Secure Systems Design and Technology Development. Veliko Tarnovo, Bulgaria
Proceedings of the International Scientific Conference, 2026. Volume I, 267-271

Challenges in the Development of Autonomous Energy Microgrids in Bulgaria

Kiril Luchkov
Department of Economics, Industrial Engineering and Management
Technical University of Sofia
Sofia, Bulgaria
kiril.luchkov@tu-sofia.bg

Mihail Chipriyanov
Department of Strategic Planning
Tsenov Academy of Economics
Svishtov, Bulgaria
m.chipriyanov@uni-svishtov.bg

Galina Chipriyanova
Department of Accounting
Tsenov Academy of Economics
Svishtov, Bulgaria
g.chipriyanova@uni-svishtov.bg

Abstract **— The study analyzes the challenges facing the implementation of autonomous energy microgrids in urban areas in Bulgaria. In principle, their potential for achieving energy independence and decarbonization has been established. However, their implementation is hindered by factors such as a certain institutional vacuum linked to the lack of an appropriate legal framework, outdated distribution infrastructure, and social barriers in the management of condominiums. A model for an "energy cluster" is proposed. The aim of the study is to facilitate the transition to a horizontal ecosystem. Within this framework, energy is managed as a shared resource. The desired outcome corresponds to achieving a high degree of sustainability and economic stability at the local level.**

Keywords — microgrids, artificial intelligence, energy communities, sustainable development.

I. Introduction

Globally, the market for decentralized energy systems is experiencing a real boom. Forecasts by the European Commission (EC) for the transition to Net-Zero predict that over 50% of European households will generate their own clean energy by 2030. This trend is driven by the widespread penetration of the sharing economy in the energy sector and the urgent need to relieve centralized networks. Therefore, the study of models such as „energy clusters“ is particularly important for countries in transition like Bulgaria. In our country, the lack of a flexible framework risks isolating the local market from European technological flows.

In contemporary energy theory, the transition to “smart neighborhoods” is emerging as a leading European practice for achieving energy independence [1]. Unfortunately, however, the implementation of autonomous energy microgrids in Bulgaria remains at a standstill due to a critical institutional vacuum and outdated infrastructure [2].

This study aims to analyze the obstacles to the design and implementation of these systems in the Bulgarian urban environment. At the same time, it seeks to propose a workable mechanism for overcoming them. To achieve this goal, three main tasks have been defined:

- identifying regulatory, technical, and organizational barriers;
- assessing the potential for adapting global experience in energy trading to the specificities of local condominium ownership;
- developing a model for an “energy cluster.”

The main thesis is that transforming residential neighborhoods into active “energy communities” is possible through the creation of specialized energy clusters. The process requires synergy between blockchain and AI technologies, combined with the introduction of „regulatory sandboxes“ in national legislation to allow for the testing of decentralized models in pilot zones.

The logic of the research process and the specific stages of the applied methodology are illustrated in Fig. 1.

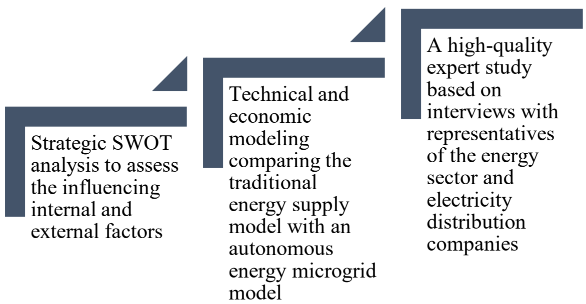

Fig. 1. Stages of the methodology used.

Source: Authors’ own research.

Online ISSN 3044-7771
https://doi.org/10.68302/std2026.vol1.166

II. Theoretical Framework and Global Experience

At the heart of autonomous microgrids lies the concept of peer-to-peer (P2P) energy trading [3]. It applies the principles of the sharing economy to the energy sector. The theoretical model of P2P platforms allows individual consumers to trade their surplus energy directly with one another [4]. This approach bypasses traditional centralized intermediaries [5]. It improves the management and utilization of locally generated renewable energy. At the same time, it creates economic incentives for investment in storage capacity. In the scientific literature, P2P trading in particular is viewed as a socio-technical innovation. Through it, market power is decentralized. This enables the formation of market-based pricing at the local level [6].

The experience gained in this field in developed Western countries provides an opportunity to study best practices. This is particularly true in countries such as the Netherlands and the Scandinavian region. In these countries, the high degree of applicability of so-called "smart neighborhoods" has been established. Projects in Amsterdam or energy communities in Denmark use blockchain for automated management of energy flows [7]. This takes place within closed communities. These case studies show that the integration of smart grids allows, in certain cases, for nearly 100% energy self-sufficiency for household needs. To ensure their success, modern digital technologies and the creation of a relevant regulatory environment are needed.

In the context of sustainable development, microgrids are a particularly important tool for increasing sustainability [8]. In general, centralized energy systems are highly susceptible to cascading failures or cyberattacks [9]. In contrast, autonomous grids can continue to power infrastructure in local mode [10]. In this way, they transform energy into a flexible and adaptive service capable of responding to external shocks.

The study seeks to answer the following research questions:

- **RQ1:** What are the critical regulatory and technical barriers preventing microgrid deployment in the Bulgarian context?
- **RQ2:** Is the proposed „Energy Cluster" model economically viable compared to the centralized status quo?

III. Materials and Methods

The scientific approach in this study is based on an analysis aimed at assessing the applicability of autonomous microgrids in the specific Bulgarian context. The methodological framework is structured in three main stages:

3.1. Strategic SWOT Analysis

A descriptive SWOT analysis is applied to assess the internal and external factors influencing the implementation of the „microgrid" model. The method facilitates the identification of the advantages of decentralized production relative to institutional weaknesses and external threats. We expect the analysis to serve as a basis for determining strategic priorities in the design of smart neighborhoods.

3.2. Technical-Economic Modeling

The comparative cost modeling method was used to assess effectiveness. A comparison was conducted between:

- Traditional model. Costs for centralized power supply, including the price of energy, grid services, etc.
- Autonomous model. Calculation of the energy cost, including initial capital investments for renewable energy sources (RES) and storage systems, operating costs, and potential savings from the absence of transmission fees.

The modeling aims to determine the point of economic efficiency for autonomous systems at current market levels in Bulgaria.

The comparative modeling is based on a standard residential block (entrance) with a total average monthly consumption of 8,500 kWh (average 420–450 kWh per household). A combined price (energy + distribution + taxes) of 0.24 BGN/kWh was applied for the traditional model. The levelized cost of energy (LCOE) was calculated in the autonomous model, considering a 30 kWp solar installation and a 15 kWh battery. Initial results show that the initial investment is significant [11]. In parallel, the operating costs per kWh in the Energy Cluster fall to approximately 0.11 - 0.14 BGN/kWh over a 15-year life cycle. This represents a potential long-term reduction in energy costs of nearly 45% compared to current market prices.

The calculation of LCOE is based on the following standard formula:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

where:

- I_t represents the initial investment,
- M_t are the annual maintenance and operational costs,
- E_t is the energy generated in year t, and r is the discount rate (assumed at 5% for this study).

3.3. Qualitative Expert Study

To validate the theoretical conclusions, a semi-structured expert interview was conducted with 9 representatives from the energy sector and the management of electricity distribution companies. The study aimed to identify the attitudes of network operators toward decentralization. The focus was on technical concerns regarding grid balancing and potential conflicts of interest during the transition to P2P trading [12]. The chosen approach provides an empirical basis for formulating management-oriented recommendations.

The empirical part of the study was carried out between January and March 2026. The selection of experts was purposeful, ensuring that participants had at least 5 years of professional experience in energy network management or regulatory issues. The interviews were conducted and lasted an average of 45 minutes each. The data collection process was designed to establish the current market sentiment regarding the implementation of decentralized systems in the Bulgarian energy sector.

The panel of experts included:

- Senior Grid Engineers from major distribution system operators (DSOs) (3);
- Legal Experts specializing in Energy Law (2);
- IT Architects for Decentralized Systems (2);
- Representatives from Renewable Energy Associations (2).

IV. RESULTS

The study's findings identify three key groups of barriers that hinder the development of autonomous microgrids in Bulgaria [13]. These shortcomings create an environment characterized by high investment risk and low operational predictability.

To quantify the expert consensus, the identified barriers were rated on a scale from 1 (lowest impact) to 5 (highest impact). The results are summarized in Table 1.

TABLE 1. EXPERT ASSESSMENT OF BARRIERS TO AUTONOMOUS MICROGRIDS IN BULGARIA

Category of Barrier	**Identified Key Issue**	**Mean Impact Score (1-5)**	**Consensus Level**
Institutional	Lack of licensing regime for local operators	4.8	Very High
Technical	Predominance of one-way smart meters	4.2	High
Socio-organizational	Fragmentation of ownership in condominiums	4.5	High
Technical	Lack of real-time data exchange infrastructure	3.9	Moderate

Source: Authors' own research.

The data in Table 1 show that the institutional vacuum and the legal status of microgrids are perceived as the most significant obstacles. Experts emphasize that technical problems can be solved through investments. At the same time, the social and legal framework requires a fundamental change in national policy.

The study also includes an analysis of the technical readiness of existing urban distribution segments. The existing technical gaps require an estimated infrastructure investment of EUR 8,000-12,000 per residential building (entrance) to achieve full autonomous compatibility and integration of intelligent management systems. The main problem in the national legal framework is the complete absence of a licensing regime for "local energy operators." Current legislation (including the Energy Act) does not recognize the microgrid as an independent legal entity capable of managing local production and consumption. Potential energy communities are forced to operate within the framework of outdated regulations designed for large centralized producers. The lack of a clear legal status blocks the possibility of legally sharing energy. It hinders the definition of pricing models for intra-community payments. All of the above makes microgrids practically illegal or economically unfeasible.

The technical analysis identifies a significant lag in the digitization of the transmission infrastructure. The effective operation of an autonomous microgrid requires the widespread deployment of smart metering devices [5]. These devices support two-way real-time metering. In Bulgaria, the majority of installed meters are designed for one-way consumption metering. This makes it impossible to precisely balance decentralized energy flows. The lack of a reliable infrastructure for data collection and exchange effectively means that smart load management and P2P trading remain technically unfeasible [14].

The socio-organizational barrier stems from the specifics of the Condominium Management Act. The process of making collective decisions on investments in shared energy assets (such as rooftop solar panels or shared batteries) is extremely difficult. This is due to high quorum requirements and the lack of effective mechanisms for enforcing shared obligations. Mistrust among owners, combined with cumbersome legal procedures for registering associations, limits opportunities for collective financing. In practice, energy democratization faces the challenge of fragmented ownership. Residential neighborhoods become a complex structure to manage, with low credit ratings and a high degree of internal conflict.

V. DISCUSSION

In response to the problem areas identified so far, we propose the creation of a so-called Energy Cluster. This is a specialized legal entity that brings together neighbors and property owners within a given neighborhood. The cluster functions as a new type of energy cooperative. It owns and manages shared assets (solar panels, batteries, charging stations). This model allows for the pooling of consumption, and the achievement of economies of scale in the purchase of equipment, as well as in maintenance. The cluster acts as an interface to the national grid. It improves the management of internal energy distribution, transforming the community into a flexible market participant.

To overcome mistrust and automate complex internal distribution processes, the model integrates blockchain and artificial intelligence (AI).

- Blockchain technology is used to create a decentralized ledger of transactions [16]. This enables fully transparent, automated, and instant energy settlements between neighbors in real time. No central accounting authority is required.
- AI algorithms take on the role of a „virtual dispatcher". They forecast consumption patterns and generation capacity. They automatically determine when to charge the batteries, when to draw energy from the shared resource, and when to

sell the surplus to the external grid. This technological synergy eliminates the human factor from operational management and ensures maximum economic efficiency of the microgrid.

The integration of AI algorithms leads to the optimization of energy flows. Simulation data shows that predictive balancing of the „virtual dispatcher“ can increase the community's self-consumption ratio (SCR) from 35% (unmanaged) to over 72% (AI-managed). By strategically discharging the batteries during the peak window from 18:00 to 21:00, the cluster can avoid the highest grid tariffs. As a result, an additional 18% annual savings in balancing costs can be achieved. This efficiency increase is crucial for the financial success of the cluster model in an environment of an unstable energy market.

To further illustrate the advantages of the proposed energy cluster, a comparative analysis was performed based on the techno-economic modeling described in the methodology. Table 2 presents the structural and economic differences between the current situation and the decentralized cluster approach.

TABLE 2. COMPARISON BETWEEN TRADITIONAL CENTRALIZED MODEL AND PROPOSED ENERGY CLUSTER MODEL

Feature	Traditional Model (Status Quo)	Proposed Energy Cluster (AI/Blockchain)
Energy Flow	Unidirectional (Grid to Consumer)	Bi-directional (P2P and Grid-interactive)
Price Control	Centrally regulated	Market-based local pricing
Grid Losses	High (due to long-distance transmission)	Minimal (localized balancing)
Decision Making	Individual/Fragmented	Collective/Automated via AI
Resilience	Susceptible to cascading failures	High (autonomous local operation)

Source: Authors' own research.

The data in Table 2 show that the Energy Cluster replaces the energy source. And more importantly, it fundamentally changes the management logic. By using artificial intelligence as a "virtual dispatcher," the community can reduce its dependence on the external grid by up to 40-60% during peak hours, depending on storage capacity. This transition shifts the focus from energy as a commodity to energy as a shared service.

Implementing this model requires the urgent introduction of so-called "regulatory sandboxes." These are controlled environments in which the legislature allows temporary exemptions from general energy regulations for specific pilot neighborhoods. In these zones, energy clusters should be granted the right to operate microgrids without the licensing regime of large electricity distribution companies, to test P2P trading models, and to apply flexible pricing. We are convinced that the experience gained from these pilot projects will serve as a basis for scaling up the concept at the national level. Provisions of the Energy Act will be refined. Overall, this will transform Bulgaria into an active participant in the digital energy transformation.

VI. CONCLUSIONS

The analysis conducted demonstrates that autonomous microgrids are a mechanism with high potential for achieving the decarbonization of the urban environment [7]. They are the only sustainable solution for integrating the mass electrification of transportation and the transition to low-carbon heating. And they do so without overburdening the existing national infrastructure. By localizing the balance between production and consumption, microgrids minimize energy losses and transform urban neighborhoods into sustainable energy units capable of maintaining their functions even during major crises.

To overcome the identified barriers, a targeted change in the regulatory framework is needed, structured as follows:

- Reform of the Energy Act. Introduction of a legal definition for „energy community" and „microgrid“. This should be combined with simplified procedures for P2P trading and intra-community energy distribution.
- Update the Spatial Planning Act. Streamline procedures for installing renewable energy sources and storage systems in condominium buildings. In doing so, priority should be given to collective investment projects.
- Promotion of a National Program for the accelerated deployment of smart meters. The aim is to provide the necessary database for the operation of AI algorithms in microgrids.

The long-term vision outlined in this study envisions a transformation of the energy sector from a vertical monopoly to a horizontal ecosystem of shared services. In this model, energy ceases to be merely a commodity and becomes a socially shared resource managed through blockchain and AI technologies. Overall, the development of "smart energy communities" will strengthen the economic stability of households. Rational solutions will be implemented toward energy democratization.

VII. ACKNOWLEDGMENTS

This research was funded by the Bulgarian National Science Fund at the Ministry of Education and Science of Bulgaria under the Funding Competition for Fundamental Scientific Research Projects 2025, based on Administrative Contract № KP-06-N95/16 of 10 December 2025, for the implementation of Research Project № KP-06-PN95/45, SUNI № BG-175467353-2025-08-0248, titled „Epistemic robustness of artificial intelligence: A universal framework for evaluation in industrial and management systems“.

REFERENCES

[1] Zinoviev, V. (2019). Challenges in the Power Supply for the Needs of Smart Cities, II International Conference on High Technology for Sustainable Development (HiTech), Sofia, Bulgaria, 2019, pp. 1-4, https://doi.org/10.1109/HiTech48507.2019.9128268.

[2] Hartono, B. S., Budiyanto, Y., & Setiabudy, R. (2013). Review of microgrid technology. In International Conference on QiR (pp. 127–132). https://doi.org/10.1109/QiR.2013.6632550

[3] Baroche, T., Pinson, P., Latimier, R. L. G., & Ahmed, H. B. (2019). Exogenous Cost Allocation in Peer-to-Peer Electricity Markets. IEEE Transactions on Power Systems, 34(4), 2553–2564. https://doi.org/10.1109/TPWRS.2019.2896654

[4] Zhou, X., Guo, T., & Ma, Y. (2015). An overview on microgrid technology. In 2015 IEEE International Conference on Mechatronics and Automation (ICMA) (pp. 76–81). https://doi.org/10.1109/ICMA.2015.7237460

[5] Mengelkamp, E., Gärttner, J., Rock, K., Kessler, S., Orsini, L., & Weinhardt, C. (2018). Designing microgrid energy markets: A case study: The Brooklyn Microgrid. Applied Energy, 210, 870–880. https://doi.org/10.1016/j.apenergy.2017.06.054

[6] Wang, H., & Huang, J. (2016). Incentivizing Energy Trading for Interconnected Microgrids. IEEE Transactions on Smart Grid, 9, 2647–2657. https://doi.org/10.1109/TSG.2016.2614988

[7] Borkovcová, A., Černá, M., & Sokolová, M. (2022). Blockchain in the Energy Sector—Systematic Review. Sustainability, 14(22), 14793. https://doi.org/10.3390/su142214793

[8] Hirsch, A., Parag, Y., & Guerrero, J. (2018). Microgrids: A review of technologies, key drivers, and outstanding issues. Renewable and Sustainable Energy Reviews, 90, 402–411. https://doi.org/10.1016/j.rser.2018.03.040

[9] Bayindir, R., Hossain, E., Kabalci, E., & Perez, R. (2014). A Comprehensive Study on Microgrid Technology. International Journal Of Renewable Energy Research, 4(4), 1094-1107. https://izlik.org/JA26PG88CE

[10] Eltamaly, A. M., & Ahmed, M. A. (2023). Performance Evaluation of Communication Infrastructure for Peer-to-Peer Energy Trading in Community Microgrids. Energies, 16(13), 5116. https://doi.org/10.3390/en16135116

[11] Anguelov, K., Angelova, M. (2021). Methodology for effectiveness in applying for grant funding for energy efficiency of enterprises, 17th Conference on Electrical Machines, Drives and Power Systems (ELMA), Sofia, Bulgaria, 2021, pp. 1-4, https://doi.org/10.1109/ELMA52514.2021.9503051.

[12] Lin, H., Guo, Y., & Xu, Y. (2026). Impact of P2P Trading on the Operation of the Distribution System Operator. In 2026 IEEE PES International Meeting (PES IM) (pp. 1–5). https://doi.org/10.1109/PESIM67009.2026.11438640

[13] Keskinis, S., Elmasides, C., Kouveliotis-Lysikatos, I., Marhavilas, P. K., Hatziargyriou, N. D., Stergiopoulos, F., Pompodakis, E., Fantidis, J. G., Makrides, G., & Delianidis, N. (2026). Integrating Safety into Microgrid Sizing: A Systematic Review. Energies, 19(9), 2098. https://doi.org/10.3390/en19092098

[14] Petrova, D. An Alternative Approach to Reducing Aging of Innovative Industrial Products in Terms of Industry 4.0, Environment. Technology. Recourses – Proceeding of the 13-th International Scientific and Practical Conference, Rezekne Academy of Technologies, Rezekne, Latvia, 2021, ISSN1691-5402, Online ISSN 2256-070X, p. 274-280. https://doi.org/10.17770/etr2021vol3.6507

[15] Baig, M.J.A.; Iqbal, M.T.; Jamil, M.; Khan, J. (2023). Blockchain-Based Peer-to-Peer Energy Trading System Using Open-Source Angular Framework and Hypertext Transfer Protocol. Electronics, 12, 287. https://doi.org/10.3390/electronics12020287

[16] Stoyanov, P., Anguelov, K. (2025). Corporate Social Responsibility Reporting: Information System Requirements, 13th International Scientific Conference on Computer Science (COMSCI), Sozopol, Bulgaria, 2025, pp. 1-5, https://doi.org/10.1109/COMSCI67172.2025.11225210.