ISSN 2786-7102 (Online), ISSN 2786-7633 (Print)
https://doi.org/10.15407/srenergy2025.02.054

UDK 621.316.1.052.6:696.6-1; 621.311(075.8)

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COMPARATIVE STUDY OF ARCHITECTURE AND MANAGEMENT SYSTEMS IN ENERGY COMMUNITIES MICROGRIDS WITH POLYGENERATION

Abstract. *This study presents a comparative analysis of well-known methods for structuring local microgrids with diverse generation sources, active consumers, and energy storage systems as a prototype of a territorial energy community. The scientific concept disclosed in this publication focuses on justifying the evaluation methods of operating modes of microgrids with polygeneration to determine their stability and energy efficiency boundaries. Scientific tasks are related to assessment advantages and disadvantages of various methods used for selecting the structure of generating sources and determining demand components to develop optimal scenarios for ensuring the resilience and energy efficiency of such networks. The study compares methods for determining the boundaries of dynamic and static stability in a polygeneration-based microenergy system; management approaches in grid-connected, islanded, and hybrid (considering self-generation) operational modes. Additionally, considered aspects of forming real-time optimal dispatch strategies, and developing market mechanisms for energy community members based on the criterion of minimizing the total cost of electricity supply. Technological efficiency of microenergy system components, economic viability, stability, and reliability were selected as criteria for comparison. The results of the comparative study make it possible to determine optimal approaches for forming the technological structure of a specific energy community, taking into account available local resources, network infrastructure characteristics, seasonal demand fluctuations, and other variables. As the analysis outcome, accents have been made with regards to energy-economic prerequisites for the development of decentralized energy systems with renewable energy sources and combined energy generation installations. It is established that managing the energy efficiency of microgrids with renewable energy sources and system-level energy storage requires the development of new models for load balancing and demand forecasting, as well as theoretical instruments for defining micro-market relationships among energy community participants, specifically – system-level electricity suppliers, local prosumers with predefined generation conditions, and end consumers.*
Keywords: energy community, polygeneration-based microenergy systems, technological structures of microgrids, islanded and hybrid operating mode, active consumer, energy management.

Nomenclature

UES	Unified Energy System
MES	Microenergy System
TC	Territorial Community
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
MG	Microgrid
EC	Energy Community
DER	Distributed Energy Resource;
EPS	External Power System
SES	Solar Energy Station
WES	Wind Energy Station
DPS	Diesel Power Station
GPPS	Gas Piston Power Station
CHPS	Combined Heat and Power Station

BEES	Battery Energy Storage System;
RES	Renewable Energy Sources
DG	Distributed Generation
DES	Distributed Energy Sources
CDT	Conditional Dynamic Tariff
CPSS	Combined Power Supply Systems
HES	Heterogeneous Electricity Sources
DERMS	Distributed Energy Resource Management System
OPF	Optimal Electricity Flows
MPC	Modelling Predictive Control
AI	Artificial Intelligence
ML	Machine Learning
EM	Energy Management
EMS	Energy Management System
DRP	Decentralized Resource Planning
P2P	Peer-to-Peer Trading Concept
TE	Transactional Energy
DSM	Demand Side Management
IoT	Internet of Things

1. Introduction

Unified Energy System (UES) is a component of Ukraine's fuel and energy complex, consisting of large hub power plants, an electricity transmission system, and high-voltage transmission lines. This structure of the United Energy System is vulnerable in the context of full-scale invasion by russian federation. If a large number of generation facilities and high-voltage transformer substations within the transmission system are damaged, a system-wide failure could occur, leading to a prolonged blackout affecting a significant number of consumers over vast territory. The energy sector is one of the main targets of russian aggressor, as it holds strategic importance for the economy and people's livelihood.

The damage to critical energy infrastructure has led to balance and network constraints within the UES, resulting in frequent electricity supply restrictions for a significant number of consumers. These restrictions negatively impact the country's economy and cause substantial social and economic losses. Given the scale of damage to existing generation capacities, decentralizing generation facilities is necessary to enhance the resilience of the UES and, thereby, to establish self-sufficient microenergy systems (MES) with their own energy sources within territorial communities (TC).

The main goal of the European Green Deal is to transform Europe into the first climate-neutral continent by 2050 [1, 2]. The project also aims to protect, preserve, and enhance the EU's natural resources, as well as safeguard the health and well-being of its citizens. The Green Deal is an integral part of the European Union's strategy to implement the United Nations' 2030 Sustainable Development Goals agenda. As part of the Green Deal, the European Commission encourages economic growth toward integrating the United Nations' Sustainable Development Goals, ensuring citizens' well-being through policies, and aligning actions with the EU's sustainability objectives [3, 4].

At the same time, the largest contribution to SAIDI and SAIFI indices comes from the reliability of 6-20 kV distribution networks of distribution system operators. Therefore, improving the reliability of distribution system operators' electrical networks requires urgent resolution. The main reason for this is the very low level of automation in such electrical networks. However, Ukraine currently lacks effective algorithms and technical solutions to significantly improve reliability indicators for distribution system operators. The length of feeders, which can sometimes exceed 50 km and the presence of a large number of line disconnectors, which can only be operated with no load are main factors which negatively impact SAIDI and SAIFI indices. The actual SAIDI level in many sections of distribution networks reaches 4,000 minutes per year, and on some 6−10 kV feeders, it exceeds 10,000 minutes (according to The State Energy Supervision Inspection of Ukraine).

A microgrid (MG) of an energy community (EC) is a set of distributed energy resources (DERs) and consumers that reside in the same area and can be disconnected from and reconnected to the main grid according to a specific algorithm [5]. The primary goal of EC is to reduce dependence on the main grid having capabilities to manage the reliability and efficiency of such microgrids. Depending on the availability of electricity supply from an external power system (EPS), the EC microgrid can operate in an isolated mode, generating and fulfilling demand using its own local energy sources. EC microenergy systems can include various types of electricity generation sources, such as Solar Energy Stations (SES), Wind Energy Stations (WES), Diesel Power Station (DPS), Gas Piston Power Stations (GPPS), Combined Heat and Power Station (CHPS) [6]. Industrial battery energy storage systems (BEES) can be one of the reliable ways to balance modern microgrids [7].

New opportunities have been raised for the development of decentralized energy supply (primarily based on renewable sources) and households power generation facilities deployment due to the transformation of the electricity market in recent years.

Decentralized energy resource management helps to achieve three key objectives:

– implementation of energy generation facilities at both the individual level and the energy community (EC) level;

– support investment into regional sustainable development projects and forming energy-independent territorial communities (TCs);

– strengthening the mutual impact of baseload generation facilities owners and energy community members on the economic model of MES operation.

Today's experience of organizing energy community (EC) structures in the context of the global "green" energy transition [8] and the decentralization of energy supply systems demonstrates a return to collective ownership and collective resources management related to self-sufficient energy production. This is achieved through the implementation of distributed generation capacities based on renewable energy sources (RES) [9]. By optimizing resource distribution and coordinating the processes of generation, transmission, storage, distribution, and consumption of energy, it becomes possible to create high-tech local infrastructure assets within a specific territorial community, facilitating the development of independent (island-mode) energy supply systems [3, 4].

The current energy policy at the community level is mostly impacted by the corporate suppliers market. Such companies do not contribute much to local budgets and most profit outflow outside the territorial community. This situation does not encourage investments in the sector. Under these conditions, regional development becomes highly challenging, as the community does not receive economic benefits and on other hand continually incurs costs for energy consumption.

The growing interest in addressing energy supply challenges for local communities, which could utilize local alternative fuels and renewable energy sources, along with the development of smart grids, is drawing attention to initiatives aimed to create and improve local microenergy systems for combined heat and power generation (CHPS) using diverse energy sources. Local communities, especially in developed countries, are undergoing transformation, seeking a shift from their traditional role as passive consumers. There is already experience in forming so-called active consumers, who are both energy consumers and producers simultaneously [7, 8]. Local energy systems have the potential to contribute to overall energy and climate goals, helping to transform energy consumption trends and reduce greenhouse gas emissions [8].

Local MES offer extensive opportunities for integrating RES by considering the specific interactions between local generation and end-user demand, as well as by coordinating the use of external power systems. Managing these networks requires new organizational approaches to optimize their operation. New energy initiatives are focused on a different logic for structuring local energy supply, aligning with the concept of "mass innovation" which aims to replace existing social and technical structures. The real world example of this new structure includes local sustainable energy production facilities, such as solar and wind power stations, biomass and biofuel production capabilities. Additionally, local cooperatives experiment with innovative solutions, such as energy storage systems and the development of smart grids [9].

2. Definition of Research Purpose

Advanced strategies for forming microgrid balancing approaches with heterogeneous power sources and adaptive dispatching can be used to optimize the operation of the energy community, achieving at the same time the desired efficiency levels. Usage of microgrids can enhance the reliability and resilience of power supply for the community, as well as reduce dependence on the main grid [10]. Expanding the use of microgrids for decentralized power supply makes it crucial to determine the best management strategy to optimize the performance of these systems [11].

The main idea of this comparative study is to evaluate different management strategies for a community microgrid, including isolated, grid-connected and hybrid control modes, and advanced management strategies that incorporate optimization methods such as optimal power distribution and dispatching based on specific economic criteria.

The purpose of this study is to evaluate and compare various control systems designed for energy communities, focusing on key factors such as resilience, economic efficiency, energy efficiency, survivability, and reliability. The research includes an analysis of distributed, decentralized, and centralized control strategies in different operational contexts. Based on this analysis, the study aims to identify the optimal design and operation modes of local microgrids to support the modern development of sustainable and resilient local energy infrastructure. To achieve this, new factors must be considered, reflecting current trends in the formation of energy-independent territorial communities and their network operations in relation to the external power system, as well as in isolated (islanded) and hybrid modes.

This study will serve as a foundation for a detailed analysis and comparison of various strategies for defining structures, control approaches for the power generation capacities of energy communities. As a result, it provides a roadmap for further research related to modeling energy balances and microgrid operating modes. Further control scenarios development should contribute to the efficient operation of microgrids by optimizing electricity generation, storage, and distribution.

There are following key strategic directions:

– centralize management as a dispatch system for controlling electricity production and distribution in energy community microgrids, which allows real-time demand-supply balancing and ensuring reliability and resilience of the energy island [12];

– decentralize management as a local control level for baseload generation of the energy community and prosumers power supply in isolated and hybrid modes with forecasted autonomous operation time. This approach enhances flexibility, resilience, and cost management for consumers [13];

– demand-side management as developing consumer-side behavior scenarios from the demand perspective to control electricity consumption during peak load periods, which helps to reduce costs and improve the reliability of the microenergy system [14];

– utilization of low power stations and energy storage systems. Energy storage systems can be used to balance demand and supply, provide backup power, and increase the usage of renewable energy sources. This is especially relevant for internal combustion engine power stations and storage systems owned by energy community members [15];

– RES usage at priority. The design and expansion of the capabilities of community microgrids (particularly their transmission capacity) should aim to integrate the maximum possible share of renewable energy sources, including solar, wind, and biomass-based primary fuels. This can help reduce greenhouse gas emissions and increase energy independence [16].

The article focuses on studying and analyzing well-known methods for microgrids functioning as a new type of self-sufficient territorial energy communities. The study and comparison of various theoretical approaches will help identify ways to improve methods for optimizing the structure of generation capacities, managing microgrids in terms of efficiency and resilience in islanded and hybrid modes, and developing optimal dispatching algorithms with demand response, and at the same time considering the market operating mechanisms among energy community participants. The operational characteristics of MG require an analysis of approaches and methods that ensure resilience, efficiency, stability, and reliability as evaluation criteria for enhancing the energy efficiency of MES under specific community conditions.

3. Decentralized and smart grids regulations in Ukraine

The main regulatory and legal acts governing the operation of distributed electricity generation include the Laws of Ukraine: “On the Electricity Market”, “On the Natural Gas Market”, “On Heat Supply”, “On Critical Infrastructure”, “On Energy Efficiency”, “On Energy Efficiency of Buildings”, “On Alternative Energy Sources”, “On Combined Production of Heat and Electricity (Cogeneration) and the Use of Waste Energy Potential”.

In Ukraine, the implementation of new technologies in the electricity sector is already actively underway, significantly impacting distribution electrical networks by elevating them to a new level of development and operation [10, 11].

The structure of electricity generation capacities is undergoing significant changes, driven by the destruction of energy infrastructure due to missile attacks and substantial increase in RES share in the overall energy balance. This transformation requires the corresponding restructuring of the network infrastructure based on modern smart grid technologies.

Ukraine’s Energy Strategy “Security, Energy Efficiency, Competitiveness” till 2035, which was approved by Cabinet of Ministers Resolution No. 605 on August 18, 2017, envisions the implementation of smart grid technologies as an effective mechanism for developing Ukraine’s power system under modern conditions. In October 2022, based on a proposal from the Ministry of Energy, the Government of Ukraine approved the Concept for the Implementation of Smart Grids in Ukraine until 2035 and adopted a detailed action plan for its realization [17]. This Concept defines “smart grids” in accordance with the terminology outlined in the Law of Ukraine “On Energy Efficiency”. Traditional power grid design approaches have historically been based on the location of large centralized production complexes and the geographic distribution of generation resources (e.g., proximity to coal deposits, availability of sufficient amount of cooling water, and the potential use of hydropower). In the past, power grids were designed and optimized based on regional or national needs. Transmission networks have traditionally served as the foundation for electricity supply and the key to ensuring supply reliability. The existing power grid forms the basis for overcoming new challenges related to ensuring reliable electricity supply. However, changes in the power grid must be implemented within long-term strategies, following a balanced and gradual approach.

UES operates as market-based model, where power plants, as generation units, function in accordance with market requirements by balancing active power and providing ancillary services to maintain the reliability and quality parameters of electrical energy. Smart grids implementation actions aims to enhance the resilience of power networks, improve the efficiency of transmission and distribution networks, facilitate the integration of RES and distributed generation (DG).

The implementation of smart grids contribute to the development of the power grid as an intelligent system for transmission, distribution, and supply of electricity from producers to consumers. This system will be integrated with communication and information technologies, ensuring enhanced power system performance and high-quality service for electricity consumers.

The rapid growth of RES, which are unpredictable in generation patterns by nature, creates challenges for the dispatching of regional power systems. Renewable energy sources could significantly impact local distribution networks, leading to variable power flows, voltage fluctuations in local grids, changes in the technical and economic performance of power networks.

At the same time, inverter-based distributed energy sources (DES) can enhance the reliability of some functions of the power system, particularly by accelerated frequency regulation, flexible and prompt power adjustments, and voltage regulation support in the grid. Additionally, energy storage systems can help balance the daily load schedule of the power system, reducing the inefficient use of DG during peak load periods.

As mentioned in the Concept [17], microgrids are one of the key components of smart grid development. This creates prerequisites for research and development aimed to adapt global best practices in microgrid implementation in accordance with international regulatory standards. Ongoing efforts focus on the implementation of International Electrotechnical Commission (IEC) standards in the microgrid sector, which include recommendations for microgrid deployment, specifications for fault tolerance systems and dynamic control, requirements for energy management system operation, stabilization of frequency and voltage in AC microgrids through active power dispatching based on monitoring and microgrid management.

Some time ago the energy sector UES was monopolistic and dominant. From the perspective of consumers, the electricity sector remains largely centralized. Electricity consumers have almost no influence on systematic processes of the energy market, particularly in terms of their own load profile. As a result, they are forced to accept the tariff policies set by electricity supply companies.

The implementation of energy exchange mechanisms and diversification of sources through distributed generation has not yet reached a high level of adoption. However, it provides consumers and their associations (energy communities) with unprecedented opportunities to achieve self-sufficiency to the extent that operating such microgrids in both grid-connected and islanded modes (without connection to the external power system) could become an economically viable option [18]. This direction has become highly relevant in light of terrorist attacks on Ukraine’s energy infrastructure by russian aggressor, which have resulted in power shortages within the energy system.

The transformation of the electricity market in recent years has created opportunities for the development of decentralized energy systems (primarily based on renewable energy sources) and the deployment of generation facilities into private households.

An energy community can be defined as an association of consumers, who reside in particular geographical areas, and together with local energy sources and networks, compose a microenergy system capable of operating both modes − grid-connected and islanded. Clearly, such networks in island mode will incorporate diverse energy sources for electricity generation, energy storage, and real-time dispatching systems [18, 19].

The adoption of microgrid standards provides the necessary conditions for regulation development, improving the efficiency of implementation and further operation of microgrids. This process includes revising and refining existing technological design standards for power systems and electrical networks of 35 kV and above, as well as developing long-term planning for the future UES energy hubs and regional networks.

The availability of a regulatory framework will enhance the efficiency of pilot projects for the implementation of decentralized microgrids, as outlined in the Action Plan for the Implementation of the Smart Grid Concept in Ukraine until 2035. This allows acquiring practical experience in designing, implementing, and operating critical infrastructure facilities, especially their potential use in island mode by activating local distributed generation sources when needed.

Draft State Standard of Ukraine (DSTU) − DSTU IEC TS 62898-2: 202_ (IEC TS 62898-2: 2018 + AMD 1: 2023, CVS, IDT) provides recommendations on the usage of microgrids, establishing rules for operation and management. Particularly in energy management systems with defined monitoring procedures and real-time database population, integration of energy storage systems, implementation of multifunctional protection systems for both non-isolated and isolated microgrids, synchronization and reconnection protocols, electricity quality control, modeling of power balancing, technical regulations and operation deployment procedures.

DSTU IEC TS 62898-3-1:202_ (IEC TS 62898-3-1:2020 + AMD 1: 2023, CVS, IDT) draft is a component of a broader regulatory document titled “Microgrids”, which focuses on providing fault protection and establishing requirements for dynamic control in microgrids, providing safe and stable microgrid operation under fault conditions and disturbances, defining protection principles and dynamic control strategies, considering the differences between traditional local energy system protection methods and new potential solutions for microgrid protection.

DSTU IEC TS 62898-3-2:202_ (IEC TS 62898-3-2:2024, IDT) draft provides a description of existing energy management systems used in real-world microgrid projects, including classification of relevant energy management system functions and recommended guidelines for their future development. This document focuses on the development of energy management systems designed for microgrids, which are integrated into decentralized energy systems or existing distribution networks.

DSTU IEC TS 62898-3-3:202_ (IEC TS 62898-3-3:2023, IDT) draft provides regulation in requirements for frequency and voltage stabilization in AC microgrids using dispatchable loads that respond to changes in frequency and voltage during while power consumption is changed. It outlines requirements for simulating self-regulation effect, achieved through continuously controlled loads and managed load reduction. The scope of this document is limited to loads connected to voltage levels up to 35 kV.

DSTU IEC TS 62898-3-3:202_ (IEC TS 62898-3-3:2023, IDT) draft provides a general overview of the definition, purpose, and application of microgrids, as well as guidelines for conducting analysis during microgrid planning. This includes resource analysis, load forecasting, operational planning for the microgrid.

4. Technological support and structural elements classification of distributed generation systems

Regional microenergy networks offer vast opportunities for integrating RES. New energy initiatives, primarily driven by a significant loss in the reliability of centralized power systems, focus on alternative approaches to structure such systems. Examples of new structural implementations include local sustainable energy production, such as SES and WES, biomass and biofuel production facilities. A growing trend in the development of energy independence for regional power systems is the widespread adoption of energy storage systems [20].

In recent years, numerous studies have been conducted on the structural-parametric synthesis of combined power supply systems for energy-efficient buildings, utilizing smart technologies and microenergy network management systems for local facilities based on Conditional Dynamic Tariff (CDT) etc [21]. The decarbonization policy requires a further increase of RES share in the energy balance of regional power systems, which have traditionally relied on fossil fuels. This drives exploration of new solutions for the optimal integration of production, transmission, and distribution processes for both heat and electrical energy. Traditionally, such energy networks were designed as separate independent systems. However, their integration highlights the need for a deeper research of electrical processes at the level of primary fuel conversion technologies and energy consumption management at the end-user level [18, 22].

Theoretical studies on processes used to form dynamic tariffs for daily energy management scenarios at local energy facilities have helped to identify patterns in the development and implementation of Combined Power Supply Systems (CPSS) [21, 22]. As of the end of 2024, the total installed capacity of household solar power plants (SES) in Ukraine exceeds 1.5 GW. This factor can significantly influence the current electricity price levels throughout the day and over longer time intervals (monthly, yearly) [11].

The study [23] presents technological solutions for electricity generation using sources that are viable for practical application taking into account economic sense. There are SES, WES, Combined heat and power (CHP) facilities operating on solid biofuel and biogas energy sources used to form local microenergy systems. Consumers, organized into energy communities, consume the electricity they generate, effectively becoming collective end-users of energy. Any surplus electricity generated from these sources can be exported to the main (centralized) grid, sold to third parties, stored in energy storage systems. The general structure of MES is illustrated in Figure 1.

To enhance the efficiency of local energy systems, particularly during peak periods, the deployment of electrical and thermal energy storage systems will be essential in the future. To meet heating demands of territorial communities centralized heating systems can be implemented using biomass, wood chips and pellets, solar collectors, heat pumps, combined (cogeneration) facilities for heat and electricity production [24]. The basic configuration of a local microgrid includes connections to the centralized power system, WES, SES, generators with internal combustion engines, thermal and cogeneration units (operating on biogas, biodiesel, and biofuels), static power supply sources, monitoring and consumers’ energy management system. This setup allows the establishment of adaptive energy balances within the community, considering primary fuel costs, electricity and heat transmission expenses, and energy distribution among consumers [25].

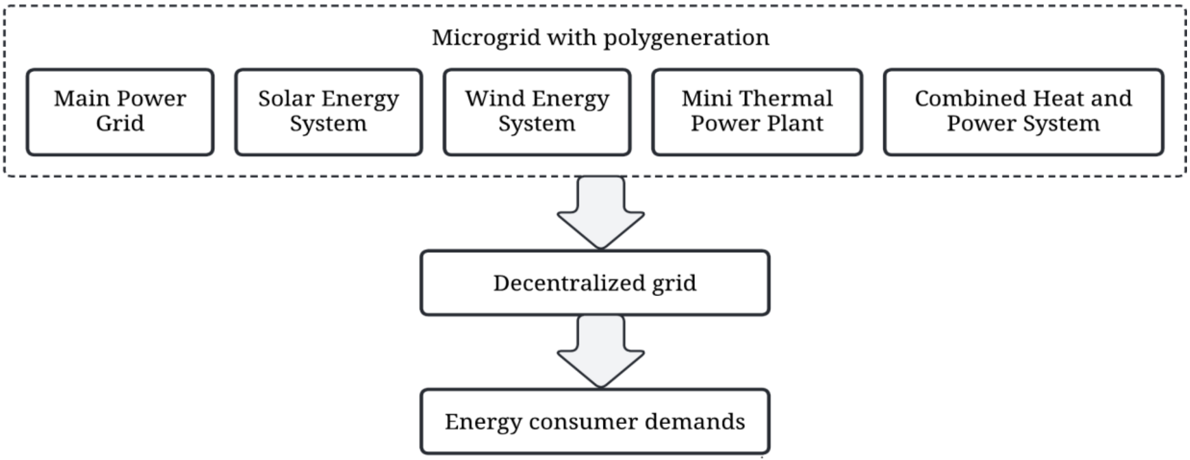

Fig. 1. Structure of Combined Energy Supply for a Territorial Community

Distributed generation (DG) primarily enables the integration of RES with energy storage systems into the existing regional power grid to meet additional demand, increase the share of green energy in the microenergy system balance, and reduce greenhouse gas emissions. However, balancing DES requires the use of additional intermediate power generation capacities or energy storage systems. The classification of technological structures in decentralized microenergy systems is illustrated in Figure 2. Primary electricity production uses thermal sources, with generation levels controlled based on demand. Sources with stochastic generation nature cannot fully participate in microenergy system balancing and require additional energy management solutions, such as storing excess electricity during overgeneration for later use in MG balancing. It is important to note that thermal energy sources have environmental impacts. However, they can utilize local energy resources, primarily solid and gaseous biofuels, as primary fuel sources [26].

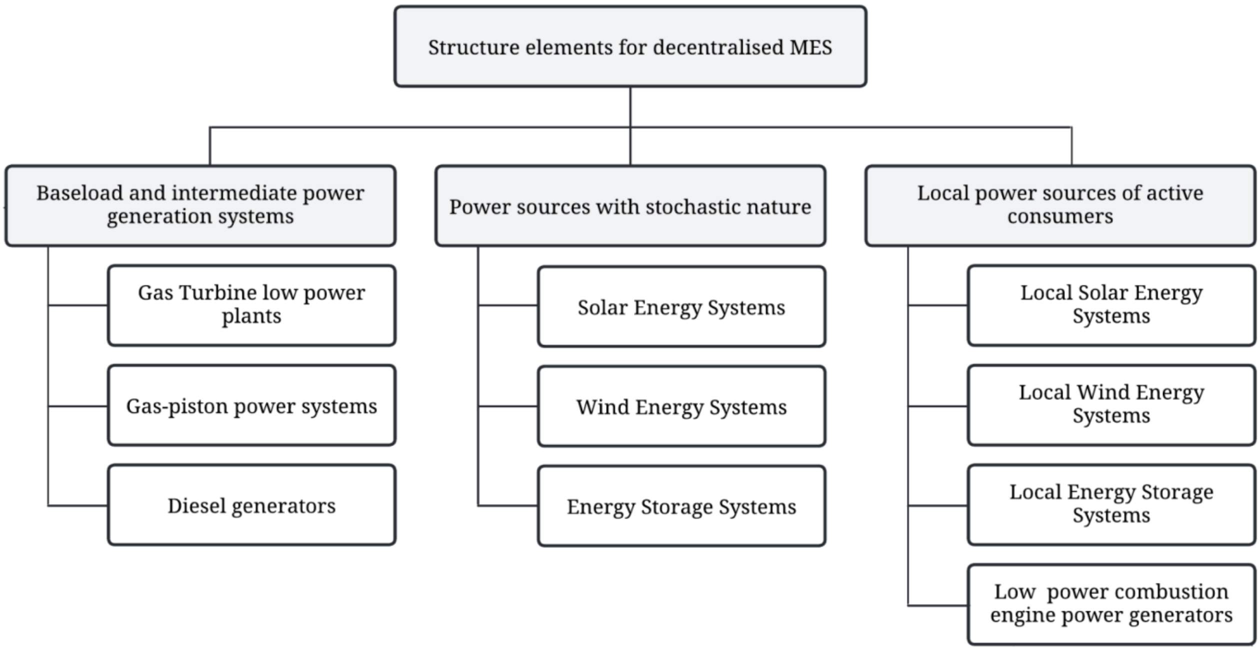

Fig. 2. Elements of technological structures in decentralized microenergy systems

Among technologically available energy storage devices, modern batteries are widely used. However, their disposal has a negative environmental impact. Compared to batteries, supercapacitors offer higher power density, faster charge/discharge cycles, longer lifespan, less environmental impact [25]. The stochastic nature of RES causes challenges for balancing MG. Increasing the share of RES to 20‒30 % of total generation can negatively affect the static and dynamic stability of MES due to the low predictability of RES generation [24]. Stable power supply requires additional control schemes from MG, which can be a replacement for the main grid with sufficient level of efficiency. Local microgrids consist of distributed generation facilities, energy storage systems, consumer loads and electrical devices which integrate RES into the distribution network to meet customer demand [26]. According to the U.S. Department of Energy, a microgrid is defined as a “group of interconnected loads and distributed energy resources within clearly defined electrical boundaries, operating as a single controllable entity with common operating modes” [24]. Microgrids operate in two modes:

– islanded mode - preferred in communities where extending the main (external) grid is economically or geographically unfeasible;

– parallel with the external grid mode - used in areas where the main power grid is accessible, allowing MG to either stay connected to reduce operational costs or operate independently (islanded) to enhance reliability in case of external grid failures.

5. Principles of microgrid management in energy communities

From the perspective of consumers as participants in energy communities, MG with local energy sources is considered as a reliable and efficient alternative for electricity supply. As stated in [25], to create a stable MG with frequency and voltage regulation, it is crucial to coordinate and actively dispatch different types of DG. Key microgrid management tasks are independent regulation of active and reactive power, maintaining voltage within standard limits, preventing system imbalances, meeting dynamic network load changes. To ensure proper operation, generation systems at different levels require appropriate control strategies. The MG management system consists of:

– local dispatching level - controls local generation sources and loads on the consumer side;

– upper-level MES dispatching system − oversees overall microgrid operation;

– energy distribution management system − ensures effective power allocation.

EC can enhance their resilience during EPS outages, while also encouraging economic development within TC and reducing energy infrastructure costs [26]. Core microgrid control functions comprise grid-connection interface operation, protection mechanisms, local facilities control. Number of researches show that MG control systems can be classified as a structured diagram on Figure 3, based on studies outlined in [27].

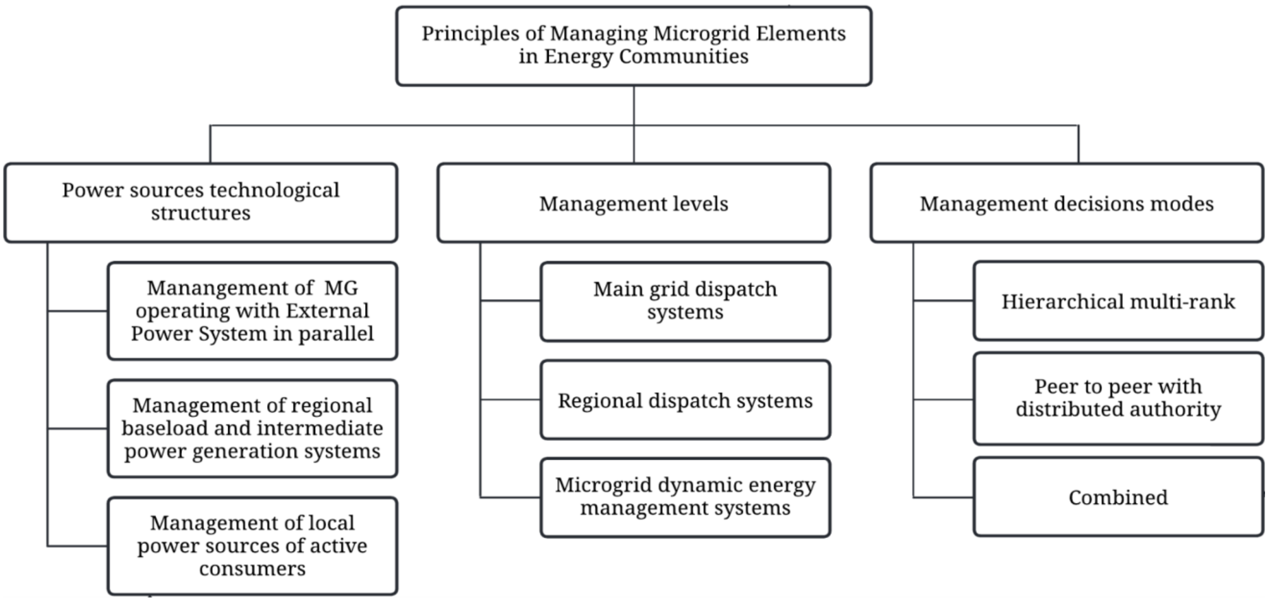

Fig. 3. Principles of managing microgrid elements in energy communities [27]

A key aspect in developing MG management algorithms is ensuring that control strategies align with technological processes related to electricity generation, storage, and distribution within the local MES [28]. The dispatching system for such MGs consists of hardware and software components designed to ensure reliable, efficient, and safe microgrid operation. The key subsystems of such a dispatching system include:

– MG power supply management with embedded functions of monitoring and controlling electricity production and distribution. It optimizes operations by activating energy sources based on demand and supply and coordinates the use of various hybrid energy sources (HES) [29];

– energy storage management which manages the charge-discharge cycles of storage systems for maximum efficiency and predicts the duration of autonomous operation of storage units [30];

– distributed Energy Resource (DER) management. Monitors and controls the power output of each individual HES source (such as solar panels, wind turbines, and diesel generators) and ensures optimal utilization of each source while maintaining the stable operation of the MG [31];

– demand-Side Management (DSM) controls electricity consumption by consumers. Includes dynamic load adjustment scenarios, such as real-time demand reduction during peak hours. Incorporates pricing strategies based on daily load balancing principles and energy efficiency measures [32];

– communication network system which enables real-time coordination and data exchange between different MES components and dispatching systems. Could consist of wired or wireless communication devices, supporting various protocols based on the data collection, storage, and processing requirements [33].

6. Aspects of control strategies for local microgrids

Specific structure of local HES, capable of operating both autonomously and in parallel with the EPS, can form a microgrid (MG) with special characteristics. Such a microgrid typically includes a limited number of consumers and provides services to critical infrastructure facilities (hospitals, water-related utilities, educational institutions, centralized heating stations, etc.) [26]. The power sources of these microgrids are often diverse, relying primarily on RES, including SES, WES, BEES.

Aspects of microgrid operation in islanded mode. The islanded (isolated) mode of MG is characterized by the MES operating independently from the EPS, relying solely on its own local resources for electricity generation and distribution [34]. In this mode, the management strategy focuses on balancing electricity demand and generation within the MG. The MES operates autonomously, requiring a control strategy that ensures real-time balancing between local electricity production and demand, fast and reliable system response to dynamic load changes, the ability of HES to cover power shortage and generate predictable electricity volumes to prevent supply outages. A generalized structure of an EC in islanded MES operation mode is illustrated in Figure 4.

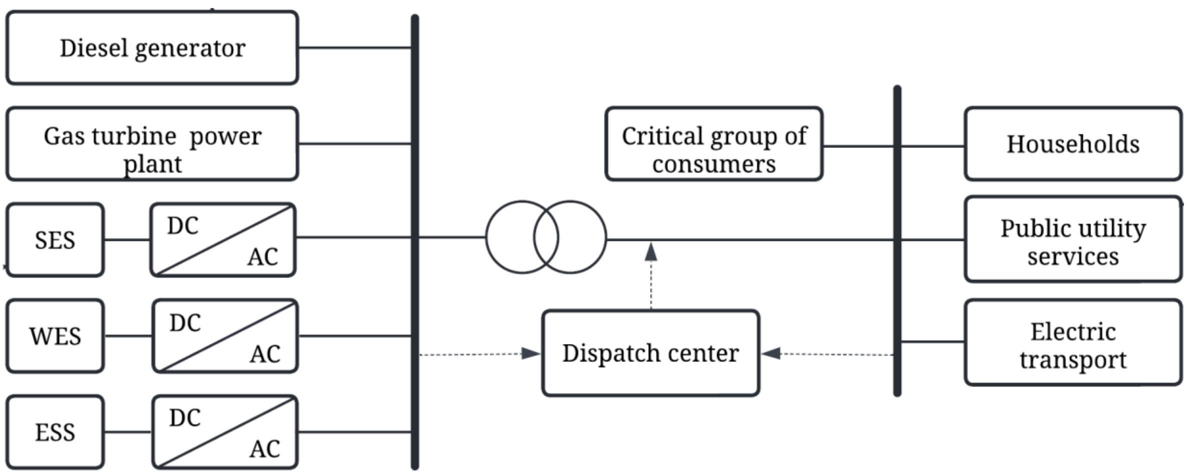

Fig. 4. Generalized structure of an energy community in islanded mode operation [34]

Dispatching scenarios in islanded mode include appropriate algorithms for load disconnection/reconnection, power balancing, voltage and frequency regulation of local power sources.

Connection of a local microgrid to the external power system. This mode is characterized by an important synchronization process with the EPS to enable power balancing and bidirectional electricity flows between the MG and EPS. The control strategy focuses on optimizing the use of local resources, minimizing electricity production costs. When connected to the grid, the MG can receive electricity from the EPS and export surplus electricity back to the EPS [35]. This mode requires coordination between MES and EPS to ensure the necessary power volumes for balancing and demand management within the MG in order to prevent any power supply interruptions. The EPS-connected mode must include voltage regulation, active and reactive power control features.

Principle of microenergy system operation in hybrid mode. In hybrid mode, MG can switch between islanded mode and EPS-connected mode to maximize the use of local resources, leverage renewable energy sources and enhance the reliability and efficiency of electricity supply [36]. The hybrid mode allows the MG to operate independently (islanded mode) and consume electricity from EPS in order to maintain system stability and ensure uninterrupted power supply. This mode requires fast and flexible dispatching, enabling automatic switching between operating modes and coordination of electricity consumption with the upper-level network dispatch system.

More advanced algorithms and technologies for optimizing the operation of MES are proposed in [37]. They include optimization of HES generation, real-time monitoring and demand control, energy storage management to enhance the MG efficiency, selection of the optimal power source and electricity distribution structures with losses minimization. Real-time monitoring and control systems provide capabilities for demand change response by adjusting electricity production and consumption with additional usage of energy storage systems that improves the efficiency and reliability of MES.

7. Analysis of microgrid operation in islanded mode

The aspects of microgrid operation related to electricity generation and distribution in islanded mode have been considered in [38]. The principles of power supply in this mode are characterized by the selection of generation sources from a wide range of options, including solar energy, ocean waves, piezoelectricity, thermoelectricity, mechanical vibrations. Some systems, for example, convert random vibrations into electrical energy, which can be utilized by wireless sensor nodes for autonomous power supply [39].

The main characteristic of islanded mode is maintaining the balance between electricity generation and demand within the energy community. Key aspects of islanded mode management in MES for an energy community:

– load management ‒ ensures alignment of electricity generation with demand within the community [40]. Load management strategies may include load exclusion (temporarily disconnecting non-essential loads) and load shifting (moving part of the load from peak periods to off-peak hours);

– local generation management ‒ ensures optimal use of local resources to balance the microenergy system and meet demand while maintaining electricity quality standards [41];

– voltage and frequency control ‒ maintains grid stability and prevents supply failures, ensuring that voltage and frequency remain within standard limits [42];

– energy storage utilization - providing short-term voltage and frequency stability support in dynamic operating conditions as well as storing excess of locally produced energy [43].

Operating a microgrid in islanded mode is critical for ensuring the stability and reliability of power supply within EC as this mode introduces significant challenges in balancing generation and demand without external grid support [44]. In islanded mode, the microgrid functions as an autonomous system, and its stability depends on its own generation capacity and energy storage resources to meet the energy needs of EC [45].

8. Microgrid operation in hybrid mode

Connection to EPS is driven by the ability to meet increasing demand while keeping MES balanced with minimal costs for electricity generation and distribution. At the same time, this ensures stable and reliable power supply. In [46], EPS is considered as a mechanism to increase the share of RES in the energy balance and enhance the resilience and reliability of the energy system. Microgrids offer many advantages, but they should be designed with additional capabilities to prevent imbalances and operational constraints.

Differences between operating modes of the microenergy system related to the use of external network capabilities are presented in Table 1.

Table 1. Differences between operating modes in the case of use EPS capabilities

Hybrid mode (parallel operation with the external network)	Islanded mode	Aspects of technological and dispatching implementation
Connection and disconnection from the external network for real-time balancing require sufficient reserve capacity from the distribution system operator	Depends only on locally produced and stored energy	Requires coordinated operation for source synchronization with the external network, as well as configuration of dispatching systems based on source prioritization and conditions for using electricity from storage systems
Power flows from the external network and generation by local sources with the lowest electricity production cost	Receives electricity from local baseload sources and the nearest own active consumers sources	Requires configuration of dispatching systems based on source prioritization and conditions for using electricity from storage systems
Dependence on EPS when forming the configuration of microenergy system sources	Depends on the main network only for backup power supply	Requires remote access to control local energy sources in real time
Comprehensive configuration of automatic control systems for DER during transitions, especially for internal combustion engines power stations	Depends on local resources for the operation of baseload generation sources and energy storage systems	Energy management system usage for demand forecasting and coordination.

Key aspects of developing control systems for MES when connected to EPS:

– active power flow management. Microenergy system balancing strategies should include limited active power consumption levels from both local sources and the external network [47]. These strategies optimize the use of local electricity generators and energy storage systems while minimizing the need to purchase electricity from the main grid;

– reactive power management. Reactive power control regulates the flow of reactive power between the community microgrid and the main network [48]. Reactive power is essential for grid stability and affects the efficiency of power generation and distribution. Optimized reactive power management improves overall microgrid efficiency;

– voltage level control. Voltage control ensures that network voltage levels remain within specified limits [49] which prevent power supply failures and maintain microgrid stability;

– parallel operation with the external network. EPS-connected mode requires coordination between the community's MES and the EPS [50]. This coordination ensures both static and dynamic stability of the microgrid in order to prevent power disruptions. Coordination of power sources includes real-time monitoring of power flow and automatic switching between hybrid and islanded modes.

To ensure seamless integration of energy sources with the external network, the automation system should be configured to prioritize sources and manage the use of stored electricity, which include following processes:

– real-time load monitoring of different consumer categories within the community [51]. It enables the prevalent usage of local power sources (such as RES, DPS, BEES) to meet consumer demands and at the same time consume EPS energy if needed;

– voltage and frequency regulation ensures the integrity of MES and maintains electricity quality within specified boundaries;

– setup shared MES and EPS dispatching system in order to real-time data exchange on electricity generation levels, energy storage capabilities [52]. It enables optimized energy flow management, allowing utilization of surplus electricity from EPS and bidirectional power flows when necessary.

– automatic mode switching ensures smooth transition between hybrid and islanded modes in case of power loss in the upper-level system. If an outage occurs in EPS, MG automatically switches to islanded mode, providing uninterrupted power supply to EC through utilization of its own DER.

9. Strategies for managing of energy community microgrid with own energy sources and active consumers

The implementation of energy market elements provides a number of opportunities to consumers and energy communities like achieving self-sufficiency, by making economically beneficially the transition to islanded operation mode.

As known, new participants have emerged in microenergy markets - active consumers (prosumers). Depending on their legal status, prosumers could make deals with aggregators and form decentralized baseload generation capacities to cover the demand of a selected group of electricity consumers (see Figure 5). For such energy communities, peer-to-peer (P2P) electricity distribution within MES is particularly relevant, allowing more efficient utilization of household energy sources. Studies [12, 18] present options of formed structures for energy supply services in self-sufficient energy islands, characterized by enhanced reliability and predictable energy efficiency. The formation of a complete energy balance within such microenergy system without energy storage, creates opportunities for optimizing energy efficiency management scenarios based on forecasting current energy supply costs.

The market mechanism between prosumers and consumers relies on the technical capabilities of balancing MES with multiple sources (both baseload and intermediary). It further encourages decentralization, giving consumers greater control over the use of energy generated within EC.

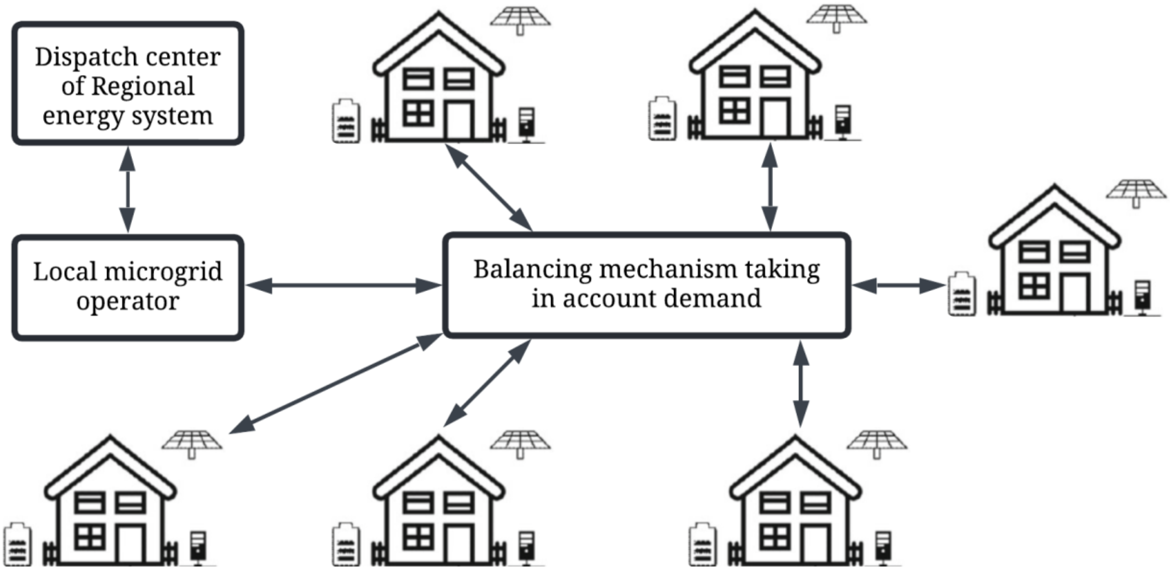

Fig. 5. Example of the technological structure of energy community microgrid with active consumers

MG management in an energy community under hybrid mode falls under management strategies used to control electricity generation and distribution, where the microgrid can operate both autonomously and in hybrid mode [53]. The main goal of hybrid mode management is to ensure reliable electricity supply while maximizing the use of local resources within the EC. Key aspects of hybrid mode management in energy community microgrid:

– automatic switching between modes which ensures optimal MES balancing using HES while also allowing connection to EPS [54];

– electricity consumption management as well as forecasting of HES & BEES generation volumes and power exchanges with EPS [55] which optimize the use of DER and maintain a balanced energy supply and demand;

– voltage/frequency control and HES coordination with the external network allow efficient hybrid mode management achieving flexibility in utilizing available DER.

A general overview of these processes described in [54, 55], and is presented briefly as a block diagram in Figure 6.

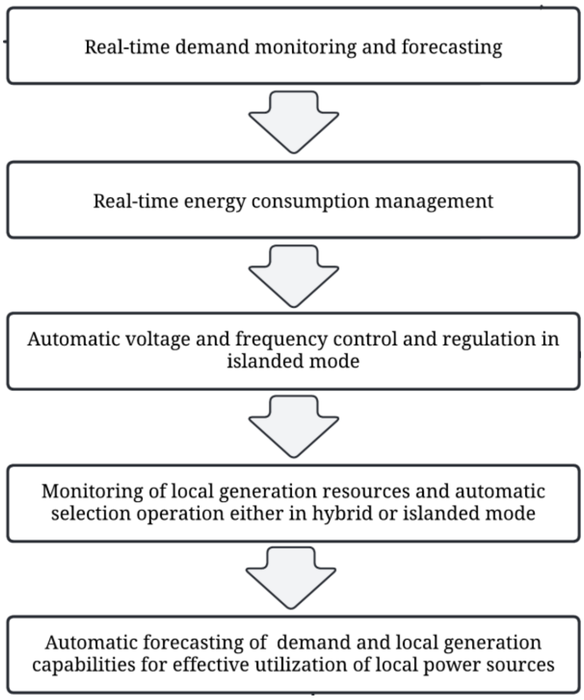

Fig. 6. Block diagram of hybrid microgrid management sequences with polygeneration [54, 55]

Above mentioned steps are continuously repeated to ensure the reliability and stability of MES in hybrid mode.

10. Strategies for managing energy community microgrids based on modern methods of electricity generation and distribution management

Advanced management strategies for community microgrids refer to innovative and comprehensive methods for controlling electricity generation and distribution in MG [56]. These strategies are designed to enhance the reliability, efficiency, and flexibility of MES while supporting the integration of RES. Some of the advanced control strategies for EC microgrids include:

– Distributed Energy Resource Management System (DERMS). Functions as a centralized system for managing electricity generation and distribution within the community microgrid [57]. Utilizes real-time data to optimize the use of HES, energy storage systems, and other DER;

– Optimal Power Flow (OPF) control based on mathematical optimization methods, focusing on modeling community energy supply costs [58]. Maximizes the use of local resources while minimizing energy production and distribution costs;

– Model Predictive Control (MPC) uses statistical data from MES operation to forecast future conditions for optimal energy resource distribution and renewable energy integration.

– Artificial Intelligence (AI) and Machine Learning (ML) technologies can optimize microgrid management for EC [59]. Algorithms analyze real-time data, make predictions on future energy conditions, and improve MES operations and RES integration;

– real-time monitoring and fault detection based on remote control and telemetry systems [60]. Detects faults in real time and initiates corrective actions to maintain MG stability.

Mentioned advanced control strategies are crucial for the future of energy community microgrids, as they enable renewable energy integration, improve reliability, and enhance efficiency [61].

By implementing enhanced control strategies, EC microgrid can improve operational efficiency and cost-effectiveness, while also increasing flexibility and resilience. Based on studies [62−70] a comparative table of different MES management strategies presented in Table 2 (”+” indicates that the control strategy is applied, while “-” indicates that it is not applicable to the respective operating mode).

Table 2. Comparison of different microgrid management strategies

Energy Community Microgrid Management Strategy	Islanded Mode	EPS-connected Mode	Hybrid Mode	Advanced control strategies
Automatic mode switching	+	+	+	+
Centralized energy consumption management	+	+	+	+
Voltage/frequency control	+	+	+	+
Energy flow management and coordination with EPS	–	+	+	+
DERMS	–	–	–	+
OPF	–	–	–	+
MPC	–	–	–	+
AI and ML usage	–	–	–	+
Real-time monitoring and fault detection based on remote control and telemetry systems	–	–	–	+

11. Aspects of energy management based on consumer’s demand response strategies for microgrid

Research of energy management systems (EMS) is classified based on the structure and composition of MES energy sources and its operating modes with EPS (grid-connected, hybrid, and islanded modes). Most publications consider all modes simultaneously, while some studies focus specifically on the operation of energy management systems with energy storage systems. Referring to Figure 7 from source [71], the classification of energy management systems considers the grid connection conditions, structuring methods, source configuration for participation in microgrid balance and control strategies.

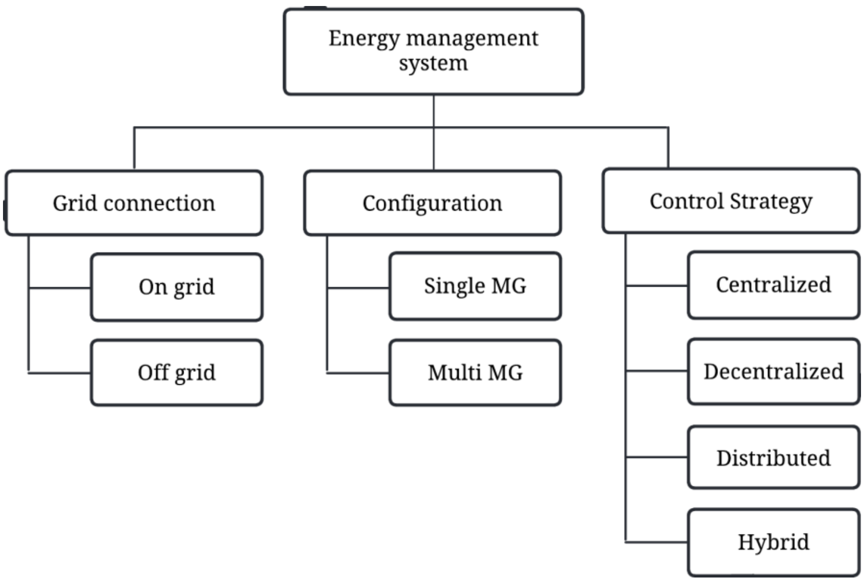

Fig. 7. Energy Management System Classification [71]

EMS based on demand response is applied in countries that have promoted adaptive tariff policies to reduce peak consumption created using mathematical models based on load variability. Consumer participation in peak demand reduction is encouraged through incentives offered by electricity distribution system operators. In [72] proposed an EM approach based on a hierarchy of distributed resources, using autoregressive moving average methods to take into consideration uncertainties. Risk assessment and the application of linearized constraint dependencies for AC networks ensure a sufficient level of computational efficiency. An additional intersystem connection is used to receive power from neighboring MGs under emergency conditions.

In [73] three different resource management strategies for MG with flexible loads are considered: fixed tariffs, real-time pricing, and time-of-use tariffs. An analysis is conducted on the factors influencing operational costs under different strategies. Optimization is implemented using a genetic algorithm and validated with statistical data from a real MG installation. The results demonstrate a reduction in operational costs without additional expenses for consumers thanks to improved utilization of RES. Three different decentralized resource management (DRP) scenarios are examined, including the impact of natural gas prices on the DR strategy. The findings indicate that an increase in natural gas prices negatively affects the DR strategy. EMS for a microgrid with three types of loads based on hybrid forecasting is proposed in [74]. The main focus is to prevent failures in centralized EMS due to data loss. The advantages of predictive methods and machine learning are combined to improve modeling accuracy and result evaluation while considering potential data loss. Taking into account resource management strategies for fixed, flexible, and stochastic loads, the mentioned optimization approach enhances computation speed and accuracy, particularly reducing forecasting errors and optimized costs by 40 % and 55 %, respectively.

The concept of peer-to-peer (P2P) trading or transactive energy (TE) is gaining traction as the future restructuring of UPS progresses [75]. This approach creates potential for utilizing DER, proactive demand-side management (DSM), and the implementation of information and communication technologies (e.g. blockchain and the internet of things) to enhance both the technical and economic efficiency of the microenergy system as a whole. An effective market framework is essential for the successful and sustainable implementation of this concept. This paper proposes a P2P energy trading structure supported by blockchain technology. The proposed framework consolidates bilateral contracts, an e-commerce platform, a double-auction mechanism, and trading functions with the main grid. These multi-layered mechanisms help to integrate various trading advantages and attributes related to electricity production and consumption. The double-auction mechanism, in particular, creates potential for leveraging market opportunities by encouraging transparent bidding among participants. To address the disadvantages of double auctions associated with MES imbalances, a quasi-ideal auction system is proposed. The analysis proposed trading structure in analysis outlines new approaches for effectively managing the microenergy market’s efficiency

The publication [76] presents smart contract platforms for shared automatic control of energy transmission within the EC network. It introduces a general form of a smart contract, which includes elements necessary for collaborative control of participants’ relationships in decentralized energy supply. Two mechanisms are proposed for coordinating control algorithms of a medium-voltage DC line that connects two separately managed 33 kV distribution networks. Smart contracts are designed considering cost and computational requirements for execution. Real data from demonstration project were used to model the medium-voltage DC line. The study proves that using smart contracts to coordinate control instructions among different parties is a feasible approach. The potential of shared control via smart contracts provides operators and regulators with the ability to define and decentralize operational responsibilities within microenergy systems.

The approaches for implementing a liberalized peer-to-peer (P2P) electricity market for distribution systems with network security are outlined in [77]. The authors developed a general framework for p2p trading in the distribution system, incorporating a dedicated utility (Figure 8). The model is formulated as a bilevel programming approach.

The utility’s functionality includes top-level tasks, where a method for calculating the settlement of payments for internal network usage in p2p trading is also proposed.

However, for the lower-level task, a instrument for p2p trading is proposed by implementing an iterative algorithm based on targeted analytical cascading of the model, where the interaction between the utility company and end consumers is presented. The numerical results obtained in [77] for the IEEE 33-bus system demonstrate that the proposed method successfully implements a liberalized p2p market while ensuring network security in distribution systems. In [78], the authors examine the shift away from the traditional top-down centralized electricity distribution concept. As the adoption of DER increases, dispatch systems are increasingly integrating intelligent computing and communication capabilities. The study presents an approach of decentralizing MES by restructuring the current operational architecture of the power grid, aligning with modern decentralization trends and focusing on peer-to-peer energy trading. The assumption is made that blockchain technology serves as an effective tool for facilitating the synergy between top-down and bottom-up approaches for power grid management (as illustrated in Figure 9).

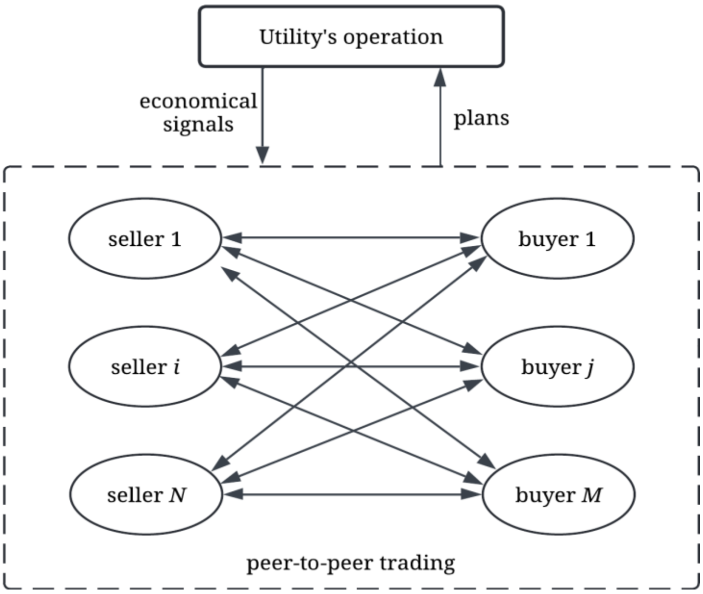

Fig. 8. Market framework for P2P trading in a distribution system [77].

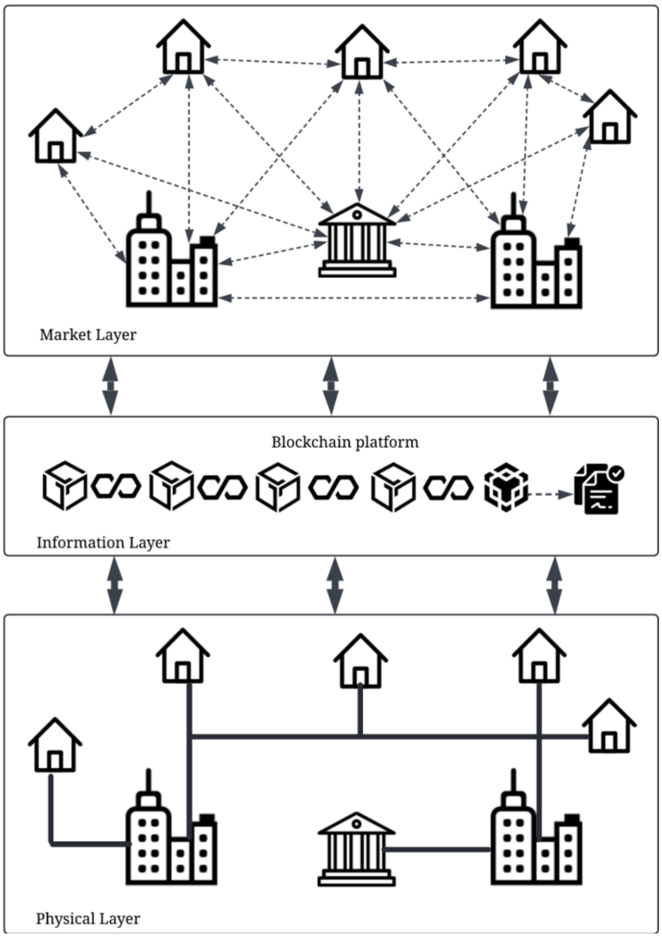

Fig. 9. Multi-layer structure of P2P energy market operation [78]

The proposed approach presents an interdisciplinary challenge and requires diverse research efforts, particularly in the application of blockchain technology in the energy sector. This requires coordinated efforts from researchers in fields such as computer science, networks and communications, electrical and energy systems. Additionally, research is needed to integrate these processes with regulatory changes to systematically and comprehensively transition between "top-down" and "bottom-up" architectures. Projects involving the implementation of DER at the distribution system level are becoming more common, allowing distributed generation assets to participate in wholesale markets [79]. However, there are many aspects of the current operational paradigm of energy systems that need improvement to really integrate "top-down" and "bottom-up" approaches to grid management. The authors of the publication have identified key future research directions regarding the connection between P2P energy trading and blockchain technologies, which are crucial for the implementation of market relations at the micro level.

12. Results Discussion and Conclusions

The conducted research provides insights into the next steps in researches about the operation of local microgrids with polygeneration to identify optimal operating modes of energy sources and principles of technological structuring and balancing through the use of HES. In this context, consumers or end-users become confirmed demand activators in the short term, enabling the implementation of advanced control approaches. This factor facilitates the development of new coordination mechanisms for the operation of energy sources, real-time demand control, and the use of primary fuel costs for forecasting energy supply expenses. Undoubtedly, decentralized electricity supply processes in the long term will achieve overall system-wide economic efficiency while fully preserving the right of prosumers and consumers to manage consumption processes.

Mentioned paradigm of relationships facilitates achieving the highest efficiency of microenergy systems with polygeneration in both hybrid and islanded operating modes, using the current electricity cost and the reliability indicators of MES as key criteria.

The increase in the share of decentralized networks will be a signal to form a new architecture for regional energy systems. The operational processes of decentralized HES functioning and respective balancing of microenergy systems including real-time demand coordination taking into account the cost of primary fuels and additional expenses associated with decentralized electricity supply, represent a relevant scientific task. This requires multidisciplinary research and holds significant practical interest.

Based on the established relationships between the nature of load profile changes and the structure of diverse sources within a decentralized microgrid, it is necessary to develop theoretical instruments and methodological support for optimizing the current operational architecture of the microenergy system based on energy efficiency criteria. This includes the acceptance of design standards and defining efficiency metrics for technological structures of polygeneration-based microenergy systems.

The research related to finding optimal operating modes for diverse energy sources in the process of balancing a local microenergy system based on the criteria of minimizing the current electricity cost at the prosumer and end-user level, considered as relevant. This is crucial for restructuring the current operational architecture of the power grid in a peer-to-peer electricity distribution model.

Summarizing the conducted research, it is important to note that the choice of a microgrid energy community management strategy will depend on several factors, including a number of MES consumers, installed generation capacities, the type of selected energy sources used at the local level, external grid use scenarios, the purpose of forming the energy community to achieve an economically viable operation of the microgrid.

Some of the most commonly used control strategies for microgrids include centralized, decentralized, hybrid, and market-based management. Each of these strategies has its advantages and disadvantages, and the appropriate choice depends on the unique requirements of each MES. It is important to note that implementing a control strategy also requires careful consideration of technical, economic, and regulatory aspects. Centralized management is characterized by a single control center that coordinates all energy resources within the microgrid. This type of management strategy is suitable for small microgrids with a limited number of energy resources. On the other hand, decentralized management allows each energy resource to operate independently and make decisions based on local information. This type of management strategy is more suitable for large microgrids with multiple energy sources.

Hybrid management approach combines aspects of both centralized and decentralized management strategies and is a suitable option for MGs that require balancing between HES, EPS at the local dispatching level. It is important to note that implementing a management strategy requires the integration of various technologies, such as communication systems, energy management systems, and control algorithms. Grid connection control ensures operational flexibility, providing access to both EPS and local generation based on HES, which can be used for revenue generation and maintaining expected reliability levels for MES of this class.

Nevertheless, microenergy systems based on DER are significantly dependent on external resources and are sensitive to power disconnections from EPS in terms of determining the current electricity cost for MES. On the other hand, operating MES in island mode enables EC members to establish self-sufficiency through local energy production and storage, thereby creating economically justified levels of energy independence. The role of EMS in island mode is to allow EC members to manage costs predictively by reducing operational expenses and enhancing the resilience of MG.

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ПОРІВНЯЛЬНЕ ДОСЛІДЖЕННЯ АРХІТЕКТУРИ ТА СИСТЕМ УПРАВЛІННЯ МІКРОМЕРЕЖАМИ ЕНЕРГЕТИЧНИХ СПІЛЬНОТ З ПОЛІГЕНЕРАЦІЄЮ

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Анотація. *Статтю присвячено порівняльному дослідженню відомих методів структурування локальних мікромереж з різнорідними джерелами, активними споживачами та накопичувачами електроенергії як прототипу територіальної енергетичної спільноти. Особливістю наукової ідеї є обґрунтування методів оцінювання режимів мікромереж з полігенерацією для визначення меж їх стійкості та енергоефективності. Наукове завдання має на меті оцінювання переваг та недоліків використання різних методів щодо вибору структури генеруючих джерел та визначення складових попиту для формування найкращих сценаріїв забезпечення живучості та енергоефективності мереж такого типу. Порівнюються методи визначення границь динамічної та статичної стійкості мікроенергосистеми з полігенерацією, управління в мережевому, острівному та змішаному (з урахуванням власної генерації) режимах, формування оптимальних у реальному часі стратегій диспетчеризації та ринкових механізмів для членів енергетичної спільноти за критерієм мінімальних приведених витрат на електрозабезпечення. У якості порівняльних критеріїв розглядалась технологічна ефективність структурних елементів мікроенергосистеми, економічність, стабільність та надійність. Результати порівняльного дослідження дають можливість визначити оптимальні підходи щодо формування технологічної структури конкретної енергетичної спільноти з урахуванням наявних місцевих ресурсів, особливостей мережевого господарства, сезонних попитів та інших змінних. Внаслідок аналізу зроблені акценти щодо енергоекономічних передумов для розвитку децентралізованих енергосистем з відновлюваними джерелами та установками комбінованого енерговиробництва. Встановлено, що управління енергоефективністю мікромереж з відновлюваними джерелами та накопичувачами електроенергії системного рівня шляхом впровадження систем енергетичного менеджменту вимагає розроблення нових моделей балансування та прогнозування попиту навантаження, теоретичного інструментарію для обґрунтування мікроринкових відносин між учасниками енергетичної спільноти − постачальниками електроенергії системного рівня, локальними активними споживачами із заздалегідь визначеними умовами генерації та кінцевими споживачами.*
Ключові слова: енергетична спільнота, мікроенергосистема з полігенерацією, технологічні структури мікромереж, острівний та змішаний режими, активний споживач, енергетичний менеджмент.

Надійшла до редколегії: 14.03.2025