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# STRATEGIC PLANNING AND ECONOMIC ASSESSMENT OF THE IMPLEMENTATION OF DIGITAL TWIN TECHNOLOGY IN GAS DISTRIBUTION NETWORK MANAGEMENT SYSTEMS

## СТРАТЕГІЧНЕ ПЛАНУВАННЯ ТА ЕКОНОМІЧНА ОЦІНКА ВПРОВАДЖЕННЯ ТЕХНОЛОГІЇ ЦИФРОВИХ ДВІЙНИКІВ У СИСТЕМУ УПРАВЛІННЯ ГАЗОРОЗПОДІЛЬНИМИ МЕРЕЖАМИ

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The article provides a comprehensive study of the economic efficiency and strategic importance of implementing Digital Twin technology for the analytical assessment of gas distribution networks in the Khmelnytskyi region under martial law and post-war recovery. The theoretical framework is based on the concept of adaptation and behavioral strategies of economic agents developed by Tetiana Obelets, which allows for the interpretation of digital transformation as a radical tool for ensuring the resilience of critical infrastructure. The study analyzes the current state of the Khmelnytskyi Branch of LLC "Gas Distribution Networks of Ukraine," focusing on financial indicators and technical loss levels. A mathematical optimization model based on Mixed-Integer Linear Programming (MILP) was developed to minimize total expenditures. It is proven that transitioning to a proactive predictive model allows for a reduction in production and technological gas losses from 14% to 5%. The role of smart technologies in enhancing the investment attractiveness of the sector and integrating biomethane projects into the regional system is substantiated.

**Keywords:** business analysis; analytical modeling; digital twins; Digital Twin; gas safety; production and technological losses; military risks; investment attractiveness.

У статті досліджено стратегічні перспективи впровадження технології цифрових двійників у систему управління газорозподільними мережами Хмельницького регіону в умовах воєнного стану та повоєнного відновлення. Обґрунтовано, що цифрова трансформація критичної інфраструктури є не лише технічним оновленням, а інструментом підвищення енергетичної безпеки, фінансової стійкості та адаптивності підприємства. Методичну основу роботи становить модель змішаного цілочисельного лінійного програмування, яка дає змогу оцінити капітальні інвестиції, операційні витрати, ризики аварій і виробничо-технологічні втрати газу. На прикладі Хмельницької філії ТОВ «Газорозподільні мережі України» показано, що перехід від реактивної до предиктивної моделі управління може знизити втрати природного газу з 14% до 5%. Визначено роль смарт-модулів, SCADA-систем та аналітики даних у формуванні Smart Gas Grid і підготовці мереж до інтеграції біометану.

**Ключові слова:** аналіз діяльності підприємства; планування діяльності підприємства; цифрові двійники; Digital Twin; газова безпека; виробничо-технологічні втрати; воєнні ризики; інвестиційна привабливість.



**Statement of the problem.** The functioning of Ukraine's energy sector under conditions of full-scale armed aggression necessitates the search for fundamentally new survival and development models by economic agents. Since February 24, 2022, the Russian Federation has been launching systematic strikes on critical infrastructure facilities, causing not only physical destruction but also a profound destabilization of macroeconomic indicators. The gas distribution system of the Khmelnytskyi region, which provides "blue fuel" to hundreds of thousands of households and industrial facilities, stands at the epicenter of these challenges. Traditional operational paradigms, based on the reactive principle of emergency response, prove ineffective in modern realities as they fail to ensure a prompt response to dynamic threats or the optimization of limited resources [2].

The object of our analysis is the Khmelnytskyi Branch of LLC "Gas Distribution Networks of Ukraine" (hereinafter – Khmelnytskyi Branch of "Gazmerezhi"), which became the official Distribution System Operator (DSO) in the region on October 1, 2023 [4]. The enterprise operates within a paradox: on one hand, it is obligated to ensure uninterrupted 24/7 gas supply during martial law; on the other, it faces rigid tariff regulation, with rates remaining unchanged (1.54 UAH per 1 m<sup>3</sup> excluding VAT) for the duration of the moratorium. The financial stability of the sector has been undermined by the accumulated debt of DSOs to the Transmission System Operator (TSO), which by the end of 2023 reached 17.85 billion UAH [6]. Under such circumstances, business analysis and strategic planning require the implementation of high-tech solutions, such as Digital Twins.

The digital transformation of gas distribution networks is not merely a technical upgrade but a critical condition for ensuring regional energy security and resilience. It allows for overcoming the "information lag" between the occurrence of a malfunction and its identification, which is a key factor in reducing production and technological losses (PTL) [1]. In the context of the Khmelnytskyi region, where total environmental damage from military actions has exceeded 2.22 billion UAH, the system's capacity for self-diagnosis and automated balancing becomes decisive for minimizing cumulative economic losses [7].

**Analysis of recent research and publications.** The theoretical foundation of our study is based on the works of domestic and foreign scholars examining critical infrastructure resilience and business adaptation during

systemic crises. Significant contributions include studies by T. Obelets, Yu. Chernenko, V. Vasylenko, S. Stepuryana, O. Kazak, and others. Specifically, the literature emphasizes that war and systemic crises create an environment of extreme uncertainty where traditional long-term planning loses its relevance, and the primary task becomes transitioning from survival strategies to models of adaptive development.

In his research, Yu. Chernenko highlights that current global challenges require utilities to shift toward innovative strategic models and implement integrated risk assessment frameworks. Regarding digitalization, O. Kazak notes that during martial law, digital transformation shifted from a long-term goal to a critical survival condition, while a transformational strategy involving a full restructuring of economic workflows ensures the highest business activity recovery index [1].

Specific issues of the gas distribution sector under digital transformation are detailed by I. Andriichuk and S. Shkindyuk, who interpret digital transformations as the application of modern technologies to enhance efficiency across all stages of operations. The authors identify the transition from "reactive" to "predictive" maintenance as a priority direction for industry development. Simultaneously, the experience of implementing similar technologies in related sectors (for example, by the DTEK holding in the Kyiv and Odesa regions) demonstrates the possibility of multi-fold reductions in technological losses, making this case relevant for scaling to gas distribution networks.

**Highlighting previously unresolved parts of the overall problem.** Despite the rapid development of digital tools for infrastructure management, the economic logic of Digital Twin implementation in regional gas distribution systems remains insufficiently substantiated. Previous studies mostly describe general digitalization trends or crisis adaptation strategies, while the issue of translating predictive analytics into measurable reductions in production and technological gas losses is not fully resolved. In addition, the specific conditions of the Khmelnytskyi region, including tariff restrictions, military risks, network wear, and the need to prepare infrastructure for biomethane integration, require a separate strategic and economic assessment.

**Formation of the objectives of the article (task statement).** The aim of the research is to develop strategic frameworks for implementing Digital Twin technology into the operational

system of the Khmelnytskyi Branch of "Gazmerezhi" and to conduct a comprehensive economic evaluation of such modernization. The study justifies the enterprise's transition from a reactive to a predictive operational model, analyzes the impact of digitalization on the reduction of production and technological gas losses, and reveals the significance of smart technologies for ensuring the energy independence of the Khmelnytskyi region amidst military challenges.

**Summary of the main research material.**

An analysis of the enterprise's performance under current conditions reveals a significant correlation between operational indicators and external military or regulatory factors. The Khmelnytskyi Branch of "Gazmerezhi," as a critical infrastructure enterprise, ensures natural gas distribution through local networks, covering the Kamianets-Podilskyi, Khmelnytskyi, and Shepetivka districts [4]. The scale of the infrastructure managed by the national operator is substantial, comprising over 227,000 km of pipelines operating 24/7. However, the state of the networks in the Khmelnytskyi region is characterized by significant physical wear and an urgent need for the modernization of gas control equipment [2].

The financial performance of the sector remains constrained. Although JSC "Khmelnytskhaz" reported a profit of 988 thousand UAH for 2023, the majority of this result was derived from financial income rather than core operating activities (where core profit amounted to 819.2 thousand UAH), while other operational activities remained loss-making (-692.9 thousand UAH). Consumer debt and the mismatch between regulated tariffs and actual costs significantly limit investment capacity. According to monitoring data, the share of capital investment within the DSO (Distribution System

Operator) tariff structure remains negligible at 0.1–2.3%, whereas labor costs and gas for technological losses account for up to 76% and 29% of funds, respectively.

Such a situation makes strategic planning critically dependent on the identification of internal efficiency reserves. The core scientific idea of this study is that digitalization through Digital Twin implementation allows for a radical revision of the expenditure item for production and technological losses, transforming them from an "inevitable burden" into a controllable parameter. In the context of T. Obelets' concept, this signifies a transition from a "survival strategy" to a "transformational development strategy," where every hryvnia invested in IT infrastructure generates a multiplicative effect through energy resource conservation.

**Mathematical Modeling and Strategic Planning.** For the economic assessment of digital twin implementation, we apply a mathematical optimization method based on Mixed-Integer Linear Programming (MILP) [2]. This approach enables informed decision-making regarding the modernization of specific network segments in the Khmelnytskyi region, minimizing total expenditures over the project's life cycle.

The objective function of our model (*minZ*) is designed to minimize costs over the calculation period *T*, accounting for the discounting factor:

$$Z = \sum_{t=0}^T \frac{1}{(1+r)^t} [ \sum_{i \in L} (C_{i,t}^{inv} \cdot x_{i,t} + C_{i,t}^{maint} \cdot y_{i,t}) + C_{risk,t} + C_{loss,t} ] \rightarrow min$$

Where:

*r* – discount rate;

*C<sub>i,t</sub><sup>inv</sup>* – capital expenditures for asset modernization (telemetry sensors, gas control units);

*x<sub>i,t</sub>* – binary investment decision variable;

*y<sub>i,t</sub>* – variable reflecting the technical condition or operational state of the network element;

Table 1

**Key Performance Indicators of the Khmelnytskyi Branch of «Gazmerezhi»**

Key Performance Indicator	Value
Distribution tariff for households (including VAT)	1,848 UAH for 1 M <sup>3</sup>
Operator Status	Branch of LLC "Gas Distribution Networks of Ukraine"
Financial result	988 thousand UAH profit
Total DSO debt to the TSO (Transmission System Operator)	17.85 billion UAH (national level)
Investment share in the tariff	0.1 – 2.3%

Source: formed by the authors based on [2; 3]

$C_{i,t}^{maint}$  – operational costs, which, thanks to the Digital Twin, become a function of the actual equipment condition;

$C_{i,t}^{risk}$  – cost of risks;

$C_{i,t}^{loss}$  – cost of technological gas losses.

The proposed objective function reflects the logic of strategic investment planning under conditions of limited financial resources. Its use makes it possible to compare alternative modernization scenarios and determine which network segments should be upgraded first in order to achieve the maximum economic effect. The binary variable  $x_{i,t}$  allows the model to distinguish between assets that require immediate investment and those that may remain under routine maintenance during the current planning period. At the same time, the inclusion of risk-related costs and technological gas losses ensures that the model considers not only direct expenditures but also hidden losses caused by accidents, leakages, and inefficient balancing.

A key advantage of the model is that operating costs become a "dynamic adaptive value." Analyzing data from pressure sensors and flow meters allows the system to identify anomalies before an accident occurs, eliminating the "information lag."

**Digital Twin Technology: From a "Black Box" to a Transparent System.** The traditional gas distribution network of the

Khmelnyskyi region operates as a "black box": the operator sees the gas volumes at the system inlet and total consumption at the outlet but has very limited control over dynamic processes inside the pipelines in real time. This leads to high hidden losses and balancing inaccuracies. The implementation of a Digital Twin based on the ISO/IEC 30173 standard changes this paradigm, ensuring convergence between the physical and digital states of assets.

Within the Digital Twin structure for the Khmelnytskyi Branch of "Gazmerezhi," we identify the following components:

- **Real-time hydraulic model:** Based on SCADA data, gas flow is modeled, allowing the identification of zones with critically low pressure or the risk of condensate formation.

- **Smart metering modules:** The transfer of 40,000 smart modules to the national operator is the first step toward creating a Smart Gas Grid. These devices automatically record meter readings, eliminating the need for manual entry and the risk of inaccurate billing.

- **Predictive analytics:** Using Python scripts to process large datasets (Big Data) allows for predicting peak loads during the heating season and preemptively adjusting pressure regulator settings [2].

The data presented in Table 2 demonstrate that the transition from a reactive to a predictive management model significantly improves

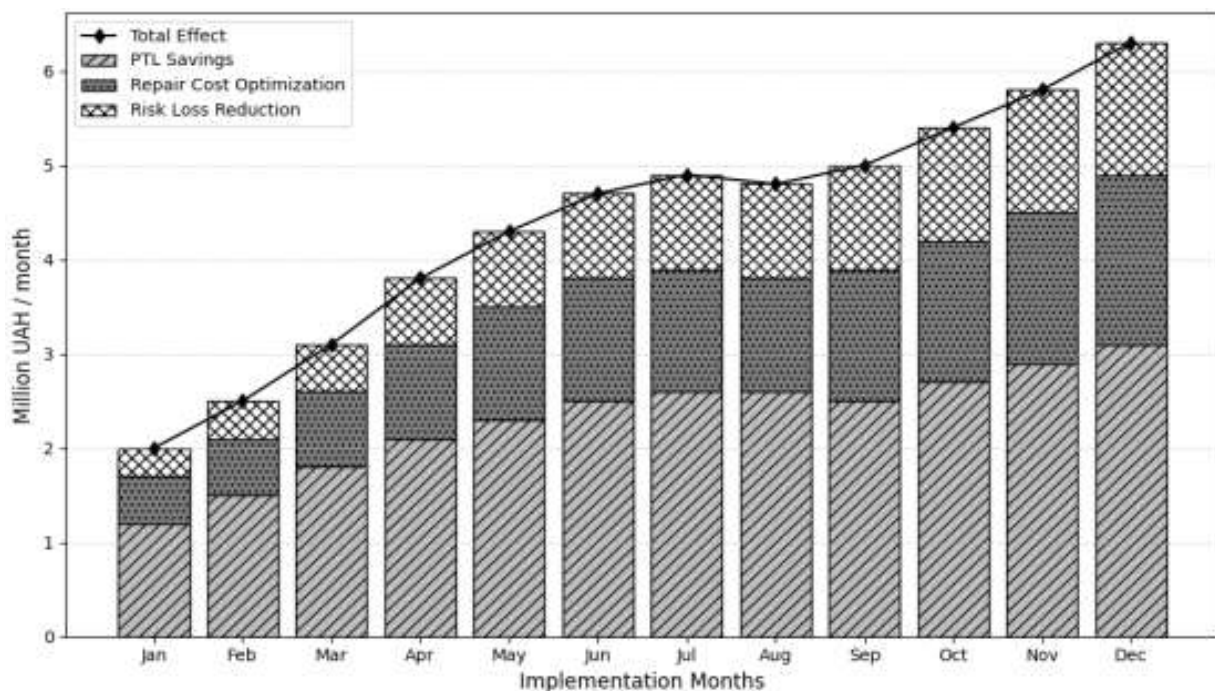


Figure 1. Structure of the projected economic effect from Digital Twin implementation

Source: formed by the authors

Table 2

**Comparative characteristics of reactive and predictive management models**

Management Model Characteristic	Reactive (Traditional)	Predictive (Digital Twin)	Effect
Production and technological losses (PTL)	~14%	~5%	2.8x reduction
Failure detection method	Consumer complaints	Automated anomaly detection	Downtime minimization
Failure prediction accuracy	<80%	>99%	Safety enhancement
Planning orientation	Historical data	Real-time data	Validity of decisions

Source: formed by the authors

the operational efficiency of gas distribution networks. In particular, the Digital Twin approach reduces production and technological losses, increases failure prediction accuracy, and strengthens the validity of strategic planning decisions.

Practical implementation of this strategy in the Khmelnytskyi region will not only stabilize the enterprise's finances but also prepare the infrastructure for decarbonization challenges. Specifically, a digital twin is a necessary condition for integrating biomethane plants, which are planned to be actively built in Ukraine by 2035. Since biomethane must be evenly distributed across the network, the system must monitor its quality and pressure at injection

nodes in real time, which is impossible without modern IT tools.

**Analysis of Military Risks and Environmental Aspects.** Military actions cause irreparable damage to the environment of the Khmelnytskyi region, indirectly affecting the operations of gas distribution enterprises. As of 2024, 33 events have been recorded in the Unified Register of Damages, with the total amount of damage exceeding 1.5 billion UAH. Land resources have been affected the most; damages from soil contamination and debris resulting from missile and bomb strikes are estimated at 1.426 billion UAH [7].

For the Khmelnytskyi Branch of "Gazmerezhi," these data serve as a signal to strengthen the

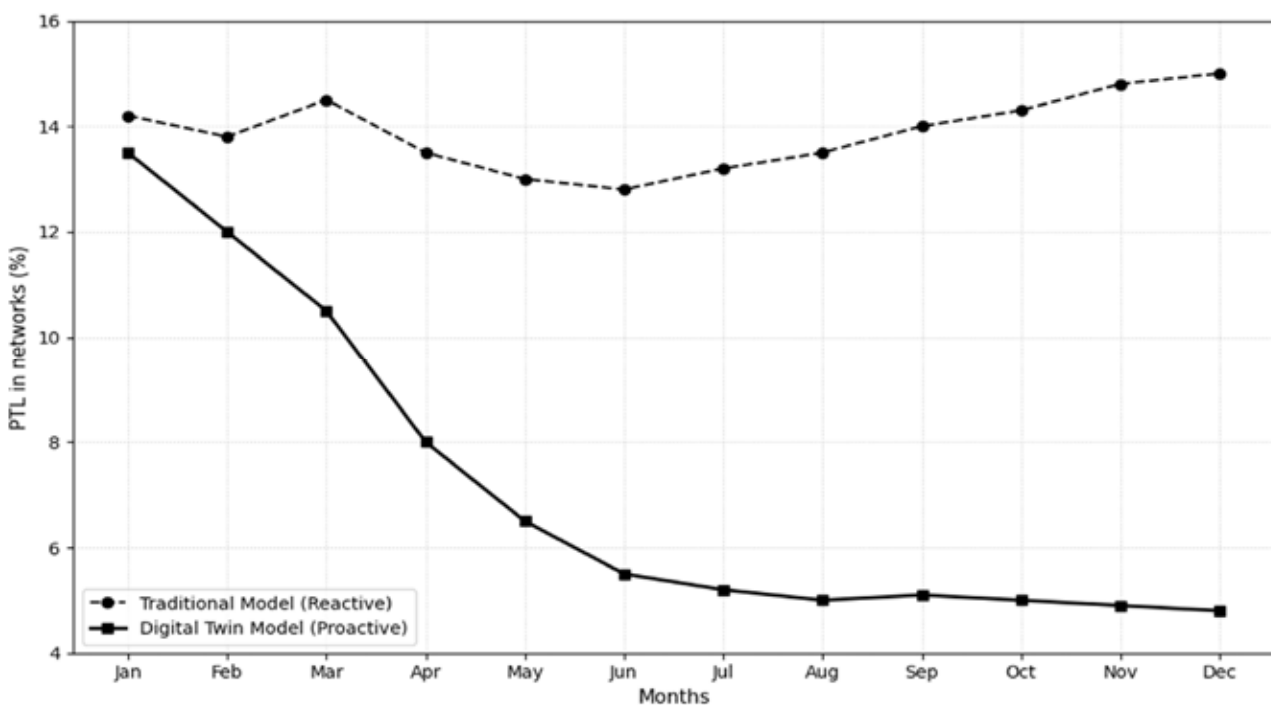


Figure 2. Forecast of production and technological gas loss reduction

Source: formed by the authors

monitoring of underground utilities. Missile strikes can cause micro-cracks in pipelines that do not lead to an immediate rupture but significantly increase hidden gas (methane) leaks, which intensifies the greenhouse effect and environmental risks. A Digital Twin allows for "stress testing" of the network after shelling by comparing reference hydraulic indicators with actual data, enabling the identification of damaged sections without large-scale excavation.

Table 3

**Environmental damage in the Khmelnytskyi region, million UAH**

Year	Environmental damage in the Khmelnytskyi region (million UAH)
2022	165,7
2023	1 070,8
2024	245,8
2025	741,2

Source: formed by the authors based on [7]

The increasing trend of damages (particularly the peak in 2023) supports T. Obelets' thesis that system resilience depends on its internal mobility and the ability for rapid reconfiguration. Operational planning must account not only for technical restoration but also for compliance with European environmental standards. This is crucial for attracting international funding based on the "Build Back Better" principle, where donors require transparent reporting on methane emission reductions and network energy efficiency.

**Strategic Prospects and Integration into the European Energy Space.** The future of the Khmelnytskyi Branch of "Gazmerezhi" is inextricably linked to synchronization with the European gas market and compliance with the REPowerEU plan requirements. The strategic development of networks envisages their gradual transformation into universal energy hubs capable of transporting not only natural gas but also biomethane and hydrogen.

To implement this scenario, business analysis and strategic planning must focus on the following priorities:

– **Decentralization and Biomethane:** Up to 40–80 individual biomethane production units with a capacity of 5–10 million m<sup>3</sup> per year

are expected to emerge across the country. As an agricultural region, Khmelnytskyi has high potential for creating biomethane clusters connected to the DSO networks.

– **Smart Metering Implementation:** Replacing conventional meters with smart-module-equipped devices will allow consumers to track their consumption via digital services, stimulating energy efficiency in accordance with Directive 2012/27/EU.

– **Cyber Resilience:** Creating a Pan-European Digital Twin requires Ukrainian operators to comply with EU cybersecurity protocols. This will ensure protection against hacker attacks on gas pressure control systems, which are elements of hybrid warfare.

The implementation of Digital Twin technology will allow the Khmelnytskyi Branch to become the "intellectual core" of the regional energy system. This will ensure not only technical reliability but also financial liquidity by separating actual technological losses from commercial (non-technical) losses (thefts), which is a prerequisite for stabilizing market settlements and exiting the debt crisis [6].

**Conclusions.** Based on the conducted research, it can be concluded that implementing Digital Twin technology in the operational system of the Khmelnytskyi Branch of "Gazmerezhi" is a strategically justified and economically efficient step. It enables the implementation of a transformational strategy for adapting critical infrastructure to the extreme conditions of martial law.

Business analysis and operational planning using the MILP mathematical model prove that digitalization ensures a reduction in production and technological gas losses from 14% to 5%. Given the current tariff moratorium, this serves as a key instrument for financial recovery. The use of smart modules and predictive analytics eliminates the "information lag," allowing the DSO to enhance the safety and reliability of gas supply.

Strategic planning for the Khmelnytskyi Branch should be based on Smart Gas Grid principles and readiness for the integration of renewable gases, particularly biomethane. This will not only strengthen the region's energy independence but also create a foundation for attracting international investment for reconstruction according to the highest EU technological standards.

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