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ASSESSING THE TECHNICAL AND ECONOMIC PERFORMANCE OF THE INTEGRATED POWER SYSTEM OF UKRAINE UNDER HIGH PENETRATION OF WIND AND SOLAR GENERATION

Abstract. *This paper presents a comprehensive assessment of the technical and economic performance of the Integrated Power System (IPS) of Ukraine under conditions of high penetration of wind and solar power generation. The relevance of the study is driven by the rapid expansion of renewable energy sources (RES), which introduces increased generation variability, amplifies power imbalances, and complicates real-time system operation and control. The study analyzes the current state of the Ukrainian power system, including structural changes in generation and consumption under wartime conditions and the associated reduction in available capacity. Particular attention is given to daily and seasonal load variability, the stochastic nature of wind and solar generation, and the limited operational flexibility of conventional generation assets. A quantitative assessment is conducted using an optimization framework based on an economic–technological forecasting methodology for determining optimal system development and operation parameters. The model explicitly incorporates battery energy storage systems (BESS), pumped storage power plants (PSPP), constraints on renewable generation curtailment, and balancing market mechanisms. Scenario-based simulations up to 2030, assuming an increase in the RES share to 45–50%, indicate that power imbalances may rise to 600–900 MW, while reserve requirements could reach 6–7 GW. The results demonstrate that the deployment of BESS with a capacity of 1.5–2 GW can reduce imbalances by 30–40%, significantly decrease RES curtailment, and yield annual savings of €80–120 million in balancing costs. The proposed approach enables a more robust evaluation of power system performance under high RES penetration and provides a methodological basis for enhancing system flexibility, reliability, and economic efficiency. The findings can support strategic decision-making regarding the modernization and sustainable development of the IPS of Ukraine.*

Keywords: renewable energy sources, Integrated Power Systems, grid stability and control, power regulators, mathematical models.

1. Introduction

The integration of large volumes of wind and solar power plants into integrated energy systems leads to significant changes in their operational and technical and economic characteristics [1–3]. The main tasks, due to their critical relevance, are the assessment of power balances, determining the need for shunting capacities and energy storage, as well as the economic effect of renewable energy integration [4–14]. In particular, much attention is paid to the development of Mathematical Models and Programming Tools for Optimizing the Composition and Operating Modes of Energy Systems Under Rapid Growth of Renewable Energy Capacities

[4–7]. Much attention is paid to optimization methodologies and models to determine the required stability and sufficient capacity in integrated energy systems based on projected electricity production volumes. [8–14]. The assessment of the effectiveness of the existing and future operational and technical and economic characteristics of the IPS with a significant share of wind farms and solar power plants in its structure is based on a comprehensive analysis of the operating modes of the power system, reliability indicators, economic feasibility and the level of integration of renewable energy sources. The main purpose of such an assessment is to determine the limits of the power system's ability to ensure reliable, cost-effective and balanced operation in the event of an increase in the share of unstable generation. In the process of assessing the existing characteristics, the actual modes of operation of the integrated energy system are analyzed, in particular, the balance of active capacity, the level of permissible maneuverability of generating capacities, the magnitude of energy system imbalances, restrictions on the permissible volumes of generation of renewable energy sources and the costs of their settlement. Considerable attention is paid to the impact of large volumes of wind and solar generation on the permissible limits at which the necessary frequency and power regulation is provided, as well as on the stability of the integrated power system under various load conditions. In order to adequately assess the prospective characteristics, possible scenarios for the development of the power system are modeled, taking into account the growth of the installed capacity of wind farms and solar power plants, the development of energy storage systems, the modernization of maneuverable generating capacities and the introduction of modern forecasting systems for the generation of renewable energy sources. As part of this analysis, options are considered for optimizing the generation structure, increasing the flexibility of the power system and reducing the cost of balancing it.

Technical and economic efficiency is determined on the basis of integral indicators, including the cost of electricity production, the cost of managing imbalances, investments in the development of grid infrastructure and energy storage systems, as well as the economic effect of reducing greenhouse gas emissions and improving energy security. A comparison of existing and future modes of operation makes it possible to determine the optimal directions for the development of the power system and to formulate recommendations for improving the efficiency of integrating large volumes of renewable generation. The results of the assessment can be used to substantiate strategic decisions on the development of the power system, increase its flexibility and ensure stable operation with a further increase in the share of wind and solar power plants in the generation structure.

Thus, the scientific novelty of the study can be summarized as follows:

– the development of an economic–technological forecasting method adapted to the conditions of the Unified Power System (UPS) of Ukraine during the wartime and post-war periods;
– the integration of scenarios into the model that account for battery energy storage systems (BESS) and pumped storage power plants (PSPP), including a quantitative assessment of their impact on power imbalances and balancing costs;
– the development of an updated set of scenarios up to 2030, taking into account current generation constraints and the structure of electricity consumption;
– the derivation of refined technical and economic estimates (power imbalances, reserve requirements, and economic effects) based on modeling over a 8760-hour time horizon.

2. Initial conditions and generation structure

To assess the efficiency of the regime and technical and economic characteristics of the power system, the existing and future generation structures of the IPS of Ukraine are considered, taking into account a significant share of wind (WPP) and solar (SPP) power plants.

2.1. State of Ukraine's energy system as of February 24, 2022 [15]

The IPS of Ukraine before the full-scale invasion on February 24, 2022 looked like this.
The hourly weighted average electricity consumption was 17.67 GWh, the annual total consumption was 154,830 GWh.

The structure of energy resource use was as follows:

− nuclear energy – 22.6 %,

- natural gas – 23.9 %,
- petroleum products – 10.7 %,
- hydropower – 11.4 %,
- renewable energy sources – 5.9 %.

The distribution of the electricity supply structure was as follows:

- nuclear power plants – 56.1 %,
- thermal power plants (CHP and TPP) – 29.3 %,
- hydroelectric power plants and pumped-storage power plants – 8.7 %,
- renewable energy sources – 5.9 %.

The distribution of the total installed capacity of electricity generation in Ukraine amounted to 55,579.2 MW, including:

- NPP — 13,880 MW (15 power units),
- TPP and CHP — 30,545 MW (112 power units),
- HPP and PSP — 6,646.7 MW (14 hydroelectric facilities),
- RES — 4,507.5 MW (by output).

The maximum power of renewable energy generated reached 17 % of the total power load schedule during daytime in 2021. [16–20].

2.2. State of Ukraine's energy system in 2025 [15]

Total installed capacity has been reduced by almost half – minus 42.1% from pre-war levels. Currently, IPS of Ukraine have 23,379.6 MW in operation:

- nuclear generation – 7,880 MW (15 power units),
- thermal generation (thermal power plants and combined heat and power plants) – 7,960 MW (30 power units),
- hydroelectric power plants and pumped storage – 4,476.7 MW (11 hydropower plants),
- renewable energy sources – 3,063.3 MW.

The consumption structure has changed very significantly:

- the hourly average consumption has more than halved – from 17.67 to 8.47 GWh;
- annual consumption has fallen from over 154 thousand to 74,897 GWh;
- the deficit during peak hours remains stable – about 2.7 GWh.

2.3. PowerSystem Performance [16, 17]

Daily Load Range:

- Minimum Nighttime Load: 10–11 GW
- Daily Maximum: 17–19 GW
- Daily Variability: 1.6–1.8

Daily load schedules:

- night load: ≈10–12 GW
- evening maximum: ≈16–19 GW (winter)
- typical peaks: 18:00–22:00

Actual consumption peaks 2025–2026 [18, 19]:

- winter peaks 17–18+ GW
- constraints due to generation deficit
- dependence on imports during peak hours

Available nuclear power capacity [20, 21]:

- 9 power units in operation
- total capacity ≈7.6–7.8 GW
- ZNPP (6 GW) not included

According to the transmission system operator's operational data, the minimum nighttime load in the Ukrainian IPS is approximately 10-11 GW, while the evening peak reaches 17–19 GW during the winter. The baseload is provided by nuclear generation with a capacity of approximately 7.6–7.8 GW. The maximum-to-minimum load ratio is 1.6–1.8, indicating significant daily unevenness in the electricity consumption schedule and the need for switching capacity, the speed of which is, respectively: for thermal power plants 2–4 %/min, for hydroelectric power plants 10–20 %/min, for nuclear power plants 1–3 %/min. Total maneuvering reserve 3–4 GW. At the same time, the amplitude of fluctuations in wind power plant generation is 40–60 % in 3–6 hours and solar power plant generation is up to 80–90 % in 1-2 hours with a maximum rate of change of renewable energy generation of 1.5–2.5 GW/h.

2.4. Power system balancing indicators [22, 23]

Generation imbalances: average imbalance 250–400 MW, peak imbalance 900–1200 MW, nbalance rate 4–6 %. The main sources of imbalance are errors in wind/solar power generation forecasts, rapid changes in weather conditions, and the limited flexibility of thermal generation.

2.5. Curtailment of renewable energy generation

With high generation from solar and wind power plants and low load, generation restrictions arise with the following parameters: annual restriction volume of 2–5 %, peak periods in spring and autumn, restriction capacity of 500–800 MW.

2.6. Economic characteristics [24–26]

Cost of electricity:

Generation type LCOE, $/MWh

- Nuclear power plants 40–90 (depends on CAPEX and country)
- Thermal power plants 70–120
- Solar power plants 35–45
- Wind power plants 30–50
- Hydropower plants 25–40

Balancing Cost [27–32]:

Imbalance cost:

As the share of renewable energy sources grows, the role of the balancing market increases. The cost of imbalances in European power systems is approximately €10–20/MWh, and total balancing costs can reach 4–6 % of the electricity market value. Annual balancing costs for systems of the Ukrainian scale: ≈€150–300 million, balancing share ≈4–6 % of the electricity market value (typical for systems with a high share of renewable energy).

3. Prospective development scenarios up to 2030

In the works [7, 33] a method of economic and technological forecasting of the parameters of optimal functioning and development of the energy system is proposed, due to the use of a modified integral criterion of the quality of the functional of economic and technological impact. It makes it possible to take into account the indicators of the development of the national economy and production in the form of quasi-dynamic functions with discrete stochastic variables, which is important for assessing the ability of the energy system to provide volumes and modes of energy and power consumption. Also, a mathematical model of the diffusion of new technologies in the energy sector is proposed, which is a generalization of the model of the mixed influence of the diffusion of new technologies by Frank Bass [34], which includes the functional of economic and technological impact. The model allows us to take into account the stochasticity of economic and technological parameters of the development of the national economy when forecasting the development of the structure of the integrated energy system in the context of rapid growth of renewable energy capacities. The proposed [7, 33] use of a set of regression models in the form of generalized logistic curves makes it possible to improve the efficiency of forecasting, taking into account that the values of the modeling parameters obtained using the method of least squares do not contradict the experimental data. On the basis of the above, a model of long-term technological renewal of the structure of the unified energy system has been developed, which allows to assess the potential for improving the components of the power system (Table 1).

The proposed method of economic and technological forecasting of the parameters of optimal functioning and development of energy systems and the economic and mathematical model of long-term technological renewal of the structure of the unified energy system, are implemented in the problem-oriented software and information complex SOPS [35], which contains software modules of models for optimizing the modes of operation of energy systems.

Table 1. Known and new/improved models

KNOWN MODELS		NEW AND IMPROVED MODELS
The Fundamental Model of Innovation Diffusion		Method of Economic-Technological Forecasting for Optimal Operation and Development Parameters of the Energy System
		Dynamic Models of Cyclical Development of Generation Systems
		Long-term Technological Renewal Model of Consumption Structure and Generating Capacity of Ukraine's Integrated Power Systems

The use of a modified model of mixed impact made it possible to calculate scenarios for the development of economic and technological coefficients (Fig. 1), which are components of the functionality of economic and technological influence, which is included in the new method of economic and technological forecasting of the parameters of optimal functioning and development of the energy system and a new generalized model of energy technology development in the form of a sum of several logistic curves (1):

$$P^k(\tau+1)=P^k(\tau)+K_m\sum_{j=1}^{J}F(k,\tau)\left\{p_j+\frac{q_j}{P^{\Sigma k}{}_j(\tau)}P^k{}_j(\tau)\right\}\left(P^{\Sigma k}{}_j(\tau)-P^k{}_j(\tau)\right), \qquad (1)$$

where: K_m – scaling factor; $F(k,\tau)=F\left[PPF(\tau),ET(k,\tau),FCF(k,\tau),EGR(\tau)\right]$ – functional of economic and technological impact, in which (Fig. 1): $PPF(\tau)$ is the regional purchasing power parity, $ET(k,\tau)$ is the efficiency of technology, $FCF(k,\tau)$ is the final cost coefficient, $EGR(\tau)$ is the economic growth rate.

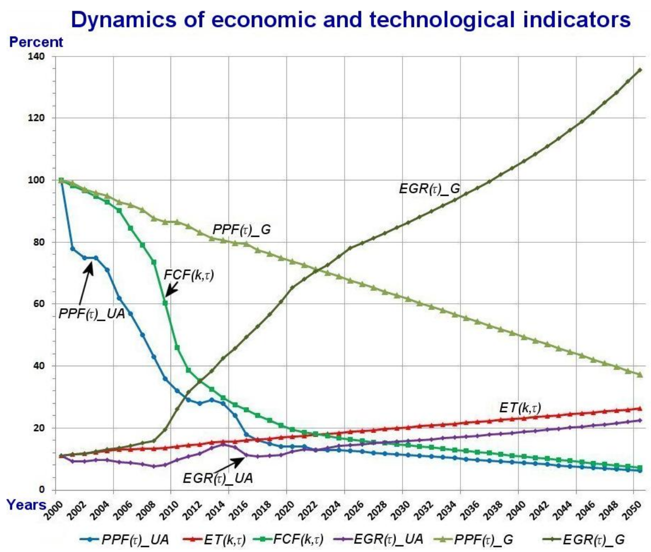

Fig. 1. Dynamics of economic and technological indicators of economic and production development for Ukraine (UA) and Germany (G)

The generalized model in the form of the sum of several logistic curves is an integral part of the model of long-term technological renewal of the structure of consumption and generating capacity of the IPS of Ukraine. According to the method of economic and technological forecasting of the parameters of optimal functioning and development of the energy system, the forecast is calculated in three stages.

At the first stage, using a generalized logistics model (1), the forecast of consumption volumes of the IPS of Ukraine until 2030 was calculated.

At the second stage, using the formulas of net benefit $NB_k = K_m(LACE_k - LCOE_k)$ and minimization of the total cost of generation $C^{\Sigma}_{S\tau} = \sum_{k=1}^{K} NB_k \cdot E^k_{S\tau} \to \min$, the ratio of capacities and volumes of generation technologies was calculated.

At the third stage, the task of minimizing the total mismatch between generation and consumption volumes (2) was solved and scenarios for the development of the IPS of Ukraine until 2030 were obtained.

$$\mu^{\Sigma} = \sum_{\tau=1}^{\mathrm{T}} \left(E^{\Sigma}_{S\tau} - E^{\Sigma}_{C\tau} \right) \ \forall \ \ u(\tau,k), \xi(\tau,k)) \to min, \tag{2}$$

4. Calculation results

Forecast of installed capacity (GW): WPP 7–8, SPP 10–12, BESS 1.5–2, PSPP 2.2. Total RES capacity 18–20. Share of RES in generation: 40–50 %.

Expected parameters

Indicator	Current status	2030
Share of RES	28 %	45–50 %
Imbalances	400 MW	600–900 MW
Curtailment	3 %	8–12 %
Necessary reserve	3 GW	6–7 GW

Efficiency of storage systems (BESS).
Installing 2 GW of storage allows: reducing imbalances by 30–40 %, reducing curtailment to 50 %, and achieving balancing savings of €80–120 million/year.

Economic effect of RES integration: reduce fuel imports by €1.2–1.6 billion/year, reduce CO_2 emissions by 15–20 million tons/year, and increase energy security by 20–25 %.

The use of the model on the horizon of 8760 hours allowed:

- Estimate annual peak and minimum imbalances;
- to determine the volume of renewable energy curtailment;
- Evaluate the use of BESS in charge/discharge modes
- to calculate the integral economic efficiency.

4.1. Example results (current scenario)

Indicator	Value	Notes
Average imbalance	320 MW	±5 %
Maximum imbalance	1.2 GW	occurs during peak RES generation
RES limitations	3 % of annual production	spring-autumn peaks
BESS usage	1.5 GW	SOC from 20 % to 100 %

4.2. Perspective scenario 2030

Indicator	Value
Share of RES	45-50 %
Need for maneuvering reserve	6–7 GW
Annual curtailment	8-12 %
Use of BESS	2 GW

4.3. Economic indicators

Indicator	Current	2030
LCOE of generation, $/MWh	45–70	35–60
Balancing costs, €m/year	180	300–350
Savings from BESS, €m/year	0	80–120
CO_2 reduction, mt/year	0	15–20

5. Discussion

The results of the modeling confirm that the key factor determining the efficiency of the IPS of Ukraine with a high share of wind farms and solar power plants is the level of flexibility of the power system. An increase in the installed capacity of renewable energy sources to 45–50 % leads to a significant increase in the amplitude of generation fluctuations, which is directly reflected in the magnitude of imbalances and requirements for capacity reserves. The analysis showed that with the current generation structure, the main balancing burden falls on thermal power plants, which have a limited rate of capacity change (2–4 %/min). In the context of abrupt changes in the generation of solar power plants and wind farms, this is not enough to ensure the stability of the system without a significant increase in balancing costs. The use of energy storage systems (BESS) demonstrates high efficiency as a tool for compensating for short-term imbalances. The simulation results show that the use of BESS can significantly smooth out imbalance peaks, reduce the load on maneuverable generation, and reduce the volume of RES constraints. At the same time, not only a technical, but also an economic effect is achieved by reducing the cost of imbalances. Promising scenarios until 2030 indicate the need for an integrated approach to the development of the energy system. A simple increase in the share of RES without a corresponding increase in flexibility leads to a deterioration in regime indicators: an increase in imbalances, an increase in curtailment and the need for significant reserves. Separately, it should be noted that the use of the method of economic and technological forecasting of the parameters of optimal functioning and development of the energy system allows taking into account both short-term and long-term effects of RES integration, including seasonal fluctuations in generation and load. This provides a more reliable assessment of the efficiency of various scenarios for the development of the power system.

6. Conclusions

The application of the economic–technological forecasting methodology, combined with a model of long-term structural transformation of the power system, has enabled the development of predictive scenarios for the IPS of Ukraine up to 2030 and a quantitative assessment of its operational and economic performance.

1. A substantial increase in the share of wind and solar generation leads to a pronounced growth in power imbalances due to the inherent variability and limited predictability of renewable energy sources.
2. At RES penetration levels of 45–50 %, average imbalances are projected to reach 600–900 MW, while the required volume of maneuvering reserves increases to 6–7 GW, highlighting the need for structural modernization of the generation mix.
3. Conventional thermal generation alone is insufficient to provide the flexibility required to compensate for rapid fluctuations in renewable generation, resulting in increased balancing costs and reduced overall system efficiency.
4. The integration of battery energy storage systems (BESS) with a total capacity of 1.5–2 GW represents one of the most effective flexibility solutions, enabling a reduction in imbalances by 30–40 %, a significant decrease in RES curtailment, and improved system stability.
5. The large-scale integration of renewable energy sources yields substantial economic and environmental benefits, including a reduction in fuel imports by €1.2–1.6 billion annually and a decrease in CO_2 emissions by 15–20 million tons per year; however, it requires considerable investments in flexibility-enhancing technologies.
6. The most promising directions for the development of the IPS of Ukraine include the large-scale deployment of energy storage systems, expansion of pumped storage capacity, and the implementation of advanced forecasting systems for renewable generation.

Overall, the results underscore the necessity of transitioning toward advanced system management paradigms based on optimization methods and digital technologies, ensuring reliable, flexible, and cost-efficient operation of the power system under high levels of renewable energy integration.

References

1. Lund, H. (2005). Large-scale integration of wind power into different energy systems. *Energy*, *30*(13), 2402–2412. https://doi.org/10.1016/j.energy.2004.11.001
2. Beraldi, P., & Sener, N. (2026). An integrated stochastic programming model for the fair and efficient operation of renewable energy communities. *Computers & Operations Research*, *191*, 107442. https://doi.org/10.1016/j.cor.2026.107442
3. Cherkashyn, M., & Nechaieva, T. (2026). Integration of renewable energy sources and energy storage systems in distribution networks: challenges, trends, and prospects for improving energy efficiency. *System Research in Energy*, *1*(85), 52–64 [in Ukrainian]. https://doi.org/10.15407/srenergy2026.01.052
4. Zaporozhets, A., Kulyk, M., Babak, V., & Denysov, V. (2025). Software and Information Complex for Modeling Integrated Multi-node and Autonomous Electric and Heat Supply Systems. *Structure Optimization of Power Systems with Renewable Energy Sources. Studies in Systems, Decision and Control*, *583* (pp. 53–71). Springer, Cham. https://doi.org/10.1007/978-3-031-83697-8_3
5. Zaporozhets, A., Kulyk, M., Babak, V., & Denysov, V. (2025). Mathematical Models and Programming Tools for Optimizing the Composition and Operating Modes of Energy Systems Under Rapid Growth of Renewable Energy Capacities. *Structure Optimization of Power Systems with Renewable Energy Sources. Studies in Systems, Decision and Control*, *583* (pp. 31–52). Springer, Cham. https://doi.org/10.1007/978-3-031-83697-8_2
6. Zaporozhets, A., Kulyk, M., Babak, V., & Denysov, V. (2025). Current Trends in Modeling and Updating the Dissemination Processes of Energy Conversion and Utilization Technologies in the Energy Sector of Ukraine. *Structure Optimization of Power Systems with Renewable Energy Sources. Studies in Systems, Decision and Control*, *583* (pp. 1–30). Springer, Cham. https://doi.org/10.1007/978-3-031-83697-8_1
7. Zaporozhets, A., Kulyk, M., Babak, V., & Denysov, V. (2025). Modeling and Synchronizing Energy Systems of Ukraine and Europe: A 2050 Perspective. *Structure Optimization of Power Systems with Renewable Energy Sources. Studies in Systems, Decision and Control*, 583 (pp. 77–130). Springer, Cham. https://doi.org/10.1007/978-3-031-83697-8_4
8. Zaporozhets, A., Babak, V., Kulyk, M., & Denysov, V. (2025). Novel Methodology for Determining Necessary and Sufficient Power in Integrated Power Systems Based on the Forecasted Volumes of Electricity Production. *Electricity*, *6*(3), 41. https://doi.org/10.3390/electricity6030041
9. Kulyk, M., Babak, V., Denisov, V., & Zaporozhets, A. (2025). Use of Battery Storage Systems in Integrated Power Systems with Large Wind Power. In V. Babak, & A. Zaporozhets (Eds.), *Systems, Decision and Control in Energy VII. Studies in Systems, Decision and Control*, *595* (455–466). Springer, Cham. https://doi.org/10.1007/978-3-031-90466-0_19
10. Kulyk, M., Babak, V., Denisov, V., & Zaporozhets, A. Structure Optimization of Power Systems with Renewable Energy Sources. *Studies in Systems, Decision and Control (SSDC)*, *583*. SpringerLink. https://doi.org/10.1007/978-3-031-83697-8
11. Denysov, V., Kulyk, M., Babak, V., Zaporozhets, A., & Kostenko, G. (2024). Modeling Nuclear-Centric Scenarios for Ukraine's Low-Carbon Energy Transition Using Diffusion and Regression Techniques. *Energies*, *17*(20), 5229. https://doi.org/10.3390/en17205229
12. Denysov, V., Babak, V., Zaporozhets, A., Nechaieva, T., & Kostenko, G. (2024). Energy System Optimization Potential with Consideration of Technological Limitations. In A. Zagorodny, V. Bogdanov, A. Zaporozhets (Eds.), *Nexus of Sustainability. Studies in Systems, Decision and Control*, *559* (pp. 113–126). Springer, Cham. https://doi.org/10.1007/978-3-031-66764-0_5
13. Denysov, V., Babak, V., Zaporozhets, A., Nechaieva, T., Kostenko, G. (2024). Quasi-dynamic Energy Complexes Optimal Use on the Forecasting Horizon. In V. Babak, A. Zaporozhets (Eds.), *Systems, Decision and Control in Energy VI. Studies in Systems, Decision and Control*, *561* (pp. 81–107). Springer, Cham. https://doi.org/10.1007/978-3-031-68372-5_4
14. Zaporozhets, A., Babak, V., Kostenko, G., Zgurovets, O., Denisov, V., & Nechaieva, T. (2024). Power System Resilience: An Overview of Current Metrics and Assessment Criteria. In V. Babak, A. Zaporozhets (Eds.), *Systems, Decision and Control in Energy VI. Studies in Systems, Decision and Control*, *561* (pp. 35–58). Springer, Cham. https://doi.org/10.1007/978-3-031-68372-5_2

15. Ignatiev, S. State of Ukraine's energy system in 2025. Your start in the energy of the future. Retrieved February 2, 2026, from https://www.iclub.energy/lection/12_investytsii-v-elektroenerhetyku-ta-enerhoefektyvnist [in Ukrainian].
16. NPC Ukrenergo. Publication of data. Retrieved March 2, 2026, from https://ua.energy
17. NPC Ukrenergo. Analytical materials. Retrieved March 2, 2026, from https://ua.energy/category/analytical-materials
18. NPC Ukrenergo. European integration. Retrieved March 2, 2026, from https://ua.energy/european-integration
19. Homepage | Energy Map. Energy Map. Retrieved March 2, 2026, from https://energy-map.info/en
20. *Hourly electricity balance of the IPS of Ukraine*. Energy Map. Retrieved March 2, 2026, from https://energy-map.info/en/datasets/8998f2ed-379f-4fa9-9076-88782b32ee4f
21. DiXi Group. 2025 – DiXi Group. Retrieved March 2, 2026, from https://dixigroup.org/en/analytic-cat/2025-en
22. DiXi Group. Analytics topics. Retrieved March 2, 2026, from https://dixigroup.org/analytic-cat
23. Structure. Energoatom. Retrieved March 2, 2026, from https://dixigroup.org/analytic-cat https://energoatom.com.ua
24. World Nuclear Association. *Nuclear Power in Ukraine*. Retrieved March 2, 2026, from https://world-nuclear.org/information-library/country-profiles/countries-t-z/ukraine
25. *Total electricity imbalance*. Energy Map. Retrieved March 2, 2026, from https://energy-map.info/uk/datasets/5a1c1c7a-cd0b-41e1-ac03-72d5332f9777
26. *Power transmission system codex*. Public Union "All-Ukrainian Energy Assembly". https://uaea.com.ua/images/pdf/power-transmission-system-codex.pdf
27. International Renewable Energy Agency (IRENA). *Renewable Power Generation Costs in 2022*. Retrieved March 2, 2026, from https://www.irena.org/Publications/2023/Aug/Renewable-Power-Generation-Costs-in-2022
28. Lazard's Levelized Cost of Energy+ (LCOE+). © 2026 Lazard. Retrieved March 2, 2026, from https://www.lazard.com/research-insights/levelized-cost-of-energy-levelized-cost-of-storage-and-levelized-cost-of-hydrogen
29. IEA. *Electricity 2025. Analysis and forecast to 2027*. Retrieved February 2, 2026, from https://www.iea.org/reports/electricity-2025
30. ENTSO-E (balancing & system costs). Retrieved February 2, 2026, from https://www.entsoe.eu/publications
31. ACER Market Monitoring Report. Retrieved February 2, 2026, from https://www.acer.europa.eu/Publications
32. NPC Ukrenergo. Balancing Market. Retrieved February 2, 2026, from https://ua.energy/market/balancing-market
33. Denysov, V. (2023). Improving the model of long-term technological update of power system components. *System Research in Energy*, 2(73), 30–37. https://doi.org/10.15407/srenergy2023.02.030
34. Bass, F. M. (1969). A new product growth for model consumer durables. *Management science*, *15*(5), 215–227. https://doi.org/10.1287/mnsc.15.5.215
35. Babak, V.P., Denisov, V.A., Zaporozhets, A.O., & Nechaeva, T.P. (2025). Computer program "SOPS". Certificate of registration of copyright for the work No. 137703 dated July 2. Ukrainian National Office of Intellectual Property and Innovations.

ОЦІНКА ТЕХНІЧНОЇ ТА ЕКОНОМІЧНОЇ ЕФЕКТИВНОСТІ ОЕС УКРАЇНИ ЗА УМОВ ВИСОКОЇ ДОЛІ ВІТРОВОЇ ТА СОНЯЧНОЇ ГЕНЕРАЦІЇ

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Анотація. *У статті представлено оцінку технічної та економічної ефективності функціонування ОЕС України за умов високої долі вітрової та сонячної генерації. Актуальність дослідження зумовлена стрімким зростанням частки відновлюваних джерел енергії (ВДЕ), що призводить до підвищеної варіативності генерації, посилює дисбаланс енергії та ускладнює роботу та керування системою в реальному часі. Дослідження аналізує поточний стан української енергетичної системи, включаючи структурні зміни у виробництві та споживанні в умовах війни, а також*

пов'язаний зі зменшенням доступних потужностей. Особлива увага приділяється змінності щоденного та сезонного навантаження, стохастичній природі вітрової та сонячної генерації, а також обмеженій операційній гнучкості звичайних генераційних активів. Кількісна оцінка проводиться за допомогою оптимізаційної системи на основі економічно-технологічної методології прогнозування для визначення оптимальних параметрів розробки системи та функціонування. Модель включає системи акумуляторного зберігання енергії (BESS), гидро акумулюючи електростанції з насосним накопиченням (PSPP), обмеження обсягу відновлюваної генерації та механізми балансування ринку. Сценарні моделювання до 2030 року, за умови збільшення частки ВДЕ до 45–50 %, свідчать, що дисбаланс потужності може зрости до 600–900 МВт, тоді як резервні потреби можуть сягати 6–7 ГВт. Результати показують, що впровадження BESS з потужністю 1,5–2 ГВт може зменшити дисбаланси на 30–40 %, суттєво зменшити обмеження ВДЕ та забезпечити річну економію на балансуванні у розмірі €80–120 мільйонів. Запропонований підхід дозволяє більш ґрунтовно оцінити продуктивність енергосистеми за умов високої долі ВДЕ та забезпечує методологічну основу для підвищення гнучкості, надійності та економічної ефективності системи. Результати можуть бути корисними для стратегічного прийняття рішень щодо модернізації та сталого розвитку ОЕС України.
Ключові слова: відновлювані джерела енергії, інтегровані енергетичні системи, регулятори енергії, математичні моделі.

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