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Review

Interconnected Smart Transactive Microgrids—A Survey on Trading, Energy Management Systems, and Optimisation Approaches

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Abstract: The deployment of isolated microgrids has witnessed exponential growth globally, especially in the light of prevailing challenges faced by many larger power grids. However, these isolated microgrids remain separate entities, thus limiting their potential to significantly impact and improve the stability, efficiency, and reliability of the broader electrical power system. Thus, to address this gap, the concept of interconnected smart transactive microgrids (ISTMGs) has arisen, facilitating the interconnection of these isolated microgrids, each with its unique attributes aimed at enhancing the performance of the broader power grid system. Furthermore, ISTMGs are expected to create more robust and resilient energy networks that enable innovative and efficient mechanisms for energy trading and sharing between individual microgrids and the centralized power grid. This paradigm shift has sparked a surge in research aimed at developing effective ISTMG networks and mechanisms. Thus, in this paper, we present a review of the current state-of-the-art in ISTMGs with a focus on energy trading, energy management systems (EMS), and optimization techniques for effective energy management in ISTMGs. We discuss various types of trading, architectures, platforms, and stakeholders involved in ISTMGs. We proceed to elucidate the suitable applications of EMS within such ISTMG frameworks, emphasizing its utility in various domains. This includes an examination of optimization tools and methodologies for deploying EMS in ISTMGs. Subsequently, we conduct an analysis of current techniques and their constraints, and delineate prospects for future research to advance the establishment and utilization of ISTMGs.

Keywords: interconnected smart transactive microgrids; interconnected microgrids; trading; energy management systems; optimization

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1. Introduction

Smart transactive microgrids (STMs) are defined as specialized microgrid systems that can autonomously regulate the generation, storage, and consumption of electricity among a network of users within a localized area [1]. They enhance both economic and environmental efficiency by employing real-time pricing mechanisms and digital technologies [2]. In a more general sense, STMs can be considered as a subset of microgrids (MGs) that incorporate principles of transactive energy, along with energy and information sharing among consumers. The United States Department of Energy (DOE) initially conceptualized this idea in the early 2000s, inaugurating the Grid Wise program in 2005 to modernize the national electric grid, which included the advancement of transactive energy systems [3].

Furthermore, the advancement of STMs has been notably propelled by the Pacific Northwest National Laboratory (PNNL), a flagship program established by the US DOE [4]. In addition to other targets, the PNNL focuses on refining STMs to seamlessly integrate renewable energy sources [5–7], energy storage systems [8,9], and electric vehicle charging infrastructure [10]. As substantiated by many studies emanating from the PNNL program and its extensions, STMs are gaining momentum, with pioneering implementations emerging in diverse environments such as universities [11], military bases, and commercial [12] and industrial facilities [13]. However, unresolved research questions persist, including the need to interconnect these STMs to bolster resilience against electrical outages and to optimize energy efficiency and cost-effectiveness through localized electricity generation.

Thus, the objective of interconnecting STMs seamlessly (termed ISTMGs—interconnected smart transactive microgrids) is to unify and optimize existing isolated clusters of geographically close, independent MGs through the use of a shared distribution bus [14]. Such an integration aims to improve the stability, reliability, and overall performance of the broader electrical grid system. Furthermore, ISTMGs are required to enhance the efficiency of electricity usage via the generation, trading, sharing, and optimization of energy among users based on the use of distributed renewable energy (DRE) systems [15,16].

The benefits of ISTMGs stem from the capability to share energy across multiple MGs. Such a capability will enable each MG to satisfy its power needs efficiently through DREs, whether in grid-connected [17] or islanded mode [18]. Furthermore, ISTMGs can reduce the present dependence on costlier, fossil fuel-based electricity grid systems by minimizing energy losses associated with long-distance transmission across such large power grid systems citehamouda2020energy. This will further alleviate congestion in existing power distribution networks, which will enhance the reliability of both individual MGs and the larger power grid [19].

However, despite the above benefits, there are still a number of significant research challenges in developing and deploying ISTMGs. Firstly, integrating heterogeneous energy sources, such as solar and wind power, along with energy storage devices, poses a major problem [7,20]. These sources often produce variable outputs, hence complicating the management of grid stability and the assurance of a constant electricity supply. Thus, the efficient coordination of various MGs will necessitate the need for advanced control and communication systems. Secondly, the establishment of equitable and transparent transactive energy markets is crucial [21,22]. Such markets will enable MG participants to buy and sell excess energy based on real-time pricing signals. However, crafting such robust and effective market systems that ensure fair compensation remains a contemporary research challenge. Thirdly, the dependence of ISTMGs on digital technologies invariably introduces cybersecurity risks [23]. As MGs become more interconnected and data-dependent, safeguarding against cyber threats becomes pertinent in order to maintain the integrity and security of the energy infrastructure. Additionally, the modification or comprehensive reform of existing regulatory frameworks will become essential to accommodate the unique attributes and requirements of ISTMGs and enabling such reforms remains an area of active research.

Thus, to fully harness the potentials of ISTMGs as well as to reap their associated benefits, it is imperative to confront the above extant research challenges, for which many solutions now exist in the scholarly literature. These solutions are aimed at improving grid resilience and the incorporation of renewable energy sources and enhancing the energy efficiency of the grid [24,25]. Thus, in this paper, an attempt has been made to furnish a comprehensive, state-of-the-art review with a specific focus on advancements in trading, energy management systems (EMS), and various optimization methods devised to tackle energy management issues within ISTMGs. Consequently, in contrast to existing survey papers, our current article makes distinct contributions as elucidated through a synthesis of the available literature, which are as follows:

1. This article provides a comprehensive summary of the recent advances in ISMTGs, thus addressing the absence of such a synthesis of the literature on trading, energy management systems, and optimization methods to tackle energy management issues in ISTMGs.

2. We categorize and elaborate on various trading mechanisms in ISTMGs focusing on the different architectures pertinent to the implementation of ISTMGs. This is necessary in order to identify robust and effective transactive energy market mechanisms that can be used to develop fair trading systems in ISTMGs.
3. The significance of energy management systems (EMS) in ISTMGs is discussed focusing on their functional attributes. We discuss the design of the optimization network architecture, delineating whether the optimization process is conducted centrally or in a decentralized manner, a synthesis that is conspicuously lacking in the survey literature. Such a discussion is needed in order to provide details of advanced control and proper communication structures that can be used to develop and improve ISTMG systems.
4. Furthermore, we highlight and elaborate on the challenges arising from the interconnected nature of various MGs within ISMTGs. This is needed in order to identify different means of addressing these challenges, thus optimizing the overall performance and reliability of ISMTGs.

The remaining content of the article is structured in the following manner: Section 2 presents a discussion of relevant survey articles to set the current article apart from earlier survey articles. Section 3 highlights an overview of ISTMGS. Section 4 introduces the ISTMG's general characteristics and definition, whereas Section 5 focuses on the developments in EMS within ISTMG. In Section 6, we focus on the various optimization assets, network architectures, as well as various optimization methods in ISTMG. Section 7 presents and discusses methods used generally in ISTMG and Section 8 identifies potential research directions for the advancement of secure, reliable, and effective ISTMG systems. Lastly, a conclusion is reached in Section 9.

2. Related Survey Papers

This section discusses other relevant survey studies that focus on the integration of ISTMG in smart grids, as summarized in Table 1. These survey articles address multiple aspects of ISTMG, including the benefits of interconnecting multiple microgrids. It has been demonstrated that such interconnections can reduce power outages while improving energy efficiency and cost-effectiveness in existing power networks. The objective of this section is to highlight the uniqueness of our current survey and to acquaint the reader with other relevant aspects of ISTMG explored in prior surveys.

For example, in [26], a comprehensive literature review on networked MGs was provided on the architectures, control, communication, and operation of ISTMGs. The significant contributions to the field were summarized, focusing on key advantages such as the optimal use of distributed energy resources (DERs), cost efficiency, and enhanced resiliency in ISTMGs. Furthermore, critical challenges including stability, protection coordination, privacy concerns, and cybersecurity risks were examined.

The survey in [3] focused on contemporary energy management studies in ISTMG, which they referred to as integrated multi-microgrids (IMMGs). Their initial attention was given to the commonly used topological structures of IMMGs. Then, energy management systems (EMS) within IMMGs were examined, particularly in relation to scheduling optimization frameworks, operational time frames, and prevalent optimization objectives. Finally, they placed emphasis on different distributed optimization techniques for IMMGs, such as dual decomposition, game theory, and other decentralized approaches.

The focus of the survey in [27] was on exploring the strategies for distributed control and communication within ISTMGs, which they referred to as networked MGs (NMGs). They discussed the underlying reasons for the development of MGs and NMGs, presenting two practical implementations. The authors elaborated on the operational objectives of NMGs and classified and characterized the associated distributed control strategies. Communication reliability concerns, including data timeliness, availability, and accuracy, were also analyzed, as these factors may impact the effectiveness of distributed control strategies in ISTMGs. Essentially, the scope of their survey was limited to typical communication reliability challenges faced by distributed control systems (DCS) in NMGs.

Table 1. Related survey papers.

Ref.	Year	Optimisation	EMS	Trading	Focus Area
[3]	2019	×	✓	×	• Provides a review of distributed optimization algorithms in ISTMGs. • Provides an overview of the recent EMS in ISTMGs. • Highlights structures for ISTMGs optimization and EMS objectives.
[26]	2019	×	✓	✓	• Presents a state-of-the-art literature review for ISTMGs. • Focuses on the analysis of ISTMG architectures, control, communication, and operations. • Provides overall operational cost reduction, and improved resiliency.
[27]	2020	×	×	✓	• Offers a thorough analysis of ISTMG communication and distributed control techniques. • Features of distributed communication networks and certain ISTMGs operating goals. • Provides classifications for distributed control techniques and their key characteristics.
[28]	2020	×	✓	✓	• Provides a state of the art review for cutting-edge research methods in ISTMGs. • Focuses on the controls, communication, optimization, and market processes in ISTMGs.
[29]	2021	×	✓	×	• Presents an in-depth review of ISTMGs elements. • Examines various renewable energy resources that constitutes a hybrid system. • Highlights various control, operational strategy, and goal configurations in an EMS in ISTMGs.
[30]	2022	×	×	✓	• Presents in-depth review of ISTMGs operating in the realm of transactive energy. • Identifies the fundamental components of transactive ISTMG models. • Discusses prosumer behavior, and business models for ISTMGs.
[16]	2022	×	×	✓	• Provides a survey of current developments in the intelligent management of MGs and ISTMGs. • Provides a picture of strategies and spot trends in the methodologies utilized for ISTMGs.
[31]	2022	×	✓	×	• Provides an in-depth examination of model predictive control (MPC) in ISTMGs. • Highlights cutting-edge applications of three forms of MPC (centralized, decentralized, and distributed). • Discusses control voltage regulation and frequency control in ISTMGs.
[32]	2023	×	×	✓	• Provides state-of-the-art review for intelligent energy management systems in residential, commercial, and educational buildings. • Analyses their strengths and limitations of IEMS in ISTMGs, • Analyses the optimization approaches in ISTMGs
[33]	2023	×	✓	✓	• Provides a cutting-edge review of the development of ISTMGs. • Focuses on a comprehensive review of alternative energy management systems. • Presents optimization scheduling frameworks in ISTMGs. • Discusses voltage and frequency control strategies in ISTMGs. • Surveys hierarchical, decentralized, and distributed control architectures in ISTMGs.
Current paper	2023	✓	✓	✓	• Provides state-of-the-art comprehensive review of the recent advancements in ISMTGs • Discusses trading mechanisms within ISTMGs. • Highlights the various platforms that can augment trading efficiency. • Discusses the significance of EMS in ISTMGs and its functional attributes. • Discusses the design of the optimization network architecture

✓—concept was discussed in the reference, ×—concept was not discussed in the reference.

In addressing challenges associated with interconnected MGs, a comprehensive examination was conducted in [29] focusing on MG components, renewable energy resources in hybrid systems, and diverse control and operating strategies in EMSs. Their survey further elucidated the primary, secondary, and tertiary stages of MGs. They aimed to contribute to the established guidelines on protection plans, transactive markets, and load restoration in MGs as adopted by specific nations.

The authors in [30] provided a comprehensive review of the operation networked microgrids (NMGs) under the transactive energy paradigm. They identified and analyzed key aspects of transactive NMG models including operational scenarios, ownership models, transactive operation designs, prosumer behavior, and business models. Their survey also reviewed real-world applications and analyzed current research trends. Similarly, in [16], the authors discussed the energy management concepts for MG systems. They emphasized the importance of integrating EMSs in MGs to improve energy efficiency and reduce energy costs. Their survey also provided an overview of different MG electrical architectures and some popular MG concepts with EMS.

In the area of model predictive control (MPC) for ISTMGs, the survey in [31] concentrated on advanced applications of three types of MPC, namely centralized, decentralized, and distributed MPCs for grid-level control in networked MGs. These forms of MPC offer a viable alternative for tasks ranging from voltage stabilization and frequency regulation to power flow coordination and economic optimization in ISTMGs. In another survey [32], the authors noted that challenges still persist in ISTMG energy management, thus prompting the exploration of intelligent EMSs for residential, commercial, and educational facilities. These systems were classified into two main categories based on the nature of control, either direct or indirect. Their survey further assessed their respective advantages, disadvantages, and optimization strategies.

The authors in [33] highlighted an advanced analysis concerning the evolution of NMGs. The focus was mainly on significant research topics, opportunities, and challenges in energy management and control. The handling of these MGs, especially in the context of fluctuating loads and unpredictable features of renewable energy sources, was identified as a challenge for distribution networks and MG operators. The study also offered a thorough evaluation of alternative EMSs, optimization scheduling frameworks, and control strategies for voltage and frequency across multiple MGs. Additionally, a complete survey of hierarchical, decentralized, and distributed control architectures was provided.

Table 1 summarizes these related survey articles, indicating their particular areas of focus for convenient reader access. Different from these surveys, a comprehensive review of ISTMG technologies is provided in our present article. We have placed emphasis on key elements including energy trading, EMS, and optimization techniques. We provide a detailed analysis of the various trading types, stakeholder roles, architectures and platforms used in ISTMG. Effective applications of EMS are outlined, and optimization tools and methods are highlighted. It is believed that the present survey will further synthesize the existing literature on ISTMGs and will be beneficial to emerging researchers whose interest may lie in the study of ISTMGs.

3. Overview of ISTMG

An ISTMG serves as a network formed by interconnecting multiple MGs. This network integrates various energy sources, loads, and storage mechanisms. While resembling a small-scale version of the primary power grid, it has the capability to function either autonomously or in coordination with it [34].

Similar to an MG, ISTMGs also possess the capability to switch between two operational modes. In grid-connected mode, it either draws power from or supplies excess energy to the electrical grid. In islanded mode, it autonomously generates and stores electricity. As shown in Figure 1, various distributed energy resources (DERs), including solar panels (PV), wind turbines (WT), small-scale generators, and storage systems, are typically integrated into ISTMGs. These resources contribute electricity to the MGs or main grid as well as store surplus energy for future use [35].

As illustrated in Figure 1, the interconnected configuration of MGs can enable the efficient distribution and optimization of energy amongst them. This feature can enhance efficiency, reliability, and resilience, thus proving particularly advantageous in remote or isolated areas where the connection to the main grid poses challenges [36]. Moreover, such a configuration can aid in the incorporation of renewable energy sources, thereby facilitating a transition to a more sustainable and decentralized energy system. Consequently, we will attempt to highlight a few primary characteristics of ISTMGs along with a brief discussion of their operational modes and benefits.

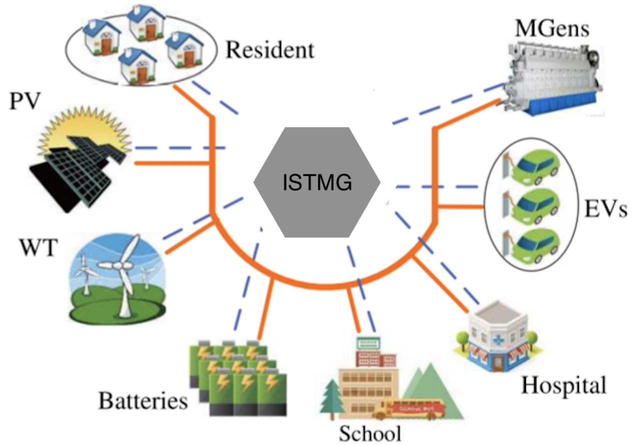

Figure 1. A high-level schematic of an ISTMG depicting the interconnected elements including MGs and DERs [37].

3.1. Characteristics of an ISTMG

There are a number of characteristics and functionalities expected in a typical ISTMG, and key aspects among these are outlined as follows:

- Integration of Distributed Energy Resources: ISTMGs are required to serve as advanced platforms for the efficient integration of DERs, such as solar panels, wind turbines, energy storage systems, and electric vehicles. By using sophisticated control algorithms and real-time data analytics, these interconnected MGs will enable the seamless pooling and optimization of energy assets located across various spatial configurations. Consequently, ISTMGs will not only facilitate autonomous energy exchanges between multiple MGs but also optimize energy supply and demand at more granular levels (i.e., below the main grid level). Thus, by deploying such intricate systems, ISTMGs will enhance the energy resilience of the larger grid, further contributing to improved grid stability, and minimal dependence on centralized energy infrastructures. This will offer a scalable and flexible solution for the future energy landscape [38].
- Control and Real-Time Monitoring: Advanced monitoring, control and management technologies are required within an ISTMG in order to continuously analyze the operational efficacy and status of DERs. Such real-time data-capturing mechanisms in ISTMGs will allow for efficient resource distribution and load balancing, thus promoting proactive regulation of energy production, its use and storage. Furthermore, such control structures in ISTMGs will facilitate the capability to identify and correct system issues, such as equipment malfunction or grid network perturbations [39].
- Transactive Energy Market: In most cases, ISTMGs should include one or more transactive energy marketplaces. Within such specialized marketplaces, the cost of electrical power is determined by a stochastic process that is impacted by a combination of supply and demand variables. This process determines the price. According to [40], multiple market actors, including owners of DERs, end consumers, and aggregators (i.e., MGs), are able to take part in energy transactions. This market-oriented approach is envisioned to improve the efficiency with which DERs are used and to foster electrical grid infrastructures that are both resilient and adaptable.
- Grid Interaction: Because of its connectivity, an ISTMG should have the capacity to exchange energy with the larger grid in both directions. This is made possible by the ability of the ISTMG to interact with the larger grid via specialized control systems. Thus, when there is a surplus of electricity generated, it is possible to send some of it back to the main grid. This will reduce the strain on the main system and result in financial gains for the owners of the ISTMGs. In contrast, an ISTMG should also be able to ensure a consistent supply of energy by drawing electricity from the main grid during times of high demand or when there is a shortage of generation [41].

3.2. Operation Modes

In this subsection, we highlight the two primary modes in which ISTMGs can function, which are as follows:

- Grid-Connected Mode: When operating in grid-connected mode, an ISTMG is physically connected to the primary power grid via a single point-of-connection (PoC). Consequently, an ISTMG is able to use this mode to receive electricity from the grid in the event that there is a high demand for electricity or when there is insufficient capacity for the generation of electricity locally. In addition, if an ISTMG generates more electricity than is required by constituent MGs, it can transmit the excess electricity back into the larger grid, which will improve the grid's overall stability [42].
- Island Mode: When an ISTMG is not connected to the primary power grid, it is said to be functioning in an islanded mode. This mode is activated whenever the primary grid is rendered inoperable, such as in the event of a power outage or a natural disaster, as well as in distant areas where it is impossible to connect to the grid. When operating in such an island mode, an ISTMG will rely only on its internal energy resources situated within each MG and its respective energy storage systems to provide all of the connected loads with the necessary amount of electricity being demanded [42,43].

3.3. Benefits of ISTMG

ISTMGs offer many benefits that contribute to an increase in the overall efficiency, dependability, and resiliency of an energy system. Listed below are some of these benefits:

- Enhanced Energy Efficiency: By generating power closer to where it is needed, ISTMGs like any MG reduce the transmission and distribution losses that are typically experienced in centralized grids. These losses occur when electricity must travel a greater distance to get to its destination. Thus, increasing energy efficiency and reducing reliance on fossil fuels are two additional benefits that come from tapping into the full potential of renewable resources and making use of local sources of energy situated within ISTMGs [44].
- Increased Reliability: Microgrids that are connected to one another can boost the reliability of the electricity supply by including energy storage devices as well as a wide array of energy sources. When they are functioning in grid-connected mode, they are able to maintain a continuous supply of electricity by drawing power from the primary grid during periods of high demand [45]. When functioning in island mode, they are able to continue generating electricity on their own, despite the fact that there may be issues with the main grid.
- Increased Resilience: The resilience of the energy system can be increased by ISTMGs because each constituent MG has the capability to operate independently in the event of an emergency or a natural disaster [46]. They decrease the consequences of power outages and guarantee that essential services can continue to be delivered by supplying a reliable source of electricity for essential facilities such as hospitals, emergency response centers, and rural settlements. This ensures that essential services can continue to be rendered without interruption.
- Local Energy Sharing: ISTMGs make it possible for multiple MGs to work together on sharing energy resources. Thus, if one MG has more electricity than another, the one with more electricity can send power to the one with less, so maintaining the system's equilibrium and ensuring a constant supply of energy. This kind of energy trading between neighbors fosters efficiency and helps communities become more resistant to disruption [47].

3.4. Summary and Inferences

This section has provided an overview of ISTMGs detailing their structure, operation modes, and benefits. Essentially, ISTMGs are responsible for networking different isolated MGs, each comprising DERs such as solar panels, wind turbines and storage systems. There will be a need for advanced control algorithms and real-time data analytics for optimal management in ISTMGs. While ISTMGs can operate in both grid and islanded modes, it is imperative that seamlessly transitioning between both modes is established and this will require advanced control systems. In summary, ISTMGs represent a sophisticated, resilient, and efficient approach to energy management, especially valuable in areas where connection to the main grid is challenging. They offer a blend of advanced technology, operational flexibility, and economic benefits, making them a key component in the transition towards more sustainable and decentralized energy systems.

4. Trading in ISTMG

Trading in an ISTMG is a procedure that refers to the purchase and sale of electricity or other energy resources among multiple participants [13]. These participants will include MGs comprising different residences, businesses, institutions and independent providers of renewable energy. Consequently, participants in ISTMGs will have the capability to generate as well as consume electricity, hence opening up the potential for dynamic energy trading. This contrasts with conventional power flow, where electricity travels unidirectionally from large power plants to consumers [48].

Thus, in order for ISTMGs to participate in this form of energy trading, research and development will be needed to implement cutting-edge technologies. Advanced tools like smart meters, communication networks, and automated algorithms will be required to enable users to monitor their energy production, consumption, and interaction with other users in real time [8]. Consequently, these technologies will form the foundation of active energy platforms or marketplaces, thus optimizing the energy flow within the ISTMG by matching consumers and sellers based on their preferences [49].

Hence, by establishing such required innovative technologies, ISTMGs will provide the capability for participants to set their own pricing for buying and selling electricity. For instance, a household generating excess solar energy can sell it to a neighboring home in need, negotiating aspects like the amount of energy, the price, and the delivery date. It is required that active energy platforms within ISTMGs will facilitate these transactions transparently, taking into account variables such as supply and demand, participant preferences, and grid stability [49].

Consequently, in this section, we will explore the applications of trading principles in ISTMGs towards transforming traditional energy systems into dynamic, interactive networks. In order to achieve this, it is crucial to note that the optimization of energy trading, balancing of supply and demand, and overall productivity hinge on the specific microgrid structure, market system, and regulatory framework in place. Thus, such specifics will be beyond the scope of this section, nevertheless, an attempt will be made to elaborate on the various types of trading that exist in ISTMG systems as well as to provide detailed insights into their workings.

To comprehend how trading is conducted in ISTMGs, it is necessary to first understand the types of commodities that can be exchanged and traded in an ISTMG. Subsequently, the use of trading principles will be deemed essential for the purpose of optimizing energy trading, effectively managing the balance between supply and demand, and enhancing productivity within an ISTMG. Thus, the next sections will discuss the transaction in an ISTMG based on money flow and then the major commodity exchanged within an ISTMG, namely energy.

4.1. Financial Transaction

Money flow in an ISTMG refers to the financial transactions that take place between participants in the network. ISTMGs allow various parties to exchange money for commodities such as electricity, services, and data, resulting in a more efficient and resilient energy system [50]. It is important to note that the concept of money exchange in ISTMGs is still in its early phases, with pilot implementations only beginning to sprout globally [51]. Nevertheless, such pilots have shown the potential to revolutionize the energy landscape by boosting renewable energy integration, demand response, and prosumer empowerment [52]. Thus, we will discuss the exchange of money in an ISTMG based on the programs it can facilitate, the technological enablers required for such exchanges, and relevant case studies, research insights and benefits.

4.1.1. Programs Facilitated by Financial Transactions

By enabling the exchange of money in an ISTMG, the following programs can be facilitated to enhance the performance of power grids:

- Renewable Energy and DER Integration: The flow of money in ISTMGs has various advantages. For starters, it facilitates the integration of renewable energy sources and other DERs by providing financial incentives for their deployment and use [53]. Participants with excess generation can sell their excess electricity to other network participants, encouraging renewable energy generation and lowering dependency on traditional centralized power plants.
- Demand Responsiveness and Energy Efficiency: It promotes demand responsiveness and energy efficiency. Participants can alter their energy consumption patterns in response to real-time pricing signals, lowering peak demand and optimizing energy expenses.
- Local Energy Markets and Prosumer Empowerment: Furthermore, money flow in ISTMGs promotes local energy markets and empowers prosumers, i.e., individuals or businesses that both consume and produce electricity [54]. Prosumers can commercialize their excess generation and actively engage in the energy market, thus leading to a more decentralized and democratized energy system.

4.1.2. Technological Enablers

In other to facilitate the exchange of money in ISTMGs, certain technologies are required, such as:

- Smart Contracts and Automation: The concept of money flow in ISTMGs will require the use of smart contracts, which are self-executing agreements with trade terms explicitly put into code [55]. Smart contracts will be essential to automate transaction settlement, ensuring secure and transparent exchanges of value between participants.
- IoT Devices and Real-Time Information: Advanced digital technologies are critical for facilitating money transactions in ISTMGs. IoT devices and sensors will provide real-time information on energy production, consumption, and grid conditions [56].
- Blockchain Technology: Furthermore, blockchain technology has emerged as a viable alternative for safe and transparent transactions in ISTMGs. Blockchain will enable the establishment of decentralized and tamper-resistant ledgers in which transaction records are distributed across multiple network nodes [57].

4.1.3. Related Work on Money Flow in ISTMGs

Various studies have been carried out to explore different aspects of money exchange in ISTMGs. In recent years, considerable progress has been achieved in the realm of financial exchange mechanisms within ISTMGs. Researchers have developed a bargaining-oriented energy trading marketplace, designed to facilitate interactions among various ISTMGs [50]. A decentralized computational algorithm was proposed for the practical determination of trading outcomes. The efficacy of this energy trading framework has been substantiated through numerical simulations, indicating that ISTMGs can achieve substantial cost reductions via energy trading as opposed to operating in isolation.

Furthermore, an investigation was conducted to elucidate a decentralized and autonomous control methodology for overseeing energy transactions among interconnected nodes within a microgrid network. The primary emphasis of this methodology lies in the implementation of competitive pricing negotiations. Such negotiations are operationalized through a sequence of dialogues between agents, where each agent possesses the latitude to either accept, decline, or propose a counteroffer. The choice among these actions is determined by an individual agent's specific valuation of energy as established in prior research [58].

Research was also conducted in [47] to elucidate a unique utility function for each MG in an ISTMG and to introduce an innovative methodology for trading, which incorporates self-benefit-driven (SBD) actions for agents representing the MGs. Within the utility function attributed to each MG, considerations for the benefits accruing from both energy import and export are included. Additionally, the formulation of the utility function is designed to consider the diverse objectives that an MG might have with respect to importing and exporting energy. To facilitate energy trading in the ISTMG environment, a centralized model based on Nash bargaining was proposed. This model aims to ensure equitable transactions through the mediation of a centralized institution [47].

It was emphasized in [59] that more research into models that control the coordinated operation of many microgrids is necessary in order to provide a reference framework for such a cooperative. The goal of this research was to act as a reference framework; thus, the authors established an operational architecture of the system, which allowed for the development of a model for the cooperative operation of several microgrids. A peer-to-peer Nash bargaining strategy was used in order to properly allocate the cumulative operational expenses and to promote each individual microgrid's active engagement in the cooperation. Despite this, typical Nash negotiating strategies were considered insufficient to accommodate the unique characteristics that are intrinsic to each microgrid. In particular, they do not take into consideration factors such as the unique contributions made by each microgrid and the distinct roles played by buyers and sellers within the system. As a result, the revenue distribution among the participating entities remains suboptimal [59].

The study in [60] aimed to optimize financial transactions in ISTMGs by employing a cooperative game theory approach for day-ahead scheduling of ISTMG operations. The proposed model was validated based on an ISTMG comprised of three MGs. Relative to the isolated MG operation, the cooperative strategy yielded a 4.4% reduction in operational costs for the ISTMG. The MGs considered in their cooperative framework also achieved financial benefits, effectively minimizing both individual and collective costs. Furthermore, the model accounts for uncertainties in load, photovoltaic generation, and energy trading prices to enhance result reliability. A price-based demand response mechanism was also incorporated to encourage flexible load usage during low-price periods, thereby reducing operational expenditures.

In order to enhance monetary transactions within ISTMGs, an innovative two-tier optimization-simulation algorithm was developed in [61]. Drawing from natural paradigms, this methodology facilitated a comprehensive techno-economic assessment to pinpoint the optimal conditions for balancing energy at minimal operational costs and maximal revenue generation. The authors demonstrated that the best settings in their study were those that promoted a tight thermal and electrical energy balance between interconnected MGs. Their results showed that energy swarm mechanisms can keep the levelized cost of energy (LCOE) lower than 0.15 EUR/kWh and an internal rate of return (IRR) of over 55%.

The research in [62] presented a community market structure to manage energy trading among MGs and with the main grid. In this structure, the individual MGs operated and bid as autonomous entities, while an independent third party coordinates the energy transaction among different MGs1. The concept of adjustable power was introduced to use the controllable units in MGs cost-effectively. The local trading prices were then determined via market clearing. The authors analyzed the economic benefits of such a trading mechanism and the value of adjustable power. The numerical results obtained demonstrated the effectiveness of the proposed framework for trading among multiple MG systems.

4.1.4. Summary and Inferences

Money flow in ISTMGs can contribute to the overall resilience and reliability of the energy system [46]. It can ensure that ISTMGs continue to operate even during disturbances or outages in the main grid or even breakdown in single MGs because they enable localized energy exchanges within the network. This is because such economic exchanges will have the ability to promote community engagement and collaboration. Local stakeholders, such as citizens, businesses, and institutions can actively participate in energy production, consumption, and trade decision-making processes. This participatory method has the potential to increase community ownership and shared responsibility for energy sustainability. Money exchange will offer participants a means for engaging in economic transactions within a network of DERs. However, in order to achieve such a full potential in establishing more efficient, sustainable, and decentralized energy systems, ISTMGs will require a robust infrastructure, established protocols, and supportive regulatory frameworks.

4.2. Transacted Commodity

The major transacted commodity in an ISTMG is energy. Energy transaction entails the purchasing and selling of energy commodities including electricity, natural gas, oil, and other energy products [59]. Participants in the market can trade energy resources, manage risks, and guarantee a steady supply of energy through this intricate process. Thus, in this section, we will briefly introduce energy trading, the platforms and participants, objectives and goals, influencing factors, pricing and risk management, technological developments, and academic research on specific topics within energy trading.

4.2.1. Objectives and Goals

Energy trading can have a variety of goals. Trading can be used by participants to secure a steady supply of energy for their operations, benefit from price variations, manage risks related to energy price volatility, and avoid unknown future energy costs [63]. In addition, the best possible use of energy resources is achieved through energy trading. While customers can buy energy when it is most advantageous for their activities, producers can sell excess energy and prevent waste. This optimization helps maintain a balance between supply and demand and improves the overall efficiency of the energy market [64]. Trading in energy also promotes efficiency and market competition. It fosters innovation, pricing transparency, and ethical business practices by letting a number of players buy and sell energy commodities. This competition may result in more effective distribution of resources and better customer price [65].

4.2.2. Influencing Factors

Many factors, including supply and demand dynamics, geopolitical developments, weather patterns, governmental laws, and technological improvements, have an impact on the energy markets [48]. These elements may have an effect on energy prices and open up trade possibilities within an ISTMG. Along with conventional energy sources, the rise in renewable energy sources like solar and wind has changed how energy is traded. Thus, in order to trade energy within an ISTMG, it is most likely that carbon credits and renewable energy certificates (RECs) will be needed and become influencing factors in order to advance green energy policies and environmental objectives [66]. These are factors that require research attention towards ensuring effective and efficient energy trading in ISTMGs.

4.2.3. Platforms and Participants

The trading of energy within ISTMGs can take place on a variety of platforms, including spot markets, futures markets, and over-the-counter (OTC) markets [54]. In an ISTMG, energy commodities can be traded for immediate delivery on spot markets, while contracts for future delivery can be exchanged on futures markets. On the other hand, OTC markets may enable specialized exchanges between buyers and sellers, thus allowing energy producers, consumers, traders, and brokers to be key actors in the energy trading market. This paradigm shift will also allow producers to create or extract energy resources, such as power plants or oil businesses so that the purchasing and selling of energy commodities can then be facilitated by traders and brokers who serve as intermediaries.

4.2.4. Pricing and Risk Management

The setting of prices is one of the crucial elements of energy trading. Many variables, including shifts in supply and demand, tensions in international relations, climatic conditions, and economic indicators, can cause variations in energy costs within an ISTMG [67]. Another additional crucial component of energy trading within an ISTMG is risk management. Energy prices have the potential to fluctuate, which puts market players in danger of losing money. To guard themselves against negative price changes, traders use risk management techniques including hedging and diversification [50]. These are areas of interest that still require research attention and thus serve as a concern for future studies.

4.2.5. Technological Developments

To enable effective and transparent transactions, it is obvious that the energy trading industry will need to rely on complex trading platforms, cutting-edge analytics, and market information systems. Participants will then be able to follow the supply and demand movements, assess market trends, and make wise trading decisions with the aid of these tools. Furthermore, the speed and effectiveness of trading will be greatly impacted by the design and capabilities of electronic trading platforms and algorithms. Thus, automated systems should be able to complete trades in a matter of milliseconds, hence enabling market participants to profit from opportunities as they arise. The analysis of large volumes of market data, the improvement of trading methods, and the improvement of decision-making processes are thus areas of research interest required for the effective deployment of energy trading capacity within ISTMG. This will also require a focus on the use of advanced data analytics and artificial intelligence.

4.2.6. Research Studies on Energy Trading

Studies have been conducted to try an improve the sharing of energy within an ISTMG. For example, the authors in [37] proposed a framework for managing power exchange between proximate residential MGs, integrated with both photovoltaic generation and battery energy storage systems (BESS). The framework considers the rate of energy change in each MG as well as the charge disparity between the BESS units for effective energy storage system (ESS) replenishment. Further research was conducted on energy trading to optimize economic benefits for prosumers through a peer-to-peer (P2P) trading framework. Specifically, the investigation conducted in [68] introduced two distinct models for energy allocation within this P2P system: (i) preferential energy sharing, and (ii) proportional energy sharing. In the preferential energy-sharing model, priority is granted to the prosumer exhibiting the highest solar availability when dispensing electricity either to the grid or within the ISTMG. In contrast, the proportional energy-sharing model allocates energy in accordance with individual MG consumption and solar electricity injection rates. These models were evaluated against the backdrop of four microgrids (MGs) within an ISTMG [68].

To facilitate energy transactions within a grid-connected ISTMG, the authors in [58] introduced a decentralized and autonomous control scheme. The relationships between network agents were characterized by assessing their reputation through historical metrics of familiarity, acceptability, and value. Experimental methods were elucidated within a nine-node network featuring diverse connectivity levels over a simulated annual period. The results indicated that particular inter-node interactions confer a financial advantage to certain MGs by reducing operational expenses.

Other research efforts focused on bi-level distributed optimized operation for ISTMGs, for example, the authors in [69] introduced a bi-level distributed optimization framework for the coordinated operation of ISTMGs under uncertain market conditions. Their framework employs a hierarchical, distributed communication architecture and functions in two distinct operational layers. At the upper level, the ISTMG interfaces with the distribution network operator in either demand response or purchase-sale modes, optimizing power trading among MGs to maximize revenue. On a foundational level, the model employs chance-constrained programming to optimize distributed energy production and storage, aiming to minimize operational costs while addressing the uncertainties related to renewable energy and load variations.

Furthermore, the authors in [47] proposed an innovative framework for energy trading in an ISTMG that considers the behavioral dynamics of MG agents. A unique utility function was formulated for each MG, encapsulating the benefits associated with both energy importation and exportation. This utility function was then further tailored to accommodate the divergent objectives each MG has in the context of importing and exporting energy. A centralized Nash bargaining model was recommended for ISTMG energy trading to ensure equitable transactions through a centralized authority.

In a separate study, the researchers in [13] examined the integration of residential, commercial, and industrial micro energy management grids (MEMGs) with a focus on external peer-to-peer (P2P) energy trading and internal energy conversion challenges. To address the complexity and high-dimensionality of these decision-making issues, they employed a multi-agent deep reinforcement learning framework that amalgamates the twin delayed deep deterministic policy gradient algorithm with the multi-agent actor–critic algorithm. The authors found that their proposed algorithm can effectively handle high-dimensional continuous action space and align with the nature of P2P energy trading with multiple MEMGs (i.e., an ISTMG), thus significantly reducing each MG's average hourly operation cost.

More research works have been conducted on the topic of community market structures for energy trading in ISTMGs and a revolutionary decentralized platform to enable energy trading in ISTMG has been studied. For example, the advancement of an innovative decentralized platform for facilitating energy exchange in ISTMG was elaborated in [70]. This architecture aimed to attract participating MGs by assuming their self-benefit-driven (SBD) behavior. The proposed system employed a sequential, round-based market-clearing mechanism, whereby the MG offering the most competitive energy price is granted the chance to optimize its revenue through surplus energy export [70].

4.2.7. Summary and Inferences

This section has provided an overview of energy trading within ISTMGs. Energy trading was defined as involving the buying and selling of energy commodities like electricity, natural gas, and oil, with the objectives of managing risks, optimizing resource use, and ensuring a stable energy supply. Various factors like supply and demand, geopolitics, and technology were identified as factors that can influence energy prices and trading strategies within an ISTMG. It was also noted that trading in an ISTMG can occur on different platforms such as spot markets, futures markets, and over-the-counter markets, involving key players like energy producers, consumers, and brokers. Research-wise, we have mentioned a number of research efforts focusing on optimizing energy sharing, employing decentralized control schemes, and the use of advanced algorithms for trading. These studies aim to maximize economic benefits, minimize costs, and adapt to market uncertainties, thereby indicating that research is actively addressing complexities and challenges in energy trading within ISTMGs.

4.3. Transacting Parties

ISTMGs comprise multiple stakeholders that interact collaboratively to ensure the optimal supply, distribution, and consumption of energy. This section highlights the principal actors and their respective roles within the ISTMG framework as follows:

4.3.1. Energy Producers

Energy producers are establishments that generate electricity using different sources such as hydropower, solar, and wind energy, thereby playing a crucial role in the functioning of ISTMGs [71]. Such entities may comprise individual stakeholders, corporations, or governmental bodies responsible for the modernization, reliability, efficiency, and security of their energy systems. Additionally, they engage in the marketing of the generated electricity to various entities, such as grid operators and energy storage companies. Consumers possessing DERs are increasingly transitioning to roles that oscillate between electricity consumption and production. Properly managed, these DERs have the potential to positively influence distribution system operations [72]. Peer-to-peer (P2P) power trading in distribution systems has been proposed as a viable approach for effectively managing and encouraging increased participation from energy producers.

4.3.2. Energy Consumers

Energy consumers include individuals, corporate entities, and government organizations that rely on energy for various applications [23]. In ISTMGs, these consumers play a critical role in maintaining the proper balance between the supply of and demand for energy. They have the flexibility to either use surplus energy or channel it back to the producers, while also managing their consumption for optimal efficiency.

4.3.3. Energy Prosumers

A prosumer is an entity that both generates and consumes electrical energy [73]. Such an entity may be an organization or infrastructure that harnesses energy through renewable resources like photovoltaic solar cells or wind turbines. Prosumers have the capability not only to purchase additional energy but also to vend it to other prosumers. They can be integrated into the larger electrical grid as a failsafe. Prosumer participation substantially augments the resilience and reliability of connected microgrids.

Prosumers contribute to more efficient and cost-effective energy production, storage, and dissemination within ISTMGs. They aid grid operators in maintaining a localized equilibrium between energy supply and demand [74]. To participate effectively in an ISTMG, prosumers must be equipped with specific hardware such as batteries and inverters, as well as monitoring and control systems. Advanced energy management systems (EMS) are indispensable for enabling prosumers to regulate their energy consumption and capitalize on surplus production. As technological advancements continue to reduce component costs, the role of prosumers within microgrids is likely to expand.

4.3.4. Energy Storage Providers

Energy storage providers play a pivotal role in maintaining the equilibrium between energy supply and demand within ISTMGs. These storage providers could be individual stakeholders, corporations, or governmental bodies offering a variety of energy storage technologies, including batteries, pumped hydro storage, and flywheel energy storage [75]. These entities are responsible for ensuring the reliability, efficiency, and safety of their energy storage solutions. Furthermore, they engage in the purchase and sale of energy to grid operators, consumers, and producers.

4.3.5. Grid Operators

Grid operators, also known as system operators, play a crucial role in the energy system. They are responsible for the reliable operation of the power grid, ensuring that electricity supply and demand are balanced in real-time [76]. This involves coordinating the generation and transmission of electricity, maintaining the quality of power, and managing grid infrastructure, including ISTMGs and isolated MGs. This would further entail overseeing energy storage systems, coordinating the distribution of generated energy to consumers, and maintaining equilibrium between energy demand and supply within the grid. Additionally, the operator ensures adherence to legal and regulatory frameworks and administers invoicing and payment processes.

4.3.6. Regulators

Specific governmental organizations, which are referred to as regulators in this context, are tasked with the responsibility of exercising regulatory control over the entire power grid including ISTMGs. These bodies have been given the responsibility of ensuring that the grid components (including ISTMGs) function in a manner that is compliant with the applicable laws and the legal limits [77]. They define requirements for the operation of MGs and ISTMGs relating to safety, energy efficiency, and environmental sustainability. In addition, regulators are the ones who are in charge of handing out permissions and licenses to ISTMG service providers who are involved in the generation of energy, the storage of energy, and other functions linked with the grid.

In summary, stakeholders are crucial for the success of ISTMGs. Their significance varies based on factors like project scale, complexity, ownership model, local regulations, and market dynamics. These stakeholders are vital for proficiently managing energy storage systems, enabling energy distribution, and maintaining energy demand-supply equilibrium within the ISTMG.

4.4. Trading Architectures

The constituent MGs within an ISTMG are interconnected through advanced communication and control mechanisms. These technologies enable real-time communication, coordination, and energy exchange among the comprising MGs [78]. The overarching objectives of any architecture are to enhance energy reliability, optimize consumption, and seamlessly integrate renewable energy sources. In this section, we discuss notable architectures for trading purposes in an ISTMG as follows:

4.4.1. Centralized

Centralized architectures consist of MGs interconnected to conduct trading activities through a central platform [79]. Each MG in this configuration has the ability to create, consume, and store energy. MGs can also exchange energy with one another in accordance with their respective demands and resource availability. The central platform thus serves as a middleman for energy exchanges, thus enabling MGs to trade tricity among one another. Participants can submit bids and offers for energy, which the central platform matches and settles. The ISTMG system's total energy market is made more efficient and transparent by this centralization of trading activity.

By using centralized trading, owners of MGs can access a larger pool of energy resources and optimize their patterns of energy generation and consumption. They can decide when to buy or sell energy by taking advantage of price differences, seasonal fluctuations, and other factors. This encourages the MG network to use resources in a more sustainable and balanced manner. In recent years, research has been conducted on centralized trading in ISTMGs. For example, the authors in [47] proposed a distinct utility function for each MG as well as a new approach to energy trading that takes actions for MGs' agents into account. For each MG, the function contains benefits for import and/or export. A centralized Nash bargaining model was adopted to guarantee fair settlements via a central body [47].

In another study, the authors proposed using a cooperative game to plan the day-ahead operation of centralized multi-MG systems (MMG) [60]. Their proposed approach typically schedules MGs to reach a global optimum for the multi-MG system's cost. By engaging in transactions with one another, each MG can reduce its operational costs to a minimum [60]. The authors in [80] noted that the use of DERs in MGs has resulted in technological complications in establishing centralized systems. Consequently, the authors proposed a novel lightning search algorithm (LSA) technique that is based on day-ahead optimized scheduling controllers with an aim to achieve optimal power generation and distribution at the lowest possible cost. The authors also developed an improved controller for constituent MGs in order to cut down on the expenses of operating DERs and to ensure that the charge–discharge operation of the energy storage system is carried out in the most efficient manner feasible.

In general, the idea of centralized architectures within ISTMGs can improve the coordination and effectiveness of energy exchange among various MGs. It can encourage a more dependable, adaptable, and sustainable energy system and provide participants with the ability to make data-driven decisions.

4.4.2. Decentralized

In a decentralized energy trading architecture, multiple producers and consumers interact directly, obviating the need for a centralized authority, as illustrated in Figure 2. In this architecture, there are multiple central nodes but no single point of control, i.e., instead of a single centralized server, there might be multiple central nodes that tasks or data are distributed across. Thus, in an ISTMG, each MG has the capability to generate, store, and consume energy, as well as trade surplus energy based on individual needs and preferences. Such a decentralized framework leverages advanced technologies, such as smart meters, sensors, and communication protocols, to facilitate real-time communication and coordination among energy resources and grid-connected devices. This enhances the efficiency of information exchange about energy availability, demand, and pricing.

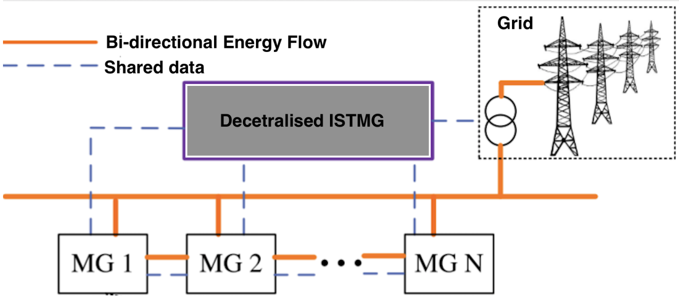

Figure 2. Decentralized trading in ISTMG [81].

Recent research has explored decentralized trading in ISTMGs, driven by the growing integration of renewable resources into modern electrical grids, necessitating financial, technological, and policy shifts [58]. The study focused on an autonomous control approach for the optimized management of energy transfers between nodes in a grid-connected MG network. Further research has concentrated on enhancing the efficiency and reliability of ISTMGs [82]. Their work proposed optimal day-ahead scheduling for an assembly of interconnected hydrogen, heat, and power-based MGs, factoring in hydrogen refueling stations (HRSs) and electric vehicle parking lots (EVPLs) as integral components of a robust decentralized energy management framework.

Another study in [70] introduced an innovative decentralized platform designed to facilitate energy trading in ISTMGs. Their platform employs a sequential round-based market clearing strategy, where the MG offering the most competitive energy pricing is permitted to export surplus energy, thereby maximizing its gains. In summary, decentralized energy trading within ISTMGs promotes the evolution of a more efficient, resilient, and sustainable energy system. This approach fosters the integration of renewable energy, catalyzes a shift toward decentralized energy infrastructures, and empowers individual participants to actively engage in the energy market.

4.4.3. Peer-to-Peer

A peer-to-peer (P2P) energy trading architecture operates on a decentralized framework within localized energy networks as depicted in Figure 3. However, it does differ from a typical decentralized architecture. In the case of a P2P architecture, every node (i.e., MG) is equal, and they interact directly with each other. It is designed for ad hoc, flexible, quick-to-reconfigure systems. It eliminates the need for centralized utilities, thus allowing participants to engage in direct energy transactions. Participants primarily generate their electricity using DERs and these DERs offer the flexibility to either consume the generated electricity instantaneously or store it in energy storage systems for future use. Should a participant's energy demand exceed their supply, the architecture enables the procurement of electricity from any other MG.

Some research works have explored P2P architectures; for example, in [68], the authors elucidated the potential for prosumer cost optimization through P2P energy trading. The study introduced two energy-sharing models: (i) preferred energy sharing and (ii) proportional energy sharing. The former accords priority to the prosumer with maximum solar availability for selling electricity either to the grid or within the community. Similarly, in [83], the authors developed trading models to facilitate MG interactions within a multi-agent network in P2P architecture. They proposed price negotiation strategies for both islanded and grid-connected ISTMGs and they presented a two-stage blockchain-based settlement consensus mechanism for ensuring reliable electricity trading transactions.

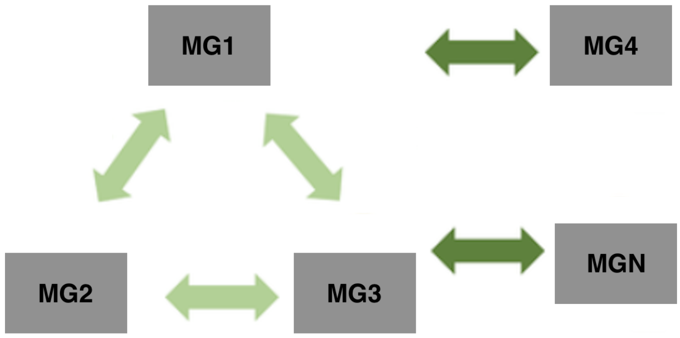

Figure 3. Peer-to-peer trading in ISTMG.

Other studies, such as in [13], explored challenges and opportunities in both internal and external P2P energy trading across residential, commercial, and industrial ISTMGs. Collectively, these researchers advocate that P2Pr trading in ISTMGs serves as an innovative avenue for energy distribution, thus enabling communities to actively participate in energy transitions and contribute to a resilient and sustainable energy landscape.

4.4.4. Hierarchical

A hierarchical architecture consists of MGs organized in a layered or tiered structure. Each layer typically has a specific function and interacts only with the layer immediately above or below it. The hierarchical model can simplify a complex ISTMG by breaking it down into manageable, discrete levels. In this configuration, MGs are organized in a hierarchy based on attributes such as size, capability, and other factors. A centralized authority may oversee the entire network's performance, optimizing system efficiency and reliability by monitoring energy supply and demand as illustrated in Figure 4.

Figure 4. Hierarchical trading architecture.

Within such a hierarchical framework, multiple tiers of trading can exist. At the local level, individual MGs can engage in peer-to-peer transactions to effectively meet local demand or exchange surplus energy. At an intermediate level, trade may occur between different MGs within a specified region, facilitating energy redistribution for system stabilization. These exchanges can also involve larger-scale energy transfers or balancing services.

At the apex of the hierarchy, the central authority may engage in trade with the MGs, making strategic decisions concerning energy procurement, resource distribution, and inter-regional energy transfers. Advanced digital technologies enable real-time monitoring, data exchange, and automated controls, thereby ensuring the security and efficiency of energy transactions throughout the network.

Recent research has focused on the development of a nested market clearing algorithm designed to yield optimal trading outcomes in both intra- and inter-MG markets [6]. The work in [84] has examined energy trading models involving independent market operators (IMOs), proposing a collaborative hierarchical dispatch system for multiple stakeholder MGs under uncertain conditions. Similarly, the authors in [38] emphasized the primary control level in a hierarchical structure for interconnecting autonomous MGs.

Hierarchical trading within an ISTMG ecosystem offers several benefits. These include improved grid resilience, enhanced integration of renewable energy sources, and smarter resource allocation. Within each MG, the system promotes energy independence and resilience through localized trading and peer-to-peer connections. At a higher level, the coordinated approach contributes to a more sustainable and effective energy environment.

4.4.5. Summary and Inferences

We have discussed four architectures for energy trading within ISTMGs, namely centralized, decentralized, peer-to-peer (P2P), and hierarchical architectures. In a centralized architecture, MGs are interconnected through a central platform that serves as a middleman for energy exchanges, improving efficiency and transparency in the market. Decentralized architectures remove the need for a central authority, leveraging advanced technologies like smart meters for real-time coordination and fostering the integration of renewable resources. P2P architectures operate on a decentralized framework but emphasize direct interactions between equal nodes, enabling flexible and quick transactions. Hierarchical architectures organize MGs in tiers, allowing for local P2P transactions and larger-scale energy transfers under the oversight of a central authority. Each architecture offers distinct advantages and challenges as summarized in Table 2, from optimizing resource usage and reducing costs to facilitating renewable integration and enhancing system resilience. Recent research has proposed various methods to enhance these models, focusing on things like algorithms, game theory, and optimal scheduling to make these systems more efficient and sustainable.

Table 2. Different ISTMG Architectures for Trading.

Ref.	Trading Architecture	Focus	Advantages	Disadvantages
[47,60]	Centralized	A central entity controls and facilitates the energy trading process.	Efficient energy allocation. Simplified coordination. Regulatory compliance. Established governance.	Single point of failure. May hinder innovation. Less autonomy for participants. Higher transaction costs.
[70,82]	Decentralized	No single controlling entity, participants interact directly with each other.	Enhanced transparency. Reduced need for intermediaries. Lower administrative costs. Resilience to single failures.	Coordination challenges. Potential for market manipulation. May lack standardized rules. Scalability concerns
[68,83]	Peer-to-Peer	Direct exchange between individual participants without intermediaries.	Lower transaction costs. Empowers energy producers. Potential for better prices. Supports local energy generation.	Limited scalability. Lack of regulatory oversight. Requires advanced technology. Complexity of energy balancing.
[6,84]	Hierarchical	A structured system with tiers of participants and intermediaries.	Clear hierarchy and decision making. Efficient resource allocation. Balances local and centralized control. Easier integration of various sources.	Information flow bottlenecks. Higher reliance on intermediaries. Reduced autonomy for lower tiers. Complexity of tier interactions

4.5. Trade-Enabling Technologies

Trade-enabling technologies are digital interfaces/technologies that aid in facilitating the transaction of electrical power between MG operators, utility companies, and end-users. By employing state-of-the-art technologies, ISTMGs can ensure the secure and efficient trading of energy, to the mutual economic benefit of both providers and consumers. The advent of such technologies signifies a paradigm shift in energy trading and such trade-enabling technologies possess the capacity to revolutionize the energy market landscape. In this section, we will examine the different enabling technologies and assess their impact. Additionally, these technologies are expected to optimize energy resource allocation, mitigate wastage, and promote the incorporation of renewable energy sources into the grid. By maximizing resource utilization, they can contribute to a more sustainable and cost-effective energy milieu. The following subsections outline these key technologies instrumental to the advancement of intelligent trading in ISTMGs:

4.5.1. Blockchain Technology

Blockchain technology plays a pivotal role in fostering secure and transparent trade platforms in ISTMGs. It facilitates an immutable ledger of energy transactions, thereby mitigating the risk of fraud and data manipulation. Extensive studies have delved into blockchain-based smart contracts that eliminate the need for third-party intermediaries during auditing or transaction dispute resolution between energy producers and consumers [71]. Such studies have illuminated the use of blockchain in enhancing transactive resilience within MGs through the implementation of smart contracts.

For example, in [23], the authors formulated an innovative framework employing blockchain technology to ensure secure data transactions between individual MG components and central control units. Their framework also integrated stochastic programming with the point estimate method (PEM) for optimal scheduling. Thus, their hybrid PEM–blockchain approach substantiated the ISTMGs' capacity to reliably, economically, and securely meet residential energy demands. Furthermore, it was noted in [53] that the integration of blockchain technology into the energy market will significantly advance the commercial exchange of electrical energy. It will enable decentralized, secure virtual transactions, facilitate smart contract management, and contribute to the inclusion of prosumers in MG energy transactions.

For an in-depth systematic review of blockchain technologies for energy transactions, readers can refer to [85]. It discusses the background and development process of blockchain in energy trading, surveys and analyzes its applications, and highlights important directions in this field. This can help readers understand the current state of research, identify gaps, and guide future work in blockchain for energy trading purposes. Moreover, the review of studies and projects based on blockchain-based energy trading can provide practical insights for those planning to implement such systems.

4.5.2. Internet of Things (IoT)

Another significant technology advancing energy trading in ISTMGs is the Internet of Things (IoT). IoT facilitates the aggregation of data from a multitude of smart grid sensors and devices, thereby enhancing energy production, consumption, and efficient energy trading. In a recent study, the authors in [86] developed a novel transactive energy management (TEM) system specifically designed for IoT-enabled smart homes within ISTMGs. Their research offered a comprehensive suite of options that can enable smart homes to engage in both vertical and horizontal energy transactions. Vertical transactions involve interactions between smart homes and other MGs for activities such as surplus solar energy feed-in and demand response services, aimed at mitigating grid load. Horizontal transactions, on the other hand, refer to peer-to-peer energy trading between smart homes.

Furthermore, resilience in ISTMGs necessitates real-time, innovative solutions. To this end, the authors in [87] presented an IoT-based digital twin (DT) framework capable of safeguarding a network of MGs against multiple attack vectors. Their framework included a mathematical formulation for the IoT cloud provision of the energy cyber–physical system and its DT, thus enabling effective control system interactions.

Moreover, other authors have proposed a transformative model for transactive energy grids endowed with distributed intelligence across all its components [88]. Their model conceptualizes the distribution grid as a nested arrangement of virtual MGs, each functioning as an individual market. Such a construct enables versatile energy exchanges, including peer-to-peer, participant-to-market, and market-to-market transactions, while ensuring grid security. The proposed vision leverages the proliferation of DERs and evolving energy requirements to augment grid resilience under both normal and exigent circumstances.

4.5.3. Artificial Intelligence (AI)

Artificial Intelligence (AI) technologies are being integrated into ISTMG trading platforms for the evaluation of ISTMG data and the forecasting of energy supply and demand. Such applications contribute to improved energy trade and efficient distribution of energy resources. In terms of research efforts, the authors in [89] focused on creating an innovative energy paradigm encompassing integrated smart systems that span from field-level hardware to cloud-based platforms. This digital transformation was realized through the amalgamation of IoT and AI technologies. Such an ecosystem is envisaged to enable energy transactions between prosumers via energy markets. Furthermore, they elaborated on various DERs and demand response programs, as well as the digital components that underpin the OT + IT (Operational and Information Technologies) systems for transactive energy and smart microgrids comprising ISTMGs.

In a separate study, the authors in [90] shed light on the synergistic role of machine learning and AI in fortifying IoT-enabled energy systems. Their research aims to make these systems more resilient, secure, and effective in operation by addressing extant challenges. Their study also delineated the structural framework of IoT-enabled smart energy systems, discussed associated security vulnerabilities, and explored the potential of advanced technologies to enhance system efficacy. Similarly, a comprehensive stochastic framework for optimally operating and managing systems with significant renewable energy penetration was introduced in [91]. Here, their proposed model accounted for the fluctuating charging demands of electric vehicles and the stochastic nature of renewable energy sources. Furthermore, they outlined a machine learning-based probabilistic approach, using support vector machine and point estimation methods, aimed at maintaining system operations within a secure zone while considering their inherent variability.

4.5.4. Distributed Energy Resources (DERs)

Distributed energy resources (DERs) such as solar panels and wind turbines are increasingly being integrated into MGs to facilitate energy production. Trading platforms within such MGs and ISTMGs aim to enable the exchange of surplus energy, thereby optimizing energy production and consumption levels. In terms of the inter-networking of such DERs, the authors in [9] advocated for P2P energy trading, which will be predicated on intelligent information systems to foster economic viability. Their method employs a distributed real-time P2P trading strategy that amalgamates energy trading with overall energy management. Consequently, MGs equipped with RESs and energy storage systems (ESSs) can dynamically coordinate storage scheduling, energy supply, and trading activities.

Furthermore, to minimize instances of load shedding during autonomous operations in an MG, interconnecting islanded neighboring MGs is an effective strategy, particularly when operating within a self-healing network and when excess generation capacity is available. To this effect, a hierarchical control framework for such interconnected MGs was proposed in [38], further emphasizing the importance of a primary control level to ensure equitable load sharing among parallel DERs in the system. In the context of centralized energy management systems, DERs have introduced a range of complexities within MGs. To mitigate these issues, an innovative lightning search algorithm (LSA) technique, coupled with a day-ahead optimized scheduling controller, was proposed in [80]. The proposed controller aims to furnish an optimal power supply at minimized costs, which includes the efficient utilization of energy storage systems [80].

4.5.5. Summary and Inferences

In this section, we have outlined a few notable technologies required to enable advanced energy trading within ISTMGs and their impact on the energy market landscape. These technologies are summarized in Table 3 with an aim to highlight their advantages and disadvantages. For example, blockchain technology has been emphasized for its role in ensuring secure and transparent energy transactions, eliminating the need for third-party intermediaries and facilitating smart contracts. The IoT will enhance the aggregation of data from multiple sensors and devices for efficient energy production and consumption. It can enable both vertical and horizontal energy transactions among different grid participants and improve grid resilience. On the other hand, AI is instrumental in evaluating and forecasting energy supply and demand, and it often works synergistically with IoT to enhance energy systems. Last but not least, DERs, such as solar panels and wind turbines, are integrated into ISTMGs to optimize energy production and consumption. These DERs are part of a comprehensive system that includes innovative control algorithms and strategies to maximize efficiency and minimize cost. Together, these technologies represent a paradigm shift in energy trading, thus contributing to a more sustainable and cost-effective energy environment.

Table 3. Energy Trading Enabling Technologies in ISTMG.

Technology	Description	Advantages	Disadvantages
Blockchain	A decentralized and secure digital ledger that records transactions across multiple computers.	Enhanced security and transparency. Eliminates need for intermediaries. Enables peer-to-peer transactions. Tamper-resistant records. Streamlined settlement and verification.	High energy consumption. Scalability challenges. Complexity of implementation. Regulatory uncertainties. Limited integration with legacy systems.
IoT	Interconnected devices that communicate and exchange data.	Real-time data collection and analysis. Optimizes resource utilization. Enables demand response and automation. Enhanced predictive maintenance. Remote control and monitoring.	Privacy and security concerns. Complexity of managing vast data streams. Compatibility issues with diverse devices. Initial investment in IoT infrastructure. Reliability and connectivity challenges.
AI	Algorithms and machine learning techniques that enable computers to simulate human intelligence.	Data-driven insights and predictions. Automates decision-making processes. Personalized energy management. Adaptive optimization and load forecasting. Enhances energy efficiency and grid stability.	Dependence on high-quality data sources. Ethical concerns and biases in algorithms. Complexity of implementing AI solutions. Initial training and setup costs. Limited understanding of decision rationale.
DERs	Local, small-scale power generation and storage systems that can be managed and controlled individually or as a collective.	Increased grid resilience and reliability. Supports renewable energy integration. Reduces transmission losses. Enables demand-side management. Empowers local communities.	Complex integration into existing grids. Variability and intermittency of resources. Initial setup and maintenance costs. Regulatory and policy challenges. Lack of standardized DER management.

4.6. Pricing Schemes

In this section, we highlight the different pricing models available for use within ISTMGs towards optimizing both its operational efficiency and economic profitability. These schemes are discussed as follows:

4.6.1. Fixed Pricing

The fixed pricing model offers a consistent energy pricing mechanism, uninfluenced by temporal variations or market fluctuations. While easily comprehensible and conducive to price stability for consumers, this model is suboptimal in the context of ISTMG systems, as it neither incentivizes energy storage nor promotes renewable energy utilization. In the evolving landscape of distribution systems (DS), the concept of ISTMG is gaining prominence. Thus, effective coordination of these ISTMGs is crucial for enhancing both operational efficiency and system reliability. In this context, a transactive energy (TE) framework was proposed for the coordinated energy management of networked MGs. Here, the distribution network operator (DNO) orchestrates a transactive market with the MGs as an alternative to direct coordination signals and fixed pricing mechanisms [92].

Furthermore, the existing literature, such as in [93], has advocated for the application of batch reinforcement learning (RL) in MG energy management. Within this framework, an intelligent agent was formulated using batch RL techniques. The agent aimed to minimize grid energy transactions by employing a fixed pricing model. In a dynamic environment, this RL agent optimized battery scheduling, thereby regulating the battery's operational state.

4.6.2. Real-Time Pricing (RTP)

Real-time pricing (RTP) is an adaptive pricing mechanism that adjusts energy costs in real-time according to supply and demand fluctuations. This model facilitates consumer responsiveness to price variations, thereby optimizing energy consumption. In ISTMG environments, RTP can provide timely information on energy costs, promoting the use of energy storage and renewable resources effectively. It can ensure that energy production and storage capacities are adapted dynamically based on current pricing.

In this regard, the study in [94] developed an economic dispatch framework aimed at minimizing the total operational costs of direct current (DC) MGs through the implementation of RTP. Each generation source within the MG, inclusive of the utility grid, possessed an associated operational cost. This enabled the networked MGs to achieve system efficiency while satisfying the utility's demand-response requirements [94].

Other research efforts, such as in [95], have explored load demand management within grid-connected MGs. By using RTP, the system was conceptualized as a power dispatch problem among distributed energy sources, with the objective of reducing grid operational expenses. A cooperative power dispatch algorithm was then proposed to govern energy exchanges within the ISTMG, premised on fluctuating demands and supplies. This was achieved via the grid's communication infrastructure and a predefined set of purchasing prices at specific MGs [95].

4.6.3. Time-of-Use (TOU) Pricing

The time-of-use (TOU) pricing scheme is a prevalent paradigm in the field of energy economics. According to this pricing model, the cost of energy varies depending on the diurnal hours it is used. Consumers are given an incentive to shift the way they use energy via higher prices during peak hours and lower prices during off-peak periods. This helps to lessen the amount of demand that occurs during peak hours. The TOU pricing model can further facilitate energy storage in MGs by encouraging the conservation of energy during intervals of low cost and the use of that energy during intervals of high cost. This strategy also encourages the incorporation of renewable energy sources such as solar power, which prove to be particularly useful during times of high energy demand.

Research-wise, the authors in [96] developed a TOU price optimization model focused on user-side MGs. Their objective was to minimize the overall expenditure of the power supply chain while refining end-user charging and discharging behaviors. Their research analyzed the bullwhip effect in power supply chains, emphasizing demand amplification and variability, and examined strategies for optimizing end-user behavior through distributed energy storage and pricing. In another study, the authors [97] introduced a hybrid electricity market model incorporating three distinct pricing mechanisms: (1) day-ahead time-of-use pricing for macrogrid energy purchases, (2) internal pricing mechanisms for energy sharing among interconnected MGs, and (3) biannual market pricing. This model serves to facilitate the equitable exchange of electricity across various scales of grids.

Additionally, the work by [98] presented an optimization framework to minimize operational costs in residential grid-connected MGs under a TOU pricing scheme. The authors used the popular Hybrid Optimization Model for Electric Renewable (HOMER) software version 3.13.3 for comprehensive net present cost modeling, simulation, and optimization, encompassing both traditional and renewable power sources, energy storage systems, and loads. Similarly, the authors in [99] proposed a scheduling technique for dispatching energy storage units in MGs, incorporating real-time electricity pricing into the model. Their strategy also accounted for the initial stored energy levels as a variable in the optimization process, rather than a predetermined value.

4.6.4. Net Metering

Net metering serves as an economic incentivization strategy that credits prosumers for surplus energy contributed back to the electrical grid. This pricing structure fosters the use of renewable energy technologies, including solar power, by allowing the feedback of surplus energy into the grid. The concept is applicable in ISTMG environments, thus promoting not only renewable energy uptake but also energy storage capabilities. In this case, the surplus energy in an ISTMG can either be stored for subsequent use or fed back into the grid.

In [100], the focal point was the creation of a hybrid microgrid system combining photovoltaic and wind energy, employing net metering as its core mechanism. For the empirical analysis, the academic building of Mehran University of Engineering and Technology in Pakistan was selected. NASA's meteorological data were integrated into the HOMER software to evaluate the feasibility of renewable energy sources. In a separate article [101], the authors advocated for the modeling and optimization of a Hybrid Microgrid System (HMGS) featuring a net-metering compensation scheme, realized through a swarm-intelligence algorithm. Their study scrutinized the impact of varying net-metering compensation levels on cost-effectiveness, the proportion of renewable energy sources (RES), and the Loss of Load Probability (LOLP), employing real-world data from a region in Spain [101].

In another study [102], the authors assessed the prospective incorporation of both feed-in and net metering tariffs within MG infrastructures. Such MGs were examined for their potential to bolster the broader energy network, especially during outage events. Critical facilities, including military installations, healthcare centers, and nuclear power stations, were noted to have already started deploying such MG systems for operational resilience.

4.6.5. Summary and Inferences

In this section, we have discussed four different pricing models that can be employed within ISTMGs to optimize operational efficiency and economic profitability. These schemes include the time-of-use (TOU), real-time (RTP), fixed, and net metering pricing models and they are summarized in Table 4, stating their pros and cons. Specifically, the TOU pricing offers varying costs depending on the time of day and is effective for shifting energy use away from peak hours. It also supports the integration of renewable energy and energy storage. The RTP model dynamically adjusts prices in real time based on supply and demand, promoting energy storage and the use of renewables. The fixed pricing, while easy to understand and stable, does not incentivize energy storage or the use of renewable resources and is therefore considered suboptimal in ISTMG systems. The net metering option credits prosumers for surplus energy fed back into the grid, thereby promoting the use of renewable technologies and energy storage. There have been various research efforts made to optimize these pricing models through simulations, algorithmic solutions, and real-world data, and we have mentioned a few of these efforts. These models play a critical role in coordinating ISTMGs efficiently, especially as they gain prominence in the evolving landscape of distribution systems. By establishing the most appropriate pricing scheme and employing successful marketing methods, ISTMG operators can position themselves as industry leaders and outrank their competitors in the energy market.

Table 4. Types of pricing schemes.

Ref.	Pricing Scheme	Pros	Cons
[92,93]	Fixed	Predictable bills. Simple and easy to understand. Stable for budgeting.	Does not encourage energy conservation. No incentive to shift energy usage. Unfair for users who consume less.
[94,95]	Real-time	Encourages energy conservation. Rewards users for using energy off-peak. Reflects actual market demand.	Can lead to volatile and unpredictable bills. Complex and harder to understand. Requires advanced smart metering infrastructure.
[96,97]	Time-of-Use	Encourages off-peak energy use. Reflects changing demand and supply. Can help reduce strain on the grid. Incentivizes adoption of energy storage.	Requires behavior adjustment. Complex and harder to predict bills. Penalizes those with limited schedule flexibility. Initial confusion about peak/off-peak timings.
[101,102]	Net Metering	Supports adoption of renewable energy. Offsets energy costs with excess generation. Simple setup for residential solar systems.	May lead to excess generation and grid stress. May not be available in all regions. Reduces utility revenue for grid maintenance.

5. Energy Management Systems

An energy management system (EMS) is a framework of computer-aided tools used to monitor, control, and optimize the performance of the generation and distribution of electrical energy [103]. Within the context of ISTMGs, EMSs play an indispensable role in facilitating the seamless exchange of energy and information among different interconnected MGs and their constituent elements, including generators, storage systems, and loads, as illustrated in Figure 5.

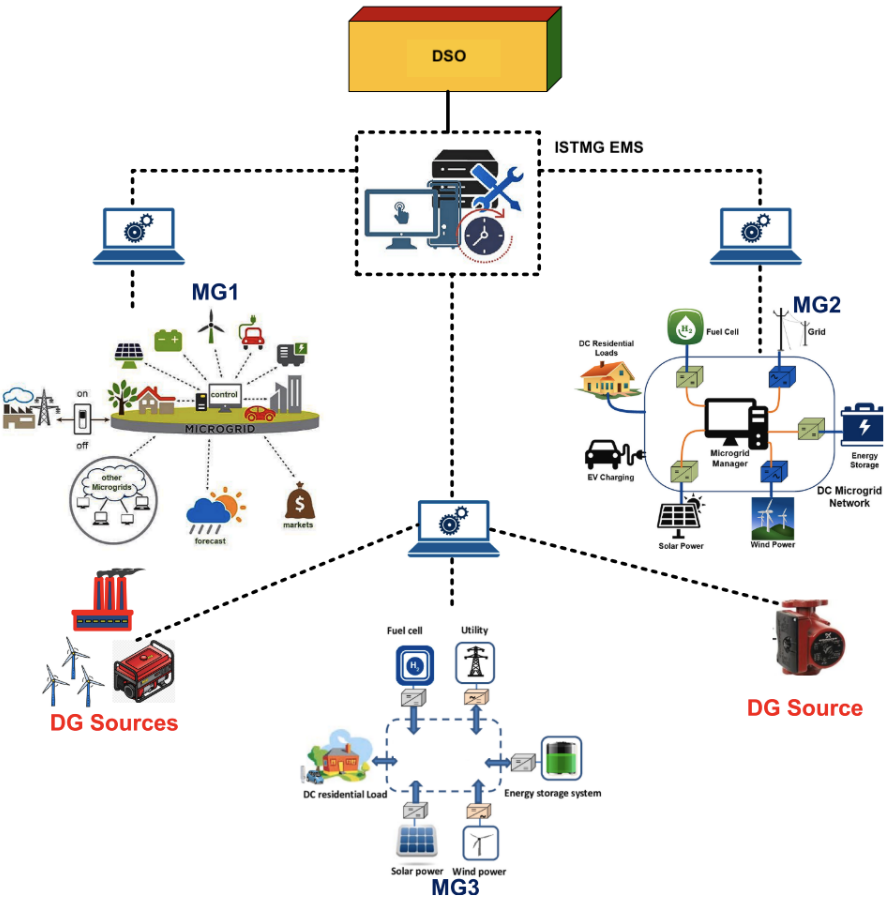

Figure 5. Energy management systems (EMS) as envisaged in ISTMG [104].

An EMS enables real-time balance between energy supply and demand by continually monitoring the energy metrics of each MG. It then formulates allocation strategies to optimally distribute energy resources. Additionally, the EMS coordinates energy transactions among multiple MGs, ensuring fair pricing and mitigating system congestion or imbalances. Through advanced analytics and forecasting capabilities, the EMS equips ISTMG operators with predictive insights into fluctuations in energy supply and demand, thereby aiding in cost reduction, carbon footprint minimization, and overall system stability and resilience enhancement. In subsequent sections, we will highlight the benefits of EMS, its function in an ISTMG, and potential architectures for deploying EMSs in ISTMGs and we will conclude some application areas for its use.

5.1. The Benefits of EMS

EMSs in ISTMGs are instrumental in achieving robust, efficient, and sustainable energy distribution networks. While they can be integrated with the larger power grid network, ISTMGs ideally focus on optimizing energy resources within confined geographical domains. Thus, it is necessary to use EMSs to establish control over such localized areas of energy generation and distribution. In achieving this, EMSs pose a number of key merits in ISTMGs, which are enumerated as follows:

- Enhances Energy Resilience: EMSs can enable an ISTMG to operate autonomously during external grid failures, thereby ensuring uninterrupted electricity supply to critical infrastructures such as healthcare facilities, emergency services, and communication systems. This resilience is attributed to their seamless transition between grid-connected and islanded operational states.
- Optimizes Energy Efficiency: EMS-enabled ISTMGs can facilitate the efficient allocation of energy production, distribution, and consumption. By synergizing various renewable energy sources, such as photovoltaic cells and wind turbines, with advanced energy storage solutions, EMSs help to minimize energy wastage and reduce distribution losses [105].
- Facilitates the Integration of Renewable Energy: EMSs can enable ISTMGs to incorporate renewable energy sources into the overall energy mix. This adaptability can allow for the proficient management of intermittent energy sources like solar and wind within an ISTMG [11].
- Localizes Energy Independence: EMSs ensure that ISTMGs are able to power communities and enterprises to enhance their localized energy autonomy. This self-reliance is made possible by the algorithmic controls and management services rendered by EMSs for local energy production, storage, and governance, thereby reducing dependency on centralized energy distribution frameworks [106].
- Dynamic Energy Pricing: Through transactive mechanisms, EMSs enable dynamic energy pricing based on real-time demand and supply, offering economic advantages to both producers and consumers.
- Cybersecurity: Advanced EMSs can offer robust security features that protect the grid from cyber-attacks, ensuring that energy data and transactions are secure.

Essentially, EMSs in ISTMGs aim to provide a wide range of advantages that support a future where energy is more dependable, effective, and sustainable. They are essential to the modernization of the energy sector and the development of a stronger, more dependable grid.

5.2. Functions of EMS in an ISTMG

It is important to consider the functions of EMSs in ISTMGs and their significance in managing energy systems within an ISTMG. Thus, the main purpose of an EMS is to monitor, control, and optimize the performance of energy systems. By examining the fundamental functions of an EMS within an ISTMG, we can better comprehend how it accomplishes specific tasks to ensure that such interconnected MGs operate efficiently, reliably, and stably. We discuss these main functions as follows:

5.2.1. Control

EMSs act as the core control unit within ISTMGs to ensure the reliable and effective operation of many intricately connected energy systems, such as multiple solar panels, wind turbines, batteries, and traditional generators. Thus, EMSs must ensure that ISTMGs are able to function in an island or connected mode with the primary electrical grid, hence forming a larger network that aims to improve energy resilience and maximize resource utilization. For instance, to maintain a balance between supply and demand, an EMS continuously regulates the energy demand inside an ISTMG and modifies the output of DERs. This is essential to avoid resource overloads or under-utilization. Secondly, because of changes in generation and consumption, ISTMGs are exposed to a variety of dynamic situations. By altering variables including frequency, voltage, and power factor, an EMS uses sophisticated control algorithms to preserve grid stability.

There are many notable research efforts concerned with the design of EMSs for ISTMGs, for example, the authors in [107] explored the application of Reinforcement Learning (RL) techniques in an EMS, specifically using the deep Q-network (DQN). They used the DQN to learn an optimal policy for operating the elements of an ISTMG based on the agent–environment interaction when particular operation actions are taken in the ISTMG. The results obtained were satisfactory, as concluded by their comparison with the perfect information optimal operation computed with a traditional optimization model and with a Naive model.

Researchers in [108] looked into the challenge of inefficient demand response (DR) mechanisms in ISTMGs that may lead to severe issues like rising consumer costs, rebound peaks, and a lack of network optimality. They proposed a bilevel EMS where the users' behavior and dissatisfaction were modeled in the first level of optimization to develop the best DR program for each user. Then in the second level, the power system constraints were considered to prevent voltage and current deviation from their statutory limits. An iterative transactive energy management method was proposed and incorporated into the central EMS (CEMS) to fairly limit the excess power of the interconnected MGs one day ahead for voltage and current regulation. The results obtained indicated that their proposed structure was effective in preventing discomfort issues, voltage deviation, and the creation of rebound peaks in the ISTMG.

Additional research effort was invested in [12] to meet the demands of electric vehicles (EVs), residential, commercial, and industrial users with the main grid contribution, with an objective to present an EMS to optimally control cross-sectoral energy flow between MGs consisting of various RESs, hydroelectric power plants (HPPs), and wind turbines (WTs). They proposed an EMS to interconnect MGs through a multiport converter (MPC). Their system was investigated under different conditions, e.g., load increment, demand response (DR), and $N - 1$ criterion in separate, interconnected, and island conditions. Their results showed that their proposed solution can decrease the total costs as well as peak demand and enhance reliability under different conditions.

In summary, the idea of control in EMS within ISTMGs would incorporate many technologies and strategies targeted at improving the performance of these energy networks. ISTMGs are made to work effectively and resiliently by careful monitoring, coordination, and decision making, and in line with the broader objectives of sustainable energy management.

5.2.2. Monitoring

Monitoring is a crucial function of an EMS for the effective management of ISTMGs. It involves the constant and real-time tracking of a range of indicators and metrics within ISTMGs. This data-driven approach enables operators and control systems to make informed decisions to optimize ISTMG performance. For example, real-time data will be collected from a variety of sensors, meters, and smart devices throughout the ISTMG, providing valuable information on energy generation, usage, and storage, as well as important parameters like voltage and frequency.

Furthermore, monitoring sheds light on the performance and status of individual DERs within each MG, such as solar cells and wind turbines. It also keeps track of the charge and discharge states of energy storage devices. Operators can monitor energy consumption trends across different loads in real time, aiding in the identification of usage patterns, peak demand periods, and areas requiring improvement. Monitoring also includes keeping tabs on grid variables like voltage and frequency, with deviations from established norms indicating potential issues that may require corrective action. All this information can be displayed via user-friendly graphical interfaces on the EMS or web interface, thus helping operators make sense of complex data sets quickly and efficiently.

Research is ongoing to improve the efficiency of monitoring interconnected microgrids. One research focus in [109] aims to transition distribution networks from hierarchical to distributed structures, with the growing use of distributed generators (DGs) and smart devices posing challenges for system dispatch. To address these challenges, the authors recommended the coordination of large numbers of DGs within ISTMGs through an EMS to ensure both safe and profitable operations [109]. In other studies, researchers in [110] proposed a secure distributed transactive energy management (S-DTEM) scheme to monitor multiple ISTMGs. The goal here was to maintain information privacy by only sharing trade volumes and pricing information with other MGs during energy transactions [110]. Another study aimed to meet multiple energy demands by optimally scheduling a network of hydrogen, heat, and power-based MGs a day in advance [82]. This includes monitoring various DGs and loads in settings like hydrogen refueling stations and electric vehicle parking lots [82].

In summary, monitoring is an essential part of EMS in ISTMGs. It plays a vital role in the real-time management of energy production, usage, and distribution. By providing actionable insights, monitoring contributes significantly to the stability, efficiency, and reliability of ISTMGs.

5.2.3. Optimization

Optimizing energy management in ISTMGs is crucial for their effective and cost-efficient functioning. Thus, this involves the strategic application of advanced algorithms in EMS to manage energy resources, load, and grid stability. These algorithms determine the best way to allocate available energy, ensuring each DER operates at peak efficiency. This not only encourages the use of renewable energy but also minimizes reliance on fossil fuels. Real-time adjustments of DER outputs are also necessary to keep the energy supply and demand in balance, thereby maintaining grid stability and avoiding resource overuse or under-utilization. Consequently, EMSs aim to achieve such optimization requirements to minimize operational costs by considering factors such as energy pricing, generation costs, and fluctuating demand. It also plans the scheduling of energy generation, storage, and usage to minimize peak demand charges and total energy costs.

EMSs also achieve optimization by taking into account the interconnections between various MGs and the primary grid. It fine-tunes energy flows and exchanges to maximize economic benefits while ensuring grid stability. For example, in [41], their research introduced a new framework for MG scheduling and distribution feeder reconfiguration (DFR), considering market prices, renewable energy output, and load uncertainties. Their framework aims to enhance customer experience while lowering overall operating costs [41]. Other research works have explored ISTMGs as an evolving grid architecture for future distribution systems. For example, recent efforts in [92] focused on improving operational effectiveness and reliability, emphasizing the importance of coordinated energy management within ISTMGs. Accordingly, their study presented a transactive energy (TE) framework for such coordination.

Furthermore, optimizing energy trading between interconnected MGs can potentially elevate the economic and reliability aspects of power system operations. From a transactive energy perspective, the authors in [34] proposed a distributed energy management strategy for interconnected Combined Heat and Power (CHP)-based MGs with demand response.

Their key idea was to establish complementary energy exchange between adjacent MGs through a multiport electrical energy router (i.e., an EMS). This was pursued in response to the situation of increasing renewable-energy penetration and the need to alleviate dependency on energy storage equipment. Their EMS, based on multiport bidirectional voltage source converters (VSCs) and a shared direct current (DC) power line, served as an energy hub, enabling flexible energy flow among the adjacent MGs and the main grid. Their results demonstrated the validity and reliability of the idea for MG interconnection as well as the corresponding control strategies for flexible energy flow. In summary, optimization in EMS within ISTMGs is a strategic approach that leverages sophisticated, data-driven algorithms for effective energy management. This enables ISTMGs to meet their goals of sustainability, resilience, and reliability by making the most of resource utilization, cutting costs, and keeping the grid stable.

5.3. Types of EMS in ISTMG

Various EMSs exist for ISTMG applications and these EMSs are usually tailored to fit specific architectures within the ISTMG. In this context, we will explore the different types of EMSs and the techniques they employ, according to the architectural frameworks they are designed for, as follows:

5.3.1. Centralized

A centralized EMS (CEMS) plays a crucial role in overseeing and coordinating ISTMGs. In this type of EMS, a single central controller manages the entire network of interconnected MGs. It is responsible for monitoring, control, and optimization tasks for the whole system, including distributed renewable energy sources (DRES). In CEMS, because all decisions are made centrally, there is no need for complex coordination between different MGs. The system can achieve global optimization more efficiently, thus ensuring that resources are used in the most cost-effective manner. However, as the number of MGs grows, the computational burden on the central EMS increases. And if the CEMS fails, it can disrupt the operation of all interconnected MGs.

In terms of specific CEMS proposed in the literature, we have provided a summary of such CEMS in Table 5. For example, in [108], the authors considered the inefficient demand response (DR) mechanisms within an ISTMG, which can lead to significant challenges such as increased consumer costs, fluctuating demand peaks, and overall system inefficiency. To tackle these issues, the authors proposed a CEMS to handle all operations in the MGs, focusing on voltage and current regulation and preemptively controlling excess power generation. In a separate work, the authors in [44] advocated for a centralized EMS to effectively manage loads, meet the charging requirements of plug-in hybrid vehicles, and coordinate the generation of linked renewable resources. Their CEMS considered both internal and external markets for MGs' effective participation in energy trading, which involves the energy exchange among MGs and the utility grid (UG). Their study implemented a hybrid scenario and copula-based Monte Carlo techniques to assess the intermittency associated with load demands, plug-in hybrid vehicle charging demands, and correlated RER generations. Their results suggested a 1.5% and 3.2% reduction in the operational cost of the ISTMG compared with the particle swarm optimization algorithm considering the best charging strategy during the summer and winter seasons.

Furthermore, users can benefit from ISTMGs equipped with distributed generators (DGs), energy storage systems (ESSs), and diesel generators. However, challenges such as the intermittent output of DGs, high ESS costs, and fossil fuel depletion pose barriers to economical operation. To mitigate these issues, the authors in [111] proposed a CEMS aimed at reducing consumer energy costs. Their CEMS can also manage diesel generators, energy storage systems, and other DGs within the ISTMG framework. In summary, a CEMS acts as the backbone for the smooth operation of ISTMGs. It enhances system efficiency, reliability, and resilience by optimizing various critical functions like energy distribution, load balancing, and fault detection. As the energy landscape evolves, a robust centralized EMS is increasingly vital for maintaining a sustainable and reliable energy distribution network.

Table 5. Centralized EMS in ISTMG.

Ref.	Optimise	Control	Monitor	Application Areas	Methods
[107]	✓	✓	✓	DRES	RL-Deep Q-Network (DQN)
[112]	✓	✓	×	Peak load/ESS/ PV/demand response	MPC
[108]	✓	✓	×	Demand response	Deep neural network
[44]	✓	×	×	DRES/EV	Fuzzified jellyfish search optimization algorithm
[111]	✓	×	×	DG/ESS	Fuzzy logic-based approach
[64]	✓	✓	×	DRES	Gaussian-process regression forecasting
[113]	✓	×	×	DRES	GT-Coalition Game approach
[39]	✓	×	×	DRES	Unscented transform technique

✓—Ref. includes the function in its method, ×—Ref. does not include the function in its method.

5.3.2. Decentralized

In a decentralized EMS (DEMS), each MG has its own EMS that operates independently of the others. These local DEMSs are responsible for the control and optimization of their respective MGs while communicating with each other for coordination. Such DEMS are often highly scalable, as adding new MGs does not increase the complexity of any existing EMS. It has no single point of failure, hence the system is more resilient to localized disruptions. Nevertheless, without a global controller, the system might not achieve the overall optimal state and each DEMS has to communicate and negotiate with others, which can be complex and time-consuming.

With regards to research on DEMS, the study in [57] proposed a method for scheduling energy both within and between different MGs. The authors considered energy scheduling for electric vehicles (EVs) with the intention of building a DEMS for electric cars (EVs) in order to manage them and lower the cost of the energy they use [57]. Furthermore, there are difficulties resulting from the constant and intense use of DGs and smart devices in ISTMGs. A decentralized energy-management approach for an ISTMG was proposed in [109] as a solution to these problems in order to coordinate a large number of DGs for sustaining safe and profitable operations in the electricity market environment.

Trading energy in ISTMGs has the potential to increase system economy and reliability from a transactive energy perspective. In [34], a DEMS with demand response was presented for networked operations of combined heat and power (CHP)-based MGs to control MGs that are heat and power (CHP) based, as well as their energy requirements. Summarily, there are many types of DEMS in the literature and we have provided a summary in Table 6. We note that DEMS provides an opportunity for handling the complexity of ISTMGs as energy systems continue to develop.

Table 6. Decentralized EMS in ISTMG.

Ref.	Optimise	Control	Monitor	Application Areas	Methods
[105]	×	✓	✓	DRES/ESS	Large-scale complex optimization
[57]	×	×	✓	DG/EV	Blockchain technologies
[109]	✓	×	✓	DG	Convex ADMM
[114]	×	✓	✓	DG/EV	Modal analysis and time-domain simulation
[34]	✓	×	×	DR	Dynamic search directions
[72]	✓	×	✓	DR	Distributed misbehavior-localization algorithm
[82]	✓	×	✓	DG/EV	ADMM

✓—includes function in its method, ×—does not include function in its method.

5.3.3. Nested

Within the context of ISTMGs, nested energy management systems (NEMSs) are strategically significant because they enable a hierarchical method of energy coordination and optimization. Each level of EMS control in this design tackles a certain component of the interconnected system's operation. Essentially, an NEMS can be considered a hybrid model that combines elements of both centralized and decentralized systems. In this case, it possesses CEMS functionalities to oversee a group of DEMSs, which can also operate independently. While an NEMS offers the benefits of both centralized and decentralized architectures, allowing for both global and local optimizations, nevertheless, they are complex to design and implement due to the presence of multiple layers of control. A summary of research efforts concerned with NEMSs is presented in Table 7 stating the functional parameters that each proposal offers.

Table 7. Nested EMS in ISTMG.

Papers	Optimise	Control	Monitor	Application Areas	Methods
[5]	✓	×	×	DRES, EV	C&CG algorithm
[115]	✓	✓	×	ESS/PV	RNN
[106]	✓	✓	✓	DRES	Cooperative game theory
[116]	×	✓	✓	BESS	MPC
[117]	×	✓	✓	BESS	Rolling horizon optimization
[118]	✓	✓	×	DRES	MPC
[84]	✓	✓	×	DRES	ATC algorithm
[69]	✓	✓	×	DRES, ESS	Bi-level distributed optimization model

✓—includes function in its method, ×—does not include function in its method.

In [5], the authors proposed a specialized NEMS for China, designed to address the country's unique technical requirements, market conditions, and regulations. Their aim was to manage challenges arising from the growing adoption of distributed energy resources and electric vehicles. This is particularly critical for ISTMGs that rely on renewable energy sources and face unpredictable demand. In developing their NEMS, the robust operation of multi-energy MGs with renewable energy and load uncertainties was formulated as a two-stage robust optimization problem. A real-life case study in China, Beijing Goldwind Industrial Park, was conducted to demonstrate the proposed architecture and method. Their results showed that by exporting surplus generation to the external customers and bulk power grid via the NEMS, the revenue generated in ISTMG was improved significantly compared to the traditional business mode.

Furthermore, in [24], the authors presented an NEMS for day-ahead scheduling of networked MGs. The surplus power existing in the inner level MGs was reflected as a resource and deficit as a load to the outer level MGs. The operational cost of the ISTMG using NEMS was shown to be lesser as compared to conventional decentralized or hybrid energy management strategies. Summarily, the strategy in using NEMS will promote efficient resource utilization, enhance system reliability, and strike a balance between overall system coordination and the agility required for individual MGs to operate seamlessly together.

5.3.4. Summary and Inferences

In this section, we have provided a review of the different types of EMS deployable in ISTMGs, categorizing them into centralized, decentralized, and nested EMSs as summarized in Table 8. We have highlighted that centralized EMS (CEMS) use a single controller for system-wide optimization, offering high efficiency but suffering from single-point failure risks and computational burdens. Decentralized EMS (DEMS) use local controllers in each MG for flexibility and scalability but may struggle with achieving global optimization. Nested EMS (NEMS) combines aspects of both centralized and decentralized systems, offering both local and global optimizations but are complex to design and implement. Various methods ranging from deep neural networks to fuzzy logic are used for system optimization in these different types of EMSs. While CEMS are often more efficient but less resilient, DEMS offer robustness at the cost of efficiency. NEMS tries to offer a balance between the two but adds complexity. Across these types, researchers aim to optimize various factors including load balancing, energy distribution, and fault detection to improve the efficiency, reliability, and sustainability of energy systems and we have discussed a few of these research works.

Table 8. Summary of the different types of EMS.

Ref.	EMS Architecture	Advantages	Disadvantages	Methods Used
[44,108,111]	Centralized	Reduction in disputes. Decreased operation costs. Utilization of each MG's efficient components. Reduced external trading due to simple standards and implementation. High operational reliability with strong privacy protection.	Dependence on central controller. Heavy computation burden. Sensitive to single-point failure. Weak plug-and-play functionality. Failure to preserve customer privacy. Sensitive to small system modifications. Lack of adaptability and flexibility. Difficult to establish a consensus for all MGs.	PSA, CA, MILP, DRO-based algorithm
[34,105,109]	Decentralized	Robust plug-and-play capabilities. High efficiency of calculation. High tolerance for communication errors. High reliability in the face of single-point failures.	Challenging to reach agreement on all MGs. Lack of awareness of system-level resources and high operating costs. Low-resiliency landed mode. P2P communication is expensive. Energy sharing between ISTMG at a high level.	C&CG algorithm, ML, ADMM, LSCO, DSD algorithms
[5,115]	Nested	Less operation cost. High resiliency. Relatively high plug-and-play flexibility compared to with centralized. Reduction on communication and computation burden of central EMS. Strong privacy protection. Steady operation of MGs when outermost EMS fails	All MGs operate independently. High dependence on communication networks. Computational time exponentially expands as the of MGs increase. High complex structure	C&CG algorithm.ML. MILP

5.4. EMS Application Areas

In the previous sections, we have emphasized the significance of EMS in ISTMGs, noting that EMSs serve as the core device setup to provide operational efficiency, grid stabilization, and overall optimization of energy management. Following this importance, in this section, we mention a few notable specific areas of applications of EMSs as follows:

5.4.1. Distributed Renewable Energy Sources (DRES)

Given the variable nature of renewable energy and fluctuating demand, efficient EMSs are critical for optimal ISTMG performance. Various EMS solutions such as predictive modeling, real-time monitoring, demand-side management, and energy storage have been proposed to enhance grid stability and resource utilization. Through such advanced EMS technologies, ISTMGs can also better manage DRES components like solar panels, wind turbines, and biomass generators [5].

However, to address challenges arising from the increased adoption of DRES and electric vehicles, a comprehensive energy management framework is required for ISTMGs. To this effect, the authors in [107] proposed an EMS framework that achieves robust operation and optimization, even in the presence of load and renewable energy uncertainty [107]. They explored the application of Reinforcement Learning (RL) techniques, specifically the deep Q-network (DQN). Their results were satisfactory, as concluded by their comparison with the perfect-information optimal operation computed with a traditional optimization model, and with a Naive model.

Further research has been conducted on control systems that require minimal complex modeling, calibration, and optimization processes [44]. The authors' aim in [44] was to reduce the operational costs of these ISTMGs in integration DRESs. To achieve this, the authors have developed an EMS that aims to maximize profits while minimizing operational costs. In summary, the integration of DRES in ISTMGs necessitates robust EMS. Such EMS systems effectively address challenges related to energy variability, demand fluctuations, and grid stability through various strategies including predictive modeling, real-time monitoring, and energy storage.

5.4.2. Energy Storage System (ESS)

Electric vehicles (EVs), electric bikes (EBs), and battery energy storage systems (ESS) are essential for enhancing the stability and reliability of ISTMGs. A well-designed EMS for ESS is critical for optimizing these benefits by intelligently regulating energy flow, enhancing grid resilience, and optimizing resource use. This is achieved through the integration of demand response, real-time monitoring, and predictive analytics.

In their study, the authors of [105] describe ISTMGs as systems featuring controllable loads in a distribution network and a connected array of distributed generators and energy storage devices. They argue that an EMS can simplify operational complexity, thereby reducing communication and control constraints. Consequently, the EMS contributes significantly to the reliability, power quality, and energy efficiency of distribution systems, especially during emergencies. Similarly, another study [119] considers the EMS as the central control unit for MGs, responsible for monitoring and regulating all operational modes, including islanded and grid-connected states. In ISTMGs, the EMS aims to fulfill system objectives and enhance the resilience of the main grid. The authors also developed a networked, distributed EMS for ISTMG systems with ESS, aiming to reduce operational costs and maximize profits through energy trading with the primary grid.

Additionally, a power exchange management strategy between adjacent residential grid-connected microgrids featuring photovoltaic generators and battery energy storage systems (BESS) was examined in [37]. Their strategy considered the rate of energy change in each MG and the charge difference between their BESS units. Their system successfully reduced the operating costs and improved the performance of the ESS.

In summary, ESSs are pivotal for the advancement of ISTMGs, and an effective EMS is indispensable. The EMS addresses challenges such as intermittency, energy imbalance, and resource optimization through real-time monitoring, predictive analytics, demand response, and seamless grid integration. The efficacy of EMS is further enhanced by employing advanced technologies such as smart control algorithms and IoT connectivity.

5.4.3. Demand Response (DR)

Demand response is a key component in the ISTMGs' energy management toolbox. Optimizing energy use, cutting costs, and improving grid stability all depend on an efficient EMS designed for demand response. The effectiveness of demand response strategies within EMS is ensured by incorporating real-time monitoring, predictive analytics, load shedding, and adaptable demand management. The system's flexibility is vital for adapting to dynamic conditions and ensuring alignment with available infrastructure and resources.

ISTMGs often incorporate renewable energy sources such as solar and wind. The EMS monitors these intermittent resources to adapt demand response tactics, aiming to maximize clean energy utilization [108]. Faulty design in demand response mechanisms within an ISTMG can result in increased consumer costs and network inefficiencies. To rectify this, the authors in [112] presented an EMS designed to equitably limit excess power in MGs. Similarly, the authors in [34] developed EMS to control the operations of combined heat and power (CHP) systems with DR toward minimizing the operational costs across various energy resources including CHP, DR, and renewables. In summary, EMSs are indispensable in managing ISTMGs, serving as the network's cognitive core. They orchestrate the complex interplay between multiple energy sources, loads, and storage devices to optimize the energy efficiency, cost, and resilience of the ISTMG. As such, EMS is poised to be a critical player in the evolution of decentralized and sustainable energy systems toward realizing viable ISTMG systems.

6. Optimisation in ISTMG

This section discusses optimization in ISTMGs, touching in general on factors such as optimization assets, network designs, and optimization methods present in the prior literature. The shift towards clean, reliable, and cost-effective energy has altered established methods in power generation, delivery, and consumption. Thus, ISTMGs like other sectors of energy management systems will demand the requirement for effective and efficient optimization strategies. Optimization is crucial for effective energy management, cost efficiency, renewable energy integration, load balancing, grid resilience, peak demand management, environmental sustainability, market participation, and real-time flexibility, and we will examine these aspects in this section.

6.1. Benefits of Optimisation in ISTMG

Optimization in ISTMGs introduces a paradigm shift in the way energy systems are managed and operated. It brings about an array of benefits that can have a profound impact on the overall performance, sustainability, and resilience of the energy system. Below are some of the key advantages that optimization brings to ISTMGs:

1. Efficiency in Energy Management: Optimization is crucial for effective energy management in ISTMGs, which often incorporate various DERs. This ensures optimal scheduling of energy production, storage, and consumption, thus maximizing efficiency by minimizing losses and enhancing resource utilization.
2. Cost Reduction: Optimization in ISTMG results in cost efficiency by dynamically adjusting energy production and consumption based on real-time demand and pricing. This eliminates reliance on expensive electricity from the main grid, thereby reducing costs for both operators and end users through strategic load shifting and demand response.
3. Integration of Renewable Energy: Efficiently incorporating renewable sources like solar and wind energy into ISTMGs is dependent on optimization. The use of optimization techniques aid to mitigate the variability of these sources by coordinating with energy storage devices and forecasting renewable energy production.
4. Load Balancing: To maintain grid stability, load balancing is essential in ISTMGs and optimization algorithms intelligently distribute the energy load among various resources, thereby preventing MG overloads and enhancing grid stability.
5. Grid Resilience: Optimization enhances the grid's adaptability to changes in supply and demand. The ISTMG can rapidly adjust to interruptions or faults, thus maintaining a stable electricity supply.
6. Peak Demand Management: ISTMG uses optimization for effective demand management. Optimization techniques used to manage load shedding and shifting non-critical loads to off-peak hours help regulate peak demand, thereby reducing system strain and overall energy costs.
7. Environmental Benefits: Optimization in ISTMG supports environmental sustainability by prioritizing renewable energy sources, thus reducing greenhouse gas emissions and the carbon footprint.
8. Market Participation: ISTMG actively participates in energy markets through optimization algorithms. This allows the ISTMG to capitalize on price fluctuations and generate revenue from surplus energy, contributing to the stability of the larger power system.
9. Real-Time Adaptation: ISTMG operates optimally under dynamic conditions, continually adapting to changes in energy supply and demand through real-time optimization. This ensures efficient operations despite fluctuations in renewable energy output or unexpected demand changes.

6.2. Optimizable Assets in ISTMG

We examine essential assets in an ISTMG that require optimization for enhanced performance. Each asset encompasses a range of both tangible and intangible factors.

Thus, proper optimization techniques are crucial to maximize the productivity and overall effectiveness of such factors in an ISTMG. Hence, optimization aims to make an ISTMG as effective and efficient as possible. In particular, asset optimization accomplishes this by leveraging various resources such as tools, software, technology, expertise, and data. These resources facilitate improved decision making, potential realization, and energy waste reduction in ISTMGs. Optimal choices regarding energy production, consumption, and storage are critical for the system's efficient and reliable operation. Consequently, we outline some of these assets and discuss their optimization implications.

6.2.1. Energy Storage Systems

ISTMGs depend heavily on energy storage systems (ESS) because they make it possible to effectively integrate and use renewable energy sources and maintain a balance between supply and demand. When demand is low or renewable energy production is high within disparate MGs, these systems store extra energy and release it when demand is high or renewable energy sources are scarce. Thus, it is essential to optimize the use of such ESSs and we examine a few of such research works in this regard.

For example, the authors in [120] established a bi-level two-stage framework based on transactive control, in order to achieve optimal energy provision in an ISTMG. At the lower level, each MG autonomously determines the optimal set points of each controllable asset by solving a cost minimization problem. This optimization was beneficial as it allowed each MG to autonomously determine the optimal set points of each controllable asset, including ESSs, thus leading to cost minimization. In [22], the authors formulated an optimization problem based on a framework for the energy scheduling of ESSs in ISTMGs in order to minimize operation costs. Their use of optimization was beneficial as it helped in reducing the operational costs of the ISTMG. Likewise, in [121], the authors discussed the coordinated control strategies for ISTMGs and ESSs. They concluded that optimization was beneficial as it improved the efficiency and reliability of the ISTMG.

In addition, the authors in [9] suggested a distributed real-time P2P energy trading method that integrates energy trading into energy management and enables MGs with renewable energy sources (RESs) and energy storage systems (ESSs) to manage storage scheduling, energy supply, and energy trading dynamically. Their proposed energy control and optimization mechanism successfully reduced energy transmission losses within the system while minimizing the time average operational costs of individual MGs. In summary, optimization strategies are crucial in managing ESSs in ISTMGs as they help to improve efficiency, reliability, and sustainability while reducing operational costs.

6.2.2. Electrical Vehicles

The concept of using electric vehicles (EVs) as energy storage systems is often referred to as "Vehicle-to-Grid" (V2G) or "Vehicle-to-Home" (V2H) technology. These technologies envision EVs as versatile energy storage units that interact with the electrical grid. The primary objectives are to enhance grid flexibility, stability, and overall system reliability while fostering the use of renewable energy. However, frequent cycling of EV batteries could affect their longevity and performance. Ongoing research aims to optimize V2G/V2H systems to balance the benefits and drawbacks concerning battery degradation. This idea has the potential to create a robust and decentralized energy grid, facilitating the evolution of smart and sustainable energy solutions.

For example, in [112], a finite-horizon optimization problem was formulated as a dual-tracking control problem with a quadratic cost function to examine peak demand reduction in an ISTMG. The optimization technique was shown to minimize the billing demand from the main grid. Another research study in [11] focused on managing power flow in a campus ISTMG to reduce peak demand. Their optimization approach combined storage and photovoltaic systems with Vehicle-to-Campus (V2C) and Bike-to-Campus (B2C) concepts to maintain high-quality service for EV and EB users while minimizing billing costs.

Furthermore, in [122], the authors presented a management strategy for ISTMGs allowing the interaction of EV with photovoltaic generation (PV) and consumer loads using a configuration that employs a shared AC bus. Their proposed management strategy demonstrated that economic and quality supply benefits can be achieved in ISTMGs. In [123], a cooperative optimization method was proposed for capacity configuration and economic dispatch of EVs in MGs considering across-time-and-space energy transmission (ATSET). Their results showed that the total costs of the ISTMG system and EV owners can be reduced by the proposed cooperative optimization method.

6.2.3. Heat Pumps

The integration of heat pumps into ISTMGs presents an opportunity to enhance both the efficiency and flexibility of localized energy systems. Heat pumps can provide dual services—heating and cooling—making them versatile components in the energy infrastructure. Optimization can thus be leveraged to improve their performance significantly, and their interaction with the larger energy system.

Optimization can assist in demand-side management by determining the optimal times for heat pump operation. Specialized algorithms can be designed to consider various factors such as electricity prices, external temperature, and overall system load to decide when it is most cost-effective and energy-efficient to operate the heat pumps [124]. Similarly, by intelligently controlling the operation of heat pumps, optimization algorithms can help balance the energy load across the ISTMG. For instance, heat pumps can be instructed to operate during periods of low demand, thereby providing a level of inherent energy storage by pre-heating or pre-cooling buildings. This was pursued in [125] where a distributed control strategy was proposed for a bottom-up Energy Internet (EI) architecture that provides power-sharing functions for ISTMGs with DERs and regulated loads (heat pumps). They emphasized that model-based distributed control methods are insufficiently flexible to deal with the complex uncertainties associated with multi-energy demands, distributed energy resources, and loads. Furthermore, the primary goal of their proposed scheme was to address unreliability issues for future power systems that occur with existing centralized control schemes that use a top-down architecture.

Furthermore, optimization can help find the most efficient operating conditions for heat pumps in real time. Parameters such as pump speed, coolant flow rate, and cycle timing can be continuously adjusted based on real-time measurements and forecasts to maintain optimal efficiency [126]. In addition, heat pumps can be synchronized with renewable energy generation profiles in ISTMG. Then, optimization algorithms can be used to direct heat pumps to operate at times when there is surplus renewable energy, thereby making better use of renewable resources and reducing the carbon footprint of heating and cooling operations.

6.2.4. Photovoltaic

The integration of photovoltaic (PV) systems is increasingly becoming a focal point in the design and operation of ISTMGs. However, the variable nature of PV generation (affected by weather conditions, time of day, and seasonal changes) poses a challenge for maintaining a stable and efficient ISTMG. This is where optimization techniques come into play, offering a range of solutions to improve the use of PV energy in ISTMGs.

Stochastic optimization techniques can model the randomness in PV generation due to variable weather conditions. By using weather forecasts, these methods can optimize the generation and storage schedules to maximize the use of PV energy while maintaining grid stability. For example, in [118], a hierarchical stochastic energy management system was proposed for the operation management of ISTMGs. At the upper level, a central entity was responsible for coordinating the operation of MGs. At the lower level, a decision-making approach based on chance-constrained model predictive control was adopted for local operation management of each MG taking into account different sources of uncertainties, more especially putting focus on the photovoltaic systems.

Mixed-integer linear programming (MILP) is effective for optimizing complex systems with both continuous and discrete variables, like the power output of PV panels and the on/off status of inverters. It can be used to optimally schedule these resources within an MG or across ISTMGs. The authors in [127] provided a comprehensive study on the nature of solar PV for MGs. They discussed energy optimization approaches and their economic impact on MG systems including ISTMGs. Also, techniques such as particle swarm optimization (PSO) and ant colony optimization (ACO) can be used for solving multi-objective problems. They are particularly useful in optimizing the configuration of PV installations to maximize energy yield and in managing the routing of PV energy through the network. For example, the study in [128] explored the viability of self-organizing control algorithms to manage multiple distributed energy resources within a distribution network and reduce electricity costs to one or more ratepayers having such resources installed on-site. Such research provides insight into the transition from a traditional power distribution architecture into a flexible smart network that is better prepared for future technological advances, renewable energy integration, and customer-side control.

6.2.5. Wind Turbine

Wind turbines serve an important role in ISTMGs, as they function as localized energy generation, which can then be delivered in an ISTMG. Many wind turbines are coupled with smart sensors and control systems that can modify their output in real time based on demand and supply signals. Thus, integrating wind energy sources into ISTMGs poses unique challenges due to the intermittent nature of wind resources. Hence, the adoption of optimization techniques can improve the use of wind turbines in these networks, enhancing overall system efficiency, reliability, and sustainability.

Effective wind energy management starts with accurate forecasting. Optimization techniques such as machine learning algorithms or time-series analysis can predict wind speeds and directions. These predictive models allow the EMS to make informed decisions about energy distribution and trading, optimizing the wind turbine's output to meet demand and market conditions. For example, in [54], the authors proposed an efficient scheduling strategy for ISTMGs that accounts for wind power unpredictability in order to lower individual MG operation costs while making profits through active energy trading with other MGs. The proposed optimization model considered MG grid topology and used the resilient optimization (RO) method to handle wind turbine uncertainty.

Furthermore, existing studies have developed an integrated energy management strategy that synergizes proactive and reactive mechanisms to address the variability in generation and consumption in both isolated and interconnected residential microgrids. These MGs consider renewable energy sources like wind turbines capable of power exchange with the larger grid [129]. In an ISTMG, real-time optimization techniques can also be used to dynamically set the price of wind energy based on supply and demand. Using algorithms that consider factors like current wind speed, demand forecasts, and grid stability, dynamic pricing can incentivize or discourage energy trading, leading to more efficient use of wind energy.

6.2.6. Diesel Generators

Diesel generators play a crucial role in enhancing the adaptability and reliability of ISTMGs. They act as backup power sources, thereby augmenting system resilience and stability. Specifically, these generators mitigate the variability of renewable energy sources like solar and wind by providing an immediate electrical supply when renewable generation is inadequate in an ISTMG.

In areas with limited access to the main grid, such as rural locations, diesel generators facilitate localized electricity production. To maximize efficiency and minimize transmission losses, these generators can be strategically placed within the ISTMG. Advanced control and monitoring systems enable them to adjust dynamically to real-time energy prices and demand patterns, making them cost-effective. In this regard, a recent study by the authors in [130] introduced a co-optimization model for P2P energy trading in ISTMGs. Their research focused on three-phase unbalanced networks and employed upcoming soft open point technology to enhance the performance of both diesel generators and DRESs.

Other significant contributions include the development of energy infrastructures that offer multiple advantages. For example, the study in [131] deployed a variety of energy agents in each MG, such as photovoltaic cells, wind turbines, fuel cells, and storage units, and employed the unscented transformation technique for uncertainty analysis and realistic simulations.

6.2.7. Summary and Inferences

In this section, we have discussed the optimization of various assets in ISTMGs for enhanced performance and sustainability. For energy storage systems (ESS), optimization helps in managing renewable energy resources by balancing supply and demand, and thus reducing operational costs. Electric vehicles (EVs) are considered mobile energy storage units (Vehicle-to-Grid or Vehicle-to-Home technologies), and optimization aims to maintain a robust, decentralized energy grid while minimizing the impact on battery longevity. Heat pumps offer dual services (heating and cooling) and are optimized for cost-effectiveness, energy efficiency, and load balancing. Photovoltaic (PV) systems, due to their variable nature, benefit from stochastic optimization techniques that account for weather variations to stabilize grid operations. Wind turbines also require optimization, particularly predictive models, to manage their intermittent nature and improve energy trading strategies. Diesel generators act as backup power and are optimized for real-time energy prices and demand, contributing to the overall resilience and adaptability of ISTMGs. Across all these assets, optimization techniques vary from machine learning algorithms to complex mathematical models, and they aim for improved decision making, reliability, and reduced operational costs.

6.3. Optimization Architectures in ISTMG

This section focuses on the optimization architecture within ISTMG, examining its two principal forms: centralized and decentralized. These architectures shed light on the specific mechanisms by which optimization occurs.

6.3.1. Centralized

Centralized optimization refers to the process of coordinating and optimizing various components and operations centrally within an ISTMG. The focus of this approach is to explore techniques that enhance efficiency when all the sub-systems are not only interconnected but are also in communication with other MGs. This form of coordination and optimization is essential due to the variety of assets involved, including RESs, ESSs, load dispatch centers, and more. Understanding the architecture behind these optimizations is crucial for maximizing both efficiency and resilience in such complex environments.

One key area of interest is identifying the operational mode in which the optimization takes place. Specifically, there are two modes: grid-connected mode and island mode. In the grid-connected mode, optimization occurs with the ISTMG connected to the main grid and possibly other ISTMGs. On the other hand, the island mode refers to an individual ISTMG operating in a standalone capacity, not connected to the main grid or other ISTMGs. Understanding the optimization strategies for each mode is essential for ensuring system resilience and operational stability.

For a quick view of the various optimization methods employed for centralized optimization in ISTMGs, a detailed summary is provided in Table 9. This table highlights techniques that contribute to enhancing resilience and stability in the microgrid ecosystem. Research-wise, various methods have been proposed for centralized optimization. One such study outlines an efficient approach for managing power flow exchanges within a campus-integrated MG for the purpose of peak load reduction or shaving [11]. This MG consists of several elements including photovoltaic parking shades, energy storage systems, electric vehicles and bikes, as well as loads. These components are intelligently coordinated through an enhanced metering infrastructure and a smart control unit. Another research in [132] proposed a centralized approach aimed at reducing the total network expenses, which encompasses the costs of power generation, unit startup and shutdown, and power exchange among multiple MGs and the main grid. Their study employed the Unscented Transform to model uncertainties associated with wind turbine and solar output, load demand variations, and energy price fluctuations. This provides a more realistic assessment and thereby aids in decision making for centralized optimization.

Table 9. Summary of centralized-based optimization methods and the assets optimized.

Ref.	Methods Used	Assets Optimized						
		ESS	EV	WT	PV	DG	EB	BESS
[11]	MPC	✓	✓	×	×	×	✓	✓
[132]	CSA	×	×	✓	✓	×	×	✓
[8]	MPC	×	✓	×	✓	×	×	✓
[44]	PSO	✓	✓	×	×	×	×	×
[64]	MPC	×	×	×	✓	×	×	✓
[91]	BEO	✓	✓	×	×	×	×	×
[131]	PSO-RL,GA-RL	✓	×	✓	✓	✓	×	×
[34]	ADMM	✓	×	×	×	✓	×	×
[133]	MINLP	✓	×	×	×	×	×	×
[80]	LSA	✓	×	×	×	×	×	×
[134]	ADMM	✓	×	✓	×	✓	×	×
[17]	MPC	✓	×	×	×	×	×	×

See algorithm abbreviations—Alternating direction method of multipliers (ADMM), crow search algorithm (CSA), model predictive control (MPC), particle swarm optimization (PSO), bat evolutionary optimization (BEO), reinforcement learning (RL), genetic algorithm (GA), agent-based optimization (ABO), distributionally robust optimization (DRO), lighting search algorithm (LSA), mixed integer linear programming (MINLP). ✓—asset was optimized in the method, ×—asset was not optimized in the method.

Furthermore, a study by [80] proposed the primary objective of a centralized controller to be the reduction in DER running costs and the optimal charge/discharge scheduling of the ESS. The centralized controller aimed to deliver power optimally while keeping costs at a minimum. This included making the most effective use of ESSs to ensure both efficiency and sustainability. In summary, centralized optimization in ISTMGs is a multifaceted subject with diverse approaches and methodologies. The optimization may take place either when the ISTMG is connected to the main grid or in an isolated island mode, and the ultimate goal is to enhance system resilience, stability, and efficiency through intelligent coordination and control. Various research studies have been conducted to explore and develop methods for achieving these goals, further enriching the body of knowledge in this rapidly evolving field.

6.3.2. Decentralized

Decentralized optimization refers to the process of achieving optimization in a distributed, non-centralized manner. This is particularly relevant in the context of individual ISTMGs operating in island mode, meaning that they are not connected to the main electrical grid. In this architecture, the initial stage of optimization occurs while the ISTMG is in island mode. Once optimization has been completed, the ISTMG can then re-connect to the main grid. Several methods of decentralized optimization exist to enhance the resilience and stability of ISTMGs. A detailed summary of these methods is presented in Table 10, with the associated techniques outlined in the footnotes.

Table 10. Summary of decentralized-based optimization methods and the assets optimized.

Ref.	Optimization Method	Assets Optimized						
		ESS	EV	WT	PV	DG	HP	BESS
[13]	MADRL	✓	×	×	✓	✓	✓	×
[135]	ADMM	✓	×	✓	×	×	×	✓
[136]	MILP	×	×	×	×	×	×	✓
[109]	ADMM	×	×	✓	×	×	×	×
[128]	ABO	×	×	×	✓	✓	×	×
[130]	DRO, ADMM	×	×	×	✓	✓	×	✓
[137]	ADMM	✓	×	×	×	✓	×	×
[138]	MINLP	✓	✓	✓	×	×	×	✓
[82]	ADMM	✓	✓	×	×	×	×	×
[54]	ADMM	✓	×	✓	×	×	×	×
[125]	MPC	✓	×	×	✓	×	✓	×
[129]	MILP	✓	×	✓	✓	✓	×	×

See algorithm abbreviations—Multi-agent Deep Reinforced Learning (MADRL), alternating direction method of multipliers (ADMM), mixed integer linear programming (MILP), agent-based optimization (ABO), distributionally robust optimization (DRO), mixed integer linear programming (MINLP), model predictive control (MPC). ✓—asset was optimized in the method, ×—asset was not optimized in the method.

From the research point of view, the authors in [28] examined decentralized optimization by considering both the external P2P energy trade problem and the internal energy conversion issues within interconnected residential, commercial, and industrial MG Energy Management Groups (MEMGs). Their method was well-suited to handle high-dimensional continuous action spaces, aligning with the inherent characteristics of P2P energy trading within many MEMGs [28]. Other research, such as in [129] provided an innovative energy management methodology that amalgamates both proactive and reactive approaches. This dual strategy was designed to address the uncertainties tied to generation and demand in ISTMGs. Within this framework, the ISTMG considered the optimization of various RESs, a diesel generator, and a storage device, while also possessing the capability to interchange electricity with the main grid.

Further contributing to this field, the authors in [136] proposed the establishment of a power exchange strategy specifically for ISTMGs using decentralized optimization. Their strategy formed part of a larger remote area network and incorporated optimized dispatchable distributed generators (D-DGs) as integral members of a master control unit (MCU). Their MCU analysis took into consideration equal cost distribution, thereby making the system more economically efficient. In summary, the role of optimization in ISTMGs is pivotal. These dynamic energy systems hold immense potential to meet the growing demands for reliable, safe, and cost-effective energy solutions. Through the use of decentralized optimization, ISTMGs can achieve various objectives including cost-effective energy management, load balancing, enhanced grid resilience, peak demand management, and environmentally sustainable energy utilization. Furthermore, they enable active participation in energy markets while offering real-time flexibility.

6.3.3. Summary and Inferences

This section explores the optimization architectures in ISTMGs, focusing on centralized and decentralized approaches and their impact on energy systems. Centralized optimization involves coordinating and optimizing various components of an ISTMG, including RESs, ESSs, and load dispatch centers. This approach is vital for enhancing efficiency and resilience, particularly in modes where the ISTMG is connected to the main grid or operating independently (island mode). Research in this area includes developing efficient power flow management techniques for reducing peak loads and employing stochastic models to handle uncertainties in energy generation and prices.

Decentralized optimization, on the other hand, is relevant for ISTMGs operating in island mode, optimizing processes in a distributed manner before reconnecting to the main grid. This approach is crucial for enhancing ISTMG resilience and stability. Research in decentralized optimization includes developing methods to manage P2P energy trade and internal energy conversions in interconnected microgrid groups, innovative energy management methodologies that address generation and demand uncertainties, and power exchange strategies for remote area networks.

Overall, both centralized and decentralized optimization in ISTMGs are critical for achieving objectives such as cost-effective energy management, load balancing, grid resilience, peak demand management, and sustainable energy utilization. These systems enable active participation in energy markets and provide real-time flexibility, making them essential in the evolving landscape of smart energy systems.

7. Methods and Research Areas in ISTMG

ISTMGs employ an intricate system to regulate the local distribution and use of energy. At the core of ISTMGs are a set of advanced techniques that are aimed at achieving three primary objectives: optimizing the flow of energy across the network, enhancing efficiency, and bolstering the overall resilience of the system. These methods often incorporate state-of-the-art technologies such as IoT devices, machine learning algorithms, and real-time data analytics, enabling a smarter and more adaptable energy infrastructure. In addition to providing an overview of these innovative techniques, this section also reviews research works particularly focused on various topics pertinent to the management of ISTMGs. The inclusion of these academic works serves to highlight the cutting-edge developments in the field and offers a comprehensive understanding of the current landscape.

7.1. Artificial Intelligence (AI)

The rapid expansion of artificial intelligence (AI) technologies has seen the field branching out into diverse applications, including energy management within MGs and ISTMGs. The essence of AI lies in the ability to equip machines with capabilities typically requiring human intelligence, thereby automating and optimizing various tasks. The field is continuously evolving, with newer methods being developed and existing techniques refined to address many complex challenges. In the context of energy management, machine learning and deep learning have emerged as particularly important applications of AI.

The role of AI in energy management is quite extensive, spanning a variety of strategies and technologies. Specific AI methodologies such as artificial neural networks and fuzzy systems are showing promise in the management of microgrids and ISTMGs. These technologies offer innovative ways to control and optimize the performance of ISTMGs, either as standalone solutions or as part of an optimization process. In terms of AI research in ISTMG, a summary of articles in this regard is provided in Table 11, highlighting various strategies and their applications.

One notable study in [93] delves into the use of batch Reinforcement Learning (RL) for energy management within an MG. Motivated by recent advances in batch RL technologies, the research aimed to maximize the self-consumption of locally produced photovoltaic energy. They achieved this by designing a closed-loop control policy for the optimal scheduling of a storage device, using the fitted Q-iteration algorithm—a widely used batch RL technique. In another study [139], the authors focused on managing the power that is fed from an MG into the main utility grid. This was accomplished by a unique approach that integrates the dual decomposition (DD) transactive control methodology with the fitted Q-iteration RL technique. By controlling the power injection via a price signal set using the DD technique, the MG manager can offer flexible services to the distribution system operator while maintaining a stable grid connection.

On a related note, voltage and frequency stability within an ISTMG were examined in [140] using an iterative learning controller (ILC). The MGs were modeled to include renewable sources like solar and wind energy, as well as fuel cells and batteries. Simulation results were conducted via MATLAB/Simulink, and the results indicated that the proposed ILC outperformed other controllers in voltage and frequency regulation. Additional research in [107] explored MG operation via RL, particularly using deep Q-networks (DQN). Their work showcased how a DQN can learn optimal policies for the operation of MG components, with the ultimate goal of minimizing operating costs. In another study [131], a novel intelligent priority selection-based reinforcement learning (IPS-RL) method was proposed for efficient energy trading in a peer-to-peer architecture. Their method was tested on various types of agents within ISTMGs, including photovoltaic systems, wind turbines, fuel cells, and tidal systems.

Efforts are also being made such as in [91] to integrate Vehicle-to-Grid (V2G) technology within MGs to offset the negative impacts of electric vehicle charging demands. This involves machine learning-based probabilistic approaches that take into account the uncertainty of renewable energy sources. Similarly, a mixed-integer nonlinear programming optimization technique has been developed to manage urban microgrids, focusing on cost-reduction strategies [141]. In the context of ISTMG, a multi-agent deep reinforcement learning approach has been proposed in [13] to manage internal and external P2P energy trading. This approach can handle the complexities associated with high-dimensional data and uncertainty.

Summary and Inferences

In summary, AI technologies are increasingly being applied in the energy sector to enhance the efficiency and resilience of MGs and ISTMGs. These applications span from basic control policies to complex energy trading algorithms, leveraging a variety of AI techniques to address specific challenges. This burgeoning field continues to offer innovative solutions, as documented in numerous recent research studies summarized in Table 11. Essentially, the application of AI spans from machine learning and deep learning to more specific methodologies like artificial neural networks, fuzzy systems, and reinforcement learning. These techniques are instrumental in optimizing the performance of MGs and ISTMGs, evident in case studies focusing on batch reinforcement learning for storage device scheduling, transactive control methods for power management, iterative learning controllers for voltage stability, and deep Q-networks for cost minimization. Emerging trends like Vehicle-to-Grid integration and multi-agent deep reinforcement learning highlight the dynamic evolution of AI in this field, offering a valuable perspective for researchers seeking to innovate and enhance energy management systems.

Table 11. Summary of various AI approaches in ISTMG.

Ref.	Focus	Application Area	Operation Mode	Method	Results
[93]	Develop EMS to optimally schedule the operation of a storage device	BESS	Grid-connected	RL	The developed framework is benchmarked with a model-based technique, and the simulation results show a performance gap of 19%.
[139]	A technique for managing the power fed into the main utility grid from a microgrid	BESS	Grid-connected	RL	A 10% increase in power injected to the grid is obtained compared to a theoretical optimal benchmark. a 10% increase in power injected to the grid is obtained compared to a theoretical optimal benchmark.
[140]	To control voltage and frequency of microgrids	PV, WT, BESS, HP	Grid-connected	Fuzzy logic and RNN	The results show that the proposed ILC is more effective in controlling voltage and frequency when compared to other controllers
[107]	To keep microgrid operating expenses, including the cost of unserved power, to a minimum	DRES	Islanded mode	RL	The comparison of the findings with the perfect-information optimal operation computed using a conventional optimization model and with a Naive model shows that the results are highly excellent.

Table 11. *Cont.*

Ref.	Focus	Application Area	Operation Mode	Method	Results
[131]	To quickly identify and counteract harmful assaults for efficient energy trading based on peer-to-peer architecture.	PV, WT, DG, ESS	Grid-connected	Support vector machines (SVM), RL, particle swarm optimization (PSO)-RL, and genetic algorithms (GA)-RL	improved time of detecting incorrect data intrusion by the proposed method as compared to other methods.
[91]	To develop an approach that manages the erratic nature of renewable energy sources and the high demands of mobile charging for electric vehicles	EV	Grid-connected	support vector machines	The proposed formulation optimizes the total networked microgrid cost equality meeting several.
[141]	Developed an urban microgrid EMS that is based on the predictive control and reduction in electricity costs for the urban microgrid management	DRES	Grid-connected	MINLP, Deep Learning	Electricity price reduction for the MGs, compared to conventional distribution systems and basic operation schemes.
[15]	Managing and trading energy across ISTMGs	DRES, ESS	Grid-connected	RNN	In comparison to traditional RL-based methods, the suggested RL method exhibits superior effectiveness, practicality, and lower computational costs.
[13]	To solve these two complex decision-making problems with enormous high-dimensional data and uncertainty	DRES	Grid-connected	deep approach	demonstrates that the suggested method greatly lowers the average hourly operating cost for each MG.
[125]	To deal with the complex uncertainties associated with multi-energy demands and DERs	DRES	Grid-connected	MADRL method	Shows MAATD3 approach can deliver precise control. The operational cost using MAATD3 was 9.6% less than calculated using TD3 and 41% less than OPF.

7.2. Game Theory

Game theory (GT) is gaining prominence in addressing complex interactions within ISTMGs. Specifically, in [33], the authors studied how GT can be employed to model and optimize the complex, dynamic relationships within ISTMGs. Indeed, there is a growing research trend in this regard, with a few as summarized in Table 12.

It is envisaged that the future power grids will primarily consist of a network of ISTMGs, leveraging renewable energy sources such as solar, wind, and EVs. However, the inherent inconsistencies of these renewable energy sources will pose a challenge for ISTMGs in reliably supplying the needs of all the prosumers connected to them. Consequently, the concept of GT has gained consideration, for example, in [142], GT was used to develop feasible game-theoretic pricing mechanisms for ISTMGs, accounting for energy losses, current costs, and production. In another study [63], a non-cooperative game-theoretic strategy was developed based on a double auction process for ISTMGs, employing the Nash equilibrium technique. Here, MGs act as potential players attempting to maximize their gains. Various scenarios were formulated to assess the effectiveness of this mechanism, also taking into account uncertainties like MG loading requirements and wind speed. Similarly, a hierarchical bi-level controller was proposed in [106] using static, non-cooperative GT to model interactions among participants. Their research was specifically useful in controlling Micro-Hybrid MG (MH-MGs) with distributed energy resources and it was shown to be effective in optimal power allocation among market players.

Table 12. Summary of various game theory approaches in ISTMG.

Ref.	Focus	Application Area	Operation Mode	Method	Remarks
[142]	Develop a pricing mechanism for interconnected smart microgrids based on potential game theory	PV, WT, EV	Grid-connected	Game theory	Multi-agent deep reinforcement learning based distributed control architecture for interconnected multi-energy microgrid energy management and optimization.
[63]	To develop a Nash equilibrium technique based on a double auction process for ISTMG Nash equilibrium technique	DRES	Grid-connected	Non-cooperative game-theoretic strategy	Demonstrated that the suggested gaming strategy might boost potential financial gains or lower energy provision expenses.
[106]	To model the interactions among participants of multiple home microgrids	DRES	Island mode	Non-cooperative game-theoretic strategy	Result of this algorithm meets the objectives of each player in the market while offering the best and most appropriate power allocation. Furthermore, it is determined how much money each player made.
[7]	(DSO) to make use of the operational scheduling of local flexible resources in MGs in an effort to reduce the system's flexible ramp-up.	PV, WT, EV	Grid-connected	Stackelberg game method	Implementing the bi-level optimization model has resulted in decreasing the ramp-up of the MMG system from 36 MW/h to 5 MW/h and 10 MW/h.
[143]	To control the dynamic nature of EVs increases the uncertainty in the transactive distribution system.	EV	Grid-connected	Bayesian Coalition Game (BCG) based algorithm	The is a reduction in power loss as well as a reduction in the operation cost.
[46]	To provide the microgrids with an additional avenue to sell their surplus power.	DRES	Grid-connected	Game-theoretical approach	The proposed technique decreases main grid outages by 85.6%, demonstrating its effectiveness in boosting system resilience.
[60]	Schedules microgrids to reach a global optimum for the multi-microgrid system's cost	DRES	Grid-connected	Cooperative game approach	Shows that as compared to the isolated mode, the suggested cooperative model reduces the cost of the MMG.
[144]	To develop a trading and scheduling mechanism for energy exchange between ISTMGs	DRES	Grid-connected	Game theory-based approach	When compared to the Nash and Kalai-Smorodinsky solutions, the proposed bargaining solution has a fairness index of 0.974, while these solutions have 0.946 and 0.954, respectively.

Furthermore, with an ever-increasing rate of RES installations due to their eco-friendly nature and declining costs, system operational management faces new challenges, including system flexibility limitations. To mitigate this, distribution system operators (DSOs) can use local flexible ramp resources. For example, a Stackelberg game approach was proposed in [7] to operationalize the scheduling of these resources within MGs. Moreover, the concept of energy trading between MGs holds great promise. This enables one MG to meet the energy needs of another MG or even an interconnection of MGs dynamically based on changes in supply and demand. One novel approach in [143] used a Bayesian Coalition Game (BCG) based algorithm for this purpose. Another paper proposed a market mechanism specifically designed for peer-to-peer power trading among MGs to improve the system's overall resilience [46].

In terms of day-ahead scheduling, a cooperative game model has also been proposed to schedule ISTMG systems [60]. The model in [60] optimized costs across the network and employed price-based demand response to offer consumers potential savings. The concept of Shapley value was used to fairly distribute the system's optimum cost among MGs. For the sustainable development of ISTMGs, trading and scheduling mechanisms are indispensable. Thus, research based on Danish renewable energy production and consumption was presented in [144], wherein the authors employed a lexicographic egalitarian bargaining strategy for two participating MGs. They conducted a comparison with established methods of inter-MG trading, showcasing the efficacy of GT-based models.

Summary and Inferences

Summarily, GT offers a rich set of tools for modeling and optimizing the complex interactions within ISTMGs. As the sector evolves, these GT models will play an increasingly vital role in ensuring the efficient, resilient, and sustainable operation of future energy systems. Key applications include developing game-theoretic pricing mechanisms, employing non-cooperative GT strategies for maximizing gains in MGs, and utilizing concepts like Nash equilibrium and the Stackelberg game for operational management and scheduling. GT also facilitates energy trading between MGs, improving system resilience and cost optimization. Cooperative game models and lexicographic egalitarian bargaining strategies are explored for effective day-ahead scheduling and inter-MG trading, thus highlighting the role of GT in enhancing the efficiency and sustainability of ISTMGs amidst growing renewable energy adoption.

7.3. Model Predictive Control (MPC)

To optimize the operational efficiency of ISTMGs, advanced control techniques are increasingly critical. One such approach is model predictive control (MPC), a method known for its ability to make decisions optimizing system performance while complying with operational constraints [16]. MPC is pivotal in ISTMGs for maintaining grid stability, managing energy resources intelligently, and adapting to changing conditions. In the context of complex networked MG systems, MPC ensures the energy is managed efficiently, reliably, and sustainably. A summary of research papers on this subject is provided in Table 13.

For example, the study in [145] introduced a scheduling optimization strategy aimed at peak load shaving in institutional MGs. These MGs were designed to integrate various components such as advanced metering and communication infrastructure, battery energy storage systems, roof-mounted solar PV panels, and diverse loads. Their primary objective was to formulate an optimization framework that collaborates with an MPC scheme. This integration was demonstrated to effectively control MG operations while ensuring high-quality services for EV owners. Another noteworthy contribution was identified in [17], where the authors proposed a real-time conditional self-restoration energy management system (CSR-EMS) based on MPC. Specifically designed for ISTMGs integrated with RESs and ESSs, they proposed a CSR-EMS system that can economically achieve self-restoration and grid-assisted restoration under energy deficiencies or faults. Their system operates in two layers: the lower layer focuses on local operations to mitigate the fluctuations from RESs, while the upper layer keeps an eye on the real-time operational status, directing power exchanges among MGs during abnormal conditions.

For ISTMGs that cater to a wide range of EVs, residential, commercial, and industrial loads, the authors in [12] offered a comprehensive solution to control cross-sectoral energy flows. Their approach entailed the installation of a new interconnection line between two MGs using MPC techniques, as well as considering the techno-economic benefits of these new cables, converters, and necessary battery storage systems. Their research underscored the importance of local energy trading through ISTMGs and also highlighted that effective control mechanisms are essential for successful operation. With an increase in variable renewable energy generation, the focus in [64] was on forecasting and the optimization of ISTMGs using a Gaussian-process regression forecasting and MPC algorithm. Their study revealed that despite offering superior solutions in terms of lower electricity costs, a longer time horizon results in higher battery cycling rates.

Table 13. Summary of various model predictive control (MPC) approaches in ISTMG.

Ref.	Focus	Application Area	Operation Mode	Method	Remarks
[145]	Effective scheduling optimization approach for lowering/shaving the peak load in an integrated microgrid for institutional buildings	BESS, PV, EV	Grid-connected	MPC	The proposed approach shows that it is able to lower/shave the peak load in an integrated microgrid as compared traditional methods.
[17]	To propose a real-time conditional self-restoration (CSR-EMS) for ISTMG based on the MPC approach	DRES, ESS	islanded and grid-connected modes	MPC	The suggested CSR-EMS can automatically use inexpensive electricity from IMGs and the main grid to maximize the economic advantage of the IMG system under problematic circumstances. It can also maintain load-demand balance to achieve conditional self-restoration during IMG irregularities.
[64]	Forecasting and optimizing microgrids operation with variable renewable energy generation	DRES	Grid-connected	Gaussian-process regression forecasting and MPC algorithm	By exchanging data among the microgrids, we show improvements in renewable and load projections.
[8]	To minimize consumer and prosumer savings while lowering peak load on nearby transformers	BESS, PV, EV	Grid-connected	MPC	Prosumers and consumers can save more money with the planned TC, which can also lessen the peak demand brought on by EV charging in the distribution networks and mitigate undesirable grid effects.
[11]	To manage the power flows exchanges in a campus integrated microgrid for peak reduction/shaving objectives	BESS, EB, EV	Grid-connected	MPC	The control technique effectively reduced peak demand, but static weighting values have poor accuracy compared to dynamic weighting factors. PV generation and energy storage systems with V2C and B2C capabilities can reduce peak load.
[146]	Creates opportunities for the modular coordination of technologically disparate building subsystems for cost-effective operation while maintaining user comfort.	DRES	Grid-connected	MPC-based modular coordination method	Results demonstrate the cost-saving potential of MPCs in various configurations and draw attention to the proposed modular approach as a potential integration strategy.
[147]	In the presence of time-varying building demand, renewable energy output, and energy price fluctuations, MPC optimizes overall energy and microgrid running costs.	DRES	Grid-connected	MPC-based modular coordination method	Comparing the suggested approach to the transactive control technique, which results in savings of 34%, the cost of battery deterioration is reduced by about 8 times.
[118]	Restrict uncertainty inside the microgrids network and reduce unplanned power exchange with the main grid while taking system cost into account.	DRES	Grid-connected	Chance-constrained MPCl	A significant cost decrease for multi-microgrid systems was made possible by implementing the suggested methodology.

The study in [8] examined the management of BESS in residential networked MGs. These MGs included loads, EVs, and rooftop solar PV systems. They proposed transactive control (TC) mechanisms that aim to optimize BESS scheduling using MPC, targeting the reduction in peak loads and increasing consumer savings. In the area of building energy management, a modular coordination method between building zone comfort control and MG energy flow was proposed in [146] using MPC. Additionally, the authors in [147] provided an extensive study on MG energy flows and operation costs considering fluctuating energy prices and potential active building participation in the energy market. Lastly, the authors in [118] suggested a hierarchical stochastic energy management system for ISTMGs. At the highest level, a central organization coordinates MG utilization. The power reference values to be exchanged within and between the MGs and the main grid were calculated and communicated based on scheduling determined at this central level. At the lower levels, each MG's local operation was using a chance-constrained MPC approach.

Summary and Inferences

In summary, many research works are extensively exploring various facets of MPC applications in ISTMGs. These studies span from load scheduling and optimization to self-restoration mechanisms, from cross-sectoral energy flow control to advanced forecasting techniques, and from battery storage management to building energy systems. By integrating these insights, ISTMGs stand to benefit from enhanced resilience, efficiency, and sustainability. Key research in this area demonstrates that MPC can effectively manage energy resources, optimize system performance, and maintain compliance with operational constraints. Notable applications include peak load shaving in institutional microgrids, real-time energy management systems for self-restoration, and integration with renewable energy sources and energy storage systems. Studies also emphasize the importance of MPC in controlling microgrid operations, especially in complex networked systems, to ensure efficient, reliable, and sustainable energy management. This includes optimizing battery energy storage systems in residential networks, managing cross-sectoral energy flows, and implementing advanced forecasting and optimization techniques. Additionally, MPC is pivotal in handling variable renewable energy generation, reducing operational costs, and facilitating local energy trading. The research underscores the importance of MPC in managing the intricate balance between energy supply and demand, highlighting its role as a critical component in the future development of smart and sustainable energy systems.

7.4. Multi-Agent Systems

To achieve effective management and optimization of ISTMGs, multi-agent systems play a crucial role. ISTMGs are composed of multiple smaller MGs that are interconnected and can feature diverse energy sources, varying demand profiles, and distinct operating constraints. These complexities necessitate the adoption of advanced control systems, for which multi-agent approaches are particularly suited [148]. In this context, each MG in the ISTMG can be conceptualized as an intelligent agent, cooperating with others to fulfill system-wide objectives while adhering to localized constraints. The use of multi-agent systems in ISTMG has been highlighted in many research articles, which are summarized in Table 14. These research efforts address a range of topics, from market-based control mechanisms to innovative algorithms for real-time coordination between MGs and the distribution system operators (DSOs).

One notable application of multi-agent systems is in the smart village MG control automation in [149], which aims to achieve intelligent and practical control through price-based demand response energy management. Their research employed a model-based design methodology to construct an adaptive control algorithm, which integrates renewable energy sources into modular MG systems. Through the use of distributed market-based controls and multi-agent transactive principles, the system was demonstrated to automatically adjust to fluctuations in supply and demand. Addressing the problem of energy imbalance within an MG, the research [150] has proposed the use of auction mechanisms within multi-agent systems. Their primary objective was to align current energy demand with actual energy production, particularly important when the MG includes unpredictable energy sources such as wind and solar.

Other research has examined the application of multi-agent systems to demand-side management (DSM) in settings like commercial buildings and residential areas [151]. A hierarchical transactive energy-based multi-agent framework was proposed in [151], which comprised energy management demand agents (EMDAs) that coordinate various appliances at the building level. In a separate article [67], a comprehensive energy management system was developed to handle the complexity introduced by MGs in distribution networks. Their EMS employed a two-phase energy management strategy to level off projected energy imbalances and to facilitate transactions in an auction-based electricity market between MGs. Additionally, challenges such as uncertainties related to DERs were tackled through innovative techniques like multi-agent deep reinforcement learning (MADRL) [125]. Unlike traditional model-based methods, MADRL offers a model-free, data-driven approach that adapts to varying energy demands. Another study in [152] offered solutions to close the gaps in the existing research, which suffers from large iterations and dependencies on predictions. The authors introduced a multi-agent learning-based stochastic dynamic programming (MASDP) approach, which employs market-based information interactions for more straightforward coordination between MGs and DSOs.

Table 14. Summary of various Multi-agent approaches in ISTMG.

Ref.	Focus	Application Area	Operation Mode	Method	Remarks
[149]	to provide practical and intelligent control capabilities for smart village microgrid	DRES	Islanded mode	Multi-agent transactive architecture	The proposed approach ensures a more dynamic decentralized system with lower local energy market volatility, fewer load device curtailments, fewer peak loads, the potential for peak shifting, and the ability for prosumers to earn extra money by selling power back to the microgrid during peak hours.
[150]	To manage the unbalanced energy in a microgrid via an auction technique. to regulate and reduce the differences between the current energy demand and the actual energy production	PV, ESS, WT	Islanded mode	Multi-agent architecture	Results demonstrate that the system works well and compensates for imbalances quickly, even when up to 20 devices agents are assumed to function on separate computers.
[151]	To establish an EM framework that will allow the many appliances in the buildings to operate in unison.	DRES	Islanded mode	Hierarchical transactive energy-based multiagent framework	Outcomes of the suggested framework are shown to show how lowering peak demand and naturally supplying demand response can help prevent the need for expensive generation units.
[125]	Manage uncertainties connected to DERs and multiple energy demands handled by model-based distributed control methods.	DRES	Grid-oriented	Multiagent deep reinforcement learning (MADRL) method, model predictive control	Results show that the suggested MAATD3 approach can deliver precise control. The operational cost calculated using MAATD3 was 9.6% less than calculated using TD3 and 41% less than calculated using OPF.
[152]	To examine real-time coordination of MGs and DSO while taking into account multivariate uncertainty	DRES	Grid-oriented	multi-agent learning based stochastic dynamic programming (MASDP)	When compared to other widely used distributed algorithms and policies, MASDP uses less computation time, adjusts to high-dimensional uncertainty, and does not require forecasts or extensive iteration.
[153]	To create bid strategies for ESSs to engage in TE markets. To account for the losses brought on by energy transactions between ESSs and microgrids.	ESS	Grid-oriented	Multiagent DRL approach	It has been found that the suggested approach, which uses a combination of local and global ESSs, may successfully strengthen the balance between supply and demand in microgrids.
[13]	To develop an EMS that efficiently converts and stores energy to minimize costs and environmental damage	DRES	Grid-oriented	Multi-agent DRL technique	The suggested approach is compatible with P2P energy trading with numerous MEMGs and is capable of handling the high-dimensional continuous action space.
[154]	To combine the ideas of microgrid and transactive energy.	DRES	Islanded mode	P2P energy transaction model agent-based	The results enable the majority of players/agents to experience a decline in energy prices inside the microgrid.

The potential for ESSs to contribute to the management of MGs was explored in [153], with novel market models being proposed to incentivize both local and global storage contributions. Reinforcement learning techniques like simulated-annealing-based Q-learning were employed to create optimal bidding strategies for ESSs. To complement energy trading activities, their system employed a sophisticated current-tracing-based loss allocation mechanism. Lastly, P2P energy trading within ISTMGs was investigated in [13] where the authors used advanced machine learning techniques, combining twin delayed deep deterministic policy gradient algorithms with multi-agent actor–critic algorithms to handle complex decision-making scenarios. In summary, multi-agent systems offer a robust framework for addressing the complex challenges posed by the management and optimization of ISTMGs. Through a combination of innovative algorithms, market mechanisms, and advanced learning techniques, these systems are pushing the boundaries of what is possible in the realm of intelligent energy management.

Summary and Inferences

The research on ISTMGs emphasizes the crucial role of multi-agent systems in managing complex, interconnected MGs with diverse energy sources and demand profiles. These systems enable intelligent, dynamic control and coordination within MGs, employing advanced approaches like transactive architectures for real-time adaptation to supply and demand fluctuations, auction mechanisms for energy balancing, and hierarchical frameworks for demand-side management. Innovations include the use of multi-agent deep reinforcement learning for managing uncertainties in distributed energy resources and stochastic dynamic programming for efficient real-time coordination with distribution system operators (DSOs). Additionally, research extends to the development of market models for energy storage systems and peer-to-peer energy trading, using sophisticated machine learning techniques for optimal decision making. This section has discussed advancing intelligent energy management in ISTMGs using multi-agent systems, thus offering insights into efficient, adaptive, and comprehensive control strategies within modern energy systems.

7.5. Stochastic Programming

One of the key methods ISTMGs employ to enhance reliability and efficiency is stochastic programming techniques. These methods offer a robust framework for tackling uncertainties and variabilities related to renewable energy generation, load changes, and market prices [148]. By deploying these techniques, ISTMGs can make well-informed decisions, optimizing both efficiency and resilience in real-world applications. However, the application of stochastic programming in ISTMGs is not without its challenges. Factors such as the accurate definition of probability distributions, computational efficiency, and optimization techniques need to be considered to maximize the benefits of stochastic programming [148]. By mastering these aspects, ISTMGs can be designed to navigate through uncertainties and variabilities, ensuring a dependable and efficient operational environment. For an overview of research efforts discussing these stochastic programming approaches in ISTMGs, refer to Table 15.

From a research point of view, a novel power exchange strategy was proposed in [136] that is particularly useful for large remote area networks. This strategy leverages dispatchable devices (D-DG) that form part of the master control unit (MCU). The MCU then employs the equal cost increment approach to anticipate power exchanges with neighboring MGs, especially during instances of load imbalance or overcrowding. The proposed MCU also takes into account sudden changes in non-dispatchable generators (N-DGs) and load, enhancing the system's resilience. This optimization problem was then solved using mixed integer linear programming (MILP) techniques and was validated through MATLAB simulations in stochastic environments [136]. Research has not only confined itself to centralized mechanisms but has also ventured into decentralized approaches. For instance, the study in [130] proposed a data-driven and distributionally robust co-optimization approach for

P2P energy trading within ISTMGs. This work integrated the alternative direction method of multipliers (ADMM) and devised a unique pricing mechanism that turned out to be superior to traditional robust optimization (RO) and stochastic programming (SP) models in terms of handling uncertainties.

Table 15. Summary of various stochastical programming approaches in ISTMG.

Ref.	Focus	Application Area	Operation Mode	Method	Remarks
[136]	To estimate how much power might be exchanged with neighboring MGs in the event of overcrowding	DRES	Grid-oriented	Stochastic-MILP	The operational cost is reduced
[129]	To effectively address the uncertainties related to generation and demand in the islanded and interconnected operation of residential microgrid	DRES, DG	Islanded mode, Grid-oriented	Stochastic-MILP model	The suggested framework guarantees savings of 24.12% over the grid-connected operation without DR for a year when using the supplied MG parameters and the uncertainty.
[155]	To handle the ever-increasing penetration of networked microgrids	DRES	Islanded mode	Stochastic-MILP model	The proposed approach is superior in various ways compared to the existing transactive management schemes
[130]	Propose a co-optimization approach for P2P energy trading and network operation for ISTMG ISTMGs (MGs)	DRES	Grid-oriented	RO and stochastic programming (SP) models	By reducing the operational cost of MGs via a P2P trading strategy, the results validate the effectiveness of the proposed scheme and demonstrate enhanced performance compared to RO and SP-based models.
[156]	Improve system security while also lowering system risks, mitigating financial fraud, and reducing operational costs.	DRES	Grid-oriented	Stochastic-MILP model	Results demonstrate the high efficacy and efficiency of the suggested model and support its virtues in terms of economy and dependability.
[152]	The real-time coordination of MGs and DSO while taking into account multivariate uncertainty.	DRES	Grid-oriented	Multi-agent learning based stochastic dynamic programming (MASDP)	When compared to other widely used distributed algorithms and policies, MASDP uses less computation time, adjusts to high-dimensional uncertainty, and does not require forecasts or extensive iteration.
[61]	To carry out a techno-economic analysis and identify the ideal conditions for achieving an energy balance with the lowest possible operating expenses and the highest possible revenues.	DRES	Islanded mode	Stochastic-sequential least squares programming (SLSQP) method	The outcome demonstrates that the configuration based on green hydrogen is still very attractive even though the total financial performances (IRR) are lower.
[133]	To take advantage of the potential capabilities of the advocated energy conversion facilities in satisfying electrical, heat, and water demands at the lowest operating cost	DRES	Islanded mode	Centralized stochastic optimization technique	The networked MCMGs' overall running costs can be decreased by the central operator.

Furthermore, the continuous advancement in the energy landscape has paved the way for cutting-edge operational paradigms. For example, the research in [156] discussed the use of transactive energy technology to create a dynamic balance in ISTMG systems with 100% REss integration. A hybrid model that combines stochastic programming and information gap decision theory (IGDT) was used to handle the intermittent nature of the system. Emerging technologies like blockchain are also making inroads into the energy management frameworks in ISTMGs [39]. By leveraging blockchain technology, benefits such as enhanced system security, reduced financial risks, and lowered operational costs can be realized. In terms of computational approach, a stochastic framework based on the unscented transform method was deployed in [39] to handle uncertainties related to renewable energy sources.

Similarly, the research in [61] presented a sophisticated optimization-simulation approach, which included a sequential least squares programming (SLSQP) algorithm and a novel multi-objective self-adaptive evolutionary algorithm, for better operational efficiency. This research was particularly interesting as it conducted a sensitivity analysis of hydrogen costs in both off-grid and on-grid settings. Lastly, centralized optimization techniques were also explored for energy transactions in networked multi-constrained MGs (MCMGs) [133]. By adopting a transactive energy management (TEM) strategy and an integrated demand response program, the central operator can enhance both the flexibility and the operational cost efficiency under extreme uncertainties.

Summary and Inferences

The section highlights the significant role of stochastic programming techniques in improving the reliability and efficiency of ISTMGs. Researchers in this field can draw valuable insights from the way these techniques address uncertainties in renewable energy generation, load changes, and market prices. However, challenges such as defining accurate probability distributions, ensuring computational efficiency, and selecting optimal optimization techniques are crucial for maximizing the benefits of stochastic programming.

Key findings include various applications of stochastic programming, ranging from the optimization of power exchanges in large networks to decentralized approaches for peer-to-peer energy trading. Innovative strategies like mixed integer linear programming (MILP) for managing power exchanges and the use of alternative direction methods of multipliers (ADMM) in decentralized systems are notable. Additionally, the integration of cutting-edge technologies such as transactive energy technology, information gap decision theory (IGDT), and blockchain enhances system resilience and efficiency.

The research also emphasizes the importance of hybrid models in handling the intermittent nature of renewable energy sources and the potential of blockchain in improving system security and reducing costs. Computational techniques like the unscented transform method and multi-objective self-adaptive evolutionary algorithms are also crucial in managing uncertainties and operational efficiency. Centralized optimization techniques in networked multi-constrained MGs (MCMGs) using transactive energy management (TEM) strategies highlight the progress in the field.

Overall, these findings underscore the necessity for continued innovation in stochastic programming and related technologies to address the evolving challenges in the field of renewable energy management and ISTMGs.

7.6. Metaheuristic Approaches

ISTMGs are essentially a confluence of smaller, localized MGs designed to improve reliability and efficiency. They often incorporate an array of RESs, energy storage technologies, and demand-side management techniques. Thus, due to the inherent complexity and variability in these systems, conventional optimization methods frequently fall short of identifying optimal solutions within a reasonable time frame. Such techniques are well suited for solving complex, nonlinear optimization problems and are particularly beneficial in managing ISTMGs [33].

Metaheuristic techniques are inspired by various natural phenomena, such as annealing and swarm dynamics. They provide an effective way to tackle the complexities, nonlinearities, uncertainties, and multi-objective characteristics inherent in ISTMGs. For instance, professionals and researchers can leverage these techniques to operate ISTMGs efficiently while minimizing costs and optimizing energy management. Thus, a summary of research efforts focusing on the use of metaheuristic approaches in ISTMG is presented in Table 16.

In the context of network uncertainties, an optimal power distribution framework for ISTMGs was proposed in [157]. This framework enables MGs to operate in an interconnected fashion, thus enhancing network reliability while also facilitating power exchange with the main grid. A probabilistic model was employed to optimize power sharing among the interconnected MGs, targeting the lowest operational cost for each small-scale energy resource (SSER) and load. Algorithms like the imperialist competitive algorithm (ICA) and particle swarm optimization (PSO) were used for optimization and were compared against the Monte Carlo simulation (MCS) approach for validation [157]. The research in [34] also considered combined heat and power (CHP)-based MGs with demand response. They proposed a distributed energy management technique. The optimization scheduling model used was decentralized and employed a dynamic sub-gradient search algorithm to solve it iteratively. Other studies have focused on stochastic paradigms for ISTMG management, incorporating uncertainties such as load demand, price projections, and renewable energy outputs. These paradigms use metaheuristic algorithms such as the crow search algorithm for optimization purposes [132].

Table 16. Summary of various metaheuristic approaches in ISTMG.

Ref.	Focus	Application Area	Operation Mode	Method	Remarks
[157]	To improve network dependability in addition to exchanging electricity with the main grid	DRES	Grid-oriented	imperialist competitive algorithm (ICA) and particle swarm optimization (PSO) algorithms	The findings demonstrate that smart distribution networks' operational costs can be reduced by the best possible power sharing between MGs and the main grid.
[34]	study proposes a distributed energy management technique for interconnected combined heat and power (CHP)-based microgrids	DRES	Islanded mode	distributed iterative algorithm	Consideration of generating cost, trading price, load characteristics, and DR cost leads to a reduction in operation expenses and increases the flexibility and interactivity of power consumption.
[132]	a novel stochastic paradigm for the management and operation of ISTMGs (MGs)	DRES	Grid-oriented	crow search algorithm	Shows the reduction in all network expenses. Reduction in the price of power generation by units.
[80]	to create an optimized controller for the microgrid to reduce DER operating costs and operate the energy storage system's charge/discharge process	DRES	Grid-oriented	lightning search algorithm (LSA) technique	The results obtained showed that the suggested optimization controller outperformed existing optimized controllers in terms of energy and cost savings.
[131]	A study on optimal power sharing in ISTMGs under uncertainty	DRES, ESS	Grid-oriented	A study on optimal power sharing in ISTMGs under uncertainty	To avoid excessive activities that could reduce battery life, the EMS optimization algorithm could be further enhanced by taking into account the cost of each charge and discharge cycle of the battery.
[91]	To ensure optimal operating as well as managing of these power systems with high penetration of renewable energy	DRES,EV	Islanded mode, Grid-oriented	bat evolutionary optimization	The optimization technique assist in quickly solving the stated stochastic problem in all circumstances before requiring 100 iterations.
[23]	to reduce the overall running costs of the microgrids while simultaneously boosting the social factors through optimal switching, which benefits the customers.	DRES	Islanded mode, Grid-oriented	crow search (CCS) technique	The findings indicate that the ideal switching might lower the overall operating cost from $22,716 to $21,935 (a reduction of 3.56%).
[44]	to effectively participate in energy trading, which involves both the exchange of energy among MGs and utility grid (UG)	DRES	Grid-oriented	fuzzified jellyfish search optimization technique	Compared to the conventional business model, the microgrid's revenue increased dramatically.

Furthermore, the integration of DERs into MGs has created challenges for existing centralized energy management systems. In response, the authors in [80] proposed unique optimization techniques such as the lightning search algorithm (LSA) to minimize DER operating costs while optimizing ESSs. Similarly, hybrid control methods combining advanced algorithms were explored in [158] for the energy management of interconnected renewable energy sources. Social and economic factors have also been considered in other research works, with frameworks aiming to reduce overall running costs while enhancing customer benefits. Metaheuristic techniques like the corrected crow search (CCS) algorithm have been employed to find optimal operating points for MGs, leading to significant cost reductions [23]. Energy management frameworks were developed for both internal and external markets, using metaheuristic techniques like the fuzzified jellyfish search optimization to balance multiple conflicting objectives [44].

Summary and Inferences

This section highlights the crucial role of metaheuristic approaches in ISTMGs. Traditional optimization methods often struggle with the complexity and variability of these systems. In response, metaheuristic techniques, inspired by natural phenomena like annealing and swarm dynamics, are employed due to their effectiveness in handling nonlinearity, uncertainty, and multi-objective optimization in ISTMGs.

Key research efforts in this domain include the development of optimal power distribution frameworks for ISTMGs to enhance network reliability and facilitate power exchange. Techniques like the ICA and PSO have been used, often validated against methods like the Monte Carlo simulation (MCS). Additionally, decentralized optimization models for combined heat and power (CHP)-based MGs with demand response have been proposed, employing algorithms like dynamic sub-gradient search.

The integration of DERs has prompted the adoption of unique optimization techniques such as the LSA for minimizing DER operating costs while optimizing ESSs. Hybrid control methods and algorithms like the CCS and fuzzified jellyfish search optimization are being explored for efficient energy management and cost reduction, considering both social and economic factors. These studies aim to develop energy management frameworks that can efficiently handle internal and external market dynamics, balancing multiple conflicting objectives in ISTMGs. This research is crucial for professionals and researchers in the field, as it provides innovative approaches for efficient and cost-effective management of complex energy systems.

8. Research Challenges and Future Works

ISTMGs are a complicated and expanding area of study in the field of distributed energy systems. They are made up of several MGs that are linked together as well as to the main grid, thus allowing them to share resources, trade energy, and improve dependability and resilience. However, because of their increased complexity and the requirement for good coordination, they also offer new research problems. A number of these challenges are listed as follows:

- Cooperative game theory: Cooperative game theory offers a robust framework for handling energy transactions in ISTMGs. Using cooperative game theory, MGs can receive noticeable benefits when they cooperate, as compared to non-cooperative approaches. However, while it helps in maximizing the overall utility of the system, it does pose significant challenges. The major drawback is the vulnerability regarding shareholder privacy, as extensive information must be shared among the MGs. Additionally, there may be gaps in the full awareness of each party's costs, capacities, and preferences.
- MPC approach: The MPC approach has been extended to integrate battery degradation models, particularly aimed at optimizing the operations of ESSs, EVs, and energy buildings (EB) units. However, this approach involves solving optimization problems at every time step, a process that becomes computationally burdensome for large-

scale ISTMGs or systems with multiple ESS units. In ISTMGs, MPC controllers also need to interact with various components and other controllers, leading to high communication overhead and subsequent delays and inefficiencies. These problems will require research efforts to devise viable solutions.

- EMS: The hierarchical EMS is particularly useful for islanded ISTMGs. Scenarios such as a large floating PV field under pitch motion, which results in fluctuating power output, are considered in ISTMGs. Although advantageous over previous methodologies, such EMS systems have limitations. For instance, errors stemming from inaccurate measurements and communication latencies persist in different EMS systems. Additionally, poor energy storage management systems continue to be a challenge, leading to elevated operational costs and reduced longevity of energy storage systems.
- Column and constraints generation (C&CG) algorithm: Managing optimization in ISTMGs is often complicated due to the varying outputs of DERs and fluctuating demand profiles. The Column and Constraints Generation (C&CG) algorithm struggles to develop an accurate and effective collection of columns and constraints given this complexity. Real-time decision making is vital for ISTMGs, and the computational demands of C&CG make it less suited for such applications. Further research will thus be required to improve the performance of the C&CG algorithm for use in ISTMGs.
- Machine learning: Machine learning techniques are employed to process high-dimensional datasets from DRER, ESS, wind turbines (WT), PV, and various load types like heat pumps in residential, commercial, and industrial settings. Despite its potential, issues such as model overfitting particularly in deep recurrent neural networks (deep RNN) result in subpar performance. In addition, the use of the Mamdani-based fuzzy logic controller (FLC) for distributed generation management involves high computational demands and time consumption. Research attention will thus be required in this regard to improve performance in ISTMGs.
- Security: Blockchain-based architectures have been developed to enhance the security of energy management systems. Although they are promising in many respects, the vulnerability to fake data injection attacks remains a concern. To address this, researchers have developed reinforcement learning strategies integrated with blockchain to detect such attacks. However, the high dimensionality of ISTMGs makes the reinforcement learning training and decision-making process computationally intensive, thereby increasing the time required for detecting fake data injection attacks (FDIA). Consequently, future research works will be required to improve the response time of such security algorithms to detect FDIA events in ISTMGs.

9. Conclusions

In this paper, we have presented a survey aimed at shedding light on three key aspects of interconnected smart transactive microgrids (ISTMGs), namely trading, energy management systems (EMS), and optimization, which are critical elements of any viable ISTMG framework. ISTMGs are important for revolutionizing the future landscape of energy distribution and management globally. However, despite their enormous potential, there are challenges that need to be addressed to ensure their successful deployment, scalability, and long-term viability. Thus, there has been a recent growth in the number of research efforts directed towards the development and deployment of viable ISTMGs, nevertheless, there has been little to no proper synthesis of the existing literature in these three key areas of ISTMGs. Consequently, our survey has provided an extensive overview of energy trading models, supporting architectures, transaction platforms, and the various stakeholders involved in ISTMGs. We emphasized the crucial role of EMS in efficiently managing energy flow, ensuring reliability, and improving operational performance within ISTMGs. Additionally, we discussed optimization techniques for assets and network architectures, highlighting their advantages and disadvantages based on specific ISTMG scenarios and constraints. Furthermore, we offered a comprehensive review of methods and techniques used in ISTMGs, drawing from extensive literature research. This information will be valuable to both practitioners and academics, offering insights into current best practices and areas requiring further investigation in ISTMGs. Our findings from this survey indicate that there are multi-faceted complexities inherent in developing ISTMGs, underscoring the crucial necessity for multidisciplinary collaboration to address these challenges. Secondly, given the unique requirements of ISTMGs, the effective management of energy flow, reliability assurance, and overall operational performance hinges significantly on the role played by EMS, thus warranting further research in EMS systems for ISTMGs. Thirdly, the optimization of various MGs is important as it significantly impacts the overall performance of ISTMGs. Thus, to overcome these challenges, a coordinated effort involving researchers, industrial stakeholders, and policymakers is indispensable. The overarching goal should not solely focus on achieving optimal energy trading but also on establishing a resilient, efficient, and sustainable energy ecosystem.

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