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Exemplary Model of AI-Supported Adaptive Optimization Energy Flow Control in Smart City Microgrids: A Simulation-Based Scenarios

Ass. Eng. Iliyan Vasilev, PhD
PHD student, Faculty of Pedagogy, Sofia university- Bulgaria, ORCID: 0009-0008-0863-1516

ABSTRACT: The paper focuses on the possibilities for developing a model for adaptive control of electricity flows in urban microgrids using AI support into the Internet of Things networks. The goal is the requirement for smarter, more adaptive and sustainable methods in controlling local energy systems. This is critical for distributed generation and the growing incorporation of renewable energy resources. The study is conceptual in nature and aims to develop an integrated model that combines physical energy infrastructure, IoT-based data acquisition, the analytical capabilities of artificial intelligence, and a logic for adaptive real-time decision-making. It is analyzed the theoretical foundations of adaptive management in microgrids, the design of model development of multilayered architecture, and the interaction between physical and information flows. Particular attention is given to the role of intelligent monitoring devices, forecasting and optimization algorithms, as well as the coordination between local generation, storage, consumption, and exchange with the main grid. The proposed model is analyzed through comparison with traditional, optimization-based, and AI-driven models discussed in the scientific literature, and it is argued that the integration of AI and IoT enables higher adaptability, improved load balancing, more efficient use of local energy resources, and better integration of renewable energy sources in the urban energy environment. The proposed model provides a conceptual framework for the intelligent management of electricity flows in urban microgrids, emphasizing its potential for further development and application in sustainable energy systems.

KEYWORDS: urban microgrids, adaptive control, electricity flows, artificial intelligence, Internet of Things, smart energy systems, energy management, renewable energy sources

INTRODUCTION

Developing models for adaptive management of electrical energy flows with AI- driven mechanisms and IoT for energy systems is more provoked by the two facts: increasing the urban areas and the decentralization of energy production. One last is the widespread adoption of renewable energy sources. Urban microgrids serve as a key element of modern energy infrastructure. This fact is based on that they promote some level of flexibility and sustainable management of local energy resources. Traditional approaches to managing electrical energy flows are less sufficiently effective. They usually have limited ability to adapt to changing conditions like complex loads. The development of artificial intelligence and the Internet of Things create new opportunities for intelligent, adaptive, and automated management, which necessitates the development of new conceptual models integrating these technologies within urban microgrids. This transition to smart governance is closely linked to the principles of Industry 5.0, which emphasize human-machine collaboration to build sustainable and adaptive urban ecosystems (Nikolov, 2025a).

The main objective of the study is to develop and substantiate a conceptual model for adaptive management of electrical energy flows in urban microgrids through the use of artificial intelligence and IoT technologies. To achieve this objective, the following tasks are undertaken:

- analysis of existing approaches to microgrid management;
- examination of the capabilities of AI and IoT in the energy sector;
- development of an architecture for an adaptive model;
- evaluation of its applicability and effectiveness in an urban environment.

The object of the study is urban microgrids as part of intelligent energy systems, characterized by the integration of various energy sources, consumers, and storage systems. The subject of the study is the process of adaptive management of electrical energy flows in these microgrids through the application of artificial intelligence algorithms and Internet of Things infrastructure. The main thesis argued in this report is that the integration of AI and IoT in the management of urban microgrids enables the creation of adaptive systems that significantly improve the efficiency, reliability, and sustainability of electrical energy flows compared to traditional centralized or semiautomated approaches.

The methodological approach of the study is based on system analysis- first and secondly- the conceptual modelling with comparative analysis. Methods include a theoretical review of the scientific literature, analysis of existing technological solutions, and the synthesis of a conceptual model. The AI techniques that are used as tools are: machine learning and optimization algorithms, as well as IoT platforms and sensor. Simulation are may also be used for theoretical validation of the proposed framework. The scope of the study is limited to the conceptual development of a model for adaptive management, without including real experimental implementation or empirical testing in a real environment. The focus is placed on urban microgrids, while national or cross-border energy systems are not examined in detail. The limitations of the study cores in the assumptions related to the availability of sufficiently developed IoT infrastructure and widely access to reliable data. An additional limitation is the complexity of real energy systems, which may require more in-depth empirical research for full validation of the proposed model.

Theoretical Framework of Adaptive Management of Electrical Energy Flows in Urban Microgrids through AI and IoT

The theoretical framework of adaptive management of electrical energy flows in urban microgrids through artificial intelligence and the Internet of Things has emerged as a priority area in the study of intelligent energy systems. All that is clearly explainable by traditional centralized models that are increasingly unable to meet the requirements for flexibility, resilience, autonomy, and the integration of renewable energy sources. The microgrids on that behalf, are prompted as a fundamental element of the future energy architecture of the smart city combining local generation, storage, load management, and coordinated interaction with the main grid. A key element of this architecture is the integration of renewable energy sources - such as solar, wind, and biomass - into urban infrastructure, which requires the use of smart meters to support system decarbonization (Nikolov, 2024a).The energy management systems in microgrids with accent on AI and IoT as efficiency factors and adaptability are reviewed by Hoummadi et al., (2025), Joshi et al., (2023), Tasmant et al., (2025). Energy management in microgrids is understood as a process of dynamically balancing generation, consumption, storage, and electricity exchange under conditions of uncertainty caused by fluctuations in demand, the instability of renewable sources, and infrastructure constraints. It is because of this that the focus of research has moved from traditional control strategies towards adaptive and prediction-based strategies that can work in real-time conditions. Effective management under such circumstances entails the application of optimization and control (Cabrera-Tobar et al. 2022).

According to Thirunavukkarasu et al. (2022), these approaches facilitate the attainment of a proper equilibrium in regard to technical, economical, and ecological factors. The environmental factor can be precisely measured through specific sustainability indicators, such as carbon emissions ($CO2$) and fine particulate matter ($PM10$) levels, which determine the real ecological footprint of the smart city (Nikolov, 2025b). The IoT becomes a key element in the process because it creates the basis for data acquisition, communication, and processing. This is possible trough smart meters, sensors, controllers, and communication modules with transition toward proactive, real-time datadriven management (Kirmani et al., 2022; Keshinro et al., 2020; Ogundeko et al., 2016).

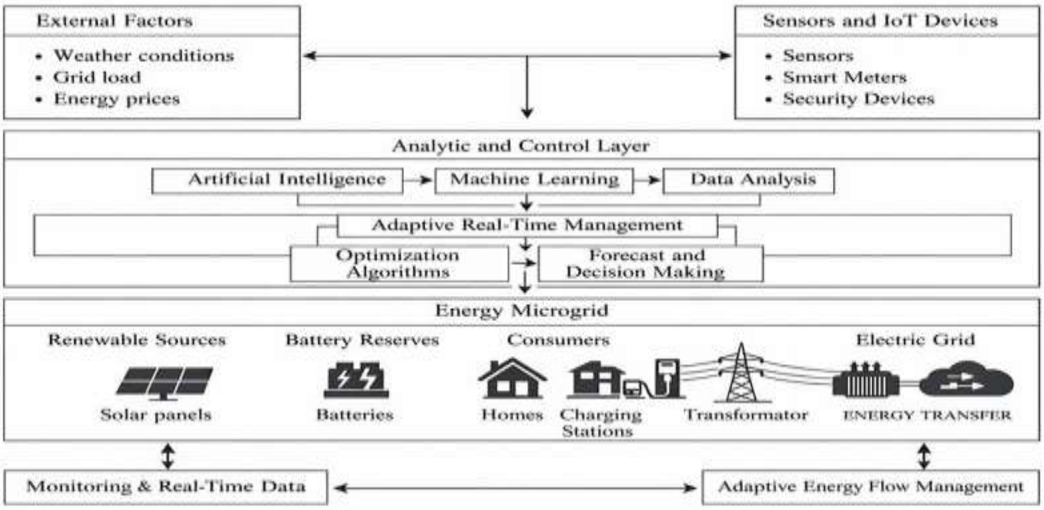

Figure 1. General architectural diagram of the model

The digital infrastructure in Figure 1. enables artificial intelligence to function as an analytical and managerial mechanism, transforming data into forecasts, recommendations, and automated decisions. Algorithms as Machine, Deep and Reinforced Learning (ML,DL,RL), are used for load forecasting, demand estimation, battery management, anomaly detection, and resource redistribution. Many researches shows benefits of forecast estimation accuracy in interconnected microgrids with multiple distributed energy sources (Joshi et al., 2023; Singh et al., 2024). Altin &Eyimaya, (2018), Amoura et al., (2023) report that the intelligent coordination of generation, storage, and load is crucial for improving energy efficiency and reliability for hybrid systems and microgrids. Multilayer architectures and the cooperation model between cloud and edge computing gives faster and more adaptive real-time responses, particularly in urban environments (Keshinro, 2023).

Energy source diversification and shift towards interlinked and collaborative microgrids widen the scope of energy independence, resilience, and collaboration (Hoummadi et al., 2023; Rodriguez-Gil et al., 2024). However, there is also a downside to these reports, which include various issues that need to be addressed:

[1] interoperability (Kirmani et al., 2022),
[2] cybersecurity and data protection (Khan et al., 2022),
[3] communication reliability (Khan et al., 2022),
[4] regulatory frameworks, and
[5] the scalability of solutions (Tasmant et al., 2025).

One significant limitation of most of the existing literature includes the inability of conducting the analysis within actual urban environment settings due to the lack of availability of more robust models (Cabrera-Tobar et al., 2022; Thirunavukkarasu et al., 2022). In this sense, the future development of adaptive management in urban microgrids will depend on combining technological innovation with practical applicability, standardization, security, and integration into the broader smart urban infrastructure.

Methodology and Tools for Developing a Model for Adaptive Management of Electrical Energy Flows in Urban Microgrids through AI and IoT

The methodological framework of the study is based on a systemic, conceptual, and comparative-analytical approach that integrates knowledge from the fields of energy engineering, information technologies, and artificial intelligence. The basis for the approach is the realization that the urban microgrid can be regarded as a complicated system, consisting of different components and elements of the energy system interacting with each other. The theoretical basis of the research suggests that it is necessary to create a strong model whose validity will not depend on any experimental verification, but rather on its logical substantiation and comparative evaluation. The leading methodological approach is the critical review of the literature, through which the main trends in the development of energy management systems, the role of artificial intelligence, and the significance of IoT technologies are identified. This approach is complemented by comparative-inference analysis, which allows the proposed model to be positioned in relation to traditional, optimization-based, AI-driven, and IoT-oriented solutions, thereby substantiating its distinctive features and advantages.

The development of the model includes the following stages:

[1] Analysis of the energy system and identification of the main components and parameters of the microgrid.
[2] Conceptual modeling and construction of the multi-layer architecture of the system.
[3] Selection of an algorithmic toolkit for forecasting, optimization, and adaptive management.
[4] Development of the logic of adaptive control and real-time response mechanisms.
[5] Comparative analysis of the proposed model against existing solutions based on key criteria.

The tools used within the methodology are predominantly analytical and conceptual in nature. The primary tool is the scientific literature, which serves as a basis for identifying existing models and approaches. Through a systematic review of publications, the main characteristics, advantages, and limitations of different solutions are identified, enabling the construction of a comparative framework.

Another important tool consists of logical and architectural diagrams, through which the structure of the proposed model is presented. That gives clear visualization of data flows, relationships between components and control logic. The comparative matrices are used to systematize information about different models according to predefined criteria. Also they facilitate the analysis and enable an objective evaluation of the position of the proposed model relative to existing solutions.

Model for Adaptive Management of Electrical Energy Flows in Urban Microgrids through AI and IoT

This model offers an intelligent and hierarchical structure that utilizes artificial intelligence and the Internet of Things (IoT) to control energy distribution within city microgrids. The design of the model is such that it is adaptive, hence contributing towards effective energy utilization in urban settings. Its core idea is based on the understanding that the modern urban microgrid does not function as a static energy structure, but as a complex cyber-physical system in which the production, consumption, storage, and redistribution of electrical energy are continuously influenced by multiple internal and external factors. Effective management of electrical energy flows cannot rely on fixed rules. It requires a system that can sense current conditions, interpret them, and make adaptive decisions in real time.

The basic part of the model is the idea of continuous interaction between the physical energy infrastructure and the digital environment for monitoring, analysis, and control. The microgrid incorporates all local sources of energy, storage facilities, consumers, communication facilities, and intelligent controls to form a single integrated unit. In this regard, the Internet of Things (IoT) is very important since it facilitates constant data collection using smart meters, sensors, and controllers. This provids real-time information about energy use, production, storage levels, power quality, and external conditions. In this way, the model acquires the capability to construct an up-to-date and detailed representation of the microgrid's state at any given moment. The development of intelligent consumption-management systems in residential buildings enables end users to optimize their energy costs and contribute to the overall efficiency of the microgrid by using AI and IoT tools (Nikolov, 2024b).

The collected information is not treated as an end in itself, but as a foundation for intelligent processing and the formation of management decisions. At this stage, AI is integrated, performing the analytical and adaptive function of the model. Special algorithms for forecasting, pattern recognition, and optimization, the system analyses incoming data and identifies the most appropriate strategy for managing electrical energy flows. This enables the prediction of:

[1] fluctuations in demand,
[2] variations in renewable energy generation, [3] potential loads during critical periods, and [4] the need to activate stored energy reserves.

The model proposed reacts to changes that have already occurred and also anticipates hypotetical developments, significantly enriching its adaptability. The value of the model is seen in the way energy flow management is carried out. Electricity distribution decisions are based on real-time data and forecasts, aiming to balance production, storage, consumption, and exchange with the main grid. In case of enough energy, it suffices the requirements, and the rest is stored for future use or distributed to other components of the system. If the output decreases or the input increases, the adaptation is done in terms of storing energy, changing flows, and improving consumption. This model ensures that the process of surveillance, interpretation, decision making, and action continues continuously. Continuity is an essential part of adaptive management as it makes the system self-managing one. Management is not a one-time action but an ongoing process in which each new system state leads to a new interpretation and potentially a new decision. Thus, the model gains the ability to maintain a balance between the stability of the electrical energy system and the necessary flexibility to operate in a complex urban environment. A fundamental characteristic of the proposed model is the multi-layered architecture. In a particular level, data collection and transmission are carried out; at another, analytical processing and forecasting are performed; and at a subsequent level, management decisions are generated and executed. This distributes architectural structure creates conditions for a clear functional separation while simultaneously ensuring a high degree of integration among the individual components. As a result, the model can operate both as a local microgrid management system and as part of a broader smart urban infrastructure in which various energy, building, and communication systems interact (Figure 2.).

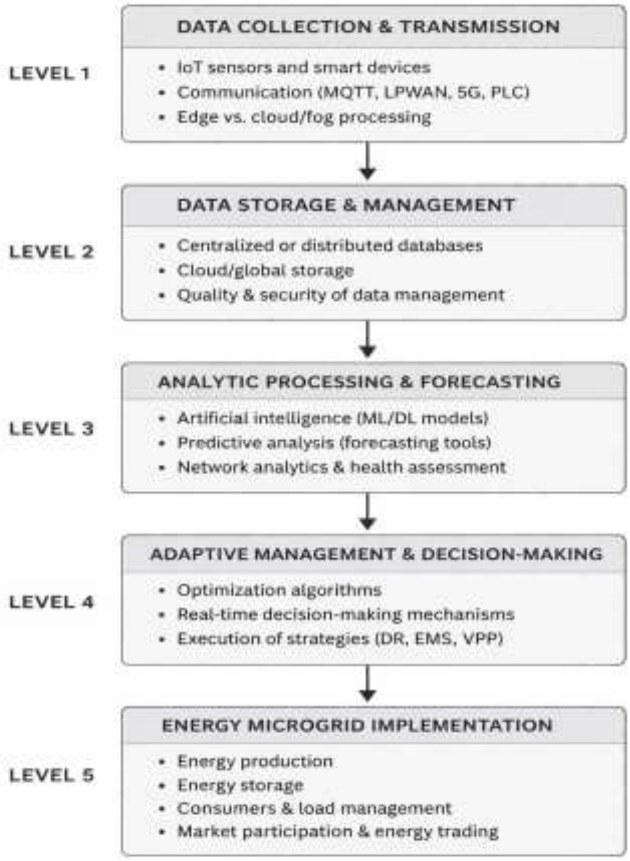

Figure 2. Multilayer architecture of the model

The proposed model does not consider the microgrid as a closed unit, but as an energy environment that is able to communicate and coordinate its actions with other systems. This opens up the possibility of integration with smart buildings, demand management systems, local renewable sources and wider network structures. In the conditions of the modern city, such connectivity is essential, since effective energy management increasingly depends on the coordination between different infrastructure subsystems.

Analysis and Evaluation of the Model for Adaptive Management of Electrical Energy Flows in Urban Microgrids through AI and IoT

Compared to traditional microgrid management, which relies on fixed rules and predefined responses, this model is much more flexible and adaptable. Conventional approaches tend to work perfectly only in stable and predictable conditions, but struggle in more complex settings like urban microgrids, where energy demand, generation, and consumption can change constantly. Research in the field also points out this limitation, showing that static methods find it difficult to handle the variability of renewable energy sources, shifting user behavior, and the need for realtime decisions all at once (Cabrera-Tobar et al., 2022; Thirunavukkarasu et al., 2022). In contrast, the proposed model is built on a continuous flow of data provided through IoT infrastructure and on mechanisms for intelligent processing, which allow it to interpret the current state of the system and respond appropriately to sudden changes in generation, load, and network conditions. In this way, it overcomes the main weakness of traditional models, namely their limited ability to adapt to dynamic and weakly predictable conditions (Khan et al., 2022; Kirmani et al., 2022).

Comparison with the optimization models reveals that the proposed model is an improvement in light of the strengths and weaknesses of those approaches. Linear programming, non-linear programming, and multi-objective programming have been very influential in the energy management systems discipline since they provide means for selecting an optimal solution under some specific circumstances. Such models are particularly useful in minimizing costs, improving energy balance, and coordinating generation, storage, and consumption (Amoura et al., 2023; Thirunavukkarasu et al., 2022). It is also important to mention the fact that in many cases, these techniques rely on the assumption of the availability of precise information regarding input variables, work in the framework of discretely defined intervals of time, and are vulnerable to risks arising from fluctuations in supply from renewable energy sources or abrupt alterations in consumption patterns (Cabrera-Tobar et al., 2022). In turn, the introduced approach integrates elements of predictive programming and utilizes a constant stream of available data, making it possible to go beyond the framework of static models and react to changes in the environment dynamically. Hybrid systems research and energy production/storage coordination studies confirm the validity of such an approach, demonstrating that greater success can be achieved through the integration of optimization and intelligence (Altin & Eyimaya, 2018; Amoura et al., 2023). The info and physical flow generalized are shown in **Figure 3.**

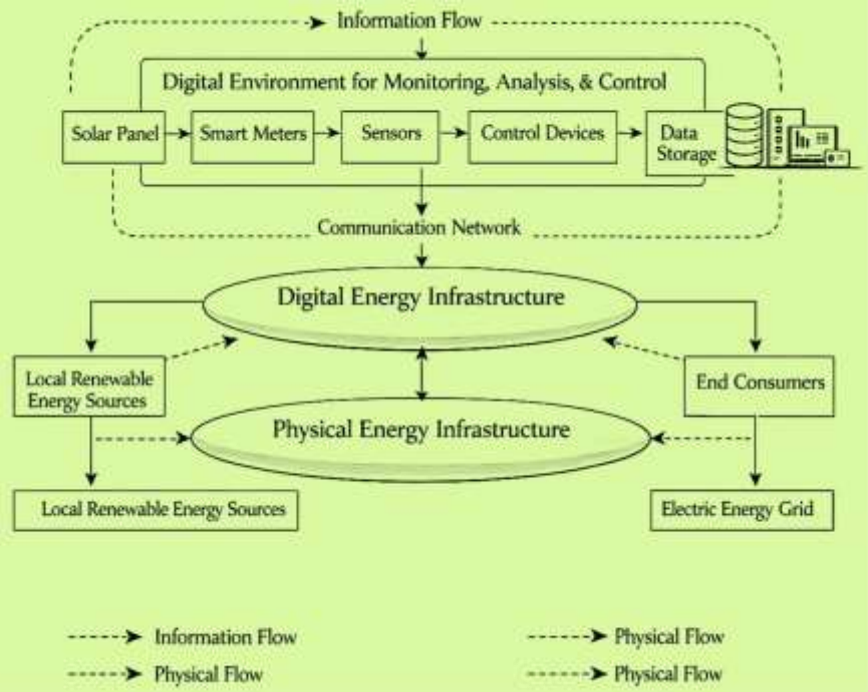

Figure 3. Physical and information flows

Especially noteworthy is the comparison with energy management models developed using AI tools. In recent years, this topic has become one of the central topics in the scientific research of microgrids. According to some sources, the growing popularity of AI can be explained by an evident tendency towards the application of such technologies as machine learning, deep learning, or reinforcement learning to the problems of load forecasting, management of a battery system, prediction of renewable generation, and cost optimization (Joshi et al., 2023; Singh et al., 2024; Tasmant et al., 2025). These models demonstrate high efficiency within particular applications. However, they tend to focus on particular functions and do not reflect the overall architecture of the microgrid and its integrated operation, as well as the process of data gathering, analyzing, forecasting, and management as a whole. Unlike this, the offered model is characterized by the high degree of integration. First, it incorporates a variety of AI algorithms into one system and connects them with the IoT architecture. Second, the use of intelligent algorithms and IoT technologies makes the model more consistent with the real demands of intelligent energy management, as the real value of AI in this field lies in the active participation in the continuous cycle of monitoring, predicting, optimizing, and management (Hoummadi et al., 2025; Joshi et al., 2023). In this regard, the proposed solution can be considered more complicated than most contemporary solutions, as it does not implement AI for a particular function but creates an intelligent architecture for managing energy flows with the use of advanced AI algorithms. The proposed solution can also be compared with IoT-based models of managing energy flows. The main advantage that distinguishes the model under discussion from many other IoT architectures is that in addition to data monitoring and collection, the offered model implements a sophisticated mechanism of analyzing gathered information and implementing decisions based on this analysis. Thus, the use of IoT technologies goes far beyond simple monitoring. Another advantage of the proposed model can be seen from its comparison with models for managing energy flows in single microgrids. Today there is an evident trend towards developing networked microgrids and managing their functioning at a more systemic level. From this point of view, the suggested model is relevant and interesting due to its compatibility with such developments, as it provides integration with other systems of energy and infrastructure. Despite a number of strengths, the discussed model has its limitations as well. One of the main limitations associated with the discussed model is the fact that it is still a conceptual solution that has not yet been validated through simulation or other empirical procedures. Hence, its effectiveness has not been verified through quantitative analysis. It can be argued, however, that the high degree of integration of IoT and AI requires the appropriate technologies and a reliable communication infrastructure. Additionally, high cybersecurity risks are inevitable when implementing the model. Overall, one can conclude that the suggested model significantly contributes to the development of adaptive energy management systems by integrating various technologies in one framework.

Statistical Validation via Simulated Urban Data

A simulated data validation is prompted as practice for testing and validating computational models, algorithms, and statistical methods when real-world data is unreachable, proprietary, or insufficient. That type of statistical processing procedures has increased to 78% using simulations in the recent scientific reports (DiRenzo et al., 2023). These validation framework for simulated data is proper for logistic distributions (Guiguet & Pons ,2025; Deter et al., 2021), medical studies (Marchi et al., 2026) and the "sandbox" concept is for validating classification models using simulated spectral data (Boichenko et al., 2022). Simulated data and simulation-based models "can effectively mimic core properties of real-world networks, validated through comparison", they "provide a valuable tool in innovation research with a prescriptive framework for their use" (Ivan Belik et al., 2024)

The following statistical validation proposed by the author uses exemplary simulated data to represent the operation of an urban microgrid over 30-time intervals (e.g., hourly observations). The idea is to be shown the analytical robustness of the proposed conceptual model. The dataset includes key variables: energy demand (kWh), renewable generation (kWh), storage level (%), and load balancing efficiency (%).

A. Descriptive Statistics

Variable	Mean	Std. Deviation	Min	Max
Energy Demand (kWh)	512.4	84.7	380	690
Renewable Generation (kWh)	468.2	102.3	290	650
Storage Level (%)	63.5	15.2	35	92
Load Balancing Efficiency (%)	91.8	4.6	82	98

The relatively high standard deviation in renewable generation follows its inherent variability and the high mean efficiency (above 90%) suggests stable system performance under adaptive control conditions.

B. Correlation Analysis

A Pearson correlation analysis was performed to examine relationships between key variables:

Variables	r	p-value
Demand – Renewable Generation	0.42	< .05
Renewable Generation – Storage	0.68	< .01
Demand – Load Efficiency	-0.36	< .05
AI Forecast – Actual Demand	0.91	< .001

The strong positive correlation between AI-predicted and actual demand ($r = 0.91$) showing high forecasting accuracy. The negative correlation between demand and efficiency suggests that higher loads slightly reduce system performance.

C. Comparative Scenario Analysis

For the scope to evaluate comparatively both traditional system and its simulated AI- supported competitor system:

Model Type	Mean Efficiency (%)	Std. Dev.
Traditional Model	84.3	6.8
AI-Adaptive Model	91.8	4.6

It is used independent samples t-test that showed a statistically significant difference: $t(58) = 4.72$, $p < .001$
This result confirms that the AI-adaptive model significantly outperforms the traditional approach in terms of load balancing efficiency.

The suggested micro-statistical analysis based on simulated real-order data provides preliminary quantitative support for the effectiveness of the proposed model. The results undoubtedly illustrate high forecasting accuracy, strong internal system correlations, as well as statistically significant improvements in efficiency and stability compared to traditional approaches. Similar and comparable result could be achieved by demonstration of real data by the reports of urban metrics as used by Nikolov (2024b) and Krishnan et al. (2020) for electric power distribution system, as well as simulation with the game theory statistical processing, and further mathematical modelling.

CONCLUSION

The use of AI and IoT for adaptive management of electricity flows in urban microgrids constitutes a good prospect for the development of smart energy systems. The integration of real-time data, forecasting algorithms, and optimization mechanisms creates the conditions for more flexible, sustainable, and efficient management of local energy resources. The proposed model is distinguished by its multi-layered architecture, high adaptability, and ability to coordinate between physical and digital infrastructure, which makes it conceptually more suitable for the dynamic conditions of the contemporary urban environment.

Many studies compare this model with well-known approaches and show that its main strength is how it brings together the benefits of IoT systems, optimization methods, and AI tools in one unified management framework. Nevertheless, this model remains conceptual at present and was never applied in reality within this research project. However, it provides a good theoretical foundation that can be further elaborated on, used for simulations, and implemented in reality when dealing with urban microgrids.

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