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Internet of Energy based cellular structures for distributed Microgrids

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ABSTRACT

In the face of evolving global energy challenges and the urgent need for resilient, decentralized, and digitized power systems, the concept of the Internet of Energy (IoE) emerges as a transformative framework for modern energy infrastructure. This paper explores the development and implementation of IoE-based cellular structures within distributed Microgrids, with a focus on Ukraine's critical need for energy security and system restoration. Embracing the "3D" paradigm – Decarbonization, Decentralization, and Digitalization –the proposed architecture organizes energy systems into interconnected energy cells. These cells leverage distributed energy resources, demand-side management, and Energy Cloud 4.0 technologies to enable real-time energy balancing, market participation, and transactive energy operations. The paper presents a comprehensive structure for Microgrids based on IoE principles, detailing energy cell typologies, control algorithms for cost optimization, and strategies for grid flexibility and reliability. It highlights how cellular architectures can ensure autonomous operation, enhance resilience to outages, and foster integration with the European energy market. Through modeling and simulation, the paper validates the feasibility of this approach, demonstrating significant improvements in energy cost efficiency, stability, and sustainability. To organize the work and interaction of cells, 5 types of energy cells (generators, prosumers, passive consumers, electric vehicles, utility) have been identified that interact and have impacts on all participants of the Microgrid: economic impacts (changes in consumer electricity bills and revenues from energy sales), technical impacts (changes in the network scheme, approaches to network planning and operation) and social impacts (support, reliability of consumption, reduction of CO_2 emissions). The technical, economic, and social benefits of transitioning to IoE-based cellular Microgrids are a foundational element in rebuilding and future-proofing Ukraine's energy sector.

Keywords: Internet of Energy; Microgrid, energy cell; transactive energy; energy market; distributed energy resources

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INTRODUCTION

In contrast to the globalization of electricity generation and distribution control processes, which were inherent in the energy sector of the twentieth century, today, within the framework of the "3D" concept ("Decarbonization, Decentralization, Digitalization"), the localization of these processes with the widespread use of distributed energy resources distributed energy resource (DER), renewable energy sources (RES), (DER, RES, autonomous electricity sources, energy storage systems, consumer's demand side management) is promising [1], [2], [3]. This approach completely changes the structure of the energy system, implementing the Smart Grid concept, the use of challenges since February 2022 – destruction by the digitalization technologies and is extremely relevant for the energy sector of Ukraine, which has been subjected to significant constant Russian aggressor.

Today, a large-scale process of restoration and modernization of Ukraine's energy infrastructure is already underway. This process is based on new modern principles of construction and operation of the electric power industry; in particular, the necessary measures are being taken to ensure their reliable operation of damaged facilities.

Therefore, it is urgent to increase energy security through decentralization, diversification and energy-efficient, balanced and stable energy supply to critical infrastructure.

Within the framework of the new requirements for Ukraine's energy sector, it is important to lay the foundation for a modern, market-based, resilient and sustainable Ukrainian energy system, which will be well integrated with the EU system. Energy supply in the new realities should be characterized by flexibility, the possibility of balancing in the node, stability of operation, multi-agent functions, attracting all potential opportunities of DER, effective demand side management from various types of consumers, primarily active (prosumers).

LITERATURE REVIEW

The construction of local electric power systems (Microgrids) in Ukraine should be carried out on the basis of modern principles of digitalization of the electric power industry and the construction of cellular structures that allow the implementation of the hierarchy based structures, the possibility of aggregation with balancing of supply and demand, the use of Smart monitoring, an expanded range of optimal regulation according to technical, economic and environmental criteria, and the full use of available potential opportunities. Such Microgrids must implement the provisions of the "Concept of Smart Grids in Ukraine until 2023" (Cabinet of Ministers Order No. 908 of 14.10.2022) and "Strategy for the Development of Distributed Generation for the Period up to 2035 and Approval of the Operational Action Plan for its Implementation in 2024-2026" (Order of the Cabinet of Ministers of Ukraine No. 713 of 18.07.2024) [4], [5].

In Ukraine, along with solar PV, wind power systems and batteries, diesel generators which are considered as backup for the power supply of the grid are now widely used. Energy storage systems can act as additional sources of generation during peak electricity consumption, which will allow One to comply with economical modes of operation.

Due to the systematic temporary power outages associated with Russian aggression, a fairly significant number of generators, charging stations and batteries is accumulating in industry and the population, a certain number of households are equipped with solar panels and heat pumps. It is advisable to involve these energy resources in the supply (balancing) of energy in the regional context by the creation of an integrated distributed generation system.

Implementation of the EU experience, in particular those set out in the EU Directives – Directive (EU) 2018.2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from RES; Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal electricity market stimulates the creation of energy communities, considering new requirements for construction and operation. Such improvement in the energy system allows taking advantage of the digital transformation of the energy sector [6], [7].

At the present stage, the development of distributed generation is considered within the framework of the provisions of IoE (Internet of Energy), using Energy Cloud 4.0 technologies [8], [9] it allows to create new business models (Energy as a Service) [10]. A promising architecture for the implementation of IoE is the creation of new digital energy cloud platforms, when the tasks of system optimization of energy processes and information interaction are transferred to the cloud environment using parallel computing and artificial intelligence.

When building Internet of Energy (IoE) using Energy Cloud 4.0 technologies, it is assumed that groups of electric power equipment of IoE users, which have a common point of connection to electrical networks and information channels that provides communication with IoE, form an energy cell. IoE is a network of energy cells [8], [9], which includes various types of DER (controlled and uncontrolled), passive and active consumers, as well as such new elements as an energy hub, energy ports, energy routers (Fig. 1) [11].

The energy router connects to the information subsystem, network subsystem and energy subsystem in the Internet of Energy and performs the roles of energy management and transmission, information collection and communication.

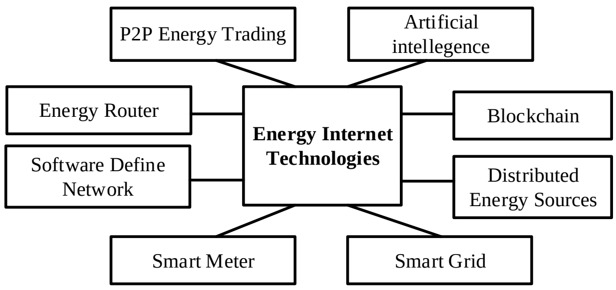

Fig. 1. **Internet of Energy technologies**
Source: **compiled by the [11]**

The Internet of Energy is a System of Systems (SoS) – a set of interconnected and interacting systems of transactive energy (a system for creating, controlling the execution and payment of smart contracts), the Internet of Things (systems of machine-to-machine interaction and exchange of control influences between energy cells and energy equipment), neural networks (systems of mode control, maintaining the power balance and ensuring static and dynamic stability of the power system) [12], [13], [14], 15].

IoT is a type of decentralized electricity system that implements Smart distributed management carried out through energy transactions between its users. The power system, built on the basis of the new architecture, must become transactive, smart, resilient and flexible.

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Distinctive features of IoE are:

– the decentralized nature of the power system, in which there are both a large number of distributed consumers and a large number of distributed electricity producers at the level of distribution networks;

– the presence of bidirectional power flows and the possibility of dynamic change of role in the power system by users;

– the presence between electric power equipment not only of electrical connections and interaction provided by electric networks, but also of information connections and interaction;

– implementation of fully decentralized smart control, which is carried out through machine-to-machine (M2M) interaction;

– the presence of a decentralized market where peer-to-peer contracts are concluded both for the purchase and sale of electricity and for the provision of system services;

– implementation of all processes and their management through direct transactions between users.

Today, there are a sufficient number of international standards that will allow the implementation of the Internet of Energy, for example, IEC 61850 – the international standard for communication in substations. It allows the implementation of any protection, control, measurement and monitoring functions and combines the ease of use of Ethernet networks with the performance and security required in modern substation operating conditions.

In [16] the cellular structure of the network is presented. Such decentralized production and storage of energy offers new opportunities for a reliable power grid structure. It is proposed to divide the grid into much smaller cells than in the traditional grid (Fig. 2a). Since all these cells contain distributed generators, they can operate independently if necessary (Fig. 2b).

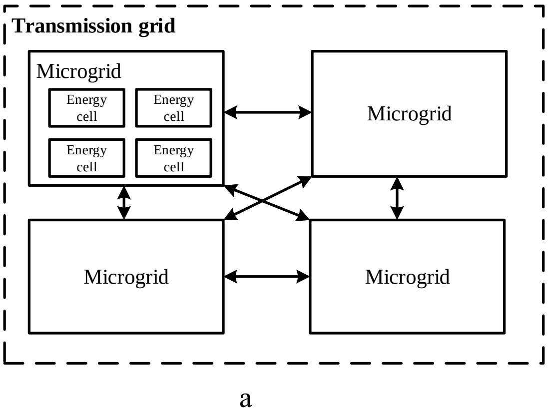
Papers [17] present an approach for building the cluster Microgrids, which are separate full-fledged Microgrids (work independently from each other) and cooperate to function as a single whole. Microgrid clustering requires additional interconnection costs between individual Microgrids, but the benefits it brings, in the form of reduced unmet load, excess energy, component size, and improved reliability, outweigh the additional upfront costs.

The paper [18] notes that it is necessary to develop energy control and management systems to ensure the safe and efficient operation of Microgrid clusters with the development and research of new control strategies, communication protocols, and distributed cluster coordination mechanisms.

As for Ukraine, work is underway to create a cellular energy network. A cellular power grid is the networking of a variety of local power generation facilities and consumers, complemented by methods and means of demand side management and system balancing. At the moment, the merger may include a variety of generators, such as petrol, diesel, gas generators, RES, and energy storage systems, and in the future, it is envisaged to gradually replace fossil fuels with renewable energy sources [19].

In contrast to the scattered approaches, [20] presents that energy cells have the ability to generate electricity using their own local generators (e.g., rooftop solar panels, small wind turbines, and diesel generators) and energy storage devices (e.g., batteries). In addition, energy cells can sell surplus electricity to others.

The energy cell concept provides household consumers with significant economic incentives to install distributed renewable energy generators on their own.



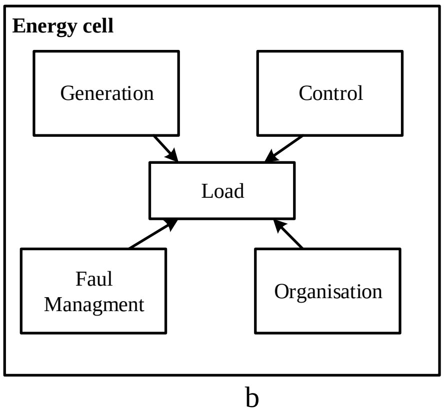


Fig. 2. **Cellular network structure (a) and individual cell structure (b)**

Source: **compiled by the [16]**

The scale of an energy cell can be the size of a city or the size of a building/residential building. The main goal is to maximize your own profit. In some cases, some energy cells may even unite to generate more profit by producing and selling electricity together.

Fig. 3 shows the architecture of the Microgrid, two types of market participants are presented: the energy cell and the cell of utility companies [20].

Depending on the nature of energy production and consumption, cells can be divided into several types [21]: consumers, producers, producers with higher consumption, and consumers with lower consumption. It is assumed that energy storage devices can be integrated with energy cells based on user preferences. Energy cells need rational decisions regarding the use of energy storage devices.

An analysis of the literature showed a lack of research on the functioning of cells, their composition, and the study of their interactions.

PURPOSE AND OBJECTIVES OF THE STUDY

The purpose of the article is to highlight new approaches to the functioning of the decentralized power industry of Ukraine based on the Microgrid, built on the principles of intelligent interaction of distributed energy resources when representing the system in the form of energy cells.

To do this, it is necessary to solve the following tasks:

– Identify individual types of energy cells by composition and functionality

– Description of optimization tasks and roles in the energy market

– Analyze the operation of the Microgrid as a set of energy cells.

– Identify the economic, social and technical advantages of the functioning of a decentralized Microgrid built on the principles of intelligent interaction of distributed energy resources when representing the system in the form of individual energy cells.

Research hypothesis: representation of a microgrid as a collection of energy cells to achieve both collective benefits and the benefits of individual cells

Research object: energy processes in energy cells and microgrids

The research uses traditional methods of the theory of electrical circuits, power supply systems of electrical complexes, simulation modeling in the MatLab Simulink system, numerical analysis using the MathCAD package, MS Excel.

Users of the Internet of Energy, with the help of their energy cells, can play various dynamically changing roles in the power system, providing each other with a variety of services, such as the sale (supply) of electricity, participation in the management of system operating modes (including participation in maintaining frequency and voltage level), the provision of energy equipment for rent or temporary remote use, the provision of power reserves for loading and unloading, and any other types of services created in the electric power industry.

IDENTIFYING THE TYPES OF ENERGY CELLS IN MICROGRID

Based on the analysis of the modern development of the energy sector, the following types of energy cells have been identified.

1. *Energy cell 1.* – Generators of electrical energy. It is a type of cell that are made up of local generators capable of generating and supplying electricity.

2. *Energy cell 2.* – Prosumers. Power consumers with local generators for energy production, which can be used as a primary or backup power source along with grid connection and storage devices.

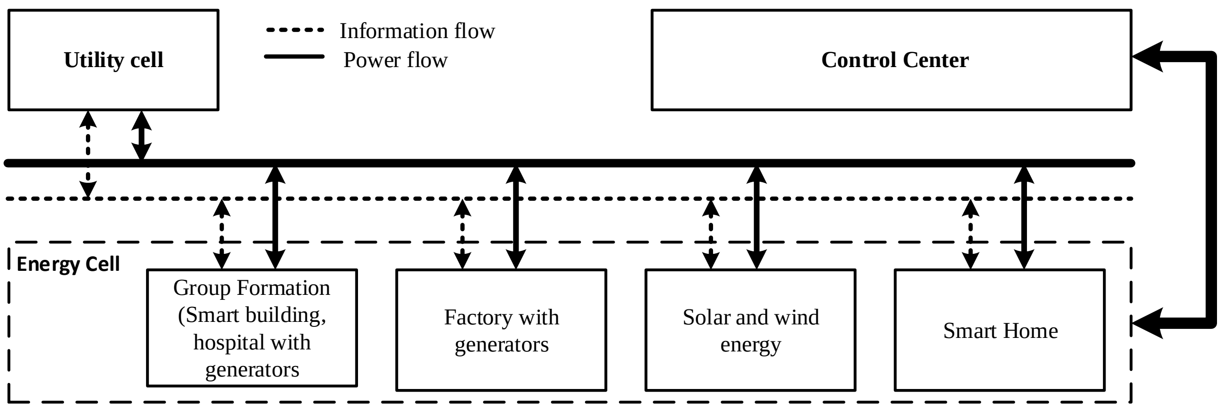


Fig. 3. **Cellular network structure**
Source: **compiled by the [20]**

In turn, such cells can be divided into two subtypes: prosumers with dominant generation, who provide themselves and can sell energy to neighboring cells, and prosumers with dominant consumption, who in turn partially cover their own needs, the rest are purchased.

3. *Energy cell 3.* – Passive consumers. Being a cell in which the collected consumers have neither storage systems nor local generators. All electricity is purchased from the grid and functions with it using the Internet of Energy.

Consumers can consist of dispatched loads and non-dispatched loads. Dispatched loads are household consumers or industrial and commercial consumers who can voluntarily redirect their consumption for a certain period. Non-dispatched loads are critical loads where redirection of electricity consumption is not possible [21]. This division is important when participating in demand response programs.

4. *Energy cell 4.* – Electric vehicles. A separate type of cells, since they can be charged from different cells, or store energy as a storage system and give it away in another cell. Often, the electric car belongs to the consumer and can be part of the cells where consumers are present.

5. *Energy Cell 5.* – Utility energy cells facilitate the transmission of electricity between energy cells by providing physical infrastructure such as wires, poles, and related devices such as transformers, smart energy meters, and more. Apart from this, they also provide ancillary services such as voltage regulation, load tracking, scheduling and dispatching, reactive power compensation, and loss compensation. They can be individual participants in the market.

Transactive energy [22] for energy cells provides:

– generation, recording, stable and secure storage of records of energy transaction parameters;

– the functioning of users' "digital wallets", stable and secure storage of their personal data and financial information;

– verification of the fulfillment of energy transaction obligations based on data received from the IoT system;

– billing of energy transactions, including ensuring the instant transfer of funds upon fulfillment of the terms of the energy transaction.

Transactive energy can be considered an internet-enabled free electricity market where all participants can safely trade at a reasonable price and near-real-time settlements to solve their common problems [23]. The local energy market in the distribution system performs two main functions – flexibility services and energy services. The difference between these services is how the parties participate in the market. When only energy supply is needed, these are energy services. But if, for example, demand response is used, then this can be considered a service of flexibility [21].

A transactive energy (TE) system is an energy trading platform created primarily at the distribution level based on the TE concept, which allows medium or small-scale production and consumption entities to directly participate in local energy markets and automatically negotiate their energy trading with each other, thereby contributing to a dynamic balance of supply and demand in local energy communities [24], [25].

Many studies have been devoted to the possibilities of implementing decentralized markets in Ukraine. Thus, the work [26] is devoted to assessing the impact of transmission network constraints on electricity exchange in the context of the integration of electricity markets into the European electricity market.

Fig. 4 presents a generalized architecture of the Microgrid with all types of cells considered; according to this structure the centralized network may be added.

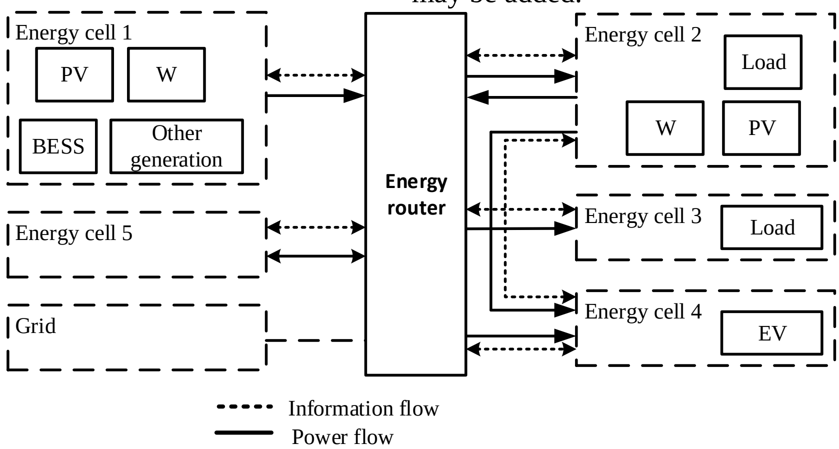


Fig. 4. **Microgrid architecture in the Internet of Energy system**
Source: **compiled by the authors**

Table 1 presents the goals of the functioning of energy cells and their role in the transactive market.

Despite the fact that each generating energy cell has the goal of selling energy to the grid at the highest prices, but to ensure reliability, in case of disconnection of individual generators or entire generator cells in systems without connection to the centralized network, other energy cells should provide consumers with the maximum possible supply, especially dispatched loads. This approach is important in modern energy systems, especially in Ukraine, in case of possible shutdowns of the centralized network.

ANALYSIS OF THE INTERACTION OF PROPOSED ENERGY CELLS IN MICROGRID

To confirm the proposed concept of building a cellular local electric power system, let us consider the architecture of the Microgrid, which consist of cells of types 1, 2 and 3 combined into one system (Fig. 5).

Table 1. **Cell types**

Cell type	Goals	Role in the transactive energy market
Energy cell 1 Electrical power generators	Profit Maximization Minimization of generation costs	Salesperson
Energy cell 2 Prosumers	Providing consumers with their own generation Minimizing costs Profit Maximization	Buyer Salesperson
Energy cell 2.1 Prosumers with dominant production	Providing consumers with their own generation Minimization of own consumption in order to make money in the energy market Maximizing profits from the sale of energy to the grid during peak hours	Salesperson
Energy cell 2.2 Prosumers with dominant consumption	Maximum energy consumption from your own sources Buying energy from outside during periods of low prices	Buyer Salesperson
Energy cell 3 Passive consumers	Minimizing costs	Buyer
Energy cell 4 Electric vehicles	Fast charging	Buyer
Energy cell 5 Communal energy cells	Ensuring reliable physical interaction between cells Participation in support services	Secondary

Source: **compiled by the authors**

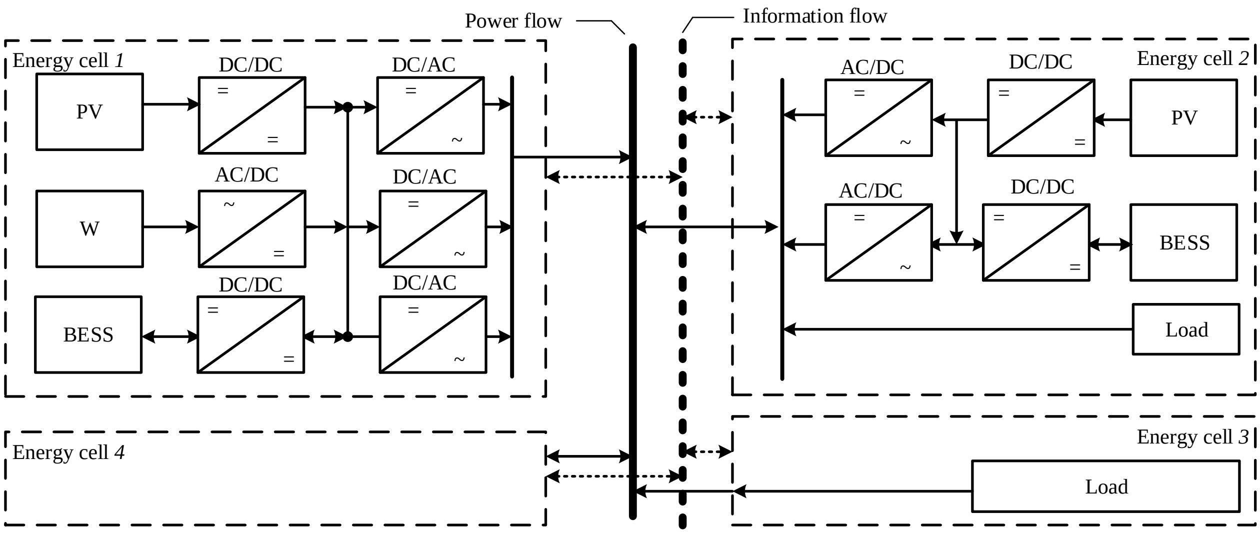


Fig. 5. **Cellular Microgrid**
Source: **compiled by the authors**

Microgrid is built and operates according to the following basic principles:

– decentralized nature;

– implementation and management of all processes takes place through direct transactions between participants;

– implementation of bidirectional power flows between system elements;

– dynamic change of types of participants in the transactive market;

– the presence between electric power equipment not only of electrical connections and interaction provided by electric networks, but also of information connections and interaction;

– implementation of fully decentralized smart control;

– the presence of a decentralized transactive electricity market;

– the presence of connections and interaction of individual cells with each other and with Microgrid, which ensures optimal functioning for users.

The type 1 energy cell consists of solar generators, a wind turbine and a storage system. The distribution system works in such a way that the selection of energy from solar sources is a priority. Depending on the price function, time of day and restrictions, the optimal distribution of power take-off from wind sources and storage systems is chosen. A cell sells energy to other cells.

A type 2 energy cell has consumers, solar generators, and storage systems. The power of solar sources is provided by its own load. In case of excess, it sells energy to other cells.

Energy cell 3 represents a group of consumers.

The exchange of energies between energy cells occurs when the power is distributed by the control system between generators.

The target function is to minimize the total costs C_{sum}:

$$C_{sum} = f(t, \mathrm{P}, C) \rightarrow \min . \quad (1)$$

To solve the target function, the developed algorithm for power distribution across all energy cells of the transactive system is used. The main concepts of the algorithm for different compositions of electric power systems are reflected in the authors' works [27], [28], [29], [30].

SIMULATION RESULTS

In such a cellular system, all electricity producers, Microgrid network operator, consumers and prosumers submit their applications and/or proposals for participation in the schedule of system load coverage through the local energy market. The criteria for Microgrid optimization, depending on the task, can be such as mutual economic benefit, reduction of energy costs, as well as efficiency and reliability of the system.

The research was conducted using developed algorithms for the functioning of individual cells and their interaction using a program in the Matlab.

Maximum power energy cell 1 – 200 kW, energy cell 3 – 180 kW, Maximum power PV Energy cell 2 – 20 kW, power load – 12 kW.

To analyze the proposed cell system in energy cell 3, the daily load graph is selected, presented at t intervals of 1 hour each (Fig. 6).

Also, Figure 6 shows the distribution of power across energy cells during their interaction.

The distribution graphs inside energy cell 1 (Fig. 7) consist of the power of the solar source, the wind source, and the storage system at each interval. The “+” sign shows the return of energy to the load, the “–” sign shows the residual power of renewable sources used to charge the storage system.

The power distribution in energy cell 2 is shown in Fig. 8.

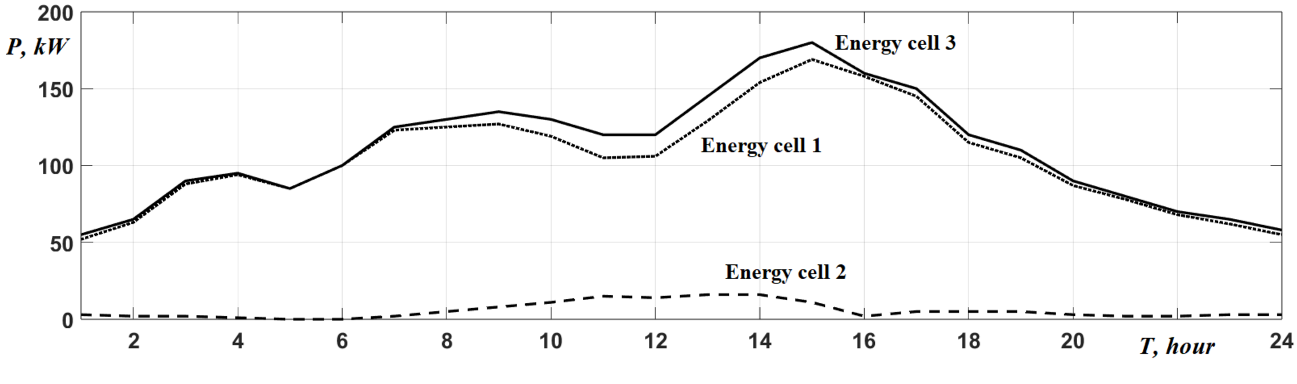


Fig. 6. **Power energy cells**
Source: **compiled by the authors**

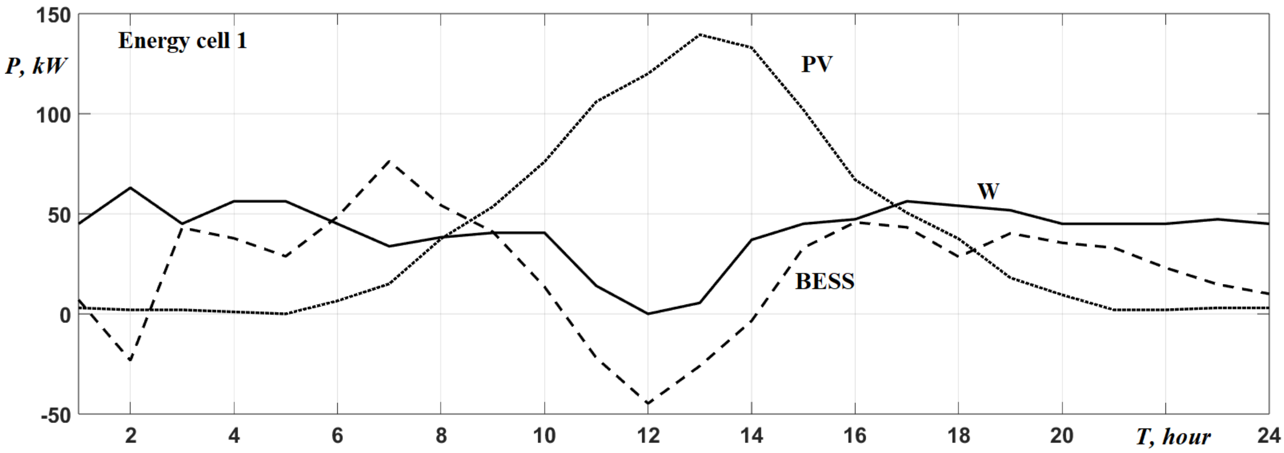


Fig. 7. **Power of energy cell 1**
Source: **compiled by the authors**

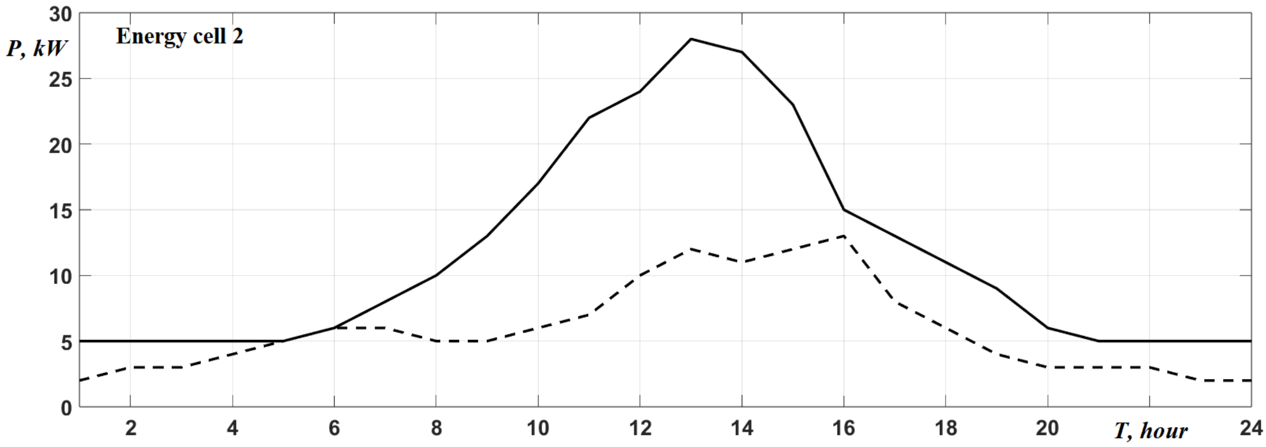


Fig. 8. **Power of energy cell 2**
Source: **compiled by the authors**

Excess energy is given to the network (in Fig. 6, the energy cell 2 curve).

Theoretical studies have been conducted, namely the representation of the system in the form of energy cells, each of which solves its own optimization problems and their interaction to achieve collective benefits, confirmed by digital modeling.

Analysis of the graphs shows that the peak load is applied for a period of 14-16 hours, and the peak of solar energy is from 12.00 to 14.00, therefore, at these intervals there is excess generation not only of individual energy cells but also in the system as a whole, therefore, at $P_{2g}+P_{1g}>P_{2c}+P_{3c}$ (P_{2g} is generation power and P_{2c} – consumption power by energy cell 2, P_{1g} is power of energy cell 1, P_{3c} is power of consumption by energy cell 3) – to avoid energy losses in the system, excess energy in energy cell 2 is given to the consumer, and excess energy in cell 1 is given to its storage system.

In further studies, other options for using excess energy are possible, such as separate energy cells with storage systems, a different priority for using energy from cells, in the presence of a centralized energy sales network.

Within the operation of cell 2, the energy satisfaction of the cell consumers is fully ensured throughout the considered interval.

Analysis of the operation of the Microgrid as a set of energy cells showed:

– providing the load with electricity;

– maximum use of renewable energy sources;

– energy return by the active consumer (cell 3) of energy to the Microgrid for its sale;

– operation without connection to the centralized network.

Unlike existing studies, a more detailed division into energy cells allows us to take into account the wishes of all participants in the local system.

The representation of electric vehicles as separate energy cells allows us to use them as additional storage systems, and to consider them as dynamic consumers when interacting with different energy cells during the day.

Based on the considered Microgrid operation modes, it is possible to allocate a separate energy cell only with storage systems, for storing aggregate surplus capacities and using it in case of a general deficit.

CONCLUSIONS

The analysis showed that the introduction of power plants built on the basis of the principles of the Internet of Energy, is the most expedient for the formation of distributed energy in Ukraine. The use of the principles of building Microgrids in the form of energy cells is an increase in the reliability and quality of power supply to energy facilities of critical infrastructure.

For the widespread use of cellular Microgrids, along with technical issues of developing the structure and laws of control, it is important to solve a complex of issues of building the appropriate regulatory and methodological support.

There are 5 types of energy cells that interact and have economic, social and technical impacts on all participants of the Microgrids. Economic impacts are impacts on consumers' electricity bills and energy sales revenues. The technical impact of local energy markets on the electricity distribution system can be observed in changes in the network scheme, approaches to network planning and operation, methods of electrical analysis of the network, maintenance programs, technical skills of personnel.

Along with technical, it is the social impact that is important: reducing electricity costs for end users, ensuring reliable power supply to all system consumers despite belonging to other cells, improving the quality of life, improving policy and decision-making, reducing CO_2 emissions.

The considered Microgrid architecture, when representing energy system objects in the form of energy cells and using the Internet of Energy, allows:

– to increase the stability and reliability of the Ukrainian energy system;

– to modernize the energy infrastructure;

– to increase the share of renewable energy;

– to consume electricity wisely;

– to influence the development of local electricity markets

– to provide financial benefits for all participants in the Microgrid.

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Коміркові структури розподілених мікромереж на основі Інтернету енергії

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ABSTRACT

З огляду на мінливі глобальні енергетичні виклики та нагальну потребу в стійких, децентралізованих та цифрових енергетичних системах, концепція Інтернету енергії (IoE) постає як трансформаційна основа для сучасної енергетичної інфраструктури. У цій статті досліджується розробка та впровадження коміркових структур на основі Інтернету енергії в рамках розподілених мікромереж, з акцентом на критичну потребу України в енергетичній безпеці та відновленні системи в умовах постійних геополітичних потрясінь. Застосовуючи парадигму «3D» – декарбонізацію, децентралізацію та цифровізацію – запропонована архітектура організовує енергетичні системи у взаємопов'язані енергетичні комірки, що включають різних зацікавлених сторін: генераторів, споживачів-постачальників, пасивних споживачів, електромобілі та комунальні вузли. Ці комірки використовують розподілені енергетичні ресурси, управління попитом та технології Energy Cloud 4.0 для забезпечення балансування енергії в режимі реального часу, участі на ринку та транзакційних енергетичних операцій. У статті представлено комплексну структуру для мікромереж на основі принципів IoE, описано типології енергетичних комірок, алгоритми керування для оптимізації витрат та стратегії гнучкості та надійності мережі. У роботі висвітлено, як коміркові архітектури можуть забезпечити автономну роботу, підвищити стійкість до перебоїв та сприяти інтеграції з європейським енергетичним ринком. За допомогою моделювання та симуляції в статті підтверджено доцільність цього підходу, демонструючи значні покращення енергетичної ефективності, стабільності та сталості. Для організації роботи та взаємодії комірок було визначено п'ять типів енергетичних комірок, які взаємодіють та мають економічний, соціальний та технічний вплив на всіх учасників мікромережі: економічний вплив (зміни в рахунках споживачів за електроенергію та доходах від продажу енергії), технічний вплив (зміни в схемі мережі, підходах до планування та експлуатації мережі) та соціальний вплив (підтримка, надійність споживання, скорочення викидів CO_2). Технічні, економічні та соціальні переваги переходу на коміркові мікромережі на основі Інтернету енергії є основоположним елементом у відбудові та забезпеченні майбутнього енергетичного сектору України.

Keywords: Інтернет енергії; мікромережа; енергетична комірка; транзактивна енергія; енергетичний ринок; розподілені енергетичні ресурси

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