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Review

State-of-the-art review on energy sharing and trading of resilient multi microgrids

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SUMMARY

Independently run single microgrids (MGs) encounter difficulties with inadequate self-consumption of local renewable energy and frequent power exchange with the grid. Combining numerous MGs to form a multi-microgrid (MMG) is a viable approach to enhance smart distribution networks' operational and financial performance. However, the correlation and coordination of intermittent power generation within each MG network pose many techno-economic challenges for energy sharing and trading. This review offers a comprehensive analysis of these challenges within the framework of MMG operations. It examines state-of-the-art methodologies for optimizing multi-energy dispatch and scrutinizes contemporary strategies within energy markets that contribute to the resilience of power systems. The discourse extends to the burgeoning role of blockchain technology in revolutionizing decentralized market frameworks and the intricacies of MMG coordination for reliable and cost-effective energy distribution. Overall, this study provides ample inspiration for theoretical and practical research to the new entrants and experts alike to develop new concepts for energy markets, scheduling and novel operating models for future resilient multi-energy networked systems/MMGs.

INTRODUCTION

Background and motivation

The participation of consumers in localized power generation and consumption employing Distributed Energy Resources envisions the self-sustaining operational concept known as autonomous microgrid (MG) networks in modern smart distribution networks.[1] With the proliferation of these renewable-based MGs globally, power distribution networks may face several technical challenges related to operational flexibility, resiliency, and reliability. As a single entity, grid-connected MG networks can efficiently handle local loads within their electrical boundaries and communicate with the utility and nearby MG networks in the event of capacity, stability, or protection problems.[2] In recent research, the notion of numerous LV microgrid networks that integrate and coordinate to maintain generation and load balance is gaining attraction. Such networks are often named Networked Microgrids, Interconnected Microgrids, Clustered Microgrids, and Multi-Microgrids (MMGs).[3] United Nations has pledged to "*ensure access to affordable, reliable, sustainable and modern energy for all*" by including energy access (SDG7) in its Sustainable Development Agenda. Thus, networked microgrids based on locally available sustainable energy resources to fulfill the future energy demand have attracted greater attention, ensuring the UN's SDGs goals.[4] Several single-neighboring low-voltage microgrids in a fixed or dynamic electric boundary can be utilized to constitute a networked MG system or a Multi-Microgrid. However, an unprecedented deployment of such networked microgrids or MMGs requires robust Information and Communication Technologies (ICTs) infrastructure to be an operational exemplar in smart distribution networks.[5]

These smart distribution networks rely on a wide range of innovative technological advancements that aim to revolutionize the traditional electrical grid into an intelligent and interconnected energy system. These technologies leverage cutting-edge concepts, including communication advances, cybersecurity protocols, and distributed sensors, to enhance the power infrastructure's efficiency, reliability, and sustainability. Communication advances in smart grids involve the integration of advanced communication technologies to enable seamless data exchange and real-time monitoring. It will facilitate the efficient two-way communication between grid components, such as power generation sources, energy storage systems, and end-users. By enhancing grid visibility and control, communication advances enable better demand response, load balancing, and fault detection, leading to optimized energy management.

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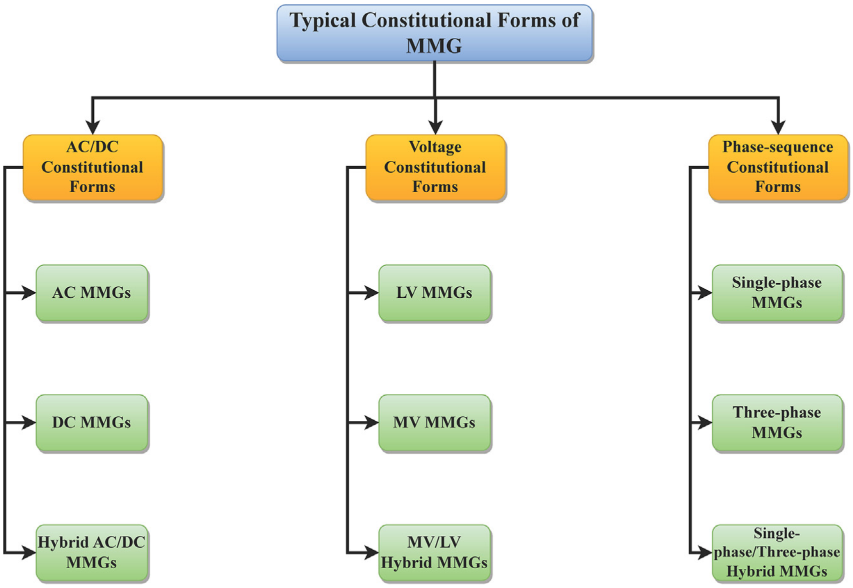

Figure 1. Typical constitutional forms of multi-microgrids

Another essential aspect is cybersecurity protocols, which are crucial in safeguarding smart grids from potential cyber threats and attacks. With increased digitization and connectivity, smart grids become susceptible to cybersecurity risks that can disrupt operations and compromise data integrity. Robust cybersecurity measures ensure the protection of critical infrastructure, data privacy, and resilience against cyber incidents, fostering trust in adopting smart grid technologies.

All the innovative technological advancements in smart distribution networks rely on the distribution of system information and control parameters. These sensors are deployed across the grid infrastructure to gather real-time data on various parameters, such as voltage, current, temperature, and power quality. The data collected by these sensors provides valuable insights into grid performance and helps identify potential issues, enabling proactive maintenance and rapid response to anomalies. In the realm of multi-microgrid research, these foundational smart grid technologies are being further developed and expanded to address the specific challenges and opportunities that arise when multiple microgrids collaborate and operate in coordination. Multi-microgrid research explores how communication advances can enable seamless coordination and information exchange between different microgrids to enhance overall system performance and reliability. Moreover, cybersecurity protocols are adapted and reinforced to ensure the secure exchange of sensitive data and operational information between microgrids.

As multiple microgrids interact, it becomes crucial to maintain a secure and trusted environment to protect against potential cyber threats that could impact the entire multi-microgrid network. Additionally, distributed sensors are deployed across individual microgrids and extended to monitor interactions between the microgrids. It provides valuable data for the central coordination control agent, allowing it to make informed decisions and optimize the operation of the multi-microgrid system. By building upon the foundation of smart grid technologies, the multi-microgrid research domain seeks to create a cohesive, efficient, and resilient energy ecosystem where multiple microgrids collaborate harmoniously, contributing to a more sustainable and reliable energy future.

The inception of multi-microgrids

The current state-of-the-art MMG in most scientific databases shows the transformation of a conventional passive distribution network into a bi-directional active distribution network with several MG networks interconnected as a networked microgrid. Typical constitutional forms in terms of the type of MMG, voltage, and phase sequence of various MMG networks are illustrated in Figure 1.[6] One benefit of interconnecting microgrids is that they can assist one another more effectively or offer ancillary support services to the utility network. For instance, if two microgrids are interconnected, disruptions or malicious cyberattacks from one microgrid can spread swiftly to the networked system or even to the bulk power grid. As a result, a networked microgrid system may often need to modify its physical topology by joining or removing microgrids.[7] However, in terms of operational demands, communication backbone requirements, and data interoperability, new energy-internet networks, especially microgrids, are very complex. Networked information systems are essential to microgrids because distributed microgrid control topologies require a close interaction between the physical and cyber levels.[8]

Further, to efficiently satisfy the rising power demand, it is crucial to coordinate the power scheduling among the networked MGs equipped with multiple DG resources. Since each MG has a unique capacity allocation and load characteristics, the efficiency with which they all run is affected by the energy exchange between MGs. When the supply and demand of energy fluctuates between different MGs, it is crucial to coordinate and optimize this energy exchange.[9]

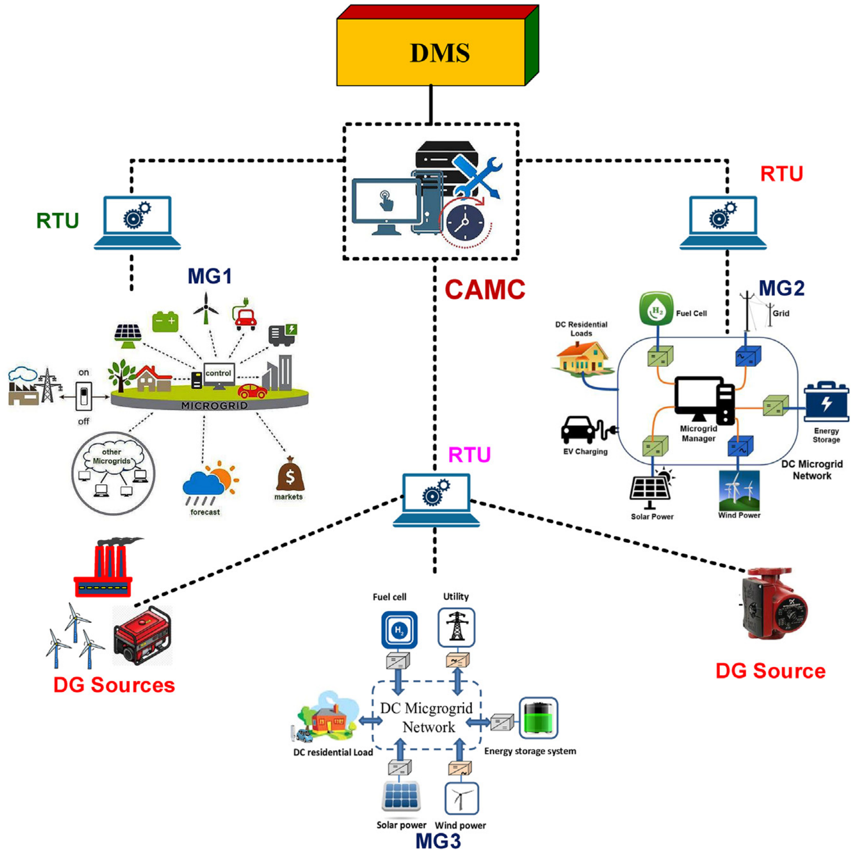

Figure 2. Central autonomous management control architecture

Seamless connectivity among MGs, intelligent automation, advanced analytics, and a user-centric perspective will all be features of ICT in multi-microgrids in the future. As multi-microgrids continue to develop as essential components of future energy landscapes, these developments will pave the path for more robust, efficient, and sustainable energy systems. Also, a sophisticated multi-microgrid architecture is necessary to facilitate MMG networks' operational and energy management functionalities. Figure 2 represents one of the earlier architectures proposed in the literature as a Central Autonomous Management Controller (CAMC).[9] CAMC is a hierarchical control integrated with the Distribution Network Operator (DNO) for handling technical and financial operations within the distribution system. It can acquire and transmit signals to all MGs, potential DERs, and loads that run under a local controller but are not part of an MG. The overall MMG architectures available in the literature can be categorized into centralized, decentralized, hybrid, and nested architectures. Centralized architecture fails to guarantee consumer privacy since a single central controller manages every piece of equipment that may be controlled for generation and consumption. However, every MG in the decentralized architecture is an independent entity with a local controller to optimize its profit. Nonetheless, it may introduce competition between microgrids, lowering system-wide performance.

The decentralized architecture is generally appropriate for the MMG system with microgrids belonging to different owners. The hybrid architecture, on the other hand, was created to address both the centralized and decentralized systems' drawbacks. It combines local controllers at the MG level with a central controller at the MMG system level, benefiting customers from a single level of privacy protection. Each MG is a level of the overall MMG system, a hierarchical structure with numerous layers known as nested architecture.[10] In centralized and decentralized architectures, the local controllers play a vital role in data acquisition between the central controller and MG components. A typical MG local controller has four layers of the control hierarchy, as depicted in Figure 3.[11] Controllers are conditioned to communicate with dedicated devices such as inverters and power meters at the most basic level. The second level includes the data transformation layer, which transforms data to conform to standardized information models (such as IEC 61850).

This layer provides a passage from the first (low-level communications) to the third (local control), where the MG components' control methods are really put into action. Last but not least, a high-level communications layer is introduced to ensure uniformity in data transfer between controllers and their environs. DERs and MGs, characterized as flexible resources with quick ramping capabilities, can help reduce ramping violations and the consequences of fluctuating demand on thermal units. DERs and MGs may provide energy and many grid services. However, minimum capability and capacity standards must be met in deregulated electricity markets to be eligible for participation. Due to

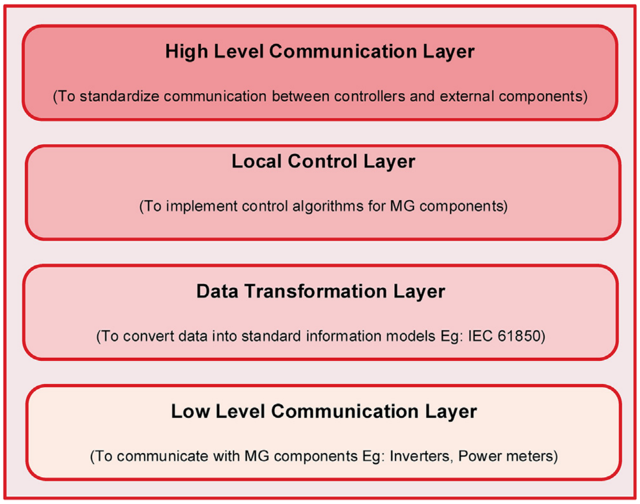

Figure 3. Conceptual representation of microgrid local controller

their relatively small size, this makes it difficult for individual DERs and MGs to participate in delivering services to the grid. The idea of resource aggregation in MMG is a workable approach to overcoming such difficulties.[12] Thus, the concept of MMG has apparent advantages in terms of the flexible operation of a Distribution Network, and other pros are listed later in discussion.

- Due to the vicinity of interconnected MGs, their operation is very economical, either in grid-connected or autonomous mode. It is because of the energy sharing between each MG from RES-based DG sources, hence avoiding fluctuating utility power import costs.
- The energy exchange between MGs occurs most often between MGs adjacent to one another, minimizing the potential energy loss experienced during long-distance transmissions.
- The MMG is better suited for future development patterns in line with the smart grid than the conventional single MG. The MMG exhibits features for futuristic low-carbon energy grids, such as maximizing the use of RES, reducing congestion on distribution lines, and improving reliability.
- When a malfunction or a regional outage occurs due to a natural disaster, an intelligent distribution MMG typically demonstrates a high level of self-healing compared to single MG networks.[13]

In enhancing multi-microgrid (MMG) systems, market participation is key aspect. Within a network of MMGs, often owned and operated by a variety of business stakeholders, there exists a dual pursuit. Each stakeholder aims to optimize their own economic benefits while simultaneously contributing to the collective profitability and efficiency of the entire MMG network. In a decentralized environment, it is then vital to coordinate the mutual energy benefit between each microgrid. The implementation of electricity markets can boost producer profits while lowering consumer costs. As a result, allowing microgrids access to power markets can make integrating microgrids easier. Price-based DR solutions provide users with various electricity pricing options at various time periods in an energy market. Different examples abound in the most recent literature to encourage mutual advantages and new markets among MG clusters and DNO.[14] In recent research, the importance of individual MGs for enhancing grid resilience has received widespread recognition. Some states and utilities have implemented variously configured MGs. However, more discussion and research are still required to fully understand the financial, legal, and technical obstacles to adoption. Compared to employing individual MGs or traditional outage management strategies, operating distribution systems based on MMGs can significantly improve grid resilience in the case of large-scale failures.

Reliability, stability, security, and resilience are crucial elements in an energy grid. "Reliability" refers to a system's ability to endure and recover from harmful events without losing functioning.[15] On the other hand, "Resilience" is the ability to reduce the magnitude and duration of disruptive events, while robustness does not adequately reflect steady drop and restoration of service. Planning-oriented methods are generally sufficient to achieve a given level of dependability.[16] Resilience is connected to the system's time-varying state over a short time period and operations. Reliability evaluates the system's capacity to handle credible occurrences without load shedding.[17] Both methodologies assess the system's performance in its operational state over time. Since an uncontrollable minor catastrophe might disrupt megawatt flows, centralized power stations, bulk power transmission, and substations in the distribution network are possible sites prone to instability in power networks. ICT has vastly increased the perception of the situation in the power grid environment for the enhancement of resiliency by providing real-time data about critical events. Real-time monitoring through sensors and smart devices, coupled with predictive analytics, empowers grid operators to foresee and mitigate potential issues swiftly. Remote control and automation streamline responses, allowing operators to make adjustments and address problems without physical intervention. A resilient communication network is pivotal, ensuring the seamless flow of information and enhancing cybersecurity measures to safeguard against potential threats. This technological integration not only enhances the grid's stability and reliability but also elevates its capacity to adapt and respond to the dynamic challenges of the modern energy landscape. Thus, increasing the liability of communication networks, equipment, and control centers is crucial to the power grid's security.

Regarding system dependability, the energy grid would have to be constructed and run to work under a specific set of crucial circumstances while also being able to sustain credible contingencies. In this case, the major focus of dependability improvement is on N-1 and N-2 contingencies. In the context of these self-sufficient energy systems, contingency evaluation involves assessing and planning for potential disruptions or failures within the microgrid or the larger interconnected grid. By systematically analyzing possible contingencies, such as equipment failures, fluctuations in demand, or external disturbances, microgrid operators can develop strategies to maintain continuous and reliable power supply. This proactive approach ensures that the microgrid remains resilient in the face of unforeseen events, minimizing downtime and maximizing its ability to provide uninterrupted energy to local communities.[18] The wide outages that follow such natural catastrophes highlight that while resilience cannot be guaranteed, degradation may frequently be kept to an acceptable level locally until complete services are restored at the significant grid level. By extending the role of autonomous microgrids, the potential for establishing a resilient electric system may be fulfilled. In the face of broader grid failures or disruptions, these autonomous microgrids can operate independently, ensuring a continuous and reliable power source for local communities.

Significant contributions

Some of the reviews presented in the MMG literature cover various aspects of energy management,[14] the concept of MG clusters and architectures,[19] communication protocols,[20] and MMG control strategies.[21] A detailed analysis of MMG networks' dynamic and fixed boundaries is covered in[22] to enhance their operational flexibility. The areas of research most relevant to MMG need immediate further investigation. For instance, the above-cited review articles have synthesized the basic architecture and communication protocols that have been followed and discussed the optimal operation of interconnected MG networks at length. However, the literature has not critically reviewed the coordination frameworks, energy sharing, trading, and security aspects. It should be noted that enabling MMG requires an infrastructure that includes the lowest level of communication and measurement and instrument availability with cybersecurity guarantees.[23] This article aims to help early-stage researchers, and experts develop MMG scheduling strategies with market involvement by reviewing the most recent and pertinent research studies described in the literature. This article begins by addressing the crucial concept of market participation within microgrid networks. It delves into the intricate dynamics of how microgrids can engage with energy markets, facilitating the exchange of electricity for economic and operational optimization. The discussion encompasses two fundamental approaches: centralized and decentralized. The former involves a coordinated effort, often directed by a central authority, to manage the interactions between microgrids and energy markets. On the other hand, the latter empowers individual microgrids to independently participate in market activities, allowing for greater flexibility and adaptability. This exploration into market participation lays the foundation for understanding the complex interplay between microgrids and broader energy market mechanisms.

Moving forward, this review article delves into the intricacies of energy trading between microgrids and the Distribution Network Operator. It scrutinizes scenarios where energy transactions occur through bilateral optimization frameworks, which prioritize the optimization of objectives for both microgrids and the DNO. Additionally, it explores the emerging Peer-to-Peer (P2P) energy trading trend, wherein individual microgrids engage in direct energy exchange without intermediaries. This decentralized approach can potentially transform the energy landscape, allowing microgrids to collaborate more granularly and efficiently. Furthermore, the article delves into the realm of MMG optimal dispatch and scheduling strategies. It provides an extensive overview of both conventional and state-of-the-art decentralized approaches, shedding light on how microgrids can effectively manage their energy resources to balance supply and demand while adhering to market dynamics. This article underscores the critical role of resiliency in MMG operations, examining how microgrids can withstand disruptions such as cyberattacks. A detailed case study highlights the importance of developing strategies to ensure the robust operation of microgrids even in the face of unforeseen challenges.

The remainder of this review article is organized as follows. In Multi-microgrid energy markets Section , we first briefly analyze the prospects related to MMG energy trading. Various centralized and decentralized approaches for market participation are discussed in brief. Multi-Microgrid Dispatch Section covers the MMG optimal scheduling strategies with a detailed analysis of different solution methodologies. The concept of resiliency, and resiliency metrics, resiliency operation in single and multi-microgrids are discussed in next section (Enhancing resilience in multi-microgrids). The final section covers a detailed discussion, a case study on MMG resiliency, and future trends in MMG research to benefit readership.

MULTI-MICROGRID ENERGY MARKETS

Renewable power generation plays the protagonist role in the unprecedented transformation of the energy sector. Digitalizing energy trading brings new market opportunities and competition in contrast with traditional energy schemes. The monopoly in the unidirectional centralized market structure is changing its pace toward a decentralized and bidirectional market structure involving multiple stakeholders across supply and demand. With this viewpoint, the economic, social, and environmental impacts of incorporating DERs on international platforms are reviewed in.[24] Further, the operational, regulatory, commercial, and political challenges in countries such as Germany, the United States, Australia, and the United Kingdom are briefly discussed. The deployment of RES at consumer premises necessitates the frameworks; the stakeholders will be formed to share the responsibilities and create the roles, such as prosumers and aggregators. A prosumer is an end-user who uses any device that utilizes or provides energy that can be managed effectively. When participating in the electricity market, an aggregator's role is to collect flexibility from the devices of the Prosumer and sell it to the Distribution System Operator (DSO). Hence,

Table 1. Challenges faced by Local Energy Markets

Barriers faced by Local Energy Markets[28]	
Technical	• Managing instantaneous active and reactive power balances in LEM • Smart Metering and Market flexibility management • Secure and transparent local energy trading • Data-handling and cyber security
Regulatory and Legal	• Balanced regulation for trading surplus energy to neighboring MGs • Unsatisfactory rules laid by the legislative frameworks • Taxation issues and unclear policy landscapes
Economic	• High installation costs and split-incentive problems • Creation of customer-centric business schemes in highly competitive LEM • Updating business models for reaching new market equilibria
Stakeholder-related	• Effective customer engagement • Resistance from non-prosumers with no firm understanding of technically complex concepts. • Difficulty in quantifying LEM benefits among individual stakeholders

prosumers within the local energy communities can establish a regional energy market (LEM) for trading power, abiding by legal and market participation-related agreements.[25]

Energy trading within MMG systems supports the renewable energy sector's shift toward more sustainable practices, such as the adoption of recyclable materials in power generation and storage equipment.[26] This adaptation aligns with broader environmental objectives, such as those underscored by the World Economic Forum, which promote a transition to clean energy.[27] As the electricity market evolves with an increasing share of renewable energy, it becomes imperative to employ dynamic and interactive market structures such as local energy markets (LEMs). These markets are critical for managing the intermittency of renewable energy sources and ensuring efficient resource allocation. To better allocate resources, electric power grids have used two-sided markets, such as LEMs that are designed to accommodate intermittent renewable energy generation. Transparency in the LEM architecture benefits various stakeholders, including market aggregators, retailers, DNOs, and local generation entities.[28] The key challenges faced by establishing LEM for multiple aspects are shown in Table 1.

A country-wise challenge faced with the implementation of various market-related research and development projects is provided in Table 2. Conventional power systems prevail in two types of markets, retail and wholesale, often referred to as a classic example of a natural monopoly.

However, with the deployment of renewable-based DERs, the prosumers and consumers share a common LEM platform within their neighborhood, paving a new dimension of decentralization in energy markets.[43] The conceptual representation of LEM is shown in Figure 4.[44] Three standard market models, peer-to-peer, prosumer-to-grid, and hybrid market models, are identified in the literature. A brief description of these models' pros and cons is listed in Table 3. The market participation and trading in the networked microgrids using the above market models follow numerous centralized and decentralized approaches. Further, the sub-sections will briefly discuss the state-of-the-art methodology for centralized, decentralized, blockchain-based, and game theory-based market approaches.

Centralized market approaches

The centralized market approaches in MMG networks involve the design of MGCC, which is responsible for energy management and control. The method of electricity markets and optimal power distribution play an equal role in designing an MMG network. The optimal coordination of MO, DNO, and ISO is the most challenging task in MMG architecture, where several conflicting objectives must be satisfied. With this viewpoint, a multi-objective optimization problem is formulated in[45] to generate price signals to maximize the MGO benefits, the power delivered to the network from DNO, and maintain MG storage capacity that enables secure and emergency operation for ISO simultaneously. In,[46] the authors developed a pricing strategy concerning MGCC and integrated it with an energy exchange scheduling strategy for a coordinated operation between each MG in an MMG network. The MGCC is modeled as an aggregator behavior, and an adjusted price based on load profile, storage capacity, and energy exchange costs is determined. Unlike the spot or bilateral electricity markets involving MMG, the ancillary services market[47,48] is restricted with a minimum number of reserves. In practice, 1–2 MW is required for the primary reserve, and 10–20 MW is required for the secondary and tertiary reserves to provide ancillary services.

With more localized microgeneration sources put together to form an MMG, their participation in ancillary services may be subjected to controllability and security issues.[47] Therefore, the above research work investigates the feasibility and profitability of providing primary reserves using MMG. The MMG can potentially maintain the power balance in bulk power systems in real-time by providing ancillary balancing services. However, DNO determines the desirable amount of balancing power from each microgrid under a real-time market environment through price signals.[48] At the transmission level, this real-time balancing market could be considered at sub-hourly intervals (5–15 min duration) to provide ancillary services to the grid.

Further, the market framework may be extended to the distribution level using distributed sustainable resources.[49] The authors in the above work describe how the energy transaction problem can be posed as a leader multi-followers optimization problem for energy trading between a Distribution Company (DISCO) and several MGs. On the highest optimization level, the DISCO takes on the role of leader, while the MGs play the role of followers on the lowest. Choice factors in the proposed model include the amount and price of energy exchanged

Table 2. List of R&D projects conducted on local energy markets

R&D Project[29]	Area	Market Topology	Challenges
iPower[30]	Denmark	Centralized, Hybrid	Optimal energy management of DER
Energy Collective[31]	Denmark	Hybrid	Optimal energy management of DER, effective and secure implementation of LEM, socio-economic related challenges
Interflex[32]	Europe	Hybrid	Optimal energy management of DER, optimal utilization of DR
EMPOWER[33]	Europe	Centralized	Optimal energy management of DER
DOMINOES[34]	Europe	Hybrid	Optimal energy management of DER
Flexgrid[35]	Europe	Centralized	Optimal energy management of DER, optimal utilization of DR
PEBBLES[36]	Germany	Decentralized	Optimal energy management of DER, effective and secure implementation of LEM
ENERA[37]	Germany	Hybrid	Optimal energy management of DER, effective and secure implementation of LEM
Storenet[38]	Ireland	Centralized	Optimal energy management of DER, optimal utilization of DR
GOPACS[39]	Netherlands	Hybrid	Optimal energy management of DER, effective and secure implementation of LEM
Quartierstorm[40]	Switzerland	Decentralized	Optimal energy management of DER, effective and secure implementation of LEM, legal and political related challenges
Cornwall[41]	UK	Hybrid	Optimal energy management of DER, effective and secure implementation of LEM
Piclo Flex[42]	UK	Hybrid	Optimal energy management of DER, effective and secure implementation of LEM

between MGs and DISCO. In order to represent the dynamics between DISCO and MGs, which lead to a retail market in the distribution network, a bi-level optimization problem is posed.

The increased proportion of intermittent power generation in multi-microgrid distribution networks intensifies net load fluctuations. The system faces additional challenges because of the increased fluctuation and uncertainty in net demand and its poor ramping capability. Independent system operators (ISOs) have advocated adopting a market-oriented approach to providing flexible ramping products (FRPs). This approach aims to reduce the reliance on regulation services, prioritize cost savings, and improve ramp capacity management for controlled generating units. The real-time market delivery of FRPs faces three significant challenges. The first is the high cost of installing rapid-start generators to supply FRPs, leading to an escalation in energy prices. The second challenge is ensuring the deliverability of FRPs within transmission networks. The third barrier is the need for sufficient battery backup to support the supply of FRPs during periods of high demand or limited generation capacity. It is thus necessary to propose new delivery methods in light of the issues raised by the provision of FRPs in the power networks.[50] Microgrid response to dynamic price changes is flexible through an optimization framework with higher computation efficiency. From the system-level perspective, interactive behavior among MGs can be investigated using a robust optimization approach[51] for energy transaction coordination. The coordinated distribution of limited energy resources within the group of microgrids is even more challenging to maximize collective benefits.[52]

Blockchain-based decentralized energy markets

The MMG system's operational strategies might be roughly divided into centralized and decentralized approaches. Centralized approaches depend on gathering and analyzing operational data from all entities, which might be difficult due to privacy issues and significant communication demands. Decentralized methods, on the other hand, might simplify communication while maintaining the privacy and sovereignty of MGs. Recently, the idea of transactive energy management has been put up to make it easier for DERs and prosumers to participate in local energy markets through a variety of economic-based approaches. The authors in [53] proposed a transactive energy management framework based on the alternative direction method of multipliers (ADMMs). In this situation, ADMM agents are used to carrying out the ADMM algorithm in the distribution network, while MG control units are in charge of operationally arranging local resources inside their specific MG. The proposed transactive ADMM-based framework effectively controls the distribution system with an MMG structure at the dispersed level. In other words, ADMM agents take over the central controller's duties in conventional distribution systems, enabling the dispersed control of distribution systems we see today.[53]

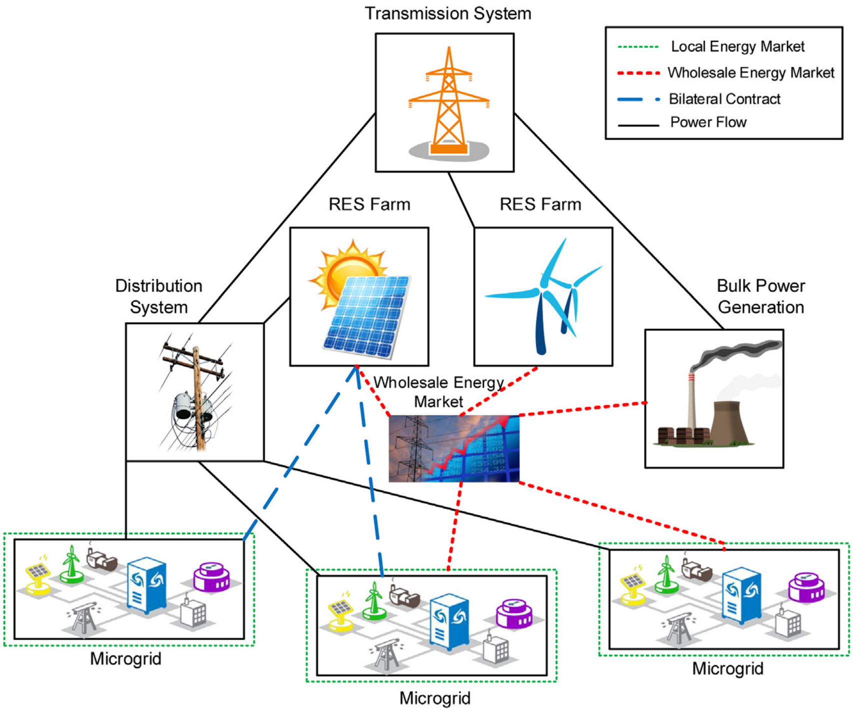

Figure 4. Conceptual representation of local energy markets

Blockchain technology is a relatively new technology that has piqued the interest of entrepreneurs, product developers, banking firms, international organizations, and academics. In 2008, Satoshi Nakamoto, the Bitcoin creator, introduced blockchain as the technological breakthrough and architecture of Bitcoin. Blockchain is a type of distributed ledger that secures the transmission of data and access by integrating data blocks in chronological order using cryptography technology. Blockchain technology has the advantages of being decentralized, reliable, transparent, immutable, and equitable. It can also be used for distributed decision-making, making it ideal for developing a system with high stakeholder trust. The conceptual representation of Blockchain Technology has five basic modules, as represented in Figure 5.

The contract execution block deals with the transaction rules laid by the stakeholders, and the data storage module uses various encryption algorithms to secure the recorded information related to business models such as MMG market models. Furthermore, as big data technology has advanced, third-party central entities have managed to master massive data. As a result, a decentralized transaction mechanism must be used to address the fairness issue caused by third-party intervention. Hence, an internal consensus mechanism that can enforce mutual trust among nodes is required so that nodes can operate stably in the deblocking chain without the involvement of a third-party organization. Third-party involvement might create threats such as sensitive data leakage, network stability breaches, and network security attacks. Henceforth, the reward system module is formulated to reward the nodes upon successful data management and privacy protection to

Table 3. Comparison of existing market models

Market Models[25]	Advantages	Disadvantages
Peer-to-peer model	• Allows for immediate economic transactions between individuals in a fully decentralized way • provides each prosumer and customer with flexibility and autonomy	• There is no guarantee that this model delivers energy meeting power quality requirements • Complex operation and high maintenance costs
Prosumer-to-grid model	• Encourages individual prosumers to form a cooperative community. • Delivers energy by satisfying various technical and economic requirements of individual customers.	• Complicated task for integration and managing prosumers data.
Hybrid Model	• Aims to benefit communities, organizations, or groups of prosumers. • Because of partnerships among a limited number of prosumer groups, it provides a variety of services and high-quality energy delivery.	• Complicated task for integration and managing prosumers data. • Complex transaction and management costs with each prosumer group.

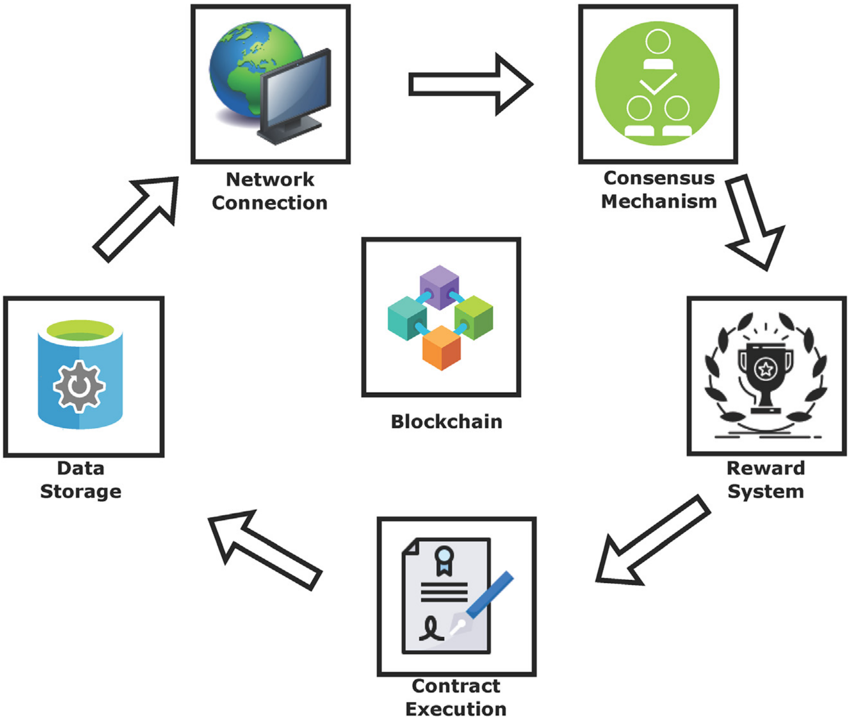

Figure 5. Illustration of blockchain technology's structural framework

encourage competitive trading behavior. With this viewpoint, energy trading with blockchain enhancements appears to be a viable option to ensure trustfulness and efficient and transparent trading practices in MMG market models.

In Brooklyn, New York, five homeowners have set up the first solar blockchain trading system, which distributes solar power generated by their rooftop panels directly to another five households.[54] In the energy sector, this project served as a model for the future implementation of blockchain technology.[55] In order to improve the efficiency and reliability of cross-chain agreements, the authors of[56] suggested a unique consensus technique based on dynamic credit evaluation. One of the energy blockchain applications seeking market clearing for MMGs is a P2P decentralized trading mechanism based on auctions.[57] In,[58] the authors offer a blockchain-based, two-layer architecture for energy transactions across many microgrids, allowing for decentralized trading at every market node. The microgrid's central node gets demand data from the lower-level trading market. It transmits it to the higher-level multi-microgrid trading market in order to facilitate an energy exchange. In Chen et al.,[59] they take into account fluctuating electric prices to ensure the safety of scheduling data among microgrids in blockchain applications. The exterior peer-to-peer energy trading problem and the internal energy conversion problem within interconnected homes, businesses, and factories are considered.[60] The implementation of P2P energy trading presents a number of risks, including the introduction of new, systemic threats such as cyberattacks. So, working out a workable plan for handling such concerns is critical. In Zhang et al.,[61] the authors focus on identifying online attacks that use bogus data injection to disrupt optimal P2P energy trade under stochastic settings. For effective P2P energy trading, this research also provides a modified Intelligent Priority Selection-based Reinforcement Learning technique for quickly recognizing and halting damaging attacks.

Game theory based decentralized approaches

Static electricity trading models in traditional energy markets are no longer feasible for trading surplus power between each MG units or between the MG and utility. Several game equilibrium methods have been widely adopted in recent literature to satisfy the market-related constraints in the presence of intermittent sources and electric vehicles. The authors in[62] formulated the MMG energy management problem in the real-time pricing market using sequential game theory. To this end, the sequential non-cooperative games model is designed to optimize the operation routines of each individual microgrid. In a similar work,[63] the effect of various power trading modes on MG boundary conditions is investigated. These boundary conditions were determined from the energy transaction rules framed concerning deficit power vacancy and price quotation. The two-level Bayesian-Stackelberg game model is proposed in[64] to establish a time-of-use price-based mechanism within the residential MG networks, considering the scheduling of EVs with uncertainty. This pricing mechanism aims to regulate peak load by encouraging EV and energy storage participation. In Yang et al.,[65] the multi-leader, multi-follower Stackelberg game approach is adopted to flexibly establish P2P transactions among MMG. Further, many distributed algorithms were proposed for MG privacy protection, allowing MGs to achieve Stackelberg equilibrium in an iterative process without disclosing their confidential data.

The terminal flexible load model suggested by the authors in[66] can provide scheduling flexibility for the seamless connectivity of the microgrid system. It reduces operational expenses while also offering schedulable space for peer-to-peer transactions. The leader-follower-based dynamic game theory approach is suggested in[67] to ensure the reliability and stability of distribution networks. In this context, the DNO sets network flow constraints and is eventually treated as a leader, and the MGO, which responds to the internal transaction prices, will be a follower. The research work[68] introduced a cooperative game theory model to establish transaction modes between rural MMG and distribution networks. The cooperative game is built on the establishment of a cooperative alliance, in which the advantages of all partners rise, or at least one party's benefits increase. In contrast, other parties' benefits remain unchanged, increasing the benefits of the alliance. On the other hand, non-cooperative game models[69,70] are considered in the transactive electricity markets in the presence of competitive MGs with individual profit-maximizing goals. Hence, the trading mechanism among those MGs is treated as non-cooperative, and this structure includes five essential elements: information, utility function, game player, strategy, and equilibrium.

Non-cooperative game theory is anchored in the concept of Nash equilibrium, where players in a game are at a standstill, with none able to benefit by solely changing their own strategy unless others do the same. This concept underpins the model suggested by Yang et al.,[71] which introduces a non-cooperative market framework for trading surplus energy among microgrids facing power shortages. Aghdam et al.[72] advances this idea, proposing a strategy for improved energy management across islanded multi-microgrid systems through distributed model predictive control. This strategy employs non-cooperative game theory in conjunction with a two-sided auction to facilitate fair and efficient energy trading between microgrids. In markets with limited energy resources, this can lead to competitive bidding, as microgrid operators aim to maximize their returns. However, while game-theoretic models provide a structured mathematical approach to address these trading dynamics, they do not always guarantee a single, stable equilibrium or ensure that the outcomes are Pareto optimal, meaning that no participant's situation can be improved without worsening another's. To maximize the "*collective advantages*"of a group, a novel approach is proposed in[73] that makes use of multi-objective optimization. Instead of consumers fighting with one another for scarce resources, a third party can arbitrate between them and offer a Pareto-optimal solution that takes into account their unique needs. From the DNO perspective, dispatch DG sources in MMG networks will be more effective with prior trading agreements among stakeholders, which would require efficient dispatch algorithms. Thus, the following section introduces and discusses different MMG dispatch strategies.

MULTI-MICROGRID DISPATCH

With high penetration of renewable energy sources (RESs) and an increasing number of proactive participants, local energy markets (LEMs) have developed as a means to navigate uncertainties while boosting energy efficiency and bolstering the energy sector's economy. Unlike traditional wholesale and retail markets, local energy markets often prevail in distribution networks, providing a platform for market players to allow energy trading and service exchanges in geographically confined areas. In the context of MG trading, the microgrid scheduling strategies are classified as direct control-based, full market-based, and semi-market-based methods.[74] The comprehensive market-based approaches also comprise competitive market-based and centralized methods from the standpoint of a single participant. Concerning networked microgrids, the coordinated functioning of the MGs and distribution network presents two significant challenges: 1) Individual MG self-scheduling in the context of intermittent and non-dispatchable RES; 2) Interactive mechanism between individual MGs and distribution network to establish a profit-making consensus. The solution methodologies for MMG optimal dispatch available in the literature are segregated into centralized and decentralized-based approaches.

Centralized approaches

The most common challenge in dispatching the DG units in the presence of uncertain loads and RES is the day-ahead scheduling problem of networked microgrids. The chance-constrained programming-based hierarchical dispatch model is proposed in,[75] where each MG network performs local optimization in the primary stage and sends the information to DNO. In the latter stage, the DNO performs global optimization and updates the information with other MGOs to reschedule. The DNO ensures operational efficiency by considering power flow constraints and setting trade prices with each entity within the microgrid ecosystem, based on the resolutions achieved at subordinate operational levels. For the enhanced coordination and sequential interactions between the DNO and MGO, the cross-layer optimal energy scheduling model[76] is introduced by considering internal and external trading prices in the MMG network. However, each MGO in the MMG network has its own self-interest in managing the internal profit-making operations and might have a disinclination to share information with neighboring MGOs due to privacy concerns. Hence, a coordination control agent[77] is necessary to preserve the privacy of MGO. Further, it facilitates the MG central coordinator to minimize the internal operating costs and maximize the social benefits of MMG. Multi-microgrids offer social benefits in that they help the entire community as a whole, not just the individual microgrid operators. These advantages result from the collective efforts and interactions between multiple microgrids operating under a single coordination control agent.[78]

The existing dispatch problem for MMG may be extended by including emission dispatch[79] in the presence of multiple integrated energy systems such as cooling, heating, and power.[80] Model predictive control,[81] another popular model-based technique, has also been suggested as an appropriate and effective solution for challenges with energy management and Economic Dispatch (ED) of MMG networks. The rapid expansion of DC-based DG sources, energy storage units, and electronic loads has recently helped us focus on DC microgrids (MGs). Compared to traditional AC power systems, the increased efficiency and simple control system of DC MGs are notable features because they eliminate redundant DC/AC power conversions and frequency and reactive power management concerns. Numerous studies have been done to use the distributed control philosophy to coordinate DC MMGs. The authors of[82] offer an MG- and cluster-based fixed-time control system designed to maximize power flow between MGs. At the lowest possible settling time, the distributed MG-control layer

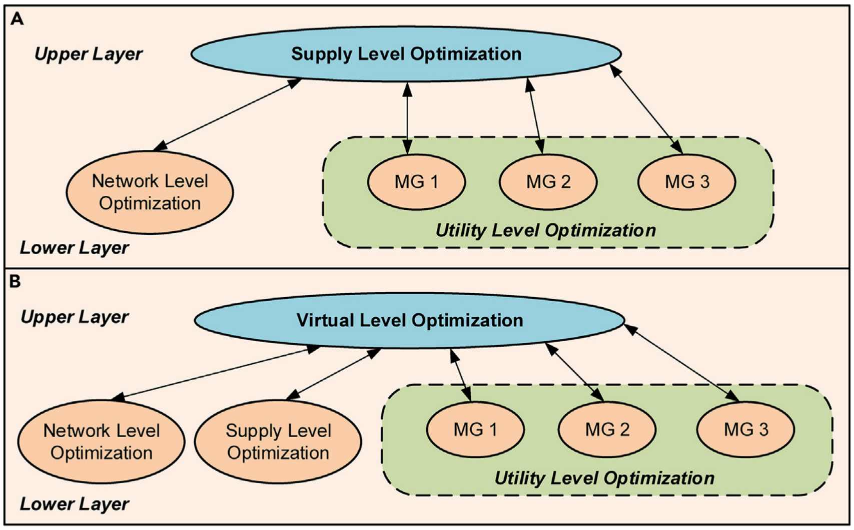

Figure 6. Conceptual scheduling optimization framework
(A) sequential optimization (B) parallelizing optimization.

returns the MG's average voltage to the value set by the cluster-control layer. It assures optimal power sharing across the MG's DGs. Furthermore, as power electronics technology advances, an increasing number of DC-type sources and loads can be used in MGs, resulting in AC/DC hybrid multi-microgrids. The existing bi-level optimization models[83] often consider the uncertainties associated with the source[84] and loads, including electric vehicles,[85] but neglect the uncertainty factors associated with the transition of MG from grid-connected/autonomous mode and other line faults. In this regard, the authors in[86] propose a two-stage robust optimization model to ensure stable operation and achieve day-ahead scheduling of hybrid MMG.

Decentralized approaches

Establishing a centralized control facility for the entire system and realizing centralized scheduling the optimization of the multi-entity power grid is difficult due to the fact that each stakeholder related to different types of MGs (residential, industrial, and commercial) will not disclose the operational information of its internal equipment, such as the solar PV and battery storage invested by an industrial MG itself.[87] Further, the proliferation of dispersed devices makes it harder to engage with information and govern the world, posing new problems for centralized control methods. The following list summarizes the drawbacks of conventional scheduling techniques.[88]

1. (1) It is ambitious to implement the necessary functionalities in large-scale and wide-area DG access, including global optimization, multi-point connectivity, and vertical hierarchical control.
2. (2) Dynamic optimization is crucial in MMG dispatch because of the significant probabilistic and time-varying attributes. However, obtaining good tracking performance with a centralized scheduling technique is challenging because of server capacity and communication delay.
3. (3) A centralized authority cannot protect the privacy of managed things adequately.
4. (4) It is impossible to adequately consider every participant's interests; therefore, it is challenging to distribute the revenue equitably.

From the viewpoint of the shortcomings mentioned above, several decentralized-based scheduling algorithms have been proposed to preserve privacy interests in MMG. Microgrids require decentralized dispatch in addition to the need for security and privacy, and they also must work together to meet the demands of the power grid. In the literature, two distinct distributed operational frameworks pertaining to coordination scheduling in MMG can be found, namely sequential distributed (SD) optimization and parallelizing distributed (PD) optimization framework.[89] As shown in Figure 6, the PD framework has an additional virtual-level optimization layer in contrast with the SD framework. In reality, no actual stakeholder is represented by the virtual coordination center.[90] It may be a decision-making platform or an independent energy management system. This virtual center coordinates the shared tie-lines further to produce consistent scheduling plans after receiving the maximum power of the shared tie-lines from the multi-stakeholders. The authors in[91] proposed a multi-agent-based approach for the real-time dispatch of DERs in a smart community-based MMG network. The smart appliances in smart homes are controlled using two-way intelligent communication to optimize the operating price, efficiency, and user's comfort. Analytical Target Cascading theory is established in[92] for decentralized dispatch using parallel coordination among the stakeholders.

The authors in[93] proposed a bi-level decentralized day-ahead schedule for islanded MMGs leveraging the carbon trading market. ADMM, a distributed method, was used to evaluate how changing carbon pricing may affect the system's operation. In addition to operational constraints, non-linear power flow constraints are considered in Xu et al,[94] and a consensus algorithm is utilized to build the ideal scheduling

Table 4. Optimal Dispatch frameworks and objectives of selected literature

Reference	Microgrid Size	Methodology – Framework	Objective
Yang et al.[71]	3	Event-Triggered Online Scheduling	Flexible energy sharing among residential MGs by integrating internal scheduling and external energy sharing
Sun et al.[74]	3	Multi-agent system-based hierarchical optimization	Multistage energy scheduling of MMG with limited information sharing
Brahmia et al.[78]	3	Distributed Model Predictive Control	To determine the economic energy dispatch of MMG under uncertain market prices
Naebi et al.[80]	2	Bilevel Optimization	To obtain the equilibria among the MMG while bidding
Qiu et al.[101]	3	Robust Optimization	Robust optimal scheduling of hybrid AC/DC MMG considering source-load uncertainties
Chen et al.[102]	3	Decentralized Adaptive Robust Optimization	Optimal dispatch of hybrid AC/DC MMG under regular and faulty communication
Zhu et al.[103]	–	Multi-Agent Framework	Multi-stage optimization of smart community-based MMG without consideration of two-way communication within the community.
Nawaz et al.[104]	4	Decentralized saddle point dynamics approach	Decentralized optimal power flow of distribution network consisting of MMG.
Guo et al.[105]	–	Decentralized Markov Decision Process	Decentralized online optimal dispatch of MMG with delayed communication

model of each microgrid's controllable distributed generations, resulting in the microgrid functioning stably in the optimal state. Although the consensus algorithm is applied extensively in MG optimization, other techniques are available in the literature, such as the distributed diffusion strategy,[95] which could converge to an optimality at a faster rate. In Tan et al.,[96] the Ward equivalent method is used to linearize power flow constraints and establish decoupling between MG and the distribution network. Two types of decentralized algorithms, primal and dual decomposition, are proposed in[97] to solve the joint scheduling robust model, which seeks to ensure coordinated operation between the distribution network and micrograms. By combining analytical target cascading and a robust model, which can be solved with a column-and-constraint generation strategy, the robust economic dispatch problem can be used in a distributed fashion by several entities, including DNOs and MGOs. In Shahbazbegian et al.,[98] the modified decomposition scheme based on ADMM is proposed to decouple the decentralized problem into master, lower-level, and upper-level problems. By doing so, the above method can enhance convergence characteristics in contrast with traditional dual decomposition.

In Chen et al.,[99] the online decentralized and cooperative dispatch problem is investigated to mitigate grid tie-line fluctuations. The effectiveness of the suggested technique in minimizing the state space and processing time is evaluated, and if the demand for real-time scheduling is met, a successful decentralized policy may be accomplished. A decentralized control architecture is reasonable considering islanded MMG's design and operational features. Each MG follows the regulation cost as a guide and logically optimizes the amount of regulation power allotted by each MG, hence enhancing the MG cluster system's overall economics. Using a weighted matrix to handle equality constraints in optimization problems and dynamic step sizes to speed up convergence, distributed optimization with a weighted gradients method[100] is developed to solve the ED problem of the MMG network. The summary of dispatch frameworks with the research objectives of selected literature is provided in Table 4.

ENHANCING RESILIENCE IN MULTI-MICROGRIDS

With the growing incidence of natural calamities, the emphasis on bolstering the resilience of power systems has never been more pronounced. Factors such as Reliability, Stability, Security, and Resilience underpin the evolution toward smarter grids. Reliability is typically seen as the system's consistent performance over extended durations under given scenarios. One could interpret reliability as a measure of a system's consistent operational efficiency. Resilience, a term frequently encountered in academic circles, captures a system's ability to withstand, adapt, and recover from adverse scenarios, maintaining at least partial functionality. A prevalent interpretation of resilience is "the aptitude to diminish the impact and/or time frame of disruptions."[106] This contrasts with "robustness," which does not capture the nuance of gradual degradation and subsequent recovery. Strategies rooted in planning are often employed to achieve a specific reliability threshold. Unlike reliability, resilience delves into the dynamic nature of a system over shorter intervals and its operation-centric behaviors. Reliability is "the system's risk quotient in managing plausible scenarios without resorting to load shedding." Both concepts revolve around assessing the system's operational continuity over time.[107] Microgrids present a pragmatic solution to the resilience enhancement conundrum. By strategically managing distributed energy resources, microgrids can disconnect from compromised segments of the distribution grid, ensuring the uninterrupted power supply to crucial local loads.

Characteristics of resilience within microgrids

The role of resilience in power system operations focuses on managing high-impact events that are rare but crucial, known as high-impact, low-probability (HILP) disturbances. To buffer against the detrimental effects of such HILP events, a shift from centralized to decentralized structures, especially in distribution systems, becomes paramount. In this transformation, microgrid and intelligent grid systems play pivotal roles, with a significant emphasis on the integration of distributed energy resources (DERs). This section underscores the resilience of algorithms that oversee routine operations encompassing everyday optimal load management, standard system monitoring and control, network flow measurement, and so forth. It is worth noting that several influential studies already factor in diverse failure scenarios and their countermeasures, as highlighted in Venkataramanan et al.[108] However, myriad avenues exist for research enhancement to bolster microgrid robustness and resilience. Here are some pivotal areas.

Common/extended failure scenarios

Predominant studies often cater to a limited set of failure scenarios, with primary grid disturbances[109] and transmission-line disruptions[110] being the focal points. Few touch upon issues such as short-circuit disruptions.[111] Concerns such as subpar DER energy output benchmarks, unauthorized switching activities, or load disruptions are not widely addressed. A clear articulation of all potential and relevant failure modes is crucial for comprehensive scheduling solutions. Moreover, the versatility of algorithms in addressing emerging and known disruptions is a topic of interest. Integrating intermediate simulation mechanisms might be a promising avenue for enhancing both adaptability and granularity.

Universal/generic failure scenarios

Some disruptions can be categorized under broader umbrellas. For instance, central grid disturbances might be perceived as a specific transmission line issue at the point of common coupling.[112] A holistic categorization of prototypical failures in scheduling paradigms is still an area ripe for exploration. As the list of considered failure scenarios grows, achieving computational efficiency while determining optimal solutions could require judicious categorization.

Interplay of granular controls

Rapid-response mechanisms during disturbances often utilize foundational controls, such as voltage and frequency adjustments.[113] However, overarching schedules might influence the efficacy of such granular controls. For instance, a generator nearing its operational threshold might impede an effective response. Immediate rectifications, such as traffic rerouting by specialized controllers, might be needed upon disruptions. A deeper dive into the synergy between foundational controls and overarching scheduling mechanisms could pave the way for consistent operations and apt emergency responses.

Techniques for fault mitigation

Among the widely acknowledged fault countermeasures are grid disconnections,[114] power flow redirections,[115] and the creation of energy islands.[116] Practical factors such as protective measures, system inertia, grid configurations, and legal stipulations are often overlooked when weighing these mitigation options. Future endeavors should enhance the comprehension of the practicality of these measures and probe into alternatives. It includes exploring distributed generation methods and energy reservoirs that can swiftly revive malfunctioning components.[117]

Given the unpredictable and dynamic nature of power systems, navigating the intricacies of microgrid resilience demands a comprehensive and adaptable strategy. Our exploration of diverse failure scenarios and their countermeasures hints at this domain's multifaceted challenges. It' is crucial, however, to be reminded that as technology evolves and our understanding deepens, the landscape of potential challenges and their solutions also transforms. Emphasizing the importance of this continuous evolution, our discussion now logically extends to how we evaluate and quantify this resilience. In the forthcoming section, we will direct our focus toward defining and understanding the metrics that provide tangible measures of resilience for MMGs and grids. It will offer a framework for assessment and lay the groundwork for more targeted advancements in ensuring our power systems are robust and dependable.

Metrics for assessing the resiliency

Research on the resilience of electrical grids often centers on their structural and organizational aspects. Yet, the inherent limitations of a power distribution system, such as constraints on voltage in power flow, boundaries on generation, and thermal limits, pose significant impediments to resilience evaluations. Historically, indices such as SAIDI, SAIFI, and MAIFI[118] were the benchmarks for gauging the temporal performance of power distribution networks. Such metrics determine the efficiency of a system in consistently delivering electricity to its entire load spectrum. The ideal design should ensure that critical loads receive power despite extreme adversities. Resilience is characterized as "the capability of a system to maintain power supply to vital loads amidst severe challenges."[119] It is important to note that historical data from 2013 may partially encapsulate current outages due to changes in documentation practices and evolving grid technologies. Current reporting practices result in an omission of approximately 87% of power outages, primarily because minor outages that fall below certain thresholds or durations are not consistently recorded. In power systems analysis, the distinctions between resiliency and reliability are both subtle and significant. Resiliency focuses on the system's capability to handle events that, while rare, have far-reaching consequences.

Table 5. Comparative overview of reliability and resilience

Key indices[120]	Resiliency	Reliability
Definition	• Resilience, on the other hand, is about the system's adaptability and recovery. It evaluates the power system's capacity to anticipate, absorb, adapt to, and rapidly recover from disruptive events, whether those events are due to natural disasters, human errors, or other unforeseen challenges.	• Reliability, in the context of power systems, primarily refers to the ability of the system to deliver power consistently without any interruptions. It is a measure of the system's effectiveness in performing its intended function under predetermined conditions for a specific period.
Event Characteristics	• Pivots around events that, though rare, can cause significant disruption when they do occur.	• Concentrates on more frequent events, which, while commonplace, have a relatively muted impact on the system.
Evaluation Framework	• Assessed within the paradigm of a system's agility and robustness in response to unanticipated challenges.	• Framed in a temporal context, where the emphasis is on outage regularity and its typical duration.
Examination Window	• The scope of resiliency evaluation spans both proactive (anticipatory measures) and reactive (post-event recovery) phases.	• Reliability is scrutinized over set intervals, marking its regular rhythm of assessment.
Load Prioritization:	• The lens of resiliency is sharply focused on essential loads, underscoring the importance of maintaining pivotal services during grid disturbances.	• Casts a wider net, enveloping both pivotal and routine loads in its ambit, ensuring an all-encompassing system view.
Interruption Spectrum	• Resiliency probes into all shades of power disruptions, from fleeting glitches to prolonged outages.	• In the realm of reliability, the spotlight is mainly on medium to extended power outages, setting aside brief hiccups.
Central Worries	• It zooms in on the span consumers have to go without power and the expedition of system rejuvenation after a setback.	• The heart of reliability rests on ensuring minimal disruption time for consumers, sidelining infrastructure rejuvenation concerns.

It emphasizes the ability of a system to prepare for, respond to, and recover from such disruptions. In this assessment, the core considerations are the preservation of critical services across all outage durations, from transient to prolonged interruptions. Key metrics for resiliency include the duration of consumer interruptions and the speed of infrastructure recovery. In contrast, reliability addresses the system's performance under more frequent yet less severe disturbances. Its metrics are inherently temporal, evaluating power outages' regularity, duration, and frequency. Both vital and non-vital loads factor into reliability assessments, with the primary focus being on medium to long-term power interruptions and the primary concern centered on limiting consumer interruption durations.

Table 5 compares the nuances distinguishing resilience from reliability within electrical systems.[120] Over time, various metrics to evaluate resilience have emerged, notably the resilience triangle and trapezoid models. The resilience trapezoid, an evolution of the triangle model, was introduced by Tierney and Bruneau in.[121] While the triangle mainly assesses system disturbances, the trapezoid delves deeper, analyzing resilience across three stages: disturbance, deterioration, and recovery. In a subsequent study, Panteli et al.[122] explored the potential of applying the resilience trapezoid methodology to the structural design of power systems.

Rieger's work[109] sheds light on a distinct resilience methodology stemming primarily from control systems perspectives. It does not seamlessly integrate into conventional power systems, but its essence is encapsulated in the Impact Resilience Evaluation curve, as shown in Figure 7. This curve depicts the system's performance degradation over specific timelines, providing a deeper understanding of its strengths and potential weak points. Metrics such as the proportion of the lost overall system load or the system's prowess in upholding crucial loads during disturbances can define the degradation benchmarks. A detailed case study on preventing cyber-physical attacks to evaluate the situational awareness of the DNO is provided in the recent study.[108] This use case will give the readers a better understanding of how to tackle and mitigate a cyber-attack and give a clear picture of various defense mechanisms to be followed in alarming situations.

The adaptability of a system, particularly its performance spectrum from optimal functioning to established resilience benchmarks, critically influences its overall efficiency. This adaptability pertains to the system's ability to undergo necessary modifications or evolutions in the face of unforeseen challenges. When a system shows an inability to recalibrate in the wake of such disturbances, this phenomenon can be termed as adaptive deficiency, indicating a decline in performance that breaches established norms. As we delve further into the intricate layers of system adaptability, Table 6 encapsulates a concise array of performance-driven metrics juxtaposed with their outcome-based counterparts, specifically tailored for appraising resilience within power systems.

With this foundational understanding, the subsequent section will pivot to address the nuances of resilient operation within Single-Microgrid frameworks and the MMG networks, further elaborating on their symbiotic relationship and operational intricacies.

Strategies for enhancing resilience in microgrid architectures

Microgrid networks, as decentralized energy systems, have witnessed rapid advancements in their structural and operational paradigms. Their evolution is particularly evident in the context of resilience, which has emerged as a key focal point in the domain of power distribution and management. Within the realm of single-microgrid networks, resilience-centric operational strategies have been widely examined. Referencing,[125] a foundational exposition on resilience-aware microgrid operational scheduling is presented. The focus here is on ensuring continuity and robustness in the face of disruptions, especially during islanding scenarios. A particularly insightful perspective emerges from,[126]

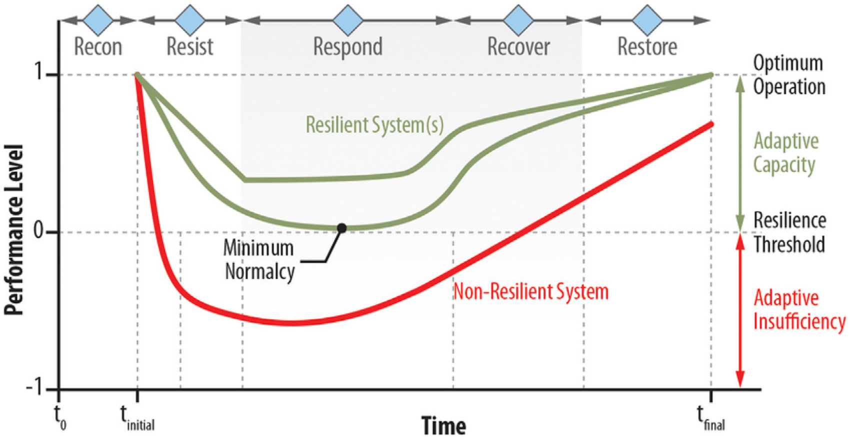

Figure 7. Evaluation of system resiliency proposed in[109,123] (Copyright 2024, IEEE and MDPI, Reproduced/adapted with permission)

which navigates the nuanced challenges of microgrid operational dispatch during such isolated operations. The study underscores the influence of central control on operational decisions, emphasizing the pivotal role of static security margins in predicting system perturbations. In refining these operations further, the strategy proposed in[127] gravitates toward robust optimization. The foundational premise here is ensuring power delivery to critical loads during isolated operations, a pivotal consideration given the challenges posed by limited online capacity. Concurrently, the approach by Hussain et al.[128] offers a robust optimization schema, intricately accounting for intrinsic operational uncertainties. Stochastic optimization further augments the realm of single-microgrid operations, as evident in Mohseni et al.[129] This technique harmoniously integrates diverse network constraints with spinning reserve necessities, offering a deterministic paradigm to the otherwise uncertain nature of microgrid operations. Furthermore, the above research probes into the interplay between demand response initiatives and distributed energy resources (DERs) scheduling amidst stochastic loads.

Transitioning to multi-microgrid networks, there is an evident expansion in the scope and complexity of resilience-centric studies. Initial endeavors, such as the concept elucidated in Chattopadhyay and Panteli,[130] advocate for provisional microgrids. These strategically positioned networks serve to reduce the onus on dispatchable DERs, subsequently enhancing the resilience quotient of the broader system. A holistic exploration in [106] introduces a risk-centric model, proposing strategies for energy scheduling across interlinked microgrid networks. It considers the intrinsic uncertainties of load and generation and offers metrics to address broader failure spectrums. Notably,[131]

Table 6. List of popular resiliency metrics

Resiliency metrics[124]	Attribute	List of notable metrics
Performance-based metrics	Power	Unsupplied Load, Supplied Load, Unsupplied Energy, Supplied Energy, Recovered Load, Recovered Energy, Generation capacity not connected, and Generation capacity connected.
	Duration	*"Load or energy curtailment duration, Customer Average Interruption Duration Index (CAIDI), Loss of Load Expectation (LOLE), System Average Interruption Duration Index (SAIDI), and Storm Average Interruption Duration Index (STAIDI)."*
	Frequency	*"Loss of Load Frequency (LOLF), System Average Frequency Interruption Index (SAIFI), Storm Average Interruption Frequency Index (STAIFI), Number of connected and disconnected customers, Number of online and offline transmission lines."*
	Probability	Loss of Load Probability (LOLP), Probability of restoration, Probability of supply interruption,
Consequence-based metrics	Economic	Cost of unsupplied load or energy, Cost of restoration, Loss of gross regional product
	Social	Decrease in labor hours, population affected employment loss metric.
	Geographic	The geographic area affected by the loss of energy
	Safety and Health	Loss of human lives and hospital beds unavailable due to interruption of power.

Table 7. Summary of collected research works on multi-microgrid resiliency

Reference	Contribution	Methodology	No. of Microgrids considered
Karimi et al.[133]	Demand-side flexibility with the resilient operation	Analytical Approach	–
Fobes et al.[134]	Transient Stability assessment	Multi-Agent System based	3
Qin et al.[135]	Dynamic boundary evaluation of MMG	Model Predictive Control	4
Younesi et al.[136]	Resiliency assessment of large-scale multi-microgrids	Distributed Diffusion Strategy	3
Zhou et al.[137]	Seamless interconnection of MMG networks	Analytical Approach	2
Farzin et al.[138]	Resiliency evaluation with Outage Management	Model Predictive Control	3
Kargarian et al.[139]	Power flow controller design scheme to enhance the resilient operation of MMG	Multi-objective nonlinear optimization	3
Bian et al.[140]	Proposing a two-stage hierarchical energy management framework for resilience enhancement.	Decentralized optimization	5
Mehrjerdi et al.[141]	Resiliency enhancement with improved load curtailment strategy	Analytical Approach	4
Baghbanzadeh et al.[142]	Distribution Network Reconfiguration for Resiliency Enhancement	Column constraint generation algorithm	4
Bintoudi et al.[143]	Enhancement of dynamic stability of microgrids	Mixed Integer Linear Programming	3
Armioun et al.[144]	Accessing resiliency in CCHP systems	Auto-regression algorithm	–
Rahiminejad et al.[145]	Resiliency enhancement under load curtailment	Analytical Approach	–
Qiu et al.[146]	Coordination of networked Microgrids	Q-Value Learning Approach	3
Shirsat et al.[147]	Resilient Load Restoration	Analytical Approach	–

introduces quantifiable metrics to gauge microgrid resilience. Here, the discourse spans from analyzing voltage sag percentages to evaluating performance degradation, with an added emphasis on system recovery dynamics post disturbances. The exigencies posed by environmental extremities and unforeseen operational challenges underscore the need for a robust resilience quantification methodology. As expounded in Gholami et al.,[132] the integration of multi-microgrid operations with energy storage systems promises heightened resilience during adverse operational conditions. This research meticulously dissects resilience into four core metrics: withstand, recovery, adapt, and prevent, offering a multi-dimensional lens to evaluate microgrid robustness.

In summation, the tapestry of resilience-centric strategies in microgrid networks, as illuminated by studies [125] through [132], is both vast and intricate. The nuanced interplay between operational paradigms, optimization strategies, and resilience metrics presents a rich avenue for further exploration, as indicated in Table 7. In this section, we have systematically dissected the resilient operation intricacies inherent to both single-microgrid and multi-microgrid networks. Through our exploration, it becomes palpable that advances in robust optimization techniques, combined with stochastic modeling and innovative energy storage mechanisms, are paving new avenues in power system resilience. Yet, as with any evolving discipline, many queries and challenges remain yet to be fully addressed. The forthcoming section aims to catalyze a deeper exploration by discussing the overarching implications of our findings, the challenges still at hand, and the prospective directions that could further revolutionize the resilience paradigm of power systems.

DISCUSSION AND FUTURE SCOPE

Discussion

Energy sharing and trading in multi-microgrid systems are pivotal for optimizing resource utilization, enhancing grid resilience, and fostering a sustainable and efficient energy ecosystem. By allowing microgrids to share surplus energy with those in need, these systems can balance supply and demand dynamically, preventing disruptions and ensuring continuous power supply.[148] Energy trading creates economic opportunities for participants, encouraging the adoption of renewable energy sources and promoting a more equitable and accessible energy landscape. This collaborative approach enhances the flexibility, adaptability, and overall functionality of multi-microgrid systems, contributing to the development of resilient, self-sustaining, and economically viable energy networks.[149] On the contrary, the restructuring of the electricity market has indeed prompted researchers to explore innovative solutions that harness the potential of smart consumers to enhance economic and technical indicators. Microgrids play a significant role in this context by offering a decentralized and flexible approach to energy generation, distribution, and consumption.[150] When accompanied by appropriate regulatory measures, energy trading among the networked microgrids introduces flexibility, optimizes resource utilization, and creates new opportunities for economic transactions, ultimately shaping more dynamic and sustainable electricity market ecosystems.[151]

In considering the imperative need for further research in MMGs, critical areas intersect with the challenges and advancements in communication technology and cyber security. Essential infrastructure components, such as robust communication systems with enhanced

Table 8. Multi-microgrid Operation Frameworks from the selected literature

Reference	Optimization Framework	Methodology	Objective	No. of Microgrids
Fan et al.[152]	Robust Optimization	Information Gap Decision Theory	Risk-averse short-term scheduling of power between DNO and MG considering uncertainties	4
Wu et al.[153]	Distributed Optimization	ADMM	Optimal operation of DG units in MMG network subjected to structural dispersion and complex composition	2
Mi et al.[154]	Bi-level programming framework	Second-order cone programming	Multi-energy transactive energy trading considering distribution network reconfiguration	3
Karimi et al.[155]	Stochastic Multi-objective Framework	Stochastic Compromise Programming	Optimal energy management of community MGs with multiple objectives, including emission and power loss reduction.	3
Wang et al.[156]	Decentralized Bi-level Framework	Stackelberg Game Theory	Optimization of flexible energy resources in the MMG network subjected to ramp-up constraints	3
Wu et al.[157]	Multi-Agent Architecture	ADMM	To make MMG more adaptable and reliable, the P2P control architecture is proposed.	–
Zhang et al.[158]	Dynamic equivalent model	Spatial-scale Model Reduction	A new technique for dynamic equivalent modeling is presented to lower the order of inverter-based MMG networks.	–
Zhang et al.[159]	Stochastic Decomposition Framework	Approximate Dynamic Programming	Real-time dynamic energy management of MMG	6

cybersecurity measures and comprehensive measurement and metering devices, are foundational for the effective implementation of MMGs. For the efficient integration of MMGs, it is also crucial to have an upgraded coordination framework with better optimization algorithms and control schemes. Regulatory approvals, tariff plans, and grid code updates are requirements that must be met before MMGs are implemented. There are several problems relating to the architecture, control, communication, and operation of networking MGs that need to be resolved if the benefits of networked MGs are to be fully realized. Because the MMG is more reliant on communication infrastructure to function reliably, ensuring robust and seamless communication channels becomes critical for its efficient and stable operation. More safety measures should be used in exchange transaction schemes that aim to improve society. Soon, 5G wireless communication technology will be a crucial enabler in MMG operations. Protecting user privacy, reducing the energy needed to power antenna arrays, and mitigating inter-cell interference brought on by denser networks are just a few of the challenges that must be overcome before the widespread deployment of 5G can occur.

The entire MMG system could crash due to the vulnerability of the 5G communication network being attacked online. Hence, in the future, EMS will still need to implement cyber-secure methods such as blockchain and peer-to-peer safe transaction methods. All MG owners must get the appropriate consensus before joining the networked system. Maintaining the data privacy of MGs using this method is necessary. In the future, different energy carriers must be linked to construct the MMG system. Hence, MMGs' already complex modeling is made even more so by the presence of multi-energy links between electricity, gas, and heat networks. Based on the critical review of recent literature on energy sharing and trading in MMG networks, several operational frameworks have been identified, as tabulated in Table 8. A brief analysis of various centralized and decentralized approaches to MMG operational scheduling is conducted.

A few open challenges in terms of volatility, scheduling, privacy, and security concerns are provided in Table 9 for the benefit of readership.

Future scope

Researchers are becoming more interested in investigating MMGs to meet the rising energy demands economically, steadily, and reliably with higher expectations of power generation from renewable-based DERs globally. As the DERs are becoming the primary source of future power generation, they demand a strong and resilient infrastructure for robust operation and substantial market opportunities are expected to arise. The following is a summary of the upcoming developments in optimal scheduling, market participation, and resilient operation of MMGs.

- The main area of study and current hot topic for MMGs is optimally operating them. The primary factors for islanded optimal functioning are stability and the capacity for continuous operation. The primary goals of the grid-connected optimal operation are to increase the clean energy utilization ratio and MMGs' economic indicators.
- Online optimum algorithms are thought to offer a wide range of potential applications in energy scheduling due to the random nature of the market- and power-related variables (electricity price, load demand, and renewable resources) in MMGs. Reduced computing complexity, high convergence performance between online and offline global outputs, and other goals should be the emphasis of online algorithm development.

Table 9. Open challenges in multi-microgrid research

Challenge	Description
Volatility	The impact of uncertainty and variability of MMGs is higher in contrast with a single-islanded MG. Hence, mitigating such volatile and intermittent characteristics is critical to overcome instability issues.
Scheduling	The dimension of energy scheduling of interconnected MMG networks with strongly coupled energy during energy scheduling rises with the number of MGs in MMGs increasing.
Privacy	Designing diversified scheduling strategies in a decentralized environment to preserve the privacy of different stakeholders such as independent MGO, utility, local prosumers, and DNO while sharing surplus energy in MMG networks.
Security	Designing a robust, resilient, interconnected MMG network equipped with state-of-the-art cyber-physical infrastructure for effective communication and control of MG flexible resources is another challenging task.

- A more in-depth examination of the impact of trading patterns and preferences on the outcomes of games between market entities is needed. "Credit" labeling has to be incorporated in-game models among market entities to alleviate unreasonable quoting actions caused by knowledge asymmetry.
- A recent study has concentrated mainly on energy trading and optimal power sharing in MMGs. However, reactive power is also a crucial component of MMGs and should be considered in energy management to increase the system's resilience and dependability. The system's best management and operation techniques should be simple to implement when the active and reactive powers are controlled simultaneously.
- Advanced communication methods, such as false data injection and MMG planning and operational level, may attract greater attention in terms of cyber-attacks and security tactics. In practice, resilience modeling would result in more accurate simulation scenarios by integrating power dynamics under imbalances.

Conclusion

The structure of the grid, the type of power source and energy storage system, the capacity allocation, and other optimal design characteristics all substantially impact the multi-microgrids' performance. Likewise, many factors must be considered while planning and designing a multi-Microgrid, and it is impossible to extrapolate the notions of a single microgrid system. In this context, we reviewed the existing state-of-the-art centralized and decentralized approaches in multi-microgrid energy sharing and trading and the intersection of these two themes. The article commenced by addressing the crucial concept of market participation within microgrid networks, delving into the intricate dynamics of how microgrids could engage with energy markets, facilitating the exchange of electricity for economic and operational optimization. The discussion encompassed two fundamental approaches: centralized and decentralized. The former involved a coordinated effort, often directed by a central authority, to manage the interactions between microgrids and energy markets. On the other hand, the latter empowered individual microgrids to independently participate in market activities, allowing for greater flexibility and adaptability. The exploration of these paradigms illuminated the nuanced relationship between microgrid operations and the energy market at large. We also delved into the dynamics of energy trade between microgrids and distribution network operators (DNOs), and the burgeoning peer-to-peer (P2P) trading models that enable direct energy exchanges, enhancing efficiency and self-sufficiency. Moreover, we explored the strategies for MMG dispatch and scheduling, highlighting innovative approaches that enable microgrids to manage their resources adeptly amidst fluctuating market conditions. It provided an extensive overview of both conventional and state-of-the-art decentralized approaches, shedding light on how microgrids could effectively manage their energy resources to balance supply and demand while adhering to market dynamics. Finally, we highlighted the paramount importance of resilience within MMG operations, detailing strategies for microgrids to fortify themselves against disruptions, including cyber threats. This review not only synthesizes current knowledge but also charts a pathway for future research, providing a pragmatic framework for the evolution of resilient and efficient MMG systems that can be leveraged by a broad spectrum of stakeholders.

List of abbreviations

Acronym	Description
AC MMG	AC Multi-Microgrid
ADMM	Alternating Direction Method of Multipliers
CAMC	Central Autonomous Management Controller
DC MMG	DC Multi-Microgrid

(*Continued on next page*)

Continued

Acronym	Description
DER	Distributed Energy Resources
DG/DGs	Distributed Generation/Distributed Generators
DISCO	Distribution Company
DMS	Distribution Managment System
DNO	Distribution Network Operator
DR	Demand Response
ED	Economic Dispatch
EV	Electric Vehicles
ISO	Independent System Operator
LEM	Local Energy Market
LC	Local Controller
LV	Low Voltage
MAS	Multi Agent System
MG/MGs	Microgrid/Microgrids
MGCC	Microgrid Central Controller
MGO	Microgrid Operator
MMG/MMGs	Multi-Microgrid/Multi-Microgrids
MV	Medium Voltage
P2P	Peer-to-peer
RES	Renewable Energy Sources
RTU	Remote Terminal Unit

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AUTHOR CONTRIBUTIONS

A. K., A. R. S., L. P. R., Y. D., and R. C. B. conceived the idea. A. K., A. R. S., and L. P. R., did all the conceptual visualizations. A. K., A. R. S.,and L. P. R., co-wrote the original article. X. H., Y. D., R. C. B., and P. K., contributed to the article editing. X. H., R. C. B., R. M. N., and P. K., assisted with the abstract, discussions, and contributed to the article editing. All authors assisted during article preparation.

DECLARATION OF INTERESTS

Authors declare that there is no competing interest.

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