance partially compensates for the limited internal expertise of many Ukrainian utilities in implementing complex cyber-physical infrastructure projects [9; 8]. Compared with domestic commercial lending under wartime conditions, these financing instruments offer substantially more favorable borrowing terms;
- mobilizing private investment through public–private partnerships based on Power Purchase Agreements (PPAs). An alternative financing mechanism that substantially reduces the capital burden on municipal utilities is the implementation of PPA models with private investors [2]. Under this arrangement, a private partner finances, constructs, owns, and operates the SPP located on the municipal utility's premises, while the municipal utility commits to purchasing the generated electricity under a long-term contract at a predetermined tariff below the expected market price of grid electricity. The principal advantage of this model is the rapid deployment of renewable generation together with the transfer of most technical and financial risks to the private investor. Its main limitations are reduced operational control over the generating asset and lower long-term financial benefits retained by the utility. A related financing option is equipment leasing, which allows utilities to repay the investment gradually using the operational

cost savings generated by the installed photovoltaic system.

An additional strategic priority for financing energy modernization during both wartime and the post-war recovery period is the effective utilization of non-repayable grants and international technical assistance provided by foreign governments and international development organizations, including European Union institutions and other international donors [10; 31]. Because water supply and wastewater utilities provide essential services to the civilian population, investments in their modernization have a strong humanitarian dimension, particularly when they enhance the continuity of drinking water supply amid repeated disruptions to the centralized electricity system. This humanitarian significance, combined with the contribution of modernization projects to climate mitigation and infrastructure resilience, substantially increases their eligibility for grant funding and other forms of concessional financial support. A comparative overview of the principal financing instruments available for supporting the low-carbon modernization of water utilities is presented in Table 5.

Integrating these financing instruments into a diversified funding portfolio enables utilities to achieve an appropriate balance between minimizing the cost of capital and maintaining strategic public ownership of critical infrastructure assets. A key factor in attracting external investment is the transparent demonstration of the environmental benefits generated by modernization projects. Replacing carbon-intensive grid electricity with on-site solar photovoltaic generation leads to verifiable reductions in indirect greenhouse gas emissions, thereby contributing to compliance with European climate objectives while creating opportunities for future participation in carbon finance mechanisms and white certificate schemes.

Furthermore, improving the energy autonomy of water supply and wastewater utilities through distributed solar generation enhances not only environmental performance but also infrastructure resilience. Reliable operation of water treatment and wastewater facilities during prolonged power outages reduces the risk of environmental contamination associated with emergency system failures and uncontrolled wastewater discharges, thereby strengthening regional environmental security and supporting the long-term sustainability of municipal services.

Taken together, these technical, financial, environmental, and institutional components form a conceptual framework for the integrated organizational-economic mechanism supporting the energy modernization of water utilities (Fig. 2). The mechanism links public policy, financing instruments, digital transformation, and energy performance into a coherent cause-and-effect structure, illustrating how coordinated interventions can improve energy effi-

Table 5 – Financing instruments for water supply and wastewater utilities decarbonization

Instrument	Cost of capital	Risk	Ownership
Municipal funding	Low	High budget burden	Full
EBRD loan	Medium	Moderate	Full
NEFCO loan	Low	Moderate	Full
PPA	No CAPEX	Low	Partial
Grant	Zero	Low	Full

Source: developed by the authors



Figure 2 – Conceptual framework for the organizational-economic mechanism supporting energy modernization of water supply and wastewater utilities

Source: developed by the authors

ciency, reduce operating costs, enhance infrastructure resilience, and accelerate the low-carbon transition of the municipal water sector.

Overall, the findings demonstrate that successful low-carbon modernization of water utilities requires the systematic integration of energy-efficiency measures, digital technologies, and distributed renewable energy generation. Moving beyond the conventional replacement of individual equipment toward the development of cyber-physical infrastructure enables utilities not only to reduce specific energy consumption by approximately 15–30%, but also to improve the operational resilience of critical municipal services under wartime conditions. The proposed strategic roadmap for deploying SPPs, supported by a diversified financing strategy and a conceptual framework for the integrated organizational-economic mechanism, provides a practical framework for strengthening municipal infrastructure resilience, reducing environmental risks, and supporting the long-term sustainable development of local communities.

Conclusions. The principal theoretical contribution of this study is the conceptualization of the energy transition and the resilience of critical municipal infrastructure as complementary rather than competing policy objectives. Unlike conventional approaches that address decarbonization, digitalization, and emergency preparedness separately, the proposed integrated framework demonstrates that investments in low-carbon technologies simultaneously enhance energy security, operational continuity, and climate performance. By combining energy-efficient engineering solutions, Industry 4.0/5.0 digital technologies, distributed solar generation, and organizational-economic and financial mechanisms within a single analytical framework, the study extends current understanding of how municipal infrastructure can remain both sustainable and resilient under war conditions and during post-war recovery.

From a practical perspective, the proposed framework provides municipal authorities and utility managers with a structured basis for strategic investment planning. By integrating technical modernization, distributed renewable generation, and diversified financing mechanisms, it supports decision-making aimed at reducing dependence on vulnerable centralized electricity networks while improving the operational reliability and long-term economic sustainability of water supply and wastewater utilities under severe financial constraints. From a policy perspective, the findings emphasize the importance of incorporating decentralized energy systems into national and municipal reconstruction strategies. They highlight the need to facilitate access to international climate finance, concessional lending, and grant programs, while aligning the modernization of municipal infrastructure with European decarbonization objectives and energy transition policies.

The study outcomes should be interpreted in light of several limitations. First, the availability of high-quality digital monitoring data remains limited across many Ukrainian water utilities, restricting the quantitative validation of some proposed organizational and managerial solutions. Second, the wartime environment is characterized by substantial uncertainty associated with infrastructure damage, disruptions to electricity supply, macroeconomic instability, and rapidly changing investment conditions, all of which may affect the practical implementation and long-term performance of modernization projects.

Future research should focus on integrating artificial intelligence and Industry 5.0 predictive technologies into municipal water management systems to improve operational efficiency and infrastructure resilience. Further studies are also needed to evaluate the techno-economic feasibility of industrial ESSs, biogas utilization, and sector coupling technologies, as well as to develop quantitative resilience indicators for assessing the performance of critical municipal infrastructure during post-war reconstruction and long-term climate adaptation.

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НИЗЬКОВУГЛЕЦЕВА ЕНЕРГЕТИЧНА МОДЕРНІЗАЦІЯ КРИТИЧНОЇ ІНФРАСТРУКТУРИ В РАМКАХ ЦИФРОВОЇ ЕКОНОМІКИ: ПЕРЕХІД ВОДОПРОВІДНО-КАНАЛІЗАЦІЙНОГО ГОСПОДАРСТВА ДО ІНДУСТРІЇ 4.0/5.0 У ВІЙСЬКОВИЙ ЧАС

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Анотація. У статті обґрунтовано стратегічні пріоритети, організаційно-економічні та фінансові механізми низьковуглецевої енергетичної модернізації водоканалів як об'єктів критичної інфраструктури України. Доведено, що в умовах воєнного стану, дефіциту енергопотужностей та постійних загроз знеструмлення підвищення внутрішньої енергоефективності й розбудова автономності водоканалів є чинниками національної безпеки, збереження життєдіяльності громад та досягнення національних цілей декарбонізації. На основі аналізу структури витрат та профілів навантаження визначено, що основна частка енергоспоживання водоканалів акумулюється на етапах забору та розподілу води, що обґрунтовує першочергову спрямованість інвестицій на енергомодернізацію цих етапів. Систематизовано ключові техніко-економічні неефективності та економічні ризики водоканалів у воєнний час. Визначено, що застарілі організаційно-технічні підходи Індустрії 3.0, засновані на механічному дроселюванні води засувками, призводять до перевитрачання коштів на електроенергію, тоді як впровадження цифрових інструментів Індустрії 4.0 і 5.0 (VSD-приводів, SCADA та IoT-датчиків) забезпечує зменшення операційних витрат

на 15–30%. Запропоновано дорожню карту розгортання сонячних фотоелектричних станцій на водоканалах із інтеграцією їх у систему енергоменеджменту підприємств. Обґрунтовано недоцільність орієнтації фінансування таких проєктів виключно на муніципальні бюджети та сформовано фінансові моделі, що поєднують часткове співфінансування громади (10–15% CAPEX), «зелених» позик міжнародних фінансових інституцій (ЄБРР, ЄІБ, NEFCO), безповоротних грантів та PPA-договорів із приватними інвесторами. Розроблено концептуальну рамку організаційно-економічного механізму підтримки енергомодернізації для оптимізації вартості капіталу та розбудови «зеленої» стійкості в комунальному секторі. Доведено, що декарбонізація, енергетична безпека та операційна стійкість водоканалів є взаємодоповнюючими цілями. Практична цінність результатів полягає у створенні прикладної системи прийняття рішень для муніципалітетів. Подальші дослідження можуть бути спрямовані на використання інструментів Індустрії 5.0, штучного інтелекту, промислових систем накопичення енергії для потреб енергомодернізації водоканалів.

Ключові слова: критична інфраструктура, водоканал, низьковуглецева енергетична модернізація, цифрова економіка, Індустрія 4.0/5.0, сонячна фотоелектрична станція, воєнний стан, сталий розвиток.

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