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Development and modelling of microgrid system architecture with redundancy from nuclear and traditional sources for critical infrastructure: Improving the reliability and security of energy supply

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Abstract. This article presented a conceptual model of an intelligent energy system with combined power sources intended to improve the continuity, stability and security of energy supply to facilities. It was based on a comprehensive approach that combines analytical, comparative and structural-functional methods. It was based on the premise that a microgrid, as a hybrid system, combines microreactors, renewable sources, and backup generators controlled by artificial intelligence to provide a stable power supply. Microreactors can reduce energy costs by 15-25%, and integrating renewable sources can increase capacity utilisation by $\approx 35\%$ when long-term storage systems are used. The hybrid architecture of "microreactors (core) + renewable sources + storage + emergency reserve" provided $>99.9\%$ availability and reduces the probability of failure to $\approx 1\%$, which meets the requirements of critical infrastructure systems. Hierarchical control is central, with local controllers coordinated by a central artificial intelligence module increasing system stability by 30-40%. The operational cycle of the Artificial Intelligence-based Energy Management System runs in real time at 1-2 second intervals, ensuring rapid load balancing, response to emergency events, and isolation of network segments in the event of a cyber threat. The regulatory requirements of the U.S. Nuclear Regulatory Commission stipulate fault tolerance, redundancy and testing in a hardware-in-the-loop environment, while phased modelling using Python for Power System Analysis, Power Systems Computer Aided Design, and Real-Time Digital Simulator minimises technical risks and increases the accuracy of system verification. The developed microgrid system model is flexible, scalable, and cyber-resilient, combining nuclear, renewable, and traditional energy sources into a single intelligent control loop, ensuring uninterrupted and autonomous power supply to critical facilities under any conditions. The results can be used in conceptual engineering, project structures, and defence agencies to create autonomous and cyber-resilient microgrid systems

Keywords: microgrid; very small modular reactor; energy storage systems; intelligent power grid management; long-duration energy storage; power grid digital twin; power grid autonomy

Introduction

The growing complexity of energy systems and their vulnerability to external factors, ranging from natural disasters to cyber-attacks and military actions, necessitate the development of new energy supply architectures intended to improve autonomy, resilience and

security. One of the effective approaches is the development of microgrid systems that combine renewable, traditional and nuclear energy sources into integrated managed complexes for critical infrastructure facilities. The feasibility of this direction was determined

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by the global trend towards energy decentralisation, increased supply reliability and the need for fault-tolerant solutions capable of functioning in isolation.

Existing research confirms that microgrid architecture is the basis for future energy systems. T.E.K. Zidane *et al.* (2025) summarised strategies for increasing the resilience of electrical networks, showing that the use of multi-level control architecture and local node autonomy increases system fault tolerance by more than 20%. This formed the concept of “resilience-based optimisation” for distributed energy systems, which became the basis for modern 21st-century approaches to microgrid management. In a study by M.K. Raza *et al.* (2024), an integrated model for combining very Small Modular Reactors (vSMRs) and renewable energy sources (RES) within a microgrid architecture was developed. This approach demonstrated for the first time the possibility of using microreactors as basic sources for local networks with hybrid reserves, which can reduce fuel costs by 25-30% in remote areas. The evolution of approaches to energy management of microgrid systems towards greater autonomy and efficiency was demonstrated by N. Qi *et al.* (2025). The study proposed a concept of long-term energy flow management without dependence on predictive models, integrating hydrogen and battery energy storage systems into a single optimisation structure. This meant that the combined use of hydrogen and batteries increases system stability and can improve the efficiency of balancing daily load fluctuations. In turn, M. Hamidieh & M. Ghassemi (2022) addressed the issues of microgrid resilience, proposing a classification of its levels: structural, operational and cybernetic. The study contributed by developing a widely applicable within resilience assessment model suitable for analysing the behaviour of critical infrastructure power grids.

The practical application of theoretical developments was confirmed by experimental research conducted by J.A.G. Archetti *et al.* (2023), who performed Hardware-in-the-Loop (HIL) validation of a microgrid control system in real time. The study proved that the combination of digital twins and physical controllers reduces power distribution error to 2%. This provided a reliable verification of algorithms in dynamic modes and became the basis for further experiments to verify real-time control. The development of protection and reliability was supported by K. Islam *et al.* (2024), developing adaptive shutdown algorithms that enabled systems to automatically respond to mode changes and reduce the risk of relay protection failures. This expanded the functionality of microgrid systems through dynamic coordination of protections and created a basis for cyber-physical adaptation of future smart grid architectures.

The application of artificial intelligence (AI) in shaping an emerging approach for energy system management was studied by M. Alam *et al.* (2025). The authors not only summarised existing algorithms but

also proposed a concept of a general AI structure capable of providing self-learning control in variable operating conditions. This created the prerequisites for a conceptual framework for building autonomous energy microgrids, where AI is the central element of control and diagnostics. The development of the idea of a practical combination of intelligent control with nuclear technologies was demonstrated by T.H. Woo & Y.I. Kim (2025), who created a model of a microgrid system for a university campus, where a small modular reactor (SMR) is used as the primary energy source. The modelling showed that the use of AI algorithms for dynamic balancing of energy flows can reduce losses by 12% without compromising network stability. This proved the practical compatibility of nuclear power sources with smart microgrid architectures, creating prospects for the creation of autonomous power systems for critical infrastructure.

Trends in the development of microgrid systems in Ukraine, analysed by V. Khai (2024), identified key barriers to their implementation: regulatory, technological and investment barriers, which, in turn, shaped the strategic directions for the development of microgrid projects in the post-war period. The study by A. Khotian & V. Rosen (2022) substantiated the prospects for the use of combined energy sources in the agricultural and industrial sectors of Ukraine. The study assessed the effectiveness of hybrid microgrid systems in the context of the national energy market, which creates the basis for further adaptation of local energy solutions to the conditions of decentralised generation.

However, despite existing research, there is a lack of a comprehensive theoretical and practical model of microgrids for critical infrastructure that simultaneously integrates SMR as a basic source with RES and uses an AI-based Energy Management System (AI-based EMS) to optimise load distribution and predict failures. Therefore, the study aimed to develop a conceptual model of an autonomous local power system for critical infrastructure based on a hybrid architecture with AI-based EMS focused on autonomy and cyber resilience. To achieve this goal, the following tasks were performed: to analyse the architecture, principles and energy technologies of microgrid systems; to develop a structural model of a microgrid system with a nuclear energy reserve; to determine the role of AI in ensuring its stability and autonomy.

Materials and Methods

The study was based on a comprehensive approach that combined comparative, analytical, normative-analytical, and structural-functional methods to form a generalised methodological basis for developing an integrated microgrid architecture with a nuclear reserve. Using comparative analysis and a structural-functional approach, the main groups of energy technologies that form the functional basis of microgrid systems – nuclear,

renewable, traditional, and energy storage systems – were systematised. The comparison was conducted based on a set of technical, economic, environmental and functional criteria covering their role in microgrid architecture, efficiency, reliability, safety level, integration flexibility and practical feasibility. The choice was determined by the fact that these energy sources cover the full spectrum of power generation technologies for microgrid architectures, ensuring a balance between autonomy, environmental friendliness and reliability. The analysis covered the identification of patterns in the choice of sources depending on operating conditions, the level of criticality of consumers and technical and economic characteristics.

Using a regulatory and analytical method, international technical standards IEEE 1547-2018 (2018) and IEC 61850:2025 SER (2025) were reviewed. Cybersecurity standards NIST SP 800-82 Rev. 3 (2023), IEC 62443 (2024) and regulatory documents in the field of nuclear safety, United States Nuclear Regulatory Commission (2025), are also covered. Technologically inclusive licensing criteria for small reactors, United States Nuclear Regulatory Commission (requirements for cyber and physical resilience of nuclear systems) (Dorman, 2023) and a practical technical guide for implementing the IEC 62443 standard in Supervisory Control and Data Acquisition (SCADA)/Operational Technology (OT) environments, used as a methodological basis for analysing the cybersecurity of microgrid systems (The ultimate guide..., 2025). These standards were chosen due to their global prevalence, cross-industry relevance, and applicability to the entire life cycle of microgrid systems. The requirements of various standards were systematised, compared in terms of their scope of application, and an agreed methodological basis for the design, testing and validation of microgrid architectures was defined.

An analytical and comparative method was used to conduct a technical and economic assessment of SMRs and their integration into hybrid microgrid systems. The analysis covered the summarisation of available technical and economic data and practices from official technical reports on the development and evaluation of microreactors for microgrid and isolated applications (List *et al.*, 2024; International Atomic Energy Agency, 2024). Programme and demonstration initiatives in the field of microgrid projects and Long-Duration Energy Storage (LDES) were analysed (United States Department of Energy, 2022; Demonstration of LDES..., 2025; REopt facilitates solar..., 2025). The case of the Project Pele defence microreactor is considered as an example of SMR integration into an autonomous microgrid infrastructure to form a conceptual model of energy architecture with a nuclear reserve, suitable for further modelling and performance evaluation, as well as determining the principles of building a hybrid architecture “SMR (nuclear) + RES + Long-Duration

Energy Storage (LDES) + reserve” as a methodological basis for modelling architecture and simulating energy flows, incorporating technical and regulatory constraints (Department of Defense..., 2024).

A comparative and analytical method was used to analyse the dynamic behaviour of a microgrid system under various operating scenarios, from normal mode to emergency shutdown. The Python for Power System Analysis (PyPSA) and Grid Laboratory for Distribution Systems (GridLAB-D) simulation platforms were used. DIgSILENT PowerFactory (DIgSILENT GmbH, n.d.) and Power Systems Computer Aided Design/Electromagnetic Transients including Direct Current (PSCAD/EMT-DC) (PSCAD, n.d.) were analysed. The use of Real Time Digital Simulator (RTDS) (RTDS Technologies, n.d.) and OPAL-RT HYPERSIM (Opal-RT Technologies, n.d.a; n.d.b) was demonstrated. The analysis was aimed at verifying the stability and balance of the hybrid microgrid architecture, as well as assessing the suitability of software simulation environments for reproducing physical and control processes in the system. These platforms were chosen as they cover the entire spectrum of modelling levels, from conceptual optimisation to physically accurate real-time system verification, reproducing both the economic and technical characteristics of the microgrid system. The simulation environments were evaluated based on a set of technical and functional criteria, including the level of detail and accuracy of modelling, support for international standards (IEEE 1547-2018, 2018; IEC 61850:2025 SER, 2025), the possibility of integration with external environments (Python, Jupyter, SCADA/HIL), the availability of tools for reproducing emergency scenarios and testing control in real time, as well as the accessibility, scalability and reproducibility of results. In addition, a systematic comparative method was used to study approaches to integrating SMRs into microgrid systems, HIL validation methods, and real-time simulation modelling. The analysis included a generalisation of solutions for ensuring the stability of microgrid architectures, determining the role of HIL modelling in testing control algorithms, and justifying the use of fault-injection simulations for testing system stability.

To generalise approaches to the use of machine learning (ML) algorithms to improve the autonomy, forecasting accuracy and cyber resilience of energy systems, hybrid AI models – short-term forecasting models and medium-term load (Time-Variant Fast Empirical Mode Decomposition – Long Short-Term Memory – AutoRegressive Moving Average with eXogenous inputs (TVFEMD-LSTM-ARMAX), Long Short-Term Memory (LSTM), Convolutional Neural Network (CNN)), algorithms for optimising power distribution based on deep reinforcement learning (Deep Reinforcement Learning – Deep Q-Network (DQN), Actor-Critic), approaches based on digital twins in combination with ML methods (regression, classification), anomaly detection methods

(Unsupervised Anomaly Detection, Autoencoders) and PyPSA/GridLAB-D (as an environment for ML-pipeline). The choice of these approaches was due to their complementarity within a single intelligent microgrid control loop. This approach formulated an integrated model of intelligent energy management, in which AI acts as the central mechanism for forecasting, optimisation and security to ensure the stable operation of the microgrid system. Using structural-functional and engineering-analytical modelling, a conceptual architecture of a microgrid system with a nuclear reserve was developed, prioritising the continuous power supply of critical facilities. This was done to form a generalised architecture of an integrated microgrid system that combines nuclear, renewable and traditional energy sources into a single intelligent infrastructure with a high level of autonomy, flexibility and cyber resilience.

Results and Discussion

Conceptual foundations, source classes, and microgrid standards. A microgrid is a local energy system capable of operating both in a connected mode with the main power grid and in an autonomous mode. The main goal of microgrid architectures is to ensure energy stability, autonomy, and reliability of power supply to critical

infrastructure facilities such as hospitals, military bases, data centres, communication systems, etc. The microgrid architecture is based on the following key principles: decentralisation (power generation takes place within a local node with the possibility of energy exchange between microgrids), multi-source (integration of renewable (solar, wind), traditional (gas, diesel) and nuclear energy sources, together with energy storage systems, to ensure uninterrupted power supply), intelligent control (use of artificial intelligence algorithms to optimise load and reduce losses), modularity (scalability and flexible connection of new nodes and generators), resilience to disturbances (ensuring isolated operation in the event of failures or cyberattacks on the main grid) (United States Department of Energy, 2022). The combination of a microreactor and renewable sources in a microgrid architecture ensures power stability even in polar regions (Department of the Air Force, 2024). In addition, a modular microreactor is considered a basic energy source for local defence and scientific power systems (List *et al.*, 2024). Energy sources in microgrids are divided into nuclear, renewable, traditional, and a separate electricity storage subsystem, which differ in technical characteristics, role in system architecture, and practical examples of implementation (Table 1).

Table 1. Functional role and examples of implementation of energy sources and storage systems in microgrids

Group	Typical technologies/power	Role in microgrid	Benefits	Issues	Real-life examples
Nuclear (microreactors, SMR)	SMR/microreactors, ~1-20 MW	Basic/critical power supply, the "core" of the system	High reliability, low CO ₂ emissions, long operation without refuelling	Regulatory barriers, capital expenditure, logistics and security	CAMP (Alaska Microreactor Program) – US Air Force initiative to develop and test a microreactor for remote military bases. MARVEL (INL) – 100 kW _e demonstration microreactor developed by the Idaho National Laboratory to test integration with local microgrids Project Pele (DoD/DOE) – 1-5 MW mobile microreactor for providing autonomous power to military facilities, with the ability to be transported
Renewable	Solar PV, wind turbines, and small hydroelectric power stations	Peak coverage, reduction in fossil fuel use	Low variable costs, zero emissions, deployment flexibility	Generation instability, need for storage facilities	REopt – pilot integration of solar systems into a rural microgrid via the REopt platform, which increased power utilisation efficiency by ~35%. LDES Demonstration – Naval Base San Diego (CEC) – The project demonstrates how LDES stabilises solar and wind sources in a military microgrid
Traditional	Diesel generators, gas turbines	Reserve/emergency power supply	Reliability in critical situations, ease of maintenance	High CO ₂ , fuel dependency, logistics costs	DOE Microgrid and Integrated Systems Programme – US government programme that includes diesel generators as backup elements in hybrid microgrids, particularly for critical infrastructure

Table 1. Continued

Group	Typical technologies/ power	Role in microgrid	Benefits	Issues	Real-life examples
Energy storage systems (thermal, hydro storage, hydrogen systems), battery energy storage systems (lithium-ion, sodium-sulphur)	From hundreds of kWh to tens of MWh	Balancing generation and load, supporting isolated microgrid operation, smoothing peak loads and RES fluctuations, and short-term power reserve for critical consumers	Increased microgrid autonomy, reduced use of diesel generators, improved frequency and voltage stability, priority power supply for critical loads	High capital costs (especially for LDES), battery degradation, energy losses during charge-discharge cycles, and increased requirements for control and protection systems	LDES Demonstration – Naval Base San Diego (CEC) – project demonstrating the use of a 1 MW/8 MWh LDES system as part of a military microgrid with PV and backup generation, DOE Microgrid and Integrated Microgrid Systems Program pilot microgrid projects with the integration of battery energy storage systems for critical infrastructure facilities

Notes: CAMP – Council for the Alaska Microreactor Program; MARVEL – Microreactor Applications Research Validation and Evaluation; INL – Idaho National Laboratory; DoD – U.S. Department of Defense; DOE – U.S. Department of Energy; REopt – Renewable Energy Optimisation Platform; LDES – Long-Duration Energy Storage; CEC – California Energy Commission; PV – Photovoltaic Systems

Source: compiled by the author based on United States Department of Energy (2022), F. List et al. (2024), Department of Defense breaks ground on Project Pele microreactor (2024), Department of the Air Force (2024), Demonstration of LDES to support Naval Base San Diego microgrid (2025), REopt facilitates solar microgrid scaling in Cameroon (2025), T.G. Lane & S.T. Revankar (2025)

The efficiency of microgrid systems is based on the principle of technological complementarity. Nuclear SMRs form the base level of energy supply, ensuring long-term autonomous operation, high reliability and low carbon emissions. At the same time, their widespread implementation is limited by high capital costs, regulatory complexity and the need for specialised infrastructure. RES (solar, wind and hydro plants) cover peak loads and reduce dependence on fossil fuels. Their implementation contributes to the decarbonisation of energy systems, but the efficiency of such sources depends significantly on the ability to store and manage energy flows. Energy storage systems (battery systems and LDES) act as a link between generation and load: they smooth out daily and weather-dependent fluctuations in RES, maintain frequency and voltage, and enable the microgrid to operate stably in isolated mode. The availability of sufficient storage capacity determines the extent to which a microgrid can operate autonomously for a long time without additional diesel generation. Traditional sources, represented by diesel and gas turbine generators, remain a necessary backup component that ensures the stability of the microgrid system during emergencies or when primary sources are unavailable. However, their high fuel dependence and significant carbon footprint limit their long-term viability. A promising direction for the development of microgrid architectures is the creation of hybrid systems, where the combination of nuclear, renewable and traditional sources, together with a developed energy storage subsystem, can achieve an optimal balance between autonomy, environmental friendliness and energy security.

The reliable operation of microgrid systems depends on the consistency of data exchange protocols and the level of cybersecurity between all components, from generators to control systems. To this end, several international technical standards are applied to ensure equipment compatibility, communication stability and protection against external influences. IEC 61850:2025 SER (2025) and IEEE 1547-2018 (2018) were applied. IEEE 1547-2018 provided the technical basis for compatibility and electrical interaction: IEC 61850:2025 SER formalised the data model (logical nodes), message formats and exchange services, and sets requirements for time synchronisation between devices. This can be used to create a unified information environment between controllers, inverters, and SCADA, and simplifies the integration of equipment from different suppliers. IEEE 1547-2018 supplemented the electrical part and defines the requirements for connecting Distributed Energy Resources (DER) (anti-islanding, ride-through, behaviour during voltage/frequency fluctuations, reactive power control – volt-var, freq-watt), which ensures a predictable and stable response of devices during network deviations.

To protect the Operational Technology (OT) level, the IEC 62443 series is applied. IEC 62443 (2024), along with practical guidelines from the Rockwell Automation guide (The ultimate guide..., 2025), recommends the “zones & conduits” approach, network segmentation, Demilitarised Zone (DMZ)/bastions for SCADA, least-privilege policies and access rights management, logging and anomaly monitoring (Security Information and Event Management (SIEM)/Operational Technology – Network Detection and Response (OT-NDR)).

NIST SP 800-82 Rev. 3 (2023) supplemented this with procedures: risk assessment methodologies, vulnerability management, incident response plans, regular configuration audits and security testing in SCADA/HIL/RTDS environments. If nuclear elements are introduced into the architecture, the design requirements are supplemented by the technology-inclusive regulatory criteria of the United States Nuclear Regulatory Commission (2025) and the risk-oriented expectations for cyber and physical resilience of the U.S. Nuclear Regulatory Commission, including additional requirements for fault tolerance, redundancy architecture, risk management strategy documentation, and system behaviour verification through HIL/field testing before operation (Dorman, 2023). Combined, these provisions require segmentation, access control, monitoring channels, and recovery procedures to be incorporated at the design stage and validated through HIL/RTDS testing before field deployment.

The modern development of 21st-century microgrid systems with nuclear reserves requires careful analysis of technical and economic feasibility and compliance with regulatory requirements. The integration of SMRs into microgrids can measurably reduce the total cost of energy: the introduction of SMRs reduces the Levelised Cost of Energy (LCOE) by 15-25% compared to diesel solutions due to higher fuel energy density and reduced logistics costs (International Atomic Energy Agency, 2024). At the same time, optimisation of RES through tools such as REopt has shown an increase in installed capacity utilisation of ~35% in the case of Cameroon, which also reduces system operating costs through better use of PV generation (REopt facilitates solar..., 2025). At the same time, the competitiveness of microreactors is highly sensitive to capital expenditures (CAPEX) and licensing time; with high capital costs or a long procedural cycle, the economic advantage may disappear (Abdusammi *et al.*, 2025). The economic model for the implementation of microgrid systems with nuclear reserves is based on the principle of “price for reliability”, where the priority is not to minimise costs but to maximise the energy stability of the facility. A hybrid architecture combining a

microreactor, energy storage systems and renewable sources is considered optimal, ensuring a high level of energy independence even in crisis conditions. The hybrid architecture “SMR (core) + RES + LDES + emergency reserve” provides a compromise between stability and economy. To implement it, integrated modelling and phased implementation with HIL/RTDS tests and pilots (DOE/INL recommendations) are advisable. The regulatory and technical environment is also important. The U.S. Nuclear Regulatory Commission (NRC) has developed adaptive approaches aimed at reducing implementation barriers while maintaining requirements for fault tolerance and cyber-physical security, which makes it possible to implement such hybrids in practice, provided that CAPEX is controlled and verification procedures are accelerated (Dorman, 2023; Demonstration of LDES..., 2025).

The development of a microgrid system architecture with backup from nuclear and traditional sources involves the creation of a modular structure that combines energy generation, storage, distribution and consumption. SMR, as the primary power source, provides long-term autonomous operation, while RES serve as peak or auxiliary installations (International Atomic Energy Agency, 2024). At the storage level, LDES and battery systems are central in balancing daily load fluctuations (Demonstration of LDES..., 2025). The distribution level was implemented through inverters and switching controllers with IEC 61850:2025 SER (2025) support, which ensures coordinated data exchange between all nodes. Control is based on intelligent algorithms that enable self-tuning and prediction of system operating modes. The hierarchical architecture with local controllers provides a 30-40% increase in the flexibility and resilience of microgrids compared to centralised schemes (REopt facilitates solar..., 2025). Together, this confirms the effectiveness of modular multi-level architecture as a basic model for microgrid systems with nuclear reserves. Flexible computer simulation environments are used to model energy flows in microgrid systems, which can be used for assessment of dynamic behaviour of the system in various scenarios, from normal operation to emergency shutdown (Table 2).

Table 2. Comparative characteristics of software environments for modelling energy flows in microgrids

Platform	Characteristic	Benefits	Issues
DlgSILENT PowerFactory	Analysis of electrical networks, verification of stability under load changes	High calculation accuracy, IEC 61850 support	High cost of a licence
GridLAB-D	Modelling of distributed systems based on weather and domestic factors	Open-source software, Python compatibility	Less detail on dynamics
PyPSA	Power distribution optimisation, economic modelling	Fully open environment, integration with Jupyter	Less support for EMT effects
PSCAD/EMTDC	Detailed electromagnetic modelling, transient processes	High accuracy of EMT analysis	Not suitable for large systems

Table 2. Continued

Platform	Characteristic	Benefits	Issues
RTDS / OPAL-RT HYBERSIM	Real-time simulation (HIL)	Verification of control algorithms in real time, co-simulation	High cost, complexity of integration

Notes: EMT – Electromagnetic Transients

Source: compiled by the author based on DlgSILENT GmbH (n.d.), PSCAD (n.d.), RTDS Technologies (n.d.), Opal-RT Technologies (n.d.a, n.d.b)

Full validation of microgrid architectures requires a combination of tools at different levels: PyPSA and GridLAB-D for scenario optimisation and economic analysis, PowerFactory and PSCAD for electrical and EMT analysis, RTDS/OPAL-RT HIL validation of control algorithms. The recommended sequence of work (scenario modelling→network/dynamic calculations→detailed EMT studies→HIL testing before field pilot) minimises engineering risks and provides quantitative verification of solutions. Open platforms provide speed and reproducibility of experiments, while commercial and HIL systems are necessary for engineering accuracy and protection verification, but come with higher costs and integration complexity. For correct integration of tools, agreed models/exchange formats, acceptance criteria (LCOE, Expected Energy Not Supplied (EENS)/Loss of Load Probability (LOLP), diesel hours) and a HIL validation plan are mandatory. The combined use of these platforms enables co-simulation, i.e. simultaneous modelling of physical processes in the electrical network and software control actions. An example of the implementation of this approach is HYPERSIM, which was synchronised with Real-Time Digital Simulator (RTDS) to assess the behaviour of the microgrid during an emergency shutdown of the main generator, which made it possible to verify the algorithms for transitioning to autonomous mode and protective measures.

The integration of microreactors as baseload power sources requires consideration of thermal cycles, power dynamics, and control time delays, with the Reactor Energy Interface (REI) concept being appropriate for ensuring frequency and voltage coordination between the nuclear module and the grid (Lane & Revankar, 2025). Tests at the Idaho National Laboratory demonstrate the practical feasibility of hybrid SMR integration into a microgrid with prioritisation of energy flows (SMR core, RES peaks, diesel/LDES reserve) and highlight the need for HIL validation of control algorithms and step-by-step technical and economic validation before scaling up (List *et al.*, 2024). To ensure the stability of energy supply to critical facilities, it is necessary to model the behaviour of the microgrid system under abnormal conditions, including sudden source failure, network overload, frequency/voltage disturbance, and cyberattack on the control controller. For such scenarios, fault injection simulation is used to simulate the failure of individual elements to test the system's response

(NIST SP 800-82 Rev. 3, 2023; IEC 62443, 2024). The simulation uses libraries of measurements from real power grids, including the Pacific Northwest National Laboratory Phasor Measurement Unit Library (PNNL Phasor Measurement Unit (PMU) Library) (Biswas *et al.*, 2023) and the Lawrence Berkeley National Laboratory Phasor Measurement Unit Event Library (LBNL PMU Event Library) (Swenson *et al.*, 2019), which can be used to train machine learning algorithms on real failure profiles. The microgrid system operates on the principle of hierarchical control, from local controllers at the node level to a central intelligent coordinator. Power distribution optimisation algorithms are implemented using deep reinforcement learning (Hadi *et al.*, 2025), and short-term load changes are predicted based on TVFEMD-LSTM-ARMAX models (Yin *et al.*, 2024). HIL modelling is used to verify the system's performance, validating real controllers (Programmable Logic Controller, Remote Terminal Unit, PMU) in a closed simulation loop, where the real-time subsystem interacts with digital twins of the microgrid to verify the stability of the system during emergency unloading (RTDS Technologies, n.d.; Opal-RT Technologies, n.d.a).

The results of the study showed that a hybrid microgrid architecture with decentralised control provides increased reliability and flexibility of the system under variable load conditions, while the combination of nuclear, renewable and traditional sources can be used for stable operation without loss of efficiency. This is consistent with M. Abbasi *et al.* (2023), identifying decentralisation, modularity and flexibility as key principles of microgrid architectures. The study emphasised that the efficiency of microgrid systems largely depends on the ability to manage in real time and coordinate between generation levels, which also coincides with the results of the current study. The integration of intelligent controllers and AI algorithms increases the adaptability of the system, and the combination of physical sources and digital algorithms forms the basis for self-regulation of the energy circuit. S. Punitha *et al.* (2024) determined that the main barriers to the large-scale implementation of microgrids are high CAPEX and lengthy licensing procedures. Regulatory uncertainty and the lack of unified technical standards materially complicate investment and equipment integration. The study emphasised the need to combine regulatory reforms, standardisation and financial mechanisms to overcome

these barriers, which is consistent with the current study. Without standardised procedures and accelerated licensing, scaling will be delayed. It is advisable to combine targeted financial instruments with accelerated, unified licensing procedures and verification of decisions through HIL/RTDS pilots to reduce risks and accelerate the scaling of microgrids.

The results of the study confirmed that the key challenge in designing microgrid systems is ensuring stable operation during autonomous mode, especially when the load changes and the connection to the main grid is lost. This correlates with the findings of M. Uddin *et al.* (2023), noting that decentralised control and distribution of energy functions between sources increase system flexibility and reliability. The presented study also determined that the combination of SMR as the base source, RES as the peak source, and backup installations as the emergency unit ensures the stability of energy supply in isolation mode. The practical relevance of the conclusions of M. Uddin *et al.* on the role of decentralisation and adaptive control in increasing the autonomy of microgrid architectures has been confirmed. P. Arévalo *et al.* (2024) showed that the integration of intelligent control (a combination of deep Reinforcement Learning (RL) for online optimisation and complex time models (TVFEMD-LSTM-ARMAX) for forecasting) substantially improves the energy efficiency of the microgrid. This is consistent with the results of this study, which found a reduction in losses and an increase in installed capacity utilisation when applying similar AI approaches. The implementation of AI in microgrids is promising, provided that there is strict data validation, HIL/RTDS testing, drift detection mechanisms with sandbox testing, ensure model interpretability (explainability), and accompanying financial and regulatory support.

The results of the study demonstrated that multi-level coordination of inverters can maintain stable frequency and voltage even under conditions of load fluctuations and transitions between “grid-connected” and “islanded” modes. This was consistent with J.D. Watson *et al.* (2021), who experimentally proved that scalable grid-forming control can synchronise local generators and maintain dynamic stability without a centralised controller. The authors showed that this

architecture ensures coordinated operation of inverters through local control loops, minimises phase deviations, and maintains real-time stability without a centralised controller. Scalable grid-forming control with local control loops ensures frequency-voltage stability and synchronisation of local generators in decentralised microgrids. B.K. Joseph *et al.* (2023) examined the architectural aspects of microgrid systems for distributed generation, emphasising decentralisation, multi-source, modularity, hierarchical control, and the need for combined modelling (electrical engineering + EMT + HIL) to verify algorithms and protections, which is consistent with the current study.

Both works emphasise decentralisation, multi-source and hierarchical control schemes and agree on the need for co-simulation (PyPSA/GridLAB-D→PowerFactory/PSCAD→RTDS/OPAL-RT) for complete validation of solutions. The difference lies in the emphasis: B.K. Joseph *et al.* primarily address technical architecture and modelling methods, while the present text additionally considers regulatory and economic constraints, SMR integration (nuclear context), CAPEX risks, and cyber/physical resilience issues. Thus, modelling the architecture of a microgrid system with nuclear backup confirms the possibility of creating an adaptive, cyber-resilient and self-controlled energy system capable of functioning independently of the centralised grid. The use of real-time hardware-in-the-loop simulations (RTDS, OPAL-RT, PyPSA) ensures reliable reproduction of the dynamics of electrical processes and can be used to evaluate the effectiveness of artificial intelligence algorithms under peak and emergency loads. Intelligent methods for controlling and modelling hybrid energy microgrids. With the increasing complexity of microgrid systems and the integration of multiple heterogeneous energy sources, there is a need for intelligent control capable of responding quickly to load changes, predicting failures, and ensuring stable network operation. These tasks are implemented using AI and ML models that combine demand forecasting, power distribution optimisation, anomaly detection and preventive maintenance. Their application improves system efficiency, reduces energy losses and ensures the stability of the microgrid infrastructure even in difficult or emergency conditions (Table 3).

Table 3. AI forecasting models, management and anomaly detection in microgrids

Model/approach	Characteristic	Example of use
TVFEMD-LSTM-ARMAX	Short-term load forecasting with high accuracy (hybrid pre-processing + LSTM + ARMAX)	Forecasting hourly/minute profiles for microgrid balance control
LSTM/CNN-based forecasting	Forecasting daily/hourly loads, identifying trends	Weather-dependent PV/wind forecasts and short-term consumption
Deep Reinforcement Learning (DQN, Actor-Critic)	Online optimisation of power distribution policies (DRL for source management)	Simulation policies for dynamic balance SMR+RES+LDES with subsequent HIL verification, HIL testing/algorithm verification

Table 3. Continued

Model/approach	Characteristic	Example of use
Digital twins+Predictive Maintenance (ML-regression/classification)	Preventive maintenance, failure prediction up to 24 hours	Creation of a digital twin of a microreactor/distribution for failure prediction and maintenance planning
Unsupervised anomaly detection/ Autoencoders	Detection of anomalies/cyber intrusions in the OT network	IDS based on anomalies in PMU data, preparatory data and validation using PMU libraries (PNNL, LBNL, pmuBAGE)
PyPSA/GridLAB-D (as an environment for ML-pipeline)	Preparation of scenarios, generation of time series, and economic assessment before training	Preparation of scenarios and generation of time series for model training/ policy testing (household/industrial load traces, RES generation, emergency, market/price scenarios, stochastic conditions and failure scenarios, HIL/ fault-injection scenarios)

Notes: ARMAX – AutoRegressive Moving Average with eXogenous inputs; PMU – Phasor Measurement Unit; DRL – Deep Reinforcement Learning

Source: compiled by the author based on Electric Power Research Institute (n.d.), B. Foggo *et al.* (2022), J.R. Lovering (2023), H.C. Bryan *et al.* (2023), F. List *et al.* (2024), International Atomic Energy Agency (2024), Department of Defense breaks ground on Project Pele microreactor (2024), B.N. Hanna *et al.* (2024), S. Chen *et al.* (2024), A. Abou-Jaoude *et al.* (2024)

Hybrid models, in particular TVFEMD-LSTM-ARMAX, demonstrate the highest accuracy in short-term load forecasting, which is critical for the stability of energy distribution in local networks. Their combination with LSTM/CNN can incorporate seasonal and weather-dependent factors, which is especially important for microgrids with a high share of RES. In the field of power flow optimisation, DRL algorithms are leading, capable of making decisions in real time without rigidly fixed system models. The use of OPAL-RT and RTDS environments for HIL validation confirms their practical suitability for testing control strategies in physically realistic conditions. Digital Twin-based models extend the functionality of the system by enabling the prediction of equipment technical condition and the transition from reactive to preventive maintenance. In parallel, Unsupervised Anomaly Detection and Autoencoders approaches, based on PMU data analysis, form the basis for cybersecurity and real-time anomaly monitoring. The PyPSA and GridLAB-D base platforms serve as an integration environment for creating training scenarios, generating time series, and validating models. They bridge the gap between theoretical approaches and practical engineering tasks, providing a comprehensive ML pipeline for modelling, training, and testing control algorithms.

This indicates a shift towards adaptive, self-learning microgrid architectures, in which AI serves as a central element for control, forecasting and security, supporting high reliability and autonomy of the energy infrastructure. Intelligent control of a modern 21st-century microgrid is based on the combined effect of several levels of artificial intelligence. The predictive level is responsible for forecasting loads and potential failures based on LSTM and ARMAX models, ensuring energy balance planning. The operational level implements real-time energy flow optimisation using DRL or

Model Predictive Control algorithms, which increases the efficiency and flexibility of the system. The protective level monitors anomalies and detects cyberattacks through an intelligent IDS integrated into the OT infrastructure. Together, these levels form an adaptive, self-learning energy network capable of independently responding to external and internal influences. The use of multi-level intelligent approaches can measurably improve the reliability and autonomy of microgrid systems, which is crucial for the energy security of critical facilities.

Given the growing demands for autonomy, flexibility and cyber resilience of energy systems, particularly for critical and remote facilities, there is a need to develop integrated microgrid architectures. Such systems must combine nuclear, renewable and traditional energy sources, ensuring stability and balancing under variable load conditions. Based on an analysis of existing technical and simulation solutions, a structural model of a microgrid system was developed, prioritising the continuous power supply of critical facilities and the possibility of scaling in real operating conditions. The system architecture has a hierarchical structure consisting of five interconnected subsystems operating in a common control loop. The generation subsystem provides basic power supply from a 5-20 MW nuclear microreactor, supplemented by solar and wind installations to cover peak loads and backup diesel or gas generators for emergency power. All sources are integrated via inverters that comply with the IEEE 1547-2018 (2018) standard, which regulates the technical parameters of interaction with distributed electrical networks. The energy storage subsystem includes LDES, lithium-ion batteries for rapid response to load changes, and an energy storage system controller subordinate to the main AI control module. This configuration ensures a balance between energy production and consumption and smooths out peak load fluctuations.

The distribution subsystem has intelligent control with full automation of switching and control functions, equipped with PMU measuring devices that provide real-time monitoring of voltage, frequency and power. International Electrotechnical Commission standards are used to unify communications. IEC 61850:2025 SER (2025) ensures compatibility and data synchronisation between all system components. The consumer subsystem is structured according to the principle of load priority: critical loads (medical, communication, and security systems) receive uninterrupted power, while non-critical nodes can be disconnected in emergency modes. Load distribution is conducted by an intelligent prioritisation algorithm that minimises power losses and maintains system stability. The central element is the control subsystem, which implements an intelligent energy management system (AI-based EMS). It performs the functions of load forecasting, coordination of generation, storage and consumption subsystems, as well as control of emergency and peak modes. A combination of PyPSA and GridLAB-D simulation environments is used to model and optimise processes, which can be used to combine physical models of the power system with algorithmic control tools (United States Department of Energy, 2022; International Atomic Energy Agency, 2024).

The proposed architecture forms a flexible, scalable, and cyber-resilient microgrid model capable of integrating nuclear, renewable, and traditional energy sources into a single intelligent circuit. Thanks to multi-level control and adaptive balancing algorithms, the system provides a high level of autonomy, making it suitable for use in military, remote and critical infrastructure where continuity of power supply is a key requirement. The interaction of energy and information flows is implemented using a closed-loop adaptive control algorithm that ensures real-time system

response. In the first stage, the sensor network (PMU, SCADA) collects data on the status of nodes and transmits it to local controllers. The information obtained is analysed by an AI-based EMS, which forecasts the load for a short period (15-30 minutes) and determines the optimal distribution of power between sources. If a tendency towards overload is detected, the AI module generates a command to discharge the LDES storage systems or increase generation from renewable sources. If a generator failure is detected, a backup diesel or gas installation subsystem is automatically activated. If a cyber threat is detected, the security analytics unit initiates isolation of the affected network segment, preventing the attack from spreading through industrial protocols. The decision-making cycle is performed in real time at intervals of 1-2 seconds, which meets the requirements for operational control of microgrid systems (United States Department of Energy, 2022; REopt facilitates solar..., 2025). This approach ensures stable system operation even in the presence of external influences, equipment failures or attempts at unauthorised interference, which is critical for microgrids with nuclear energy reserves. At the same time, integrating heterogeneous AI models into a single control loop that operates with such a time step on real equipment is a complex engineering task. Key methodological challenges include ensuring sufficient computing resources, real-time stability of DRL agents, and coordination of decisions between different levels of the control hierarchy. In this work, these aspects are considered at the level of general architectural requirements, while their detailed software and hardware implementation is appropriate for further research. For clarity, Figure 1 shows a structural model of a microgrid system that reflects the interaction of subsystems for generation, energy storage, distribution, consumers, and intelligent control.

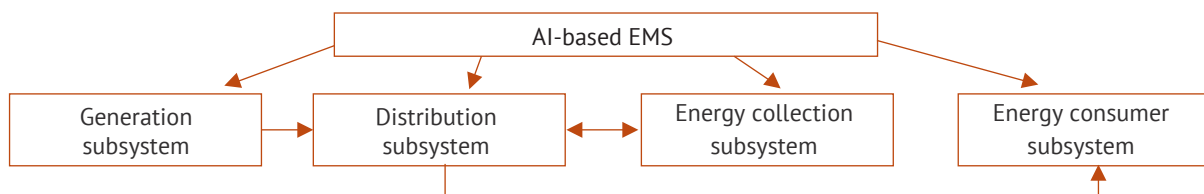


Figure 1. Architecture of an intelligent microgrid system

Source: compiled by the author based on M. Abbasi et al. (2023)

The proposed microgrid system architecture demonstrates several technical and operational advantages, which are confirmed by the results of reports (List *et al.*, 2024; Demonstration of LDES..., 2025; REopt facilitates solar..., 2025). First and foremost, it supports continuity of power supply by combining a basic nuclear source with renewable generators and energy storage systems. This combination can achieve a target availability factor of over 99.9% and reduce

the probability of LOLP to close to 1%, which meets the design criteria for critical infrastructure microgrid systems. Resilience to emergencies is ensured by the fact that the architecture supports multi-level redundancy, and control algorithms can quickly respond to failures or peak load changes. AI-based EMS control predicts system behaviour in real time, optimises energy flow distribution and reduces the risk of overloads. High intellectual adaptation is achieved using

ML mechanisms that enable the system to self-configure based on accumulated historical data. Cyber resilience issues are addressed in accordance with the requirements of IEC 62443 (2024) and NIST SP 800-82 Rev. 3 (2023) standards, which establish principles for network segmentation, access control, and real-time anomaly detection. In addition, the architecture is scalable and can be adapted for energy facilities of various capacities, from several hundred kilowatts to over 20 MW (United States Department of Energy, 2022; List *et al.*, 2024). This makes the model suitable for deployment in remote, military or industrial energy complexes, where system reliability and autonomy are critical factors. Thus, the model presents a scalable approach to microgrids with nuclear-based reserve capacity, balancing engineering reliability, control flexibility and digital security. Its implementation could form the basis for the creation of sustainable autonomous energy solutions for military, industrial and remote facilities.

The results of the study determined that the developed AI-based EMS architecture provides autonomous balancing between SMR, RES, and LDES energy sources, coordinating their operation based on adaptive DRL algorithms. The proposed solution integrates predictive, operational and protective AI layers, forming an integrated framework for microgrid optimisation, forecasting and security. This is consistent with the study by C.P. Agupugo *et al.* (2025), presenting an overview of microgrid management platforms that integrate AI and deep reinforcement learning for sustainable energy management. The results confirm the effectiveness of combining AI and DRL to create self-learning, adaptive architectures capable of autonomous decision-making and dynamic balancing of energy flows. This approach reinforced the feasibility of using an AI core as a central element of forecasting, optimisation and cyber resilience in modern microgrid systems.

P. Thulasiraman *et al.* (2023) examined the application of cyber-analytical methods for detecting anomalies in smart microgrid systems using synchronised PMU measurements. The study implemented a hybrid data analysis model that combines statistical methods with machine learning algorithms to detect cyber-attacks in real time. The approach made it possible to identify abnormal changes in phasor signals caused by deliberate interference or technical failures. The comprehensive use of OT data analytics improves the resilience of the control system. These conclusions are consistent with current research, which envisages the use of PMU and SCADA data to build an intelligent anomaly detection system capable of operating in real time. The results of both studies confirm the effectiveness of applying cyber-analytical approaches to improving the reliability, cyber resilience and responsiveness of microgrid systems, particularly in hybrid architectures with a high level of automation.

The results of the study revealed that the combination of LSTM and ARMAX models provides accurate demand forecasting and energy balance planning for microgrid systems, confirming the effectiveness of the hybrid approach for stabilising power distribution under variable seasonal and weather conditions. T. Limouni *et al.* (2025) conducted a thorough analysis of microgrid control methods, classifying LSTM, CNN, Auto Regressive Integrated Moving Average (ARIMA) and ARMAX approaches according to the accuracy of short-term forecasts and the ability to address seasonal factors. The conclusions demonstrated the feasibility of using hybrid AI models, which ensure high system stability with a large share of renewable energy sources and support the interaction of the predictive, operational, and protective levels of intelligent control. N.F.P. Dinata *et al.* (2024) conducted a systematic review of approaches to the application of deep reinforcement learning algorithms for optimising power flows in microgrid systems. The paper compares Deep Q-Network (DQN), Proximal Policy Optimisation (PPO) and Actor-Critic methods in detail in terms of their ability to make real-time decisions under stochastic load changes. The study emphasised the role of HIL validation (OPAL-RT, RTDS) in testing DRL algorithms before implementation in real power grids. In the presented study, this aspect is implemented through the operational level of AI-EMS, which distributes power between SMR, RES and LDES sources using DRL agents. The results obtained by N.F.P. Dinata *et al.* confirm the effectiveness of using DRL as the basis for adaptive control, which is also consistent with the conclusions regarding the optimisation of energy flows and ensuring the dynamic stability of the microgrid system in the results of this study.

H. Dui *et al.* (2025) proposed a Digital Twin-enhanced opportunistic maintenance model for smart microgrid systems. It is based on the Risk Importance Measure assessment, which can predict the probability of failures and determine maintenance priorities. The digital twin model reproduces physical processes in real time and updates equipment status predictions based on sensor data. Experiments have shown a reduction in the frequency of accidents and an increase in the efficiency of scheduled maintenance. The architecture developed in the current study implements a similar approach of combining ML regression with simulation modelling to determine the optimal time for maintenance. Digital twins are a key component in the transition from reactive to preventive maintenance, which increases the reliability and availability of microgrid infrastructure. In summary, the proposed architecture integrates nuclear, renewable and traditional energy sources into a single intelligent circuit with multi-level control. The system demonstrates high autonomy, flexibility, and cyber resilience, ensuring uninterrupted power supply to critical facilities even under variable load conditions and external influences. This confirms the feasibility of

using hybrid AI models, digital twins, and DRL algorithms as the basis for building sustainable, self-learning microgrid systems of the new generation.

Conclusions

The study found that microgrid architecture relies on decentralisation, multi-source power, intelligent control, modularity, and resistance to transient processes and emergency modes. Combining a microreactor with renewable sources ensures a stable power supply even in remote or harsh conditions. The 100 kW_e MARVEL demonstration microreactor confirms the possibility of integrating nuclear modules into local microgrids, while the Project Pele mobile micro-reactor (1-5 MW) demonstrates the practicality of autonomous power supply for military facilities. The base load is formed by nuclear SMRs, which provide long-term autonomous operation with low CO₂ emissions, renewable sources cover peaks and contribute to decarbonisation, and traditional diesel and gas plants serve as a backup during emergencies. The efficiency of the system is enhanced by the integration of long-term energy storage systems. Compared to diesel solutions, the implementation of SMRs can reduce LCOE by approximately 15-25%. PyP-SA, GridLAB-D, PowerFactory, PSCAD and RTDS are used for modelling, analysis and testing, while HIL modelling can be used for real-time control algorithms to be tested and engineering risks to be reduced.

The possibility of co-simulation of HYPERSIM with RTDS to assess system behaviour during emergency generator shutdown has been confirmed. Intelligent AI/ML algorithms are used to forecast load, optimise power distribution and detect anomalies. DRL, LSTM, and ARMAX optimisation models enable short-term forecasting with minute-by-minute accuracy, while a digital twin system can detect potential failures up to 24 hours before they occur. The hybrid configuration of “SMR+RES+LDES+reserve” provides a balanced combination of autonomy, environmental friendliness and safety, forming a scalable, cyber-resilient and efficient energy supply model suitable for military, industrial and remote facilities. The limitation is that the study is based on simulation and laboratory data, without full-scale experimental verification. Future research should focus on optimising the integration of AI control modules and assessing cyber resilience during the actual operation of hybrid microgrids.

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Conflict of Interest

None.

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Розробка та моделювання архітектури мікрогрідових систем з резервуванням від ядерних і традиційних джерел для критичної інфраструктури: підвищення надійності та безпеки енергопостачання

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Анотація. Ця стаття представила концептуальну модель інтелектуальної енергетичної системи з комбінованими джерелами живлення, призначену для покращення безперервності, стабільності та безпеки енергопостачання об'єктів. Вона базувалась на комплексному підході, що поєднує аналітичні, порівняльні та структурно-функціональні методи. Вона базувалась на передумові, що мікромережа, як гібридна система, поєднує мікрореактори, відновлювані джерела та резервні генератори, керовані штучним інтелектом, для забезпечення стабільного енергопостачання. Мікрореактори можуть знизити витрати на енергію на 15-25 %, а інтеграція відновлюваних джерел може збільшити коефіцієнт використання потужності на ≈ 35 % при використанні систем довгострокового зберігання. Гібридна архітектура «мікрореактори (ядро) + відновлювані джерела + сховище + аварійний резерв» забезпечила доступність $>99,9$ % та знижує ймовірність відмови до ≈ 1 %, що відповідає вимогам систем критичної інфраструктури. Ієрархічне управління є централізованим, з локальними контролерами, координуваними центральним модулем штучного інтелекту, що підвищує стабільність системи на 30-40 %. Операційний цикл системи управління енергією на основі штучного інтелекту виконується в режимі реального часу з інтервалом 1-2 секунди, забезпечуючи швидке балансування навантаження, реагування на надзвичайні події та ізоляцію сегментів мережі у разі кіберзагрози. Нормативні вимоги Комісії з ядерного регулювання США передбачають відмовостійкість, резервування та тестування в середовищі «апаратне забезпечення в циклі», тоді як поетапне моделювання з використанням Python для аналізу енергетичних систем, автоматизованого проектування енергетичних систем та цифрового симулятора реального часу мінімізує технічні ризики та підвищує точність верифікації системи. Розроблена модель мікромережевої системи є гнучкою, масштабованою та кіберстійкою, поєднуючи ядерні, відновлювані та традиційні джерела енергії в єдиний інтелектуальний цикл керування, забезпечуючи безперебійне та автономне електропостачання критично важливих об'єктів за будь-яких умов. Результати можуть бути використані в концептуальному проектуванні, проектних структурах та оборонних відомствах для створення автономних та кіберстійких мікромережевих систем

Ключові слова: мікромережа; дуже малий модульний реактор; системи зберігання енергії; інтелектуальне керування електромережею; довготривале зберігання енергії; цифровий двійник електромережі; автономність електромережі