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ANALYSIS OF KEY ENERGY CONSUMPTION MODELS IN THE CONTEXT OF MODERN UKRAINE

АНАЛІЗ ОСНОВНИХ МОДЕЛЕЙ ЕНЕРГОСПОЖИВАННЯ В КОНТЕКСТІ СУЧАСНОЇ УКРАЇНИ

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The article addresses the issue of modeling electricity consumption volumes. In the context of full-scale war in Ukraine, electricity has become one of the most significant consumption products in the country, constituting a substantial portion of the costs across nearly all sectors of the economy. As a result, forecasting, modeling, and constructing long-term estimates of electricity consumption dynamics have gained particular relevance for the country. This is a critical element in the plans for the balanced development and growth of national economic sectors in the post-war period. The energy situation presents new demands on the quality of mathematical forecasts, especially regarding integrated long-term predictions. Existing methods for long-term electricity consumption forecasting and the models developed based on them are often not used comprehensively enough, which frequently leads to significant errors in the forecasts. In the field of systems research, there have been significant changes in the understanding of the hierarchy of energy systems and approaches to forecasting. Mathematical models of energy systems have become an integral tool in the development of government forecasts and business plans for companies, and the requirements for these models have grown considerably. Forecasts and plans now need to be directly linked to the financial indicators of companies, which determine their ability to accumulate internal funds and attract external investments. This has greatly complicated the process of modeling the interrelationships between energy and the economy. This paper attempts to comprehensively assess the degree to which existing methods and models meet the new requirements and challenges in Ukraine, as well as to identify directions for their improvement. The primary goal is to develop approaches that will effectively address key issues related to the study and consideration of the interconnections between energy and the economy. Particular attention is given to the issues arising in long-term forecasting and the formation of state energy policy, which requires modernization of the analytical and modeling tools currently in use.

Keywords: forecasting, electricity market, mathematical models, econometric models.

В умовах повномасштабної війни в Україні електроенергія стала одним із найважливіших ресурсів, який відіграє ключову роль у функціонуванні національної економіки. Споживання електроенергії значно зросло, що зумовлено як військовими діями, так і необхідністю підтримки критичної інфраструктури, промислових підприємств та житлового сектора. Енергетична безпека та стабільність енергопостачання набули стратегічного значення, що робить питання прогнозування та моделювання споживання електроенергії особливо актуальними. Визначення та аналіз довгострокових трендів та закономірностей у динаміці енергоспоживання є важливим інструментом для розробки державної політики, оптимізації енергетичного балансу та забезпечення стійкого розвитку економіки після завершення війни. Однак сучасні методи прогнозування часто виявляються недостатньо точними через складну й нестабільну економічну ситуацію. Багато існуючих моделей орієнтовані на стабільні умови функціонування енергосистеми й не враховують специфічні виклики, спричинені війною, включно з руйнуванням інфраструктури, нестабільністю ринків, коливаннями у фінансуванні та змінами в структурі споживання. Сучасні підходи до прогнозування електроспоживання потребують удосконалення, оскільки класичні економетричні моделі та статистичні методи не враховують комплексного впливу со-

ціально-економічних, геополітичних та екологічних факторів. Крім того, важливим завданням стає інтеграція прогнозів із фінансовими показниками, що впливають на інвестиційну привабливість енергетичних проєктів. У зв’язку з цим необхідне використання новітніх підходів, зокрема методів машинного навчання, багатофакторного аналізу та сценарного моделювання. У цій статті проведено аналіз основних підходів до прогнозування споживання електроенергії в умовах нестабільності та визначено основні проблеми, з якими стикаються аналітики та дослідники. Обґрунтовано необхідність інтегрованого підходу до прогнозування, що враховує макроекономічні, технологічні та соціальні аспекти. Визначено ключові напрями модернізації методологічного інструментарію для забезпечення більш точної та ефективної оцінки майбутніх потреб енергосистеми України. Отримані результати мають значення як для наукової спільноти, так і для урядових структур, енергетичних компаній та міжнародних партнерів, які беруть участь у відновленні енергетичної інфраструктури України. Розроблені рекомендації можуть бути використані для формування політики в галузі енергетики, спрямованої на створення стійкої та ефективної моделі управління енергоспоживанням у післявоєнний період.

Ключові слова: прогнозування, електричний ринок, математичні моделі, економетричні моделі.

Problem statement. In the current conditions, Ukraine's energy sector faces a complex set of important and serious challenges caused by full-scale war. The destruction of infrastructure, instability in energy supply, and reduced availability of resources create unprecedented challenges for the country's energy system. One of the key aspects of effective energy resource management is the improvement of models and forecasting of electricity consumption. In these conditions, mathematical and econometric models serve as crucial tools for analyzing the current situation and formulating strategic decisions. A special role is played by the adaptation of models to the new conditions of uncertainty and risk associated with full-scale military operations. The use of such models allows for taking into account not only economic and technological factors but also the influence of socio-political instability.

The development of reliable forecasting tools for electricity consumption helps in forming a sustainable energy policy. This is crucial not only for maintaining the current operation of the energy system but also for planning its recovery in the future. Researching existing approaches and creating new models is a necessary step toward ensuring Ukraine's energy security. Therefore, there is an urgent need for a deep analysis and the development of strategies to address these issues and improve the country’s energy infrastructure.

Analysis of resent achivement and publications. Theoretical aspects of modeling in the energy sector have been the focus of attention of both Ukrainian and international researchers. The problem of electricity consumption forecasting lies in the necessity of considering a wide range of factors that influence changes in energy consumption. To date, a significant number of studies have been conducted in this field, leading to the development of various forecasting models. However, despite the progress made, work on improving these models continues, with a focus on minimizing forecasting errors and increasing their accuracy. As a result, multi-criteria models have emerged, taking into account an increasing number of factors.

The issue of electricity consumption forecasting using so-called grey models has been discussed by the author in [1]. In [2], the authors used the classical autoregressive model SARIMA for their forecasts, which allowed them to determine seasonal fluctuations in electricity consumption in Assam, India, from April 2013 to February 2023. The results of the modeling showed that "by applying the Augmented Dickey Fuller test, it is observed that the data series becomes stationary at first order difference, and the result of the Canova Hansen test reveals that no seasonal differencing is required for our considering time period." In [3], the authors applied Machine Learning models with Metaheuristic Optimization to forecast electricity consumption in educational institutions and noted that this model requires further refinement.

In [4], it is stated that “forecasting of electricity consumption is, in particular, useful for minimizing problems of overproduction and oversupply of electricity,” and forecasting models based on artificial intelligence methods are analyzed. Machine learning-based models have also been used by the authors in [5]. In [6], the authors explored forecasting methods for the electricity load of industrial facilities and developed a generalized model for adaptive energy consumption forecasting. According to the authors, adaptive models, particularly the exponential smoothing method, are the most feasible due to their accuracy and simplicity.

This body of research highlights the continued evolution of forecasting models in the energy sector, with an increasing focus on improving accuracy and adapting to new technological and methodological challenges.

Formulating the goals and objectives of the article. For a long time, research on the interconnections between energy development and the economy focused primarily on meeting the needs of short- and medium-term forecasting of electricity and fuel demand. The emphasis was placed on constructing simple econometric models that linked energy consumption dynamics to macroeconomic indicators. However, the reverse effects of factors such as production structure and energy resource costs on economic indicators – and, through them, on energy consumption – were largely overlooked.

As energy challenges become increasingly complex, it is evident that analyzing energy and economic models in isolation provides incomplete and sometimes incorrect assessments of their interrelations. Therefore, evaluating existing models and identifying their strengths and weaknesses is a critical and relevant issue, particularly in the context of present-day Ukraine.

Main content of the study. The energy sector of Ukraine's economy plays a crucial role in ensuring the functioning of all economic spheres, particularly during wartime, and significantly impacts the country's economic and social indicators. Ukraine's natural fuel and energy resources, along with the professional and scientific-technical potential of its energy sector, constitute a vital strategic asset.

As mentioned by the authors [6] modern economic consumption models emphasizing energy efficiency, renewable energy sources, and reduced reliance on fossil fuels are becoming essential tools for adapting Ukraine's economy to wartime challenges. Implementing such models enables the optimization of limited energy resources while accelerating the transition to a sustainable economy – a critical goal for a country striving to maintain energy independence and rebuild infrastructure. Rational utilization of energy potential and the adoption of innovative approaches to energy consumption lay the groundwork for economic strengthening, improved living standards, and long-term sustainable development, even under challenging wartime conditions.

Over the past decade, Ukraine has managed to preserve key elements of energy independence, ensuring the country's electricity needs are met. The downward trends in the energy sector were reversed, paving the way for gradual recovery and increased electricity production. The production structures within the sector adapted to market conditions, bolstering resilience and preparing for emerging challenges. The energy market has undergone significant structural transformations, including reforms in the electricity sector and housing and utilities sector, as well as partial privatization and liberalization. In the pre-war period, essential regulatory frameworks for economic relations in the energy sector were established, and taxation and pricing mechanisms were optimized. However, the war has introduced substantial challenges, requiring the sector to address new priorities: restoring damaged infrastructure, ensuring stable energy supplies to the population and strategic facilities, and accelerating the shift to decentralization and renewable energy sources to strengthen energy security and independence.

The reliability of energy consumption forecasts in Ukraine directly depends on the use of modern methodologies and modeling techniques. Currently, numerous approaches to electricity consumption forecasting exist, with approximately 15–20 primary methods actively employed in practice.

Different approaches are used for short- and long-term forecasting, tailored to specific tasks and objectives. Short-term forecasts focus on operational energy system management and consumption balancing, while long-term forecasts serve as the foundation for strategic planning and the development of national energy policy.

Based on the analysis of sources [1–3], it can be concluded, that there are numerous methods for modeling energy consumption, with the most common being statistical, econometric, optimization, and hybrid models. In recent years, machine learning and artificial intelligence methods have gained particular popularity, as they allow for the consideration of complex nonlinear dependencies and adaptation to changing energy consumption conditions.

Effective utilization of these methods requires access to specialized databases containing historical and current energy consumption indicators, as well as consideration of Ukraine's unique conditions, including the war's consequences, changes in economic structure, and the need for energy infrastructure restoration. Ukraine actively employs both classical and innovative methods, adapting them to current challenges. Hybrid models – combining statistical, artificial intelligence, and scenario-based approaches – are particularly promising.

Table 1

Trends in Modeling and Research on the Interconnections Between Energy and the Economy in the Ukrainian Context

Trend	Description	Relevance for Ukraine (Considering the War)	Required Actions and Measures
Assessment of the Dependency of Fuel and Energy Needs on Their Prices	Focus on the impact of price changes on demand and energy resource needs.	Sharp fluctuations in energy prices caused by military actions, sanctions, and infrastructure destruction.	It is necessary to develop pricing models that account for volatility and incorporate scenario analysis for economic recovery.
Expanding the Range of External Connections in the Energy Sector	Analysis of intersectoral linkages and the impact of energy strategies on national and regional economies.	The restoration of industry and regional infrastructure requires the integration of energy into economic recovery strategies.	The development of new regional energy supply strategies considering dependency on external sources.
Synthesis of Economic and Energy Models	The use of integrated models to account for the interdependence of macroeconomic and energy processes.	Military actions necessitate coordination between economic and energy strategies, especially under limited resource conditions.	Integration of economic-energy models to forecast the impact of recovery measures on the economy.
Development of Model-Computer Complexes	The development of advanced computer systems for modeling development strategies and energy management.	Adapting existing systems to the conditions of recovery and reconstruction of infrastructure during wartime is required.	Engaging international assistance to implement modern computer systems and forecasting methods.

Source: compiled by the author

Table 2

Features of Energy Resource Market Modeling in Ukraine

Advantages	Limitations
Forecasting and Planning: Models enable the prediction of energy production, consumption, and imports based on various development scenarios. This is crucial for planning and decision-making in energy policy.	**Data Insufficiency:** Ukraine may face limitations in accessing complete and up-to-date data on the energy sector, which complicates the development of accurate models.
Resource Optimization: Optimization models help identify the optimal allocation of resources, including fuel and infrastructure, to maximize energy production and minimize costs.	**Modeling Complexity:** Energy sector models can be highly complex and require significant computational resources and expertise for their development and implementation.
Strategy and Scenario Analysis: Models assist in developing various strategies and scenarios for energy sector development and analyzing their potential outcomes.	**Forecast Uncertainty:** Forecasts and modeling outcomes are always associated with a certain degree of uncertainty, particularly in the context of risks and fluctuations in global markets.
Risk and Variation Assessment: Models enable the analysis of various risks and variations associated with the energy sector, aiding in the development of risk mitigation strategies and informed decision-making.	**Governance and Policy Issues:** Even when a model provides optimal solutions, their implementation may depend on political and economic factors, which can be difficult to predict. **Economic Constraints:** Developing and using complex models can be a costly process, requiring investments in computational infrastructure and expert support.

Source: compiled by the author

This study examines the features and key trends in modeling and analyzing the interconnections between the energy sector and the economy, considering the realities of Ukraine.

Ukraine is currently facing unprecedented challenges in the energy sector, including the destruction of infrastructure, shortages of energy resources, and rising import costs. Under these conditions, the use of comprehensive models has become critically important for developing effective strategies. Below are key aspects requiring particular attention.

The ongoing military conflict has deepened the energy sector's dependence on fluctuations in fuel prices and imported goods. In this context, analyzing price dependencies has taken on strategic importance. Models that assess the impact of resource costs on consumption, investment, and foreign trade can aid in crafting short- and medium-term plans to minimize risks to the economy and social welfare.

The recovery of industrial capacity and export potential demands stronger integration with international partners, particularly the European Union. Energy models that analyze interactions with external markets, especially in the context of electricity exports, will enable more efficient resource use and strengthen Ukraine's position within the European energy system. Below is an analysis of the main advantages and disadvantages of their application in the context of Ukraine's current situation.

Table 3

Key Models and Their Characteristics

Model	Description	Formula	Application	Advantages	Disadvantages
1	2	3	4	5	6
Base Consumption Model	A static model to calculate energy consumption based on known power.	$E = P \times t$ *E – Total electricity consumption (kWh)* *P* – power of the consumer (kW) *t* – operating time (hours)	Used to estimate energy consumption in stable or well-known consumer conditions.	Simplicity of calculation for stable conditions. Forecasting consumption under stable circumstances.	Does not account for changes in consumption in wartime and under conditions of destruction. Limited applicability in extreme situations (e.g., infrastructure destruction)
Load Model (Dynamic)	Estimates energy consumption considering changes over time (daily, weekly).	$E(T) = \sum_{i=1}^{n} P_i(t)$ *E(t)* – energy consumption at time ttt $P_i(t)$ – power consumed per hour *t* – operating time (hours)	Applied for analyzing energy consumption throughout the day, month, or year, considering peaks and lows.	Dynamic forecasting based on historical data. Suitable for long-term planning	Requires high-quality historical data. Errors in conditions of war and extreme changes
Supply and Demand Model	Estimates the interaction between supply and demand based on various factors.	$S = f(E, P, T)$ *S* – electricity demand *E* – level of economic activity *P* – electricity prices *T* – weather conditions (temperature, seasonality)	Used to analyze how external factors (e.g., war or economic situation) affect energy demand.	Assessment of network resilience following damage and attacks. Assists in the prioritized restoration of infrastructure	Limited applicability in the context of large-scale destruction. Restoration forecasting may be inaccurate in wartime conditions

(End of Table 3)

1	2	3	4	5	6
Consumption Forecasting Model	Forecasts consumption based on historical data and factors.	$E_t = \alpha + \beta_1 T_t + \beta_2 H_t + \varepsilon_t$ E_t – electricity consumption at time t T_t – temperature at time t H_t – consumption history based on historical data α, β_1, β_2 – Model parameters ε_t – random error	Used for dynamic forecasting of energy consumption, considering seasonal fluctuations and other factors.	Can provide valuable insights into energy demand trends and help optimize energy distribution in stable conditions. It supports long-term planning by utilizing historical data to predict consumption patterns.	The model has limited applicability in extreme situations, such as during large-scale destruction or war. It may be inaccurate in forecasting energy consumption during wartime due to sudden changes in demand and disruptions in infrastructure.
Grid Resilience Model	Estimates grid resilience after damages and attacks.	$U = \frac{S_{total}}{S_{damaged}}$ U – system stability coefficient S_{total} – total available energy (before damage) $S_{damaged}$ – damaged energy volume (after destruction)	Applied to assess energy restoration and the impact of damages on the system.	Helps assess the stability of the energy network after damage or attacks, aiding in the identification of vulnerabilities. It supports the prioritization of infrastructure restoration, ensuring the most critical systems are restored first in the event of disruptions.	Its applicability is limited in the context of large-scale destruction, and it may provide inaccurate restoration forecasts under wartime conditions due to unpredictable changes and widespread damage.
Energy Efficiency Model	Assesses energy efficiency.	$\mu = \frac{E_{output}}{E_{input}}$ $\propto$– energy efficiency E_{output} – useful electricity consumption E_{input} – total energy consumption	Used to assess energy efficiency in various sectors, such as industry or household.	Can help optimize energy usage and reduce waste, leading to cost savings and improved sustainability. It provides valuable insights for long-term energy management and can contribute to better energy planning in stable conditions.	The model's applicability may be limited in situations with large-scale disruptions or extreme conditions, such as wartime, where energy consumption patterns may change unpredictably. Its predictions could also be less accurate in the face of significant infrastructure damage or instability.

Source: compiled by the author

A comprehensive approach that integrates economic and energy models is becoming increasingly relevant. Such a synthesis enables the evaluation of the impact of energy initiatives, including the restoration of networks and the transition to renewable energy sources, on key macroeconomic indicators such as employment, gross domestic product (GDP), and investment inflows.

To manage the energy sector amidst damaged infrastructure and high uncertainty, Ukraine can adopt advanced digital solutions. The application of artificial intelligence (AI) and machine learning (ML) methods will support the optimization of energy supply and the forecasting of demand. These systems must be tailored to operate under volatile conditions and resource constraints, ensuring resilience and adaptability.

Given the above, we will analyze the main electricity consumption models in the context of the full-scale war in Ukraine, considering stochastic factors and potential scenarios. This analysis aims to provide actionable insights for energy management and policy-making during periods of crisis and recovery.

Conclusions from this study and future perspectives in this direction. Flexibility in planning will allow for more effective responses to unpredictable challenges, including external threats, and enable the adaptation of strategies in line with changing conditions. The integration of artificial intelligence and big data technologies into the energy sector can significantly enhance forecasting accuracy and energy consumption management. These technologies will also help strengthen the resilience of the energy system, reduce losses, and optimize resource distribution.

A key element of the sustainable development of the energy system is the upskilling of professionals in the field of energy system modeling and analysis. Expanding educational programs, specialized courses, and international internships will help prepare personnel to implement innovative solutions and effectively manage the energy sector. This will create a foundation for modernizing the energy system, increasing its resilience, and integrating it into the global energy space. Thus, Ukraine should actively seek international support to integrate into European energy models, which will allow the use of advanced experience and modeling tools to improve the resilience of the national energy system. Such cooperation will contribute to better management of energy processes and ensure access to modern technologies and investments. The development of economic and energy sector recovery scenarios should take into account both optimistic and pessimistic forecasts.

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