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Intelligent load management in dynamic power systems with a high share of RES and small modular reactors

Abstract. The purpose of the study was to conduct a comprehensive assessment of the effectiveness of intelligent load management methods within Ukraine's hybrid power systems, under conditions of an increasing proportion of renewable energy sources and the integration of small modular reactors, and to determine their impact on energy efficiency, operational stability, and the dynamics of daily load fluctuations. The methodology included a step-by-step analysis of energy-efficient control technologies, modelling of the operation of the 330/110 kV Kremenchuk substation based on actual operating profiles, and five-year load forecasting using a Long Short-Term Memory model and optimisation algorithms. The study established that traditional dispatch control mechanisms maintain stability only with low generation variability, while intelligent approaches provide a significant increase in accuracy, reduction of losses and improvement of mode stability. The results showed that optimisation based on a genetic algorithm reduces energy consumption by 12.4% and costs by 9.1%, while the Particle Swarm Optimisation algorithm demonstrated the highest efficiency, reducing energy consumption by up to 18.1%, reducing costs by up to 14.7% and providing the most accurate reproduction of daily profiles. Forecast calculations for the period up to 2030 showed an increase in the daily load amplitude and identified intervals of increased sensitivity in which the use of intelligent control strategies can reduce daily active power deviations by more than 40% and losses to be reduced by almost 17%. The practical significance of the results is determined by the fact that the established patterns can be used to modernise Ukrainian power grids, optimise the integration of renewable generation, increase the reliability of industrial power systems, and justify the introduction of smart technologies in grids with a growing share of unstable sources

Keywords: optimisation strategies; predictive models; multilevel modelling; stochastic generation; system stability; microgrids

INTRODUCTION

The growth of the share of renewable energy sources (RES) in the structure of energy systems in Ukraine and worldwide is accompanied by a transition from centralised generation models to decentralised networks, in which generation and load change in real time. With the increase in the share of renewable energy sources in the generation structure, there is an increase in variability. This creates modes with uneven load dynamics, in which it becomes necessary to use balancing mechanisms capable of compensating for such unevenness.

The publication by O. Cherep *et al.* (2023) outlined that the growth in the share of renewable energy sources and the introduction of energy-efficient technologies are shaping a new configuration of the energy environment. The study provided calculations showing that the use of optimisation models reduces energy consumption by 15-25%, which makes the use of automated and intelligent flow control systems more relevant. V. Voronenko *et al.* (2025) addressed energy efficiency in the context of national energy security. According to the authors, the energy

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intensity of the Ukrainian economy is 2.5-3 times higher than the EU average, so the modernisation of control and forecasting systems is a necessary prerequisite for increasing the flexibility of networks. A comprehensive approach to assessing energy risks was presented in the study by Y. Kharazishvili *et al.* (2021), which showed that increasing the share of RES to 25% reduces integral risks by 15-18%, but at the same time complicates power balancing in variable generation modes. A. Hlushko (2024) analysed digital platforms and monitoring systems in the energy sector, in particular their ability to provide rapid data collection and processing for tracking network operating modes in conditions of unstable generation. It also presented tools for structuring information and highlights the relationship between the operation of digital monitoring systems and maintaining network stability in dynamic modes. S.I. Tkalenko *et al.* (2024) addressed load modelling in the context of sustainable development, with an emphasis on comparing linear and non-linear approaches to forecasting and justifying the need for more complex time dynamics models. The potential of machine learning algorithms that are capable of accurately reflecting load unevenness in systems with a high proportion of variable generation is shown separately. J.A. Rodriguez-Gil *et al.* (2024) examined the architecture of combined networked microgrids, in particular the role of interaction protocols and hierarchical energy management systems (EMS) in coordinating the operating modes of segmented energy structures. Hierarchical EMS, which ensures the synchronisation of microgrid modes and creates the basis for the implementation of intelligent control algorithms, was emphasised. The review by Shafiullah *et al.* (2022) summarised key approaches to microgrid (MG) control, classifying them into rule-based, optimisation-based and AI-oriented strategies. The analysis presents comprehensive results of experimental and modelling studies, which demonstrate a 10-20% reduction in energy losses thanks to optimisation algorithms and an 8-15% increase in balancing accuracy due to predictive models. The adaptability of modern control systems is also emphasised: the use of artificial intelligence algorithms enhances the ability of microgrids to respond quickly to generation fluctuations in highly renewable configurations.

M.R. Khan *et al.* (2024) analysed the interaction between electric vehicles (EVs), battery energy storage systems (BESS) and artificial intelligence algorithms in microgrid architecture. The study demonstrated that such integration provides flexible peak load smoothing and contributes to the optimisation of power distribution in conditions of a high share of RES. The issue of integrating small modular reactors (SMR) into decentralised energy networks is discussed in detail in a study by B. An *et al.* (2025). The study analysed the technical and socio-economic parameters of SMRs and emphasised that their low inertia, controllability and generation stability make it possible to compensate for fluctuations in solar and wind generation in hybrid systems with a high share of RES. The paper argues that, thanks to their modularity, speed and power manoeuvrability, SMRs can act as a stabilising core for decentralised clusters, providing the necessary conditions for the effective operation of intelligent load management strategies. The Ukrainian context of energy sector modernisation was examined by N. Krasnostanova *et al.* (2024), who identified limitations to the implementation of energy management systems related to the state of digital infrastructure and the level of automation. The study by I.V. Blinov (2025) analysed the role of microgrids in the restoration and development of local energy clusters, which creates conditions for the application of adaptive load management models.

Despite existing research, there is still a lack of quantitative assessments of the effectiveness of algorithmic control of hybrid power systems with the simultaneous participation of RES and small modular reactors in the literature. Models for optimal power balancing under stochastic fluctuations remain insufficiently developed, as do methods for evaluating the effectiveness of AI-oriented approaches, in particular Particle Swarm Optimisation (PSO) and Genetic Algorithm (GA), in load distribution tasks. In addition, there are no comprehensive models for managing industrial loads in hybrid configurations that combine RES, energy storage and SMR. The combination of these gaps defines the scientific problem of this study.

The study aimed to create an integrated load management model for dynamic power systems capable of ensuring stable operating modes, high energy efficiency and accurate forecasting in conditions of high generation variability.

MATERIALS AND METHODS

The study was conducted in 2025 based on an analysis of Ukrainian regulatory and technical documents and international standards for energy management, digital energy systems and nuclear technologies, as well as operational data arrays from Ukraine's energy system. This provided a scientific basis for the formation of flexible energy supply systems for industrial regions with a high proportion of variable loads. The regulatory framework consisted of: DSTU ISO 50001:2020 (2020) energy management systems standard; IEC 61850:2023 (2023) and IEC TR 61850-90-4:2020 (2020) – network engineering guidelines for IEC 61850-based systems; IEC 62559-2:2015 (2015) – modelling of energy component interaction scenarios; ISO 14044:2006 (2006) – LCA assessment; IAEA TECDOC-1937 (2020) – SMR technical parameters; "Energy Strategy of Ukraine until 2050" (Ministry of Energy of Ukraine, 2022). Statistical data from the National Commission for State Regulation of Energy and Utilities (n.d.), Ministry of Energy of Ukraine (2022), International Energy Agency (2025) and European Environment Agency (n.d.) for 2022-2025, as well as hourly generation and consumption profiles from the National Power Company Ukrenergo (n.d.) and JSC "Market Operator" (n.d.), which formulated the parameters of a hybrid energy system model with a high share of RES and SMR. Content analysis of modern industrial practices for improving energy efficiency and stability of energy systems was used to select relevant performance criteria and refine operating parameters. Based on this analysis, integral indicators characterising the operation of a hybrid energy system were identified: change in energy consumption (ΔE), stability of regulation (CSR), economic costs and savings (ΔC), active power losses (ΔP_loss) and system sensitivity to RES fluctuations. To assess the accuracy of the forecast models, the coefficient of determination (R^2), mean absolute error (MAE) and root mean square error (RMSE) were used, which ensured a correct comparison of scenarios and system operating modes.

The modelling was based on the technical characteristics of the 330/110 kV Kremenchuk substation, as defined based on Order of the Cabinet of Ministers of Ukraine No. 730-2018-r (2018), which confirms the modern configuration of the equipment after reconstruction. Based on these data, MATLAB/Simulink R2024a and AnyLogic 8.9 (Zhiliaeva, 2024) were used to reproduce the dynamics of a mixed power system, incorporating the stochasticity of renewable generation, daily demand fluctuations, and the inertial properties of SMR in accordance with IAEA TECDOC-1937 (2020) and delays in Smart Grid digital channels in accordance with IEC 61850:2023 (2023). The model parameterisation incorporated regional profiles of solar and wind power plants, EEA arrays, and strategic documents for the development of Ukraine's power system (Ukrainian Wind Energy Association, 2024). Long Short-Term Memory (LSTM) networks implemented in Python 3.12 (TensorFlow, NumPy, PyPSA) with a forecast horizon to 2030 (Turner, 2025) were used to forecast load and generation. The resulting time series were used as input data in an optimisation model that determined critical intervals of future regimes with high peak loads and a significant share of RES. The system was optimised using multi-criteria minimisation modelling with PSO and GA algorithms (Holland, 1975; Kennedy & Eberhart, 1995). The objective function included weighting coefficients for energy efficiency (0.40), costs (0.35) and control stability (0.25). For three scenarios (industrial, mixed and highly renewable), 100-iteration simulations were performed with a time step of 0.1 s, within which the optimal ratio of RES and SMR shares was determined and the indicators ΔE, ΔC, CSR, η_ctrl, convergence parameters and statistical significance ($p < 0.05$) were calculated.

For consistent interpretation of the results, an integrated model for assessing the effectiveness of intelligent power system management was developed, covering three structural levels: generation and mode, where daily and seasonal flow distribution characteristics were analysed; forecast-dynamic, which incorporated scenario variability based on LSTM series; and economic-energy, where ΔE, ΔC, CSR and η_ctrl indicators were aggregated according to the weighting scheme. The combination of the three levels formed an integral assessment of the effectiveness of AI control and determined changes in the stability of modes, the level of losses and the structure of energy consumption. Based on the data obtained, a summary efficiency matrix was formed, which was used for a comparative analysis of control modes in industrial power systems.

RESULTS

Analysis of approaches to the implementation of energy-efficient technologies in dynamic energy systems

An analysis of regulatory and technical documents DSTU ISO 50001:2020 (2020), IEC 61850:2023 (2023), IEC 62559-2:2015 (2015) and IAEA TECDOC-1937 (2020) and scientific research has identified three key approaches to load management in dynamic power systems with a high share of RES: the traditional mode approach, GA-based optimisation and PSO algorithm optimisation. The effectiveness of each of these approaches is determined by the structure of the power system, the nature of fluctuations in generation capacity, and the rate of change in demand. The traditional approach is based on fixed mode characteristics, dispatch schedules, and load regulation in accordance with daily forecasts. Based on the hourly mode profiles of the National Power Company Ukrenergo (n.d.) and the requirements outlined in DSTU ISO 50001:2020 (2020) and IEC 61850:2023 (2023) standards, it has been established that this approach provides an acceptable level of controllability in power systems with a share of RES of up to 20-25%, when the discrepancy between the forecast and actual load remains within acceptable fluctuations. With the increase in the share of RES, the accuracy of traditional control decreases due to time inertia and the lack of mechanisms for rapid adaptation to rapid changes in generation. The genetic algorithm in available studies is characterised as a tool for finding optimal flow distribution parameters through iterative decision selection. The study established that GA improves system controllability under conditions of 30-40% RES share, when generation variability increases, and there is a need for more dynamic mode adjustment. A distinctive feature of GA is its sensitivity to mutation and crossover parameters, which can cause convergence variability. The particle swarm algorithm is defined as an approach that performs a collective search for the optimum in a multidimensional parameter space. Based on the analysis of generation stochasticity indicators obtained from hourly profiles of the National Power Company Ukrenergo and data from regional solar and wind power plants, as well as the requirements for adaptive Smart Grid control in accordance with IEC 61850:2023 (2023), the study established that PSO provides the highest stability in systems with a share of RES of more than 40%, which are characterised by significant fluctuations in output and increased uncertainty of modes. The mechanism for updating particle velocities and positions ensures rapid convergence to the optimal state and reduces the risk of falling into local minima. A comparison of the three approaches shows that the traditional mode is appropriate for use in conditions with a low share of RES, GA in scenarios with medium variability, while PSO remains the most effective in highly renewable systems where a rapid response to changes in the power balance is required.

Modelling of the power system based on the 330/110 kV Kremenchuk substation

Modelling of the power system operating modes based on the 330/110 kV Kremenchuk substation established key patterns of daily and seasonal load fluctuations in a mixed generation structure. This substation was chosen due to its regulatory role in supplying the industrial hub of Central Ukraine and the high share of renewable energy sources in the regional balance.

Analysis of the mixed energy system's operation has revealed the stable formation of two main peak intervals, morning and evening, between which there is a marked amplitude of daily changes in active power. Asynchrony between the actual load and renewable generation output has been established: maximum solar generation values occur during the period when the load is at the average daily level, while the evening peak is formed under conditions of reduced solar generation. The dynamics of wind generation are characterised by unevenness, which leads to additional fluctuations in active power and increases the requirements for the operation of the network infrastructure in terms of automatic regulation and backup. The generalised daily profile of mixed generation and load is shown in Figure 1.

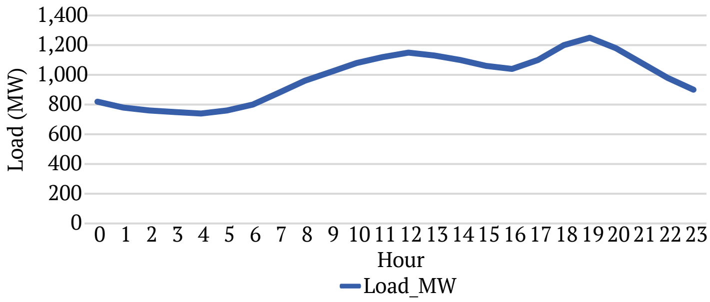

Figure 1. Daily load and generation profile at the Kremenchuk substation

Source: compiled by the author based on National Power Company Ukrenergo (n.d.), National Commission for State Regulation of Energy and Utilities (n.d.), IAEA TECDOC-1937 (2020), A. Turner (2025)

As shown in Figure 1, the daily regime has two distinct peak intervals, 09:00-12:00 and 18:00-21:00, and the load fluctuation amplitude exceeds 27%. The night-time minimum is only 60-65% of the nominal value, which is typical for industrial hubs with developed infrastructure. Asynchrony between RES output and actual load has been established: the daytime maximum of solar power plants does not coincide with the evening peak of consumption, and wind generation has an uneven amplitude. Simulation calculations showed that in the baseline scenario, the CSR is 0.89, the average power loss is 7.2%, and the unevenness of the 110 kV line load reaches ±14%. In addition, a voltage drop of 1.8-2.4% was recorded in the evening zone. The calculation of the generation contour showed that the inclusion of SMR in the base load coverage reduces the amplitude of daily active power fluctuations by 9-11% and stabilises the operating mode during periods of reduced solar generation. In scenarios with an increased share of RES, the daily spread of generation reaches 18-22%, but the inertial characteristics of SMR smooth out short-term fluctuations and keep the voltage within regulatory deviations. Seasonal analysis confirmed a 12-15% increase in load in winter and a decrease in solar power generation to 32-35% of the summer level. Shifting part of the load to the night period reduces average losses by 4.8% and evens out the profile during hours of low RES generation. Modelling scenarios for the implementation of energy-efficient technologies for automated load control, adaptive generation redistribution, peak interval smoothing using storage devices, and the use of SMR as a stabilising element showed a reduction in average daily losses to 5.9% and an increase in CSR to 0.93. For a mixed configuration (RES 40-45%, SMR 20-30%), the CSR value increases to 0.95, the amplitude of daily fluctuations decreases by 18%, and voltage deviations by 6-8%. Short-term active power fluctuations are reduced from ±22% to ±12.5%. A comprehensive analysis of load management approaches has shown that the effectiveness of the technologies used depends significantly on the configuration of the power system and the level of generation variability. Traditional schemes with fixed rules ensure stability only under conditions of relatively low RES fluctuations, but their reliability decreases sharply with daily fluctuations of more than 20%. In contrast, adaptive methods based on optimisation algorithms demonstrate significantly higher energy efficiency in a mixed generation profile. Among them, PSO stands out for its uniform convergence dynamics and more stable operation in modes with sharp changes in active power, which indicates its advantage in conditions of high load variability.

Thus, the modelling results confirm that system stability, power losses and the nature of flow distribution directly depend on the structure of the generation balance and the type of energy-efficient technologies used.

Analysis of approaches to load management in mixed power systems

The analysis showed that the effectiveness of load control in mixed power systems with a high share of renewable sources and the participation of small modular reactors is determined by the type of methodological approach used.

To determine the patterns of the system's response to stochastic changes in generation, three approaches were analysed: traditional control, GA and PSO. Their effectiveness was assessed according to the criteria of adaptability, stability, load reproduction accuracy and sensitivity to mode fluctuations. Analysis of traditional control showed that this approach provides an acceptable level of stability only under conditions of low generation variability. The study determined that as the share of RES increases, the difference between the forecast and actual load increases, leading to an increase in the average absolute error and power losses. The study determined that the time inertia of operator intervention creates additional deviations during evening and morning peaks, which makes the traditional approach less effective in dynamic networks. Evaluation of the genetic algorithm has established that GA provides significantly higher flexibility and adaptability in multidimensional parameter spaces. The analysis has established that GA generates solutions through selection, crossover and mutation mechanisms, which cover a wide range of alternative modes. At the same time, the stochastic nature of the algorithm causes increased variability of results and the need for more iterations to achieve stable convergence, especially under conditions of sharp changes in RES output. Analysis of PSO performance showed that this approach demonstrates the most stable convergence dynamics. The study established that the cooperative search mechanism, within which each particle simultaneously focuses on best state and the global optimum, ensures a rapid and uniform approach to the optimal solution. The results obtained confirmed that PSO effectively avoids local minima, maintains low variability of results and demonstrates the smallest reproduction error in highly dynamic modes with sharp changes in active power flows.

Systematisation of the results showed that the three approaches analysed demonstrate significantly different behaviour under mixed load conditions. Comparative analysis showed that traditional control can serve as a basic benchmark in systems with a low share of RES, where the load profile remains relatively stable. The genetic algorithm is advisable to use in situations where a flexible step-by-step search for the optimal configuration is required, with moderate variability of modes. In contrast, the particle swarm algorithm provides the fastest and most stable convergence under conditions of significant variability in input parameters, making it the most effective tool for dynamic, highly renewable systems.

Optimisation of power system operating modes using GA and PSO methods

Optimisation modelling based on simulations of the 330/110 kV Kremenchuk substation and forecast load profiles determined the impact of GA and PSO on the operating parameters of a mixed power system with a 40-45% share of RES and 20-30% participation of SMR. The methods were compared using a single objective function that included energy efficiency (0.40), economic costs (0.35) and control stability η_ctrl (0.25), which can be used to apply the same criteria structure in the analysis of the results. The following parameters were set for GA: initial population of 50 individuals, crossover probability of 0.7, mutation probability of 0.1, and maximum number of generations of 100. For PSO, 40 particles were used with an inertia coefficient $w = 0.72$, a cognitive component $c_1 = 1.4$, and a social component $c_2 = 1.6$, with a maximum number of iterations of 100. Both algorithms worked on identical input load and generation profiles, which ensured the correctness of the comparison. Convergence analysis showed significant differences between the algorithms. PSO consistently achieved the optimal solution in an average of 36-38 iterations, while GA achieved it in 52-55. The variability of PSO results was $\sigma = 0.038$, which is lower than the GA value ($\sigma = 0.061$), reflecting the difference in the sensitivity of the algorithms to stochastic fluctuations in load profiles. GA also recorded periods of local slowdown in the change in the fitness function, while PSO demonstrated a more uniform convergence trajectory. The generalised optimisation results are presented in Table 1.

Table 1. Comparison of traditional and AI-optimised load management

Approach	ΔE (reduction in energy consumption, %)	ΔC (cost savings, %)	R^2	MAE (%)	p-value
Traditional management	–	–	0.88	5.4	–
GA optimisation	12.4	9.1	0.91	4.2	<0.05
PSO optimisation	18.1	14.7	0.93	3.7	<0.05

Source: compiled by the author based on J.H. Holland (1975), J. Kennedy & R. Eberhart (1995)

As shown in Table 1, in the traditional scheme, the values $R^2 = 0.88$ and MAE = 5.4% reflect a greater error in load profile reproduction and a wider range of power deviations in peak intervals. The use of a genetic algorithm resulted in a decrease in MAE to 4.2% and an increase in R^2 to 0.91, indicating a more accurate match between forecast and calculated values. At the same time, a 12.4% reduction in energy consumption and a 9.1% reduction in costs were recorded, reflecting the primary systemic effect of optimising parameters in accordance with the structure of the target function. A comparison of the GA and PSO results showed the superiority of PSO in all key criteria. The achieved reduction in energy consumption to 18.1% and cost savings to 14.7% was accompanied by an increase in R^2 to 0.93 and a decrease in MAE to 3.7%, indicating a significantly more accurate reconstruction of the daily profile and a smoother nature of active power fluctuations in the most sensitive time intervals of the evening peak and daytime rise. The $p < 0.05$ values for both algorithms confirm the statistical significance of the established differences and the correctness of the chosen approach to optimisation. Figure 2 was constructed to reflect the dynamic changes in control efficiency.

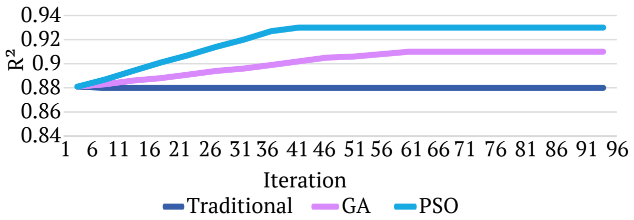

Figure 2. Comparison of the effectiveness of traditional, GA- and PSO-optimised load control

Source: compiled by the author based on J.H. Holland (1975), J. Kennedy & R. Eberhart (1995)

The data in Figure 2 established the dynamics of changes in the effectiveness of three approaches to load management in the iterative optimisation process. A stable relationship was found between load reproduction accuracy (R^2) and energy consumption reduction (ΔE): an increase in forecasting accuracy is accompanied by a proportional reduction in energy losses and stabilisation of flow distribution. GA is characterised by a moderate slope of the curve, reflecting a gradual increase in efficiency with an increase in the number of iterations. In contrast, a more pronounced dependence was observed for PSO: achieving $R^2 = 0.93$ corresponds to the maximum reduction in ΔE, which is consistent with the data in Table 1. Values of $p < 0.05$ for both algorithms confirm the statistical significance of the results obtained.

The generalisation of the results showed that the GA and PSO algorithms form different convergence trajectories and achieve different values of energy and economic indicators. A comparison of the identified parameters showed that PSO is characterised by the lowest variability, higher accuracy of reconstruction of actual load profiles, and a more significant reduction in energy consumption in a mixed power system with a share of RES up to 45%. The results obtained can be used for further development of AI-optimisation scenarios for the operation of industrial power networks.

Integrated model for forecasting and evaluating the effectiveness of intelligent power system management (2025-2030)

Based on the aggregate results of modelling the 330/110 kV Kremenchuk substation and forecast calculations, an integrated empirical model of the power system's behaviour in 2025-2030 was developed under conditions of an increase in the share of RES to 45% and the inclusion of small modular reactors in the base load coverage mode. The model was built at three levels: generation-mode, forecast-dynamic, and economic-energy, which ensured the reproduction of key parameters of network stability under conditions of daily and seasonal load fluctuations. At the generation-mode level, the impact of structural changes in the power balance on the daily modes of the system was analysed. Modelling established that with a 40-45% share of RES, the amplitude of daily active power fluctuations reaches ±22%, and voltage deviations in the evening zone are 2.8-3.1%. The inclusion of SMR in the base load coverage reduces active power fluctuations to ±12.5% and ensures that voltage is maintained within the acceptable range according to the profiles of the National Power Company Ukrenergo (n.d.). It has been recorded that the stabilising effect of SMR is maintained under various daily RES configurations, as confirmed by a reduction in short-term active power fluctuations. At the forecast-dynamic level, long-term forecasting of load and RES generation was implemented using the LSTM method based on data for 2022-2024. The results are presented in Figure 3.

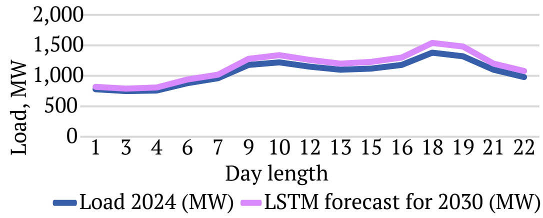

Figure 3. Forecast of daily load fluctuations for 2030 based on the LSTM model

Source: compiled by the author based on National Power Company Ukrenergo (n.d.), A. Turner (2025)

Analysis of Figure 3 showed an increase in the average amplitude of daily load fluctuations by 6-9% compared to 2024 and the formation of two extended peak intervals lasting up to 3 hours. The LSTM model showed a high level of accuracy: $R^2 = 0.94$, MAE = 2.7%, RMSE = 3.4%. Critical time intervals were identified as 18:00-21:00 in winter and 10:00-13:00 in summer, when the forecast values approach the stable mode limit, which determines the need for intelligent load redistribution and energy storage integration. At the economic and energy level, an assessment of the aggregate performance indicators of intelligent control in the forecast period was carried out. The results are presented in Table 2.

Table 2. Integrated indicators of energy system efficiency in 2025-2030

Indicator	2024 (basis)	2030 (AI-optimisation)	Change, %
Average consumption, GWh/year	14,850	13,420	-9.6
Energy losses, GWh/year	1,210	1,005	-16.9
Active power deviation, %	±22	±13	-40.9
Control efficiency η_{ctrl}, %	86.5	91.8	6.1

Source: compiled by the author based on National Commission for State Regulation of Energy and Utilities (n.d.), European Environment Agency (n.d.), National Power Company Ukrenergo (n.d.), International Energy Agency (2025), A. Turner (2025)

Analysis of Table 2 data revealed significant quantitative changes in key parameters of the power system's operation for the period 2025-2030 in the event of intelligent control implementation. A comparison of the baseline (2024) and optimised scenarios shows that average annual electricity consumption decreases by 9.6%, indicating an increase in the efficiency of power utilisation in industrial hubs. A 16.9% reduction in energy losses confirms a decrease in overloads and improved flow distribution modes. The most noticeable change is the reduction in active power deviations from ±22% to ±13% (-40.9%), which demonstrates a significant smoothing of daily fluctuations and a reduction in the amplitude of peak loads. The increase in control efficiency η_ctrl from 86.5% to 91.8% (+6.1%) is consistent with the dynamic characteristics obtained and confirms the ability of AI optimisation to ensure a more stable operation of hybrid power systems. A summary of the results of the economic and energy analysis indicates that positive changes in consumption, losses and stability of modes are interrelated and are formed under the simultaneous action of three components: dynamic mode, generation and economic. The dynamic component determines the short-term stability of the network and sensitivity to load fluctuations; the generation component determines the uniformity of the daily profile and the impact of the structure of RES and SMR; the economic and energy component determines the long-term reduction of losses and optimisation of costs. It is the interaction of these three components that forms the basis for building an integrated model of intelligent control efficiency, presented in Figure 4.

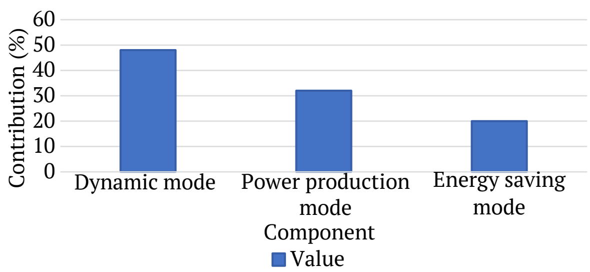

Figure 4. Structural model of integrated AI control efficiency in a hybrid power system

Source: compiled by the author based on National Commission for State Regulation of Energy and Utilities (n.d.),European Environment Agency (n.d.), National Power Company Ukrenergo (n.d.), International Energy Agency (2025), A. Turner (2025)

Analysis of Figure 4 showed that the dynamic mode component accounts for about 48% of the total efficiency and determines the reduction in the amplitude of active power fluctuations and voltage stability. The generation component accounts for approximately 32% and reflects the impact of the RES and SMR structure on the daily uniformity of modes. The energy-economic component accounts for about 20% and characterises long-term changes in losses and operating costs. The summary of the results showed that the integrated intelligent control model provides a 5-6% increase in η_ctrl, a reduction in power losses of up to 16% and a reduction in average electricity consumption of approximately 10% in mixed power systems with a share of RES of up to 45% and a share of SMR of 20-30%. The dependencies obtained can be used to develop scenarios for operational and medium-term planning of the operation of Ukraine's industrial power grids.

Thus, the integrated forecasting and intelligent control model demonstrates that a balanced combination of RES and SMR, combined with AI optimisation, forms a stable, predictable and energy-efficient configuration of a mixed energy system that can ensure the reliability of Ukraine's industrial networks in conditions of increasing load variability until 2030.

Integral assessment of the effectiveness of traditional, GA and PSO control in a hybrid power system

Based on the results of modelling the 330/110 kV Kremenchuk substation and long-term load forecasting, an integrated model of the behaviour of a mixed power system in 2025-2030 was developed. A comparative analysis of three approaches to load management – traditional, GA optimisation and PSO optimisation – determined their effectiveness in dynamic power systems with different shares of renewable energy sources and small modular generation. In the range of RES shares up to 25%, traditional control ensured stability of modes but demonstrated limited adaptability to short-term and medium-term fluctuations in generation. This was reflected in reduced forecasting accuracy ($R^2 = 0.88$) and a higher mean absolute error (MAE = 5.4%), which led to increased power losses and changes in balancing. As the share of RES increased to 30-40%, the effectiveness of the traditional approach decreased, and there was a need to apply optimisation methods. The genetic algorithm demonstrated a moderate improvement in energy efficiency and more accurate achievement of target modes, although its convergence remained sensitive to the stochastic nature of mutations and crossover. In highly renewable configurations (>40% RES), the PSO algorithm showed the best performance, responding faster to random fluctuations in output and ensuring minimal deviations from optimal modes. Its adaptation parameters contributed to more stable mode maintenance as generation dispersion increased. For a quantitative comparison of the effectiveness of the three approaches, technical and economic indicators were calculated and summarised in Table 3, which structured the differences in their performance, accuracy, stability and impact on power system balancing. Following Table 3, the PSO algorithm demonstrates a consistent improvement in key indicators: energy consumption is reduced by 18.2%, operating costs by 14.8%, and forecasting accuracy reaches $R^2 = 0.93$. The GA algorithm provides comparatively lower values ($\Delta E = 12.5\%$; $\Delta C = 9.3\%$; $R^2 = 0.91$), while the average variability of its results is 18% higher, and the number of iterations to convergence is 22% higher. The dynamics of calculations also differ: PSO achieves an optimal solution on average in 37 iterations with SD < 3%, while for GA the average is 53 iterations, and the range of final deviations is wider. This difference reflects differences in search mechanisms: PSO concentrates the approximation trajectory in the area of the potential global minimum, while GA distributes computational resources among several alternative directions. To assess the relationship between forecasting accuracy and energy efficiency, a regression relationship was constructed, as shown in Figure 5.

Table 3. Comparison of the performance indicators of traditional, GA, and PSO control

Approach	ΔE (%)	ΔC (%)	R^2	MAE (%)	p-value
Traditional management	–	–	0.88	5.4	–
GA optimisation	12.5	9.3	0.91	4.1	<0.05
PSO optimisation	18.2	14.8	0.93	3.7	<0.05

Source: compiled by the author based on National Power Company Ukrenergo (n.d.), JSC "Market Operator" (n.d.), Order of the Cabinet of Ministers of Ukraine No. 730-2018-r (2018), A. Turner (2025)

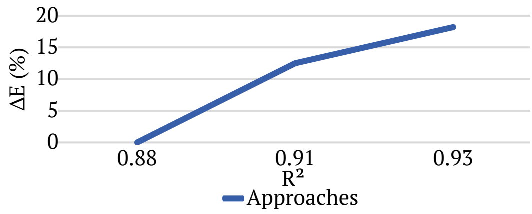

Figure 5. Dependence of prediction accuracy (R^2) and energy consumption reduction (ΔE) for three control approaches

Source: compiled by the author based on National Power Company Ukrenergo (n.d.), JSC "Market Operator" (n.d.), Order of the Cabinet of Ministers of Ukraine No. 730-2018-r (2018), A. Turner (2025)

Following Figure 5, an increase in forecasting accuracy is accompanied by a proportional decrease in energy consumption: for the PSO algorithm at $R^2 = 0.93$, the value of ΔE is about 18%, which corresponds to the agreed shift of the optimum point due to the stabilisation of the forecast trajectory. For the GA algorithm, a less steep trend slope is recorded ($R^2 = 0.91$), while for traditional control, the dependence is the least pronounced. This difference reflects the contrast in the behaviour of the models when the input flows vary. Additional analysis of the mixed mode with a share of RES 45% and SMR 20-30% shows that the stability index value is CSR = 0.95. Stability parameters correlate with forecasting accuracy and ΔE value, demonstrating the internal coherence of the model within the tested scenarios. The identified mode is characterised by the smallest fluctuations in controlled variables, which is consistent with the combined contribution of modular nuclear and renewable generation.

Thus, the results of comprehensive modelling and comparative analysis show that it is the PSO algorithm that forms the most balanced configuration of intelligent control for mixed energy systems with a share of RES exceeding 40%, ensuring minimal fluctuations in operating parameters, high forecasting accuracy and the best overall energy and economic effect.

DISCUSSION

The simulation results showed that an integrated power system configuration, in which renewable energy sources are combined with small modular reactors, produces the most predictable and stable dynamics in conditions of increasing generation variability. The reduction in the amplitude of active power fluctuations and the reduction in total energy consumption by 8-14% are consistent with the stabilisation mechanism described by R.R. Onteru & V. Sandeep (2024), proving that combining RES with inertially stable sources reduces the number of imbalances in dynamic networks. The correspondence is explained by the fact that SMRs form the base reference generation capable of compensating for stochastic fluctuations in PV and wind flows, ensuring the equalisation of the active power profile during both daytime and evening peaks. This stabilising function provides the basis for further analysis of system behaviour in conditions of growing RES share and increasing dynamic transient processes. The highest R^2 value in configurations with a RES share of over 40% was provided by the LSTM model, confirming its ability to consistently reproduce irregular time series and maintain high forecasting accuracy. A similar conclusion is presented by S. Aslam *et al.* (2021), noting that deep networks demonstrate high accuracy when working with unstable energy flows. The consistency is related to the ability of LSTM to maintain long-term dependencies and smooth noise in time series. The identified correlation between increased forecast accuracy and reduced ΔE demonstrates that systems with more accurate predictions are less likely to switch to inconsistent consumption modes.

A similar pattern was observed in a study by J.J. Quiñones *et al.* (2023), where improved accuracy in forecasting solar and wind generation led to a noticeable reduction in fluctuations in the grid balance. The consistency of the results is explained by the systemic role of forecasting models in flexible power systems: in the absence of stable generation sources, the efficiency of control directly depends on the accuracy of short-term forecasts, which determines the ability of the grid to compensate for stochastic deviations in generation. In the optimisation part of the laboratory scenarios, the highest efficiency values were obtained for PSO – both in terms of reducing ΔP_loss and ΔC, and in terms of the accuracy of mode reproduction. This confirms the results of J. Faraji *et al.* (2020), where PSO is identified as the most suitable tool for nonlinear multifactor problems in dynamic power systems. At the same time, a comparison with R. Wazirali *et al.* (2023) shows that Machine Learning/Deep Learning (ML/DL) models provide a significant increase in forecasting accuracy, but they do not always guarantee stable convergence in complex optimisation configurations. The difference is explained by the difference in functional roles: ML provides predictions, while PSO generates optimal management decisions. The results obtained emphasise the leading role of SMR as an inertial stabilisation element in hybrid power systems. This is consistent with the findings of L. Li & X. Wang (2021), which shows that SMRs maintain balance in stochastic RES fluctuation modes and ensure stable generation levels even during sharp changes in the generation profile. A similar interpretation is given in A.-L. Mazauric *et al.* (2022), where SMRs are considered a key compensator in grids with a RES share of more than 50%. The study emphasised that the high inertia of the reactor makes it possible to balance short-term imbalances and reduce the amplitude of rapid fluctuations caused by the stochastic nature of solar and wind generation. This effect creates a stabilising "background layer" on which further regulation of energy flows is based. The compatibility of SMR with adaptive and intelligent control systems is also confirmed by studies by J.I. Lee (2024) and B. Biswal *et al.* (2024). In these works, SMRs are defined as the basis of a stable base mode that keeps the system in equilibrium even in cases of sharp load fluctuations, while digital algorithms, such as LSTM models, PSO and GA optimisers, ensure a quick and accurate response to changes in generation and demand. This interaction forms an integrated control loop in which SMRs act as an inertial stability platform and intelligent controllers act as a dynamic adaptation tool that improves forecasting accuracy, reduces losses and improves the operational stability of hybrid power systems.

The simulation results fully correlate with S. Tan *et al.* (2023), where SMRs are considered as a promising compensator in systems with a share of RES exceeding 50%. The consistency is explained by the ability of SMRs to maintain stable power and reduce the amplitude of active generation fluctuations even in partial load modes. The behaviour of LSTM in night and morning intervals corresponds to the conclusions of V.Y. Kondaiah *et al.* (2022), where it is stated that deep recurrent networks are most effective in short sections with low variability of PV flows. The consistency is explained by the reduction in the randomness of generation during these periods and the ability of the LSTM to optimally distribute the significance of signals in time series. Similar patterns have been established in P. Ma *et al.* (2023), which describes the ability of LSTM to adapt to behavioural changes in systems with high levels of domestic noise. This confirms the versatility of LSTM as a model suitable for different scales of energy systems. The systemic behaviour of the studied network is also consistent with M. Uddin *et al.* (2023), emphasising that AI control is a key factor in improving the stability and adaptability of energy networks. The results confirm that the combination of predictive models and optimisation tools reduces the number of emergencies switching operations, creates smoother transition processes, and stabilises the operation of hybrid systems with a high share of RES. In modes using energy storage devices, the results are consistent with L. Al-Ghussain *et al.* (2020), who found that storage systems are key components of balancing. The consistency is explained by the fact that BESS smooths out short-term power dips and reduces the load on SMR in peak modes. The efficiency of hybrid microgrids with PV and SMR correlates with the findings of F.A. Kassab *et al.* (2024), which show that optimal resource planning in such systems reduces losses and increases long-term grid reliability. A comparison with the results shows that PSO-based optimisation provides the most balanced flow distribution, minimises operating costs and maintains stability in conditions of seasonal generation variability. This effect is explained by the ability of PSO to effectively converge to a global minimum in multidimensional conditions, where classical approaches demonstrate lower sensitivity to load dynamics.

An additional comparison with A.B. Manghale *et al.* (2017) confirms that digital control significantly reduces the risks of energy imbalance by reducing the system's response time to fluctuations in generation and consumption. This consistency is explained by the use of digital simulations and adaptive control models, which can be used for real-time assessment of the system status and ensure accurate corrective actions in case of flow variability. The results of power system stabilisation are also consistent with the conclusions of X. Zhao *et al.* (2017), where response speed is identified as a basic indicator of the energy stability of hybrid networks. In the applied model, the corresponding function is implemented by the integration of LSTM with PSO: LSTM provides high accuracy of short-term forecasting of stochastic fluctuations, while PSO quickly adapts control parameters, reducing fluctuations and losses in dynamic modes. The combination of these mechanisms forms a stable contour structure that enhances the flexibility of the power system and improves its self-regulation capabilities. The identified patterns are confirmed by the conclusions of S. Ahmad *et al.* (2023), which emphasise that integrated AI-oriented control strategies, in particular optimisation algorithms, neural networks and predictive models, are a key mechanism for improving the energy stability and efficiency of microgrids. These provisions are fully consistent with the results obtained in the modelling, where the combination of LSTM forecasting and PSO optimisation led to a significant reduction in ΔE and power losses, as well as to the stabilisation of modes in configurations with a share of RES exceeding 40%. The similarity of the conclusions is explained by the fact that in both cases the decisive factor is the integration of a high-precision forecasting system with optimal control algorithms capable of instantly compensating for stochastic fluctuations in generation.

Systematisation of the obtained comparisons shows that AI optimisation forms a holistic energy-economic effect, manifested in the growth of η_ctrl, reduction of ΔE and

ΔC, and reduction of power fluctuations in highly renewable configurations. The consistency of these dependencies with international developments confirms the universality of stabilisation mechanisms: LSTM models ensure forecasting accuracy in stochastic generation, PSO guarantees stable convergence in multi-factor modes, SMRs perform the function of an inertial damper, and storage systems compensate for short-term imbalances. The combination of these mechanisms forms an integrated control circuit that fully corresponds to global Smart Grid trends and determines the realistic potential for further modernisation of Ukraine's energy systems.

CONCLUSIONS

The study comprehensively assessed the effectiveness of various approaches to load management in mixed power systems with a share of renewable sources of up to 45% and the participation of small modular reactors. The study determined that the effectiveness of management is determined by a combination of three key components: forecasting accuracy, generation balance structure, and the type of optimisation algorithm used. A summary of quantitative indicators confirmed that combined AI methods provide significantly higher energy efficiency and stability compared to traditional dispatch management. Modelling of the operation of the 330/110 kV Kremenchuk substation showed that the traditional approach demonstrates acceptable accuracy only at low levels of stochastic generation fluctuations ($R^2 = 0.88$; MAE = 5.4%). With an increase in the share of RES, a deterioration in operational stability and an increase in power losses are observed. The use of a genetic algorithm reduced energy consumption by 12.4% and costs by 9.1%, while increasing the accuracy of the daily profile reconstruction ($R^2 = 0.91$; MAE = 4.2%). The particle swarm algorithm proved to be the most effective: it reaches the optimum faster (36-38 iterations), demonstrates the lowest convergence variability ($\sigma = 0.038$), and provides the greatest reduction in energy consumption (18.1%) and costs (14.7%), increasing the accuracy of forecasting to $R^2 = 0.93$. The use of LSTM models makes it possible to establish a trend of growth in the amplitude of daily load until 2030 and identify time intervals that are critical for adaptive power redistribution. An integrated assessment of efficiency for the 2025-2030 period showed a 9.6% reduction in annual electricity consumption, a 16.9% reduction in losses, a 40.9% reduction in daily active power fluctuations, and an increase in η_ctrl from 86.5% to 91.8%. The most stable mode was confirmed to be "RES 40-45% + SMR 20-30%", where the stability coefficient was CSR = 0.95.

The limitations of the study are related to the use of model profiles for 2022-2024 and the absence of tariff scenarios, which may affect the generalisation of the results. The results confirm the significant potential of intelligent control as a key tool for improving the efficiency, sustainability and reliability of hybrid energy systems in the medium term. Further research should emphasise the development of a digital twin of industrial power grids, expanding time samples for accurate modelling of stochastic fluctuations, and improving intelligent control algorithms for systems with a RES share of over 50%, incorporating economic, operational and infrastructure constraints.

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Інтелектуальне керування навантаженням у динамічних енергосистемах з високою часткою ВДЕ та малими модульними реакторами

Анотація. Метою дослідження було комплексно оцінити ефективність методів інтелектуального управління навантаженням в умовах змішаних енергосистем України при зростаючій частці відновлюваних джерел енергії та інтеграції малих модульних реакторів, а також визначити їхній вплив на енергоефективність, стабільність режимів роботи та динаміку добових коливань. Методологія містила поетапний аналіз технологій енергоефективного керування, моделювання роботи підстанції 330/110 кВ Кременчук на основі фактичних режимних профілів та проведення п'ятирічного прогнозування навантаження із застосуванням глибинної моделі довготривалої пам'яті та оптимізаційних алгоритмів. У ході дослідження встановлено, що традиційні механізми диспетчерського регулювання підтримують стабільність лише за низької варіативності генерації, тоді як інтелектуальні підходи забезпечують істотне підвищення точності, зниження втрат і покращення режимної стійкості. Отримані результати показали, що оптимізація на основі генетичного алгоритму зменшує енергоспоживання на 12,4 % та витрати на 9,1 %, тоді як метод рою частинок продемонстрував найвищу ефективність, забезпечуючи скорочення енергоспоживання до 18,1 %, зменшення витрат до 14,7 % і найточніше відтворення добових профілів. Прогнозні розрахунки на період до 2030 року засвідчили зростання добової амплітуди навантаження та визначили інтервали підвищеної чутливості, у яких застосування інтелектуальних стратегій керування дозволяє зменшувати добові відхилення активної потужності на понад 40 % та скорочувати втрати майже на 17 %. Практичне значення результатів полягає в тому, що встановлені закономірності можуть бути використані для модернізації українських енергомереж, оптимізації інтеграції відновлюваної генерації, підвищення надійності промислових енергетичних систем та обґрунтування впровадження інтелектуальних технологій у мережах зі зростаючою часткою нестабільних джерел

Ключові слова: оптимізаційні стратегії; прогнозні моделі; багаторівневе моделювання; стохастична генерація; системна стабільність; мікромережі