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Review Paper

A Systematic Review on Operation Management of Multi-Microgrid Systems: Objectives, Networks, and Energy Management Systems

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Abstract— *This paper presents a comprehensive review of the operation management of multi-microgrid systems. The multi-microgrid systems focus on the coordination between neighbor microgrids in the distribution systems. The microgrids integrate different distributed energy resources to supply the required loads. Renewable resources, dispatchable resources, battery energy storage systems, and demand-side management including price-based and incentive-based demand response programs are common distributed energy resources in microgrid systems. This review paper studies the application of different distributed energy resources and provides to determine the application of which distributed energy sources are significant in microgrid systems. Besides, this paper divides the multi-microgrid systems into single and multi-carrier systems. The multi-carrier multi-microgrid systems integrate the electrical, heating, cooling, hydrogen, and water systems to increase the flexibility of the system. In this paper, the structure of multi-carrier multi-microgrid systems also has been studied. This review work lists the advantages/disadvantages of different research works in multi-microgrid fields. The outlines and results of this review show that operating costs are the main objective of multi-microgrid systems. Also, uncertainty modeling for renewable energy is an integral part of energy management. Besides, the review work shows that multi-microgrid systems are developing towards multi-carrier energy systems to improve synergy.*

Keywords—Renewable energy sources, microgrids, multi-microgrid, multi-carrier system.

1. INTRODUCTION

1.1. Motivation

The traditional power systems are formed from fossil-based power plants such as steam and combined cycle power plants. These power plants are located in distant places from the end-users [1, 2]. Therefore, the generated energy passes from transmission lines and creates power losses. Also, these power sources consume fossil fuels for energy production to increase the emission of greenhouse gases. The integration of distributed energy sources (DERs) as well as renewable energy sources (RES) is known as the main solution to reduce power losses and carbon emissions [3, 4].

According to the World Energy & Climate Statistics in 2023, renewable energy sources make up 98.3% of Norway's energy production share. The share of RES in Brazil is 89.3%. New Zealand, Denmark, and Portugal are in the next rank with 87.6%, 87.2%, and 75.5%, respectively. Fig. 1 shows the penetration of RES in different countries [5].

The output power of RES is dependent on the weather conditions and their uncertainty is higher than fossil-based power plants. To control the intermittent behavior of RES, the concept of

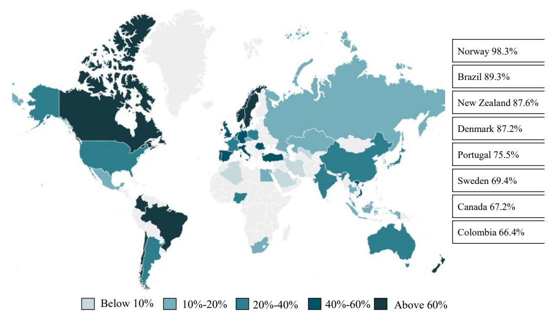

Fig. 1. Share of renewables in electricity production [5].

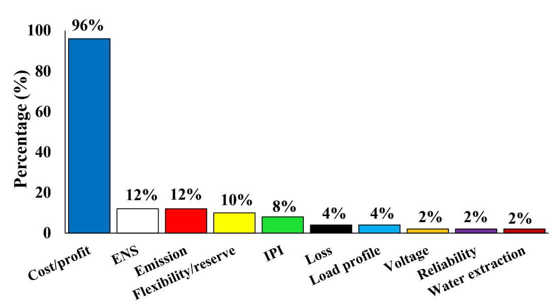

Fig. 2. Percentage of different objective functions in the MMG studies.

microgrid (MG) systems was introduced [70, 71]. The MG refers to a small-scale energy system that integrates the DERs, energy storage systems (ESS), and loads and can be operated in both

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Table 1. Comparison between this paper and other review papers.

Refs.	Year	Pros	Cons
[6]	2024	• Investigate the real projects • Study the market topologies • Focus on the reliability and resiliency of MGs	• DR programs have not been studied • The electricity networks have not been studied • The objectives of the MMG systems have been ignored • The types of DERs have not been studied • The single- or multi-carrier MMG systems have not been categorized
[7]	2021	• Study the energy scheduling framework • Compare the communication technologies • Application cases are evaluated	• The types of DERs have not been studied • The electricity network structures have not been studied • The number of MGs in the MMG system has not been categorized • The integrated MMG system has been ignored • The objectives in the energy scheduling of the MMG systems have not been evaluated
[8]	2023	• The solution procedure is studied • The objectives are considered • The electricity networks are studied	• DR programs have not been studied • The uncertainty in MMG systems has been ignored • The multi-carrier MMG systems have not been studied • The pros and cons of research works have not been defined
This paper	**2025**	• DR programs are studied • The electricity networks are studied • The objectives of the MMG systems are considered • The types of DERs are studied • Single- and multi-carrier MMG systems are categorized • The energy scheduling framework is studied	• Communication technologies have not been studied

Table 2. Objective functions in the MMG studies.

Refs.	Single objective	Multi-objective	Objectives								
			Cost / Profit	ENS	Emission	Loss	Uniform load profile	IPI	Flexibility	Reliability	Water
[9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40]	✓		✓								
[41]		✓	✓			✓					
[42]		✓	✓			✓					
[43]		✓	✓	✓					✓		
[44]		✓	✓				✓				
[45]		✓	✓		✓						
[46]		✓	✓	✓							
[47]		✓	✓	✓				✓			
[48]		✓	✓				✓		✓		
[49]		✓	✓		✓				✓		
[50]		✓	✓	✓	✓				✓		
[51]		✓	✓			✓		✓	✓		
[52]		✓	✓						✓		
[53]		✓	✓					✓			
[54]		✓	✓	✓	✓						
[55]		✓	✓	✓							
[56]		✓	✓	✓				✓			
[57], [58]		✓	✓								✓
[59]		✓	✓		✓						
[60]		✓	✓		✓						

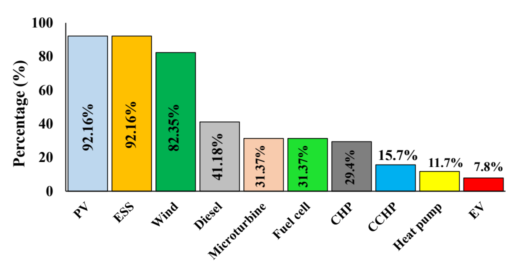

Fig. 3. Share of DERs in the MMG studies.

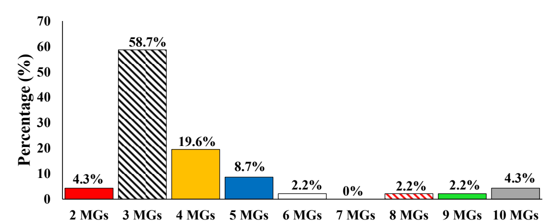

Fig. 4. Percentage number of MGs the MMG studies.

grid-connected and islanded modes [72, 73]. The MGs optimize the operation cost of the system using a combination of RES, controllable resources, and storage systems. Also, they can reduce the application of traditional fossil fuel power plants resulting in minimum carbon emissions. Therefore, MGs reduce carbon footprint and help to meet sustainability goals in their energy systems. Besides, MGs increase the resiliency of the system in the face of grid disruptions and extreme weather events because they can supply critical loads by local sources and storage systems. In addition to increasing the penetration of RES, the application of MG systems is increased. The multi-microgrid (MMG) system describes the interconnection between neighbor MGs in the distribution systems. The operation management of MGs as the MMG system increases their ability to control the uncertainty of RES in the distribution network. To this end, this paper presents

Table 3. DERs in the MMG studies.

Refs.	PV	WF	TS	Hydro	Biomass	Boiler	Diesel	CHP	CCHP	MT	FC	DR	EV	HP	Cap.	EES	TES
[41]	✓	✓								✓						✓	
[9]	✓	✓							✓							✓	
[61]	✓	✓					✓									✓	
[10]	✓	✓					✓						✓				
[57]	✓	✓			✓		✓	✓		✓	✓				✓	✓	✓
[62]	✓	✓					✓				✓	✓			✓		
[11]					✓					✓					✓		
[42]	✓	✓									✓				✓		
[43]	✓	✓							✓							✓	
[12]	✓						✓			✓					✓		
[13]	✓	✓			✓		✓				✓				✓	✓	✓
[44]	✓	✓						✓		✓	✓					✓	
[14]	✓	✓					✓				✓						
[45]	✓	✓					✓				✓				✓		
[15]	✓	✓					✓									✓	
[16]					✓											✓	
[17]	✓	✓						✓								✓	
[18]	✓	✓			✓		✓				✓				✓	✓	
[19]	✓	✓					✓				✓				✓		
[20]	✓	✓		✓		✓		✓			✓			✓		✓	
[21]	✓	✓					✓				✓				✓		
[22]	✓	✓								✓	✓				✓		
[23]	✓	✓			✓				✓		✓		✓		✓		✓
[24]	✓															✓	
[25]	✓	✓						✓		✓					✓		
[26]	✓	✓					✓				✓				✓		
[27]	✓				✓						✓				✓		
[28]	✓	✓					✓									✓	
[29]	✓	✓			✓		✓				✓	✓			✓	✓	✓
[30]	✓	✓			✓	✓	✓	✓		✓						✓	
[31]	✓	✓			✓		✓	✓		✓					✓	✓	
[32]	✓	✓			✓		✓	✓		✓	✓				✓	✓	✓
[33]	✓	✓	✓					✓		✓	✓				✓	✓	
[34]	✓				✓		✓	✓					✓		✓		
[46]	✓	✓						✓			✓				✓		
[47]	✓	✓						✓	✓							✓	
[48]	✓	✓					✓		✓	✓	✓				✓		
[49]	✓	✓						✓	✓	✓					✓		
[50]	✓	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓		✓	✓	✓
[51]		✓				✓			✓								
[52]	✓	✓			✓		✓				✓				✓	✓	
[58]		✓			✓		✓										
[35]		✓				✓										✓	
[36]	✓	✓						✓								✓	
[37]	✓	✓					✓									✓	
[38]	✓				✓						✓				✓		
[39]	✓	✓					✓									✓	
[40]	✓	✓					✓		✓	✓	✓				✓		
[53]	✓	✓					✓		✓	✓	✓				✓		
[54]	✓	✓					✓		✓	✓	✓				✓		
[55]	✓	✓						✓								✓	
[56]	✓	✓					✓		✓	✓	✓				✓		
[59]	✓	✓						✓	✓				✓		✓	✓	✓
[60]	✓	✓			✓			✓	✓	✓					✓	✓	
[63]	✓															✓	
[64]	✓	✓		✓						✓					✓	✓	
[65]	✓					✓							✓				

a comprehensive review of the operation management of MMG systems.

1.2. Literature review

In recent years, different research works have focused on the operation of MGs in the MMG system. The authors in [41] present a multi-objective optimization to simultaneously minimize the operating cost and power losses. A stochastic approach is utilized to model the uncertainty of RES, load, and electricity prices. However, the proposed model does not consider the efficiency of demand response programs in MGs. An optimal real-time energy management scheme is proposed in [9] that integrates the energy storage system in the MMG system to reduce the operating cost and carbon emission of the MMG system. The proposed model only considers the electricity requirements, and the heating, cooling, and water requirements have been not considered. Also, the uncertainty of load demands, RES, and electricity prices are ignored. A transactive energy framework is developed in [61] that studies the peer-to-peer energy trading between MGs in the

Table 4. Number of MGs in the MMG studies.

Refs.	2 MG	3 MG	4 MG	5 MG	6 MG	8 MG	9 MG	10 MG
[35], [65]	✓							
[41], [9], [57], [66], [42], [12], [13], [45], [16], [18], [20], [21], [22], [23], [24], [31], [34], [47], [48], [49], [50], [58], [38], [39], [40], [53], [54], [56], [59], [63], [64]		✓						
[61], [11], [44], [25], [28], [29], [46], [52], [36], [37], [60]			✓					
[43], [15], [26], [30]				✓				
[10], [62]					✓			
[27]						✓		
[67]							✓	
[17], [33]								✓

Table 5. Number of MGs in the MMG studies.

Refs.	Single bus	5 & 6-bus IEEE	18-bus	33-bus IEEE	40-bus	51-bus	69-bus IEEE	84-bus Taiwan Power Company	118-bus IEEE
[57], [62], [66], [43], [13], [14], [45], [16], [18], [19], [23], [25], [28], [29], [31], [32], [47], [49], [52], [58], [36], [38], [39], [40], [59], [63], [64]	✓								
[15], [21], [30], [48], [53], [54], [56]		✓							
[50]			✓						
[9], [61], [10], [11], [33], [34], [51], [35], [55], [60]				✓					
[46]					✓				
[26]						✓			
[44], [22], [37]							✓		
[12]								✓	
[27]									✓

Table 6. Deterministic and stochastic model in MMG systems.

Model	Refs.
Uncertain model	[41], [10], [62], [66], [12], [13], [44], [45], [18], [19], [20], [21], [22], [23], [25], [26], [28], [29], [32], [33], [48], [49], [50], [52], [37], [38], [40], [53], [54], [55], [56], [60]
Deterministic model	[9], [61], [57], [42], [43], [14], [16], [17], [24], [27], [30], [31], [34], [51], [58], [35], [36], [39], [59], [63], [64], [65]

Table 7. Uncertain parameter in MMG system.

Refs.	Deterministic	Stochastic	Load	PV	Wind	Price	EV	Hydro
[9], [61], [57], [42], [43], [14], [16], [17], [24], [27], [30], [31], [34], [51], [58], [35], [36], [39], [59], [63], [64], [65]	✓							
[18], [28], [32], [33], [48], [50], [37], [53]		✓		✓	✓			
[10], [62], [66], [44], [45], [19], [26], [40], [60]		✓	✓	✓	✓			
[12]		✓	✓	✓		✓		
[41], [13]		✓	✓	✓	✓	✓		
[23], [47], [52], [54], [56]		✓		✓	✓	✓		
[21], [25], [49], [55]		✓	✓	✓	✓	✓		
[22]		✓	✓	✓	✓	✓	✓	
[38]		✓	✓	✓		✓		
[67]		✓		✓				
[20]		✓			✓			✓

distribution network. The proposed model tries to minimize the operating cost of MGs. To this end, MGs integrate the battery energy storage system to cover the uncertain behavior of RES. However, the energy not supplied, power quality, and carbon emission have not been considered in the objective functions in the proposed model. Also, the demand response programs and uncertainty of RES have been ignored. The authors in [10] study the efficiency of electric vehicles on the MMG systems. A stochastic optimization framework is developed to consider the uncertainty of RES and increase the reliability of the model. However, the coalition forming between MGs in the distribution network has been ignored. Also, the efficiency of the proposed model in the multi-carrier MMG system has not been developed.

A cooperative scheduling model is presented in [67] using metaheuristic optimization algorithms in the MMG system. The results of the proposed model show that cooperative management reduces the operating cost by 6.5% compared to the non-cooperative framework. However, the uncertainty of RES and demand response programs have not been studied. A multi-objective optimization framework is developed in [57] that simultaneously minimizes the operating cost and water extraction in the multi-carrier MMG system. The proposed model integrates the electrical,

Table 8. Single and multi-carrier MMG system.

Refs.	Electricity	Heat	Cooling	Hydrogen	Water
[41], [9], [61], [10], [67], [62], [11], [42], [43], [12], [14], [45], [15], [16], [19], [21], [22], [24], [25], [26], [27], [28], [46], [35], [36], [37], [38], [39], [55], [63], [64]	✓				
[66], [13], [17], [20], [23], [29], [65]	✓	✓			
[30], [33]	✓	✓	✓	✓	
[57], [32], [50]	✓	✓	✓	✓	✓
[31], [34], [59]	✓	✓	✓		
[52], [58]	✓	✓			✓
[51]	✓			✓	
[60]	✓	✓		✓	

Table 9. Comparison of published research work from DR perspective.

Refs.	Features
[41], [9], [61], [10], [67], [43], [44], [15], [16], [17], [20], [24], [30], [34], [46], [47], [51], [58], [35], [36], [37], [39], [55], [59], [60], [63], [64], [65]	• DR programs have not been considered.
[11]	• The interruptible DR program is considered.
[12]	• The efficiency of price-based DR programs on power losses, load profile, and voltage deviation are investigated. • Only electrical DR programs are studied.
[13]	• The elasticity matrix is used for price-based DR programs. • Electrical and thermal DR programs are studied.
[45]	• Both shiftable and non-shiftable loads are considered. • Only electrical DR programs are studied. • Thermal DR programs have not been developed.
[18]	• Both price-based and incentive-based DR programs are considered. • Both electrical and thermal DR programs are studied.
[19]	• Both price-based and incentive-based DR programs are considered for electric loads. • Thermodynamic model for air conditioning is used.
[21]	• Incentive-based DR programs are considered using the piece-wise step model.
[31]	• Real-time pricing tariff is considered. • Electrical and thermal DR programs are considered. • Incentive-based DR programs have not been studied.
[32]	• Electrical and thermal DR programs are considered. • Incentive-based DR programs have not been studied. • Real-time pricing tariff is considered.
[52]	• Electrical and thermal DR programs are considered. • Price-based tariff is considered.
[68]	• Both price-based and incentive-based DR programs are studied. • Thermal DR program has been neglected.
[69]	• Incentive-based DR programs are studied. • Non-shiftable, power-shiftable, and time-shiftable loads are considered.

hydrogen, water, heating, and cooling sections to increase the reliability and synergy of the MMG system. However, the coalition forming between network MGs has not been studied. Besides, the uncertainty of RES and load demands have been ignored. A Tunicate Swarm Algorithm has been developed in [62] to study the energy scheduling of MMG systems in both grid-connected and isolated modes. The proposed model integrated the battery storage system with renewable generation to store the surplus generation

Table 10. Different energy management schemes.

Refs	Scheme	Advantages	Disadvantages
[42], [23], [26], [34], [39]	Distributed	• Providing opportunity for peer-to-peer energy trading. • It has higher privacy.	• Complex mathematical formulation. • Need more equipment (local EMS).
[67], [44], [17], [21], [28], [29], [30], [31], [32], [48], [49], [50], [52], [58], [36], [40], [53], [54], [56], [59]	Centralized	• Guarantees optimal solution for MMG system. • Lower cost of equipment.	• It has low privacy. • Peer-to-peer trading is neglected. • Coalition forming between MGs is needed.
[14], [15], [16], [17], [24], [47], [35], [37], [65]	Decentralized	• It has higher privacy. • Simple mathematical formulation.	• Peer-to-peer trading is neglected. • Cannot ensure optimal solution for MMG system. • Need more equipment (local EMS).
[12], [45], [25]	Hybrid algorithm	• Provides opportunity for peer-to-peer energy trading.	• It has low privacy. • Complex mathematical formulation. • Need more equipment (local EMS).

Table 11. Proposed model of the MMG research works (Part a).

Refs.	Model	Pros	Cons
[12]	• Single-objective optimization. • Bi-level problem. • Stochastic approach.	• Demand response programs are studied. • The electricity grid and power flow constraints are considered. • The uncertainty of renewable generation and loads is modeled.	• Carbon emission has not been considered. • Reliability indexes are not studied. • The efficiency of electric vehicles has not been evaluated. • The multi-energy MMG systems have not been developed.
[13]	• Single-objective optimization. • Stochastic approach. • Mixed integer nonlinear program.	• The electrical and thermal energy storage systems are integrated into the proposed structure. • The uncertainty of renewable generation and loads is modeled. • The heating system is integrated with the electricity system.	• Carbon emission has not been considered. • The flexibility of the system has not been considered as an objective function. • The energy not supplied has not been studied. • The electricity networks have not been considered.
[44]	• Multi-objective optimization. • Stochastic approach. • Two-stage model.	• The fuel cell and CHP unit are considered to increase the flexibility of the MMG system. • The proposed model tries to uniform the load profile. • The electricity network and power flow constraints have been applied in the proposed model. • The uncertainty of input parameters is considered.	• The role of demand response programs has not been evaluated. • The reliability of the MMG system has not been considered as an objective function. • The carbon emission has not been calculated. • The coalition forming between the MGs is not studied.
[14]	• Single-objective optimization. • Deterministic approach. • Bi-level model.	• The demand response programs are considered. • The proposed model studies the interaction between the energy service provider and MGs.	• The energy not supplied, power losses, and voltage profile have not been considered as objective functions. • The battery energy storage system has not been considered. • Environmental problems have not been modeled. • Power flow constraints have not been considered. • Electricity grids have been neglected. • The probabilistic behavior of renewable generation and loads has been ignored.
[16]	• Bi-level problem. • Deterministic approach. • Cooperative scheduling.	• Different residential, industrial, and commercial MGs are studied. • Battery energy storage systems are considered. • Cooperation between MGs is studied. • The Shapley value is used to fairly divide the cooperation profit among MGs.	• The proposed model does not consider water requirements. • Cooling and heating systems have not been incorporated into the proposed structure. • The uncertainty of load and renewable generation has not been considered. • Electric vehicles and demand response programs have not been considered. • Renewable energy resources have not been integrated into the proposed model. • Reliability, flexibility, and power losses have not been considered as objective functions.
[19]	• Two-stage scheduling. • Robust approach.	• The uncertainty of PV and WT units is considered. • Load uncertainty is considered. • Time-of-use electricity prices are used for the electricity grid. • A real-time strategy is used to control load profiles.	• Cooling, heating, and water sections have not been studied. • Hydrogen storage system has not been considered. • Electricity network has not been studied. • Power flow constraints have not been developed. • The efficiency of electric vehicles has not been studied. • Power quality indices have not been studied.

during off-peak hours. However, the power quality index and peer-to-peer energy trading between MGs have not been studied.

A hybrid day-ahead and intraday operation scheduling frameworks is developed in [66] that focuses on the power sharing between MGs in the distribution network. The proposed model formulated as two-stage framework. The first stage is responsible for day-ahead scheduling to present a low-carbon operation. The second stage considers RES fluctuations and utilize demand response programs to cover their uncertainties. However, the electricity network and power losses are not considered. The authors in [11] present a cooperative model that aims to increase the reliability of the MMG system during emergency situations. To this end, incentive-based demand response programs are utilized to reduce the penalty cost for unsupplied energy. However, the efficiency of the proposed model on the multi-energy system has not been studied. Also, coalition forming between MGs has been ignored.

Ref. [42] proposed a cooperative framework that integrated the energy storage systems in order to cost reduction. Ref. [43] studies the reliability of MGs in the stand-alone MMG system. The authors in [12] investigate the impact of demand response programs (DRP) and ESS on the reconfiguration of the MMG system. Amir et al. [13] investigated the operation scheduling of a multi-carrier MMG system where the system integrated the electrical and thermal systems to increase the synergy and efficiency of the system. A two-stage framework has been proposed in [44] that considers controllable and non-controllable resources to simultaneously minimize the operation cost and improve the load profile. The authors in [14] present a bi-level framework that models the interaction of MGs and large central production units. The large central production unit is the leader of the problem and attempts to minimize its generation cost at the upper level, while the MGs are considered the follower of the optimization framework. The authors in [45] suggested a multi-objective optimization model to simultaneously minimize the operation cost and emission of greenhouse gases using the integration of RES and

Table 12. Proposed model of the MMG research works (Part b).

Refs.	Model	Pros	Cons
[22]	• Single-objective optimization. • Two-layer energy management. • Bi-level problem. • Stochastic approach.	• The efficiency of demand response programs is studied. • The role of electric vehicles is evaluated. • The proposed model is tested on a standard electricity network. • The uncertainty of load, prices, and renewable resources is considered.	• Carbon emission has not been considered. • Power losses have not been studied. • Energy not supplied has not been considered. • The multi-energy system has not been developed.
[24]	• Single-objective optimization. • Deterministic approach.	• Power quality constraints are considered. • The interaction between the distribution network and MMG system is formulated. • Residential, industrial, and commercial MGs are considered. • The electricity network and power flow constraints are developed. • Energy trading between MGs is studied. • Harmonic power flow is performed.	• Cooling, heating, and hydrogen systems have not been integrated. • The uncertain nature of renewable generation is not considered. • Demand response programs have not been developed. • The role of electric vehicles has not been considered. • The reliability of the system has not been considered.
[27]	• Single-objective optimization. • Two-stage scheduling. • Deterministic approach.	• Peer-to-peer energy trading between MGs is formulated. • The electricity network is considered. • Energy storage systems are integrated into the MMG system.	• Energy not supplied has not been considered as an objective function. • Power losses have not been considered as an objective function. • The role of electric vehicles has not been studied. • Cooperation between MGs has not been studied. • Coalition forming between MGs has been ignored. • The uncertainty of renewable generation has been ignored.
[29]	• Stochastic approach. • Single-objective optimization.	• The efficiency of electric vehicles is evaluated. • Electrical and thermal demand response programs are studied. • Cooperation between MGs is developed. • Fair cost allocation between cooperating MGs is studied. • The uncertainty of renewable generation is considered.	• Power-to-gas and gas-to-power systems have not been considered. • Cooling systems have not been integrated into the proposed model. • Coalition forming between MGs has not been studied. • Power losses have not been formulated. • Carbon emission has been ignored.
[30]	• Single-objective optimization. • Deterministic approach.	• Electricity, cooling, and heating systems are integrated. • The power-to-gas converter is modeled. • The multi-energy system is studied. • Hybrid planning and operation of multi-energy systems are studied.	• The uncertainty of load demand and renewable generation has not been considered. • Peer-to-peer energy trading between MGs has been ignored. • Fair cost allocation has not been developed. • Power quality indices have not been studied.
[31]	• Single-objective optimization. • Deterministic approach.	• The multi-energy system is studied. • Cooperative scheduling is developed. • Fair cost allocation between MGs is developed.	• Peer-to-peer energy trading between MGs has been ignored. • The uncertainty of renewable resources has not been considered. • Power-to-gas and gas-to-power systems have not been studied. • Power quality indices have been ignored. • Carbon emission and energy not supplied have not been considered as objective functions.
[32]	• Stochastic approach. • Single-objective optimization.	• The uncertainty of renewable resources is considered. • Cooperation between neighboring MGs is studied. • Power-to-gas and gas-to-power systems are used. • Renewable generation uncertainty is modeled using a stochastic approach. • Multi-carrier energy systems are studied. • Both cooperative and decentralized scheduling are evaluated.	• Power quality indices have not been developed. • AC power flow has been ignored. • The interaction between MGs and the distribution system operator has not been considered. • Coalition forming between MGs has not been studied.
[33]	• Stochastic approach. • Single-objective optimization. • Robust chance-constrained.	• Demand response programs are considered. • Electricity network is considered. • The uncertainty of renewable generation is studied. • Hydrogen systems are integrated into the electricity network.	• Electric vehicles have not been considered. • Carbon emission and power losses have not been considered as objective functions. • Energy not supplied has not been considered as an objective function.
[46]	• Multi-objective optimization.	• Power flow and electricity network are considered. • The role of electric vehicles is studied. • The proposed model considers energy not supplied as an objective. • Both islanded and grid-connected modes are studied.	• Water systems have not been modeled. • Water storage systems and hydrogen storage tanks have not been developed. • Demand response programs have not been considered. • Cooperation between MGs has not been studied.
[49]	• Multi-time-scale scheduling. • Multi-objective optimization. • Two-stage approach.	• Demand response programs are integrated into the proposed model. • Microturbine and fuel cell units are considered to cope with renewable uncertainty. • Carbon emission is considered as an objective function. • The flexibility of the MMG system is studied. • The uncertainty of load, prices, and renewable generation is modeled using stochastic optimization.	• Electricity networks have not been considered. • Multi-energy systems have not been studied. • Water MMG systems have not been developed. • The reliability of the MMG system has not been evaluated.

DRP. In this work, we categorize the recently published works on the MMG system from different perspectives such as generation sources, objectives, uncertainty modeling, and networks. To this end, Refs. [6–8, 12–40, 42–48, 48–56, 58–60, 63–65, 68, 69, 74] ar e considered that have been published in high-quality journals. The main contribution of this review paper is that we try to consider the network structures of the MMG system. Besides, the percentage of different resources, objectives, network structures, and number of MGs are calculated. These references have been selected through the Scopus citation database. Based on the publication year, the type of article (conference or journal), and the field of study (energy management), the initial set has been refined.

1.3. Research gap challenges

According to section 1.2, most of the research works are focused on the operation management of the MMG system. Some of the research works consider the single-carrier MMG system, while little attention is paid to the multi-carrier MMG system. To the best of our knowledge, the main research gap challenges can be listed as:

Table 13. Proposed models of the MMG research works (Part c).

Refs.	Model	Pros	Cons
[51]	• Multi-objective optimization • Deterministic approach	• Decreases interaction between MGs and the main grid. • Power losses are considered as an objective function. • Electricity network and power flow constraints are considered. • Hydrogen storage tank increases system flexibility.	• Uncertainty of load demand and renewable generation has not been considered. • Demand response programs have not been studied. • Electric vehicles have not been evaluated. • Coalition formation has been ignored. • Peer-to-peer energy trading has not been studied.
[52]	• Multi-objective optimization • Stochastic approach	• Demand response programs are modeled. • Reduces extracted underground water. • Water storage tank is utilized. • Renewable generation, load, and price uncertainties are considered.	• Peer-to-peer energy trading has not been studied. • Power losses have not been calculated. • ENS and reliability indices have not been studied. • Upstream network independency has not been considered. • Harmonic power flow has been ignored. • Coalition formation has not been developed.
[58]	• Multi-objective optimization • Deterministic approach	• Minimizes extracted underground water. • Water storage tank is modeled.	• Hydrogen system has not been considered. • Demand response programs have not been studied. • Electric vehicles have not been studied. • Peer-to-peer trading has been ignored. • Coalition formation has not been developed. • Power flow and electricity network have been ignored. • Renewable uncertainty has not been studied.
[35]	• Single-objective optimization • Deterministic approach • Bi-level program	• 33-bus IEEE electricity network is considered. • Transactive energy between MGs and DNO is studied. • Converted into a single-level problem using KKT conditions.	• Carbon emission has not been considered. • Power losses and power quality have not been investigated. • Demand response, market uncertainty, renewable uncertainty, gas network and MG cooperation have not been studied.
[36]	• Single-objective optimization • Deterministic approach	• Reliability assessment is studied. • Critical and non-critical loads are considered. • Battery storage and renewable resources are integrated.	• Carbon reduction has not been studied. • Flexibility has not been considered. • Multi-energy system has not been developed. • Uncertainty has not been considered.
[37]	• Single-objective optimization • Robust approach	• Decentralized scheduling mechanism is utilized. • Power flow and electricity network are considered. • Renewable uncertainty is modeled. • Robust operation is studied.	• ENS, power losses, flexibility and upstream dependency have not been objective functions. • Demand response has been ignored. • Electric vehicles have not been studied. • Power quality has not been considered. • Integrated energy systems have not been developed.
[38]	• Tri-step energy management • Single-objective optimization • Risk-based model	• Worst scenarios for load and renewable generation are considered. • Adjustable power concept is introduced. • Demand response and battery storage are integrated.	• Coalition formation has not been studied. • Heating, cooling, hydrogen and water systems have not been considered. • Electricity network, power flow, power quality, ENS and flexibility have not been considered.
[40]	• Bi-layer model • Stochastic approach	• Isolated MMG system is studied. • Wasted energy is considered. • Privacy is ensured. • Uncertainties and adjustable power are considered.	• Grid-connected mode has not been investigated. • Hydrogen, water, heating and cooling systems have not been developed. • Coalition formation has been ignored. • Electricity grid has not been considered.
[54]	• Two-stage scheduling • Multi-objective optimization • Scenario generation and reduction	• Carbon emission is considered. • ENS is considered. • Fair cost allocation and renewable uncertainty are developed.	• Multi-energy system has not been studied. • Power losses and AC power flow have not been considered. • Peer-to-peer trading and coalition formation have been ignored.
[55]	• Multi-objective optimization • Two-stage scheduling • Risk-based model	• ENS is considered. • Electricity network and uncertainties are considered. • Renewable uncertainty is modeled.	• Demand response has not been studied. • Electric vehicles and upstream dependency have been ignored. • Peer-to-peer trading, coalition formation and multi-carrier systems have not been studied.
[56]	• Multi-objective optimization • Stochastic approach • Lexicography technique • Multi-criteria decision making	• Independence performance index is introduced. • Cost, ENS and independence are simultaneously optimized. • Renewable uncertainty is modeled. • Demand response programs are integrated.	• Coalition formation has not been studied. • Coordination among electrical, thermal, cooling and hydrogen systems has not been considered. • Power quality has not been evaluated. • Peer-to-peer trading with DNO has not been modeled.
[60]	• Multi-objective optimization • Multi-agent deep reinforcement learning	• Electrical and thermal storage systems are integrated. • Electricity, heating and hydrogen systems are integrated. • Renewable, load and price uncertainties are considered. • Electricity network is considered.	• Cooperation between MGs has not been developed. • Harmonic power flow has been ignored. • Peer-to-peer trading has not been formulated. • Fair cost allocation has not been developed.
[65]	• Bi-level problem • Deterministic approach	• Electrical and thermal systems are coupled. • Power flow constraints are considered. • Electrical and heat networks are considered.	• Demand response has been ignored. • Electric vehicles have not been studied. • Power quality and harmonic power flow have not been examined. • Carbon emission has been ignored. • Peer-to-peer trading and coalition formation have not been studied.

1. The cooperation between MGs can be found in some research works. In the cooperative mechanism, the MGs can create a big coalition to reduce their operating costs. However, proposing an analytic approach that can define the best coalition sets in the MMG system and determine the best cooperator MGs has not been found.

2. Demand response programs are one of the main tools in the MMG system to control the uncertainty of RES. Different research work studied the electrical and thermal demand response programs in the MMG system from different perspectives. However, the correlation of electric and thermal loads is not taken into account.

3. Most of the studies in the MMG energy management field are focused on operation cost reduction, and a limited number of them have also focused on the emission of greenhouse gases in addition to the operating costs. However, a hybrid framework that incorporates optimal management, environmental problems, and power quality indexes has not been developed. To this end, the harmonic power flow can be utilized to determine total harmonic distortion in voltage (VTHD) or total harmonic distortion in current (ITHD) in power systems.

This paper presents a comprehensive review of MMG energy management. Compared to different review papers, this paper evaluates the application of electrical and thermal DR programs. Also, this work categorizes the MMG system into single-carrier or multi-carrier MMG systems. The main difference between this review paper and other published review papers is that it describes the main pros and cons of each research work. Table 1 compares this paper with other review papers [6–8] in the MMG energy scheduling field.

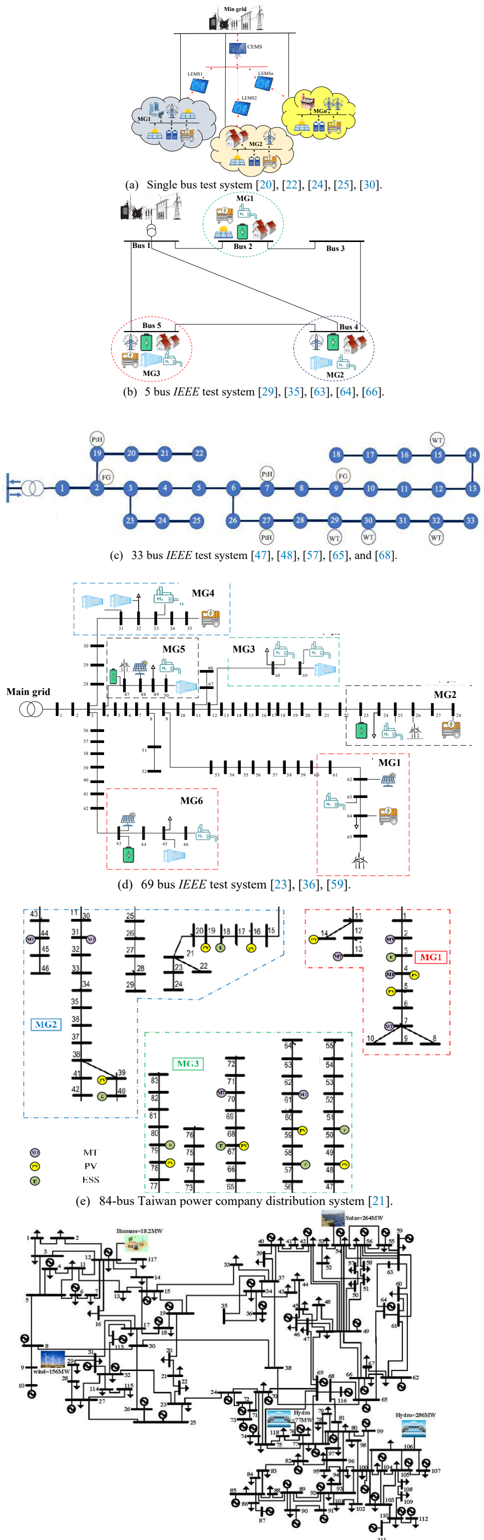
(a) Single bus test system [20], [22], [24], [25], [30].
(b) 5 bus IEEE test system [29], [35], [63], [64], [66].
(c) 33 bus IEEE test system [47], [48], [57], [65], and [68].
(d) 69 bus IEEE test system [23], [36], [59].
(e) 84-bus Taiwan power company distribution system [21].
(f) 118-bus IEEE test system [41].

Fig. 5. Structure of standard test systems.

1.4. Paper organization

The objective functions of the MMG studies are evaluated in section 2. Section 3 evaluates the distributed energy resources. Section 4 studies the number of MGs in different research works. The structure of the MMG systems is investigated in section 5. The uncertainty modeling is developed in section 6. Section 7 categorizes the MMG system into single or multi-carrier energy systems. The application of DR programs is studied in section 8. Section 9 provides the energy management schemes. Finally, the conclusion is presented in section 10.

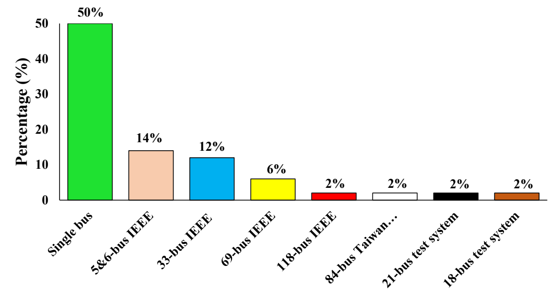

Fig. 6. Percentage of standard test systems.

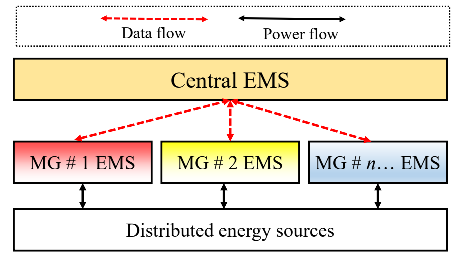

Fig. 7. Centralized energy management framework.

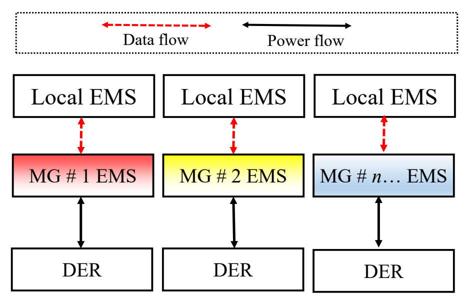

Fig. 8. Decentralized energy management framework.

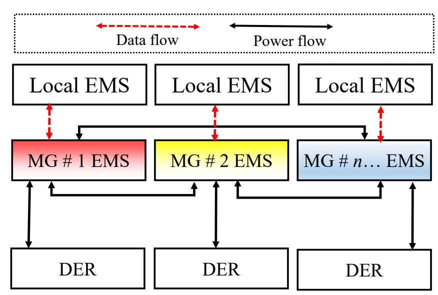

Fig. 9. Distributed energy management framework.

2. Objective functions

In the literature, the energy management of the MMG systems is formulated using mathematical optimization. Mathematical optimization refers to the selection of the best option from some set of available options with regard to some criteria. A general optimization problem is formed by minimizing or maximizing a function choosing input data from within an allowed set. In

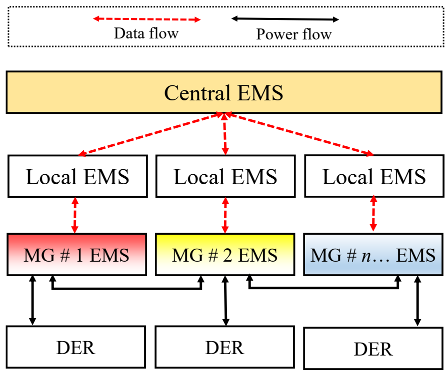

Fig. 10. Hybrid energy management framework.

the MMG system, the operator has different options to generate electricity to supply the loads. It can generate electricity from renewable generation resources, controllable distributed energy resources, or purchase electricity from the upstream network. The optimal generation of distributed energy resources will be selected based on a criterion, which is called the objective function. This objective function can be economic, environmental, technical, or hybrid of them.

If there is only one objective function, the optimization problem is known as a single objective problem. However if several economic, technical, and environmental objective functions are considered at the same time, the problem is referred to as a multi-objective model. In the single objective problems, the MMG system only considers the operation cost or profit as the objective function [12], [13], [14], [15–34]. The cost function is formed from the generation cost of the controllable resources, transactive energy with the main grid, maintenance cost of DERs, the penalty for load shedding, and incentive cost for DR programs, etc.

In multi-objective problems, the MMG system considers different criteria as objective functions. For example, the authors in [43] proposed a tri-objective model that simultaneously considers the cost, energy not supplied (ENS), and reliability index as the objective function of the MMG system. In [44], a bi-objective model is presented that tries to improve the load profile characteristic alongside with cost function. Ref. [45] simultaneously considers the cost function and emission of greenhouse gasses. Afrakhte et al. [46] proposed a multi-objective model considering the operation cost and ENS. The authors in [47] introduce the independence performance index (IPI) as one of the objective functions to reduce the transactive energy of the MMG system with the upstream network. The flexibility of the MMG system has been considered one of the objective functions in [48], [49], [50], [51], and [52] to increase the ability of the system to manage the uncertainty of RES. Ref. [58] proposed a bi-objective optimization that simultaneously minimizes the generation cost and water exaction from the underground sources. Table 2 compares the MMG studies from the objective function perspective.

Also, Fig. 2 shows the percentage of different objective functions. It can be easily seen that more than 95% of research works (single or multi-objective problems) considered the cost function or profit as one of the objective functions. The ENS and carbon emission are the second priority with 12%. The flexibility and IPI are considered in 10%, and 8% of research works, respectively. Also, little attention has been paid to voltage improvement, reliability indexes, and water extraction.

3. Distributed energy resources

Different DERs can be utilized in the MMG system to supply the required energy for their customers. Figure 3 shows the share of different DERs in the recently published works. Also, Table 3 analyzes different research works from the generation sources perspective. The generation sources can be divided into three categories such as RES, controllable resources, and ESS.

• **Renewable energy sources:** Photovoltaic panels (PV), solar thermal, wind turbine farms, and hydropower plants are considered renewable sources. The energy generation of RES is dependent on the weather conditions. Therefore, in the literature are named as non-controllable sources. Most of the research works considered PV and wind energy in their proposed model. According to Fig. 3, the PV sources and wind energy are the most popular sources that have been utilized in 92.16%, and 82.35% of research works, respectively. However, little attention has been paid to the hydropower plant and solar thermal sources.

• **Controllable resources:** Unlike RES, the output power of controllable resources can be adjusted by input fuel. The diesel generators, microturbines, fuel cells, combined heat and power (CHP) units, and combined cooling, heat, and power (CCHP) units are the main controllable sources. Fig. 3 shows that diesel generators, microturbines, and fuel cells are more popular controllable sources, and their application are 41.18%, 31.37%, and 31.37%, respectively.

• **Energy storage systems:** Energy storage systems such as battery energy storage (BES) and thermal energy storage (TES) can help the MMG system control the uncertainty of RES. The MMG system can charge the storage systems when the generation of RES is more than its consumption and discharge the stored energy when needed. This performance increases the reliability of the MMG system and reduces the load curtailments in peak hours. Also, the storage systems can help the MMG system to reduce its operation cost. The MMG system can charge their storage during off-peak hours when the electricity prices are low. The stored energy can be injected into the distribution system during peak hours to reduce the imported energy with higher prices. According to the literature, about 92.16% of the research works consider the battery storage system to control the uncertainty of RES and increase the flexibility of the system, while only 4% model the thermal storage systems.

4. Number of microgrids

The multi-microgrid concept refers to the interaction of neighbor MGs in the distribution systems. As a result, in the topic of multi-microgrid, we are faced with more than one MG. Fig. 4 shows the percentage of MGs in different studies. A comprehensive review of studies shows that more than 58% of studies have been conducted on networks with 3 MGs [42], [12, 13], [45], [16], [18], [20–24], [34], [48], [49], [50], [38], [39], [40], [53], [54], [56], [59], and [64]. Also, the studies with 4 and 5 MG are ranked next with 19.6% and 8.7%, respectively. Also, Table 4 analyses the number of studied MGs in detail.

5. Structure of networks of MMG system

The energy management of the MMG system was tested on different networks. Many research works such as [43], [13], [14], [45], [16], [18], [19], [63], etc. model the MMG system as a single bus. In this case, all of the MGs and their demands, energy storage systems, and DERs are located in one bus that can be connected or disconnected from the main grids.

On the other hand, some studies such as [42], [12], [15], [21], [22], [46], [48], [53], and [54], etc., considered the network structure and load flow constraints. In these studies, MGs are placed in different buses. For example, Ref. [42] evaluated the efficiency of the proposed model on the 34-bus radial distribution network. Ref. [12] considered the 84-bus Taiwan power company distribution system that consists of three MGs. The 69-bus IEEE test system has been considered in [44], [22], and [37]. The authors in [33], [35], [36], [55], and [60] tested the efficiency of the proposed model on the 33-bus IEEE distribution system. The ring networks 5 & 6 bus IEEE system was considered in [15],

[21], [30], [53], [54], and [56]. Fig. 5 shows the structure of different test systems.

Also, Fig. 6 and Table 5 present the percentage and detail of studied networks in different research works. As can be seen, 50% of research works model the MMG system as a single bus system. The small-scale test systems such as 5 & 6 bus IEEE test systems have been used in 14% of the research works. Also, the 33 bus and 69 bus IEEE test systems with 12% and 6% are in the net ranks, respectively.

6. Deterministic and stochastic MMG system

The MMG studies can be divided into deterministic and stochastic optimization. In deterministic optimization, the MMG operator does not consider the intermittent behavior of demand loads, renewable generations, and prices [42], [43], [14], [16]. However, in stochastic optimization, the MMG operator considers the uncertain behavior of renewable generation, loads, and market prices [12, 13, 44], [18–21]. Table 6 divides the deterministic and stochastic models.

Different methods can be utilized to model the uncertainty of uncertain variables. Some research works such as [20], [21], [22], [25], [29], [32], [47], [48], [49], [50], [40], [53], [54], and [56] use the probability distribution function (PDF) to create the possible scenarios for uncertain parameters. For example, Ref. [18] applies the beta and Weibull PDFs to model the uncertainty of PV and wind energy, respectively. The authors in [21] applied the beta, Weibull, normal, and normal PDFs to model the uncertainty of PV, wind energy, prices, and demands, respectively. Ref. [47] model the uncertainty of wind and solar energy by Weibull and beta PDFs. The authors in [22] consider the uncertainty of electric vehicles, prices, loads, and renewable generation by different PDFs. Also, Refs. [29], [32], [48], [50], and [53], only considered the uncertainty of PV and wind energy, while the uncertainty of load and prices were not considered. Unlike [48] and [53], the authors in [25], [26], [49], [40], [60] model the uncertain behavior of load demands by stochastic approach.

Unlike the stochastic approach, robust optimization was used in [23], [37], and [60] to model the uncertainty of loads and renewable generation for the worst cases. Also, the authors in [38] utilized the Information gap decision theory (IGDT) by risk approach to model the uncertainty of load and wind energy. The IGDT approach does not consider the PDF and utilizes the error between forecasted value and real parameters. Table 7 shows the uncertain parameters of different research works.

7. Single-carrier and multi-carrier MMG system

The MMG system can be divided into single-carrier or multi-carrier energy systems. In the single carrier systems, the MMG is only responsible for supplying the electricity needs [14], [45], [15], [16], [19], [21], [46], [35], and [63]. To this end, the MMG system utilizes renewable sources, controllable sources, DR programs, and battery storage systems to supply the required demands.

On the other side, the MMG system can integrate the electricity system with the heating system [13], [17], [20], [23], [29], and [65], hydrogen system [51], water system [52], [58], and cooling system [31], [32], [33], [34], [47], [50], and [59]. The integrated systems are known as multi-carrier systems. The multi-carrier system can increase the efficiency and flexibility of the system. For example, the authors in [13], [17], and [20] utilize the combined heat, and power (CHP) to simultaneously supply the electrical and thermal loads. It should be noted that the efficiency of CHP units is more than conventional gas-fired power plants.

Therefore, the application of the CHP unit increases the efficiency of the MMG system. Also, the integration of electricity and heating systems reduces the emission of greenhouse gases because the carbon coefficient of CHP units is lower than conventional gas-fired and steam power plants. It should be noted that the integration of the hydrogen system with the electricity system increases the MMG flexibility. The hydrogen system incorporated the electrolyzer, fuel cell, and hydrogen systems in the MMG system [30], [32], [33], and [50]. During off-peak hours, when the produced energy of RES is more than the loads, the surplus generation can be used by electrolyzer units to convert the water into hydrogen and oxygen. The generated hydrogen can be imported into the fuel cells to generate electricity during peak hours. The merge of electrolyzer and fuel cell units increases the power and energy flexibility of the MMG system.

Also, Refs. [31], [34], and [59] combine the electric chiller, and absorption chiller in the MMG system to convert the electricity and generated heat of CHP units into the cooling energy. When the generation of RES is high, their generated energy can be converted to cooling energy to supply the required cooling energy of hotels, apartments, and shopping centers. Table 8 categorized the MMG system into single and multi-carrier systems.

8. Demand response programs

In the MMG systems, DR programs can increase the reliability and flexibility of the MGs. The DR programs refer to programs that encourage consumers to transfer their demand to off-peak typically through monetary incentives or electricity prices [74]. Therefore, DR programs provide this opportunity for MGs to reduce their operating costs by load shifting. In the energy management of the MMG systems, different research works consider the efficiency of DR programs. An incentive-based interruptible DR program is utilized in [11] to increase the reliability of the MMG system in emergency conditions. The authors in [12] study the efficiency of the price-based DR programs on the voltage profile, load profile, power losses, and financial benefits of the MMG system. The concept of load elasticity has been utilized in [13] to determine the optimal hourly electrical and thermal load shifting in MGs using DR programs. The authors in [45] model both shiftable and non-shiftable loads to provide a cost-saving chance for the MMG system. The proposed model only evaluates the efficiency of the priced-based DR programs, while the incentive-based DR programs have been neglected. The hybrid price-based and incentive-based DR programs are studied in [18] to model the transactive energy between MGs in the distribution network. A price-based load shifting program is developed in [19] to cover the uncertainty of RES. Also, a thermodynamic model is extended for the air conditioning system to set the optimal temperature in the home.

A piece-wise step model is developed in [21] to model the incentive-based DR programs for MMG systems using direct load control. However, the thermal DR program has not been studied. The author in [31] investigates the impact of priced-based DR programs on the cooperation between MGs in the distribution network. The real-time pricing mechanism has been used to determine the optimal load shifting in the system. The role of real-time pricing tariffs for electrical and thermal DR programs on the MMG cost reduction is studied in [51]. However, the efficiency of incentive-based DR programs is neglected. The authors in [52] apply the electrical and thermal DR programs on the multi-carrier MMG system to simultaneously reduce operating costs and extract water from underground sources.

Both price-based and incentive-based DR programs are resented in [68] to decrease the difference between the ordering energy and real power consumption. In the proposed model, the DR programs and energy storage system help the MMG system to cover the uncertainty of RES. Ref. [69] considers different non-shiftable, power shiftable, and time-shiftable loads in small-scale energy systems. The aim of the proposed model is to reduce load consumption using incentive prices. Table 9 compares the different studies from the DR programs perspective.

9. Energy management schemes

The energy management in the MMG systems can be divided into centralized, distributed, hierarchical management, and multi-agent schemes.

9.1. Centralized energy management scheme

In this energy management scheme, the operation scheduling of all the MGs is determined by one central controller. The structure of the centralized energy management is shown in Fig. 7. The MGs send their information to the central controller. The central controller performs a global optimization to define the optimal scheduling for the MMG system. This management scheme can ensure the optimal solution for the MMG system. However, it cannot ensure the optimality for each MG. Ref. [44] utilizes centralized scheduling for the multi-carrier MMG system. The author in [17] evaluates the impact of energy storage systems in the MMG system using the centralized framework. The participation of the MMG system in the electricity market is studied in [21] using centralized scheduling to guarantee the optimal solution for MGs. A tri-layer centralized scheduling is developed in [48] to simultaneously consider the operating cost, demand-side flexibility, and generation flexibility. A hybrid particle swarm and gravitational search algorithm is developed in [28] to integrate renewable generation and energy storage systems in the MMG system using the centralized framework. In [49], a multi-objective centralized scheduling is presented to maximize the reserve capacity in the MMG system. Ref. [52] proposed a centralized scheduling that integrates the electricity section into the water and heating sections. Ref. [53] describes a centralized algorithm to manage the MMG system in order to maximize the independence from the main grid. Centralized two-stage scheduling is developed in [54] to simultaneously reduce the carbon emission, energy not supplied, and operation cost of the MMG system. The performance of centralized energy scheduling for isolated MMG systems is studied in [40]. The application of high-temperature heat and power storage systems in the multi-carrier MMG system is investigated in [59] using centralized scheduling. The main challenge in the centralized energy management system is that it does not consider the peer-to-peer energy trading between MGs.

9.2. Decentralized energy management scheme

In the decentralized energy management scheduling, each MG is equipped with a local energy system (Local EMS). Each local EMS is responsible to determine the optimal scheduling of its own MG. In this framework, the direct energy trading such as peer-to-peer energy trading between MGs is not provided. However, it is possible to MGs transact together by an interface such as distribution system operator. Fig. 8 shows the structure of the decentralized scheduling.

The authors in [14] developed a decentralized algorithm to model the interaction between MGs and energy services providers in the distribution network. Ref. [15] compares the centralized and decentralized schemes for the MMG system considering the role of battery energy storage systems. The authors in [16] study the performance of residential, commercial, and industrial MGs in the distribution system using a decentralized energy management system. An online decentralized energy management scheme is proposed in [17] that considers the uncertainty of renewable generations. Ref. [24] proposes a decentralized approach that simultaneously considers the energy management and power quality for unbalanced MGs. A multi-objective decentralized approach is presented in [47] that models the coordination between MGs and the distribution Companies in the retail market. The proposed model is formulated as a bi-level framework. The upper level simultaneously optimizes the profit of the operator, energy not supplied, and independence of MGs from the main grid. Also, the lower level tries to minimize the operating cost of MGs. The authors in [37] utilize a decentralized scheduling to manage the renewable-based MGs. The interconnection between the electrical and heating network in the MMG system is developed using decentralized scheduling [65]. However, the decentralized energy management system is not able to ensure the optimal solution for MGs.

9.3. Distributed energy management scheme

Fig. 9 shows the distributed energy management scheme in the MMG system. In the distributed energy management scheme, the MGs are able to exchange energy directly. This allows MGs for peer-to-peer energy trading. However, it has a more complex mathematical model rather than centralized and decentralized schemes. The authors in [42] present a distributed energy management framework to minimize the operating cost of the system. Ref. [23] presents a distributed scheduling considering the uncertainty of renewable generations. The proposed model utilizes the energy storage system to control the fluctuation of renewable resources. The energy trading between renewable-based isolated MMG systems is investigated using the distributed model in [26]. The daily energy scheduling of the multi-carrier multi-microgrid systems is studied in [34]. The reinforcement learning technique is developed in [39] to model distributed energy trading between MGs in the distribution network.

9.4. Hybrid energy management scheme

In [12], the impact of demand response programs on the MMG system is studied using hybrid centralized decentralized scheduling. A two-step hybrid energy management system is developed in [45] to maximize the penetration of renewable generation in the MMG system. The proposed model incorporates the battery energy storage system to increase the share of renewable resources in the MMG. The authors in [25] present a hybrid energy management strategy for the MMG systems. The proposed model is formulated as a two-layer approach. The first layer performs a decentralized energy management scheduling for each MG to determine the surplus and shortage of power at each time slot. The second layer performs a centralized scheduling to supply the shortage of each MG by other MGs. Fig. 10 shows the hybrid energy management scheme in the MMG system. Table 10 evaluates different energy management schemes.

Tables 11, 12, and 13 presents the advantages and disadvantages of the research works in the MMG studies.

10. Conclusion

This paper focuses on the energy management of multi-microgrid systems. The paper provides a comprehensive survey that studies the objectives, electricity network, uncertainty modeling, distributed energy resources, demand response programs, and energy management schemes. This survey shows that more than 92% of research works considered renewable generation in multi-microgrid systems. Also, the controllable resources are considered in 41% of research works. The investigation of the literature shows that the application of demand response programs in multi-microgrids consists of load reduction, power loss reduction, cost reduction, and reliability improvement. From system structure, most of the research works only considered single-carrier systems, while a few works focus on integrated multi-microgrid systems. Among multi-carrier energy systems, the heating system is more studied, while the hydrogen system needs to be more developed. In future work, the communication structures and the application of intelligent approach in the multi-microgrid systems will be reviewed.

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