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Microgrids energy management systems: A critical review on methods, solutions, and prospects

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HIGHLIGHTS

- Overview of microgrid architecture and energy management systems.
- Microgrids communication technologies comparative analysis.
- Critical review of microgrid energy management system models and solution methods.

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ABSTRACT

Renewable energy resources are currently being deployed on a large scale to meet the requirements of increased energy demand, mitigate the environmental pollutants, and achieve socio-economic benefits for sustainable development. The integration of such distributed energy sources into utility grid paves the way for microgrids. The microgrid concept is introduced to have a self-sustained system consisting of distributed energy resources that can operate in an islanded mode during grid failures. In microgrid, an energy management system is essential for optimal use of these distributed energy resources in intelligent, secure, reliable, and coordinated ways. Therefore, this review paper presents a comparative and critical analysis on decision making strategies and their solution methods for microgrid energy management systems. To manage the volatility and intermittency of renewable energy resources and load demand, various uncertainty quantification methods are summarized. A comparative analysis on communication technologies is also discussed for cost-effective implementation of microgrid energy management systems. Finally, insights into future directions and real world applications are provided.

1. Introduction

The exponential increase in global energy demand is the main cause of rapid depletion of fossil fuels and increased greenhouse gas emissions of conventional generators (CGs). To overcome these problems, the world has taken initiatives to deploy renewable energy resources (RERs) on a large scale, in order of GW, since a decade [1,2]. The RERs, such as solar, wind, biomass, hydro, and tidal power are one of the most important sources in providing clean energy and mitigating greenhouse gas (GHG) emissions for sustainable development [3]. United Nations Sustainable Development and Paris Climate Agreement goals also promote installation of RERs. In 2016, the global deployment of RERs, excluding hydro power, reached 921 GW due to the increased awareness of climate change, with China being at the top spot in deployment of RERs followed by the USA, and Germany, as shown in Fig. 1.

RERs, micro CGs, and energy storage systems (ESSs) are often described as distributed energy resources (DERs) in the literature [4]. DERs are on-site generation sources in distribution system. Hence, no transmission equipment is required for power transfer to load ends. In DERs, the RERs, particularly solar and wind energy, are volatile and intermittent energy sources. Therefore, ESSs and micro CGs are needed to overcome these uncertainties. The integration of DERs into distribution network requires the optimal sizing, control, and scheduling of these energy resources. A microgrid (MG) embodies these issues by integrating DERs into power grid, together with an ability to operate in an islanded mode during main grid failure [5]. Hence, It helps in achieving objectives of efficient transformation of the passive network into an active one, bidirectional and controlled power flow

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Nomenclature

CG	Conventional generator
DER	Distributed energy resources
DR	Demand response
EMS	Energy management system
ESS	Energy storage system
EV	Electric vehicle
GA	Genetic algorithm
GHG	Greenhouse gas
LC	Local controller
LP	Linear programming
MAS	Multi-agent system
MG	Microgrid
MGCC	Microgrid central controller
MILP	Mixed integer linear programming
MPC	Model predictive control
NN	Neural network
PEI	Power electronic interface
PSO	Particle swarm optimization
RER	Renewable energy resource

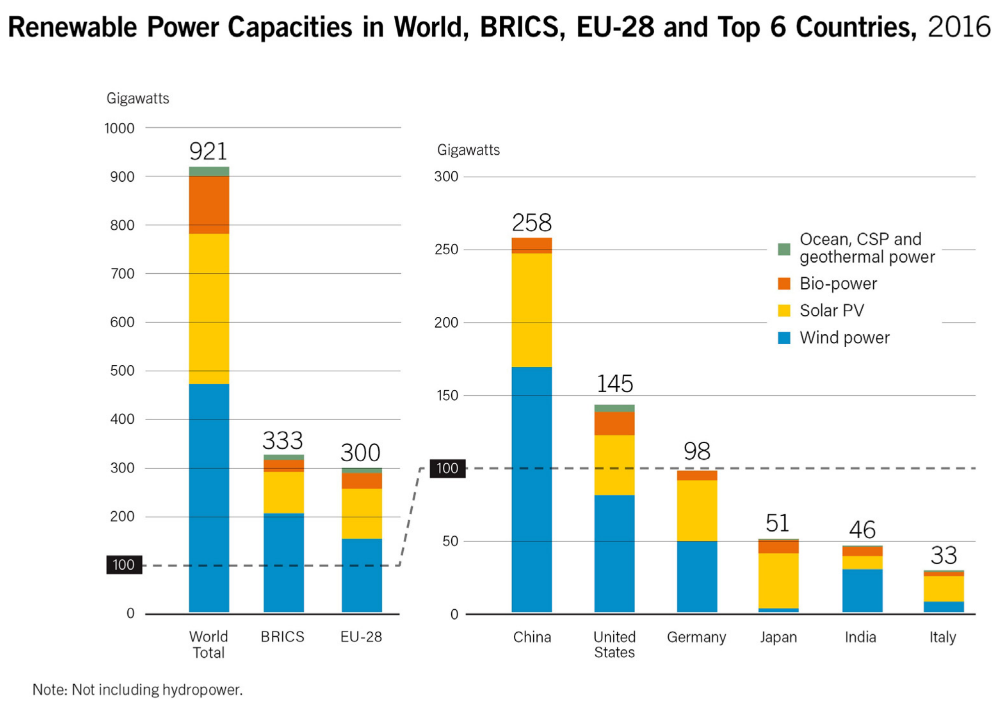

Fig. 1. Global deployment of RERs [9].

management, reliable and continuous supply, power quality enhancement, and clean environment.

MG is defined as a low-voltage distribution network of interconnected DERs, controllable loads, and critical loads. It can operate in either grid-connected or islanded mode subject to operational characteristics of the main grid [6,7]. To have a flexible operation of MG, power electronic interfaces (PEIs) and controls are integrated with DERs for power quality monitoring, continuous, and reliable power supply [8].

MGs offer several advantages such as reduction in GHG emissions, reactive power support for voltage profile improvement, decentralization of energy supply, heat load integration for cogeneration, ancillary services and demand response (DR) [8]. It also reduces line losses and outages in transmission and distribution system. The MG deployment market status, all over the world, is presented in Fig. 2. Autonomous basic MGs are defined as microgrids that cannot meet the load demand for 24 h a day. However, autonomous full MGs have provisions for supplying energy to load end for all the day. Autonomous basic MGs are

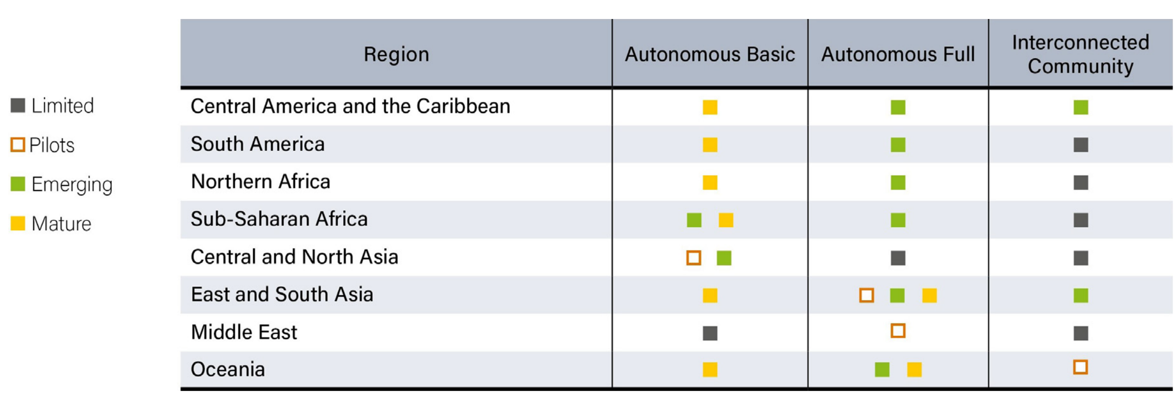

Fig. 2. MG market status [9].

already deployed in all over the world except in Middle East, while autonomous full and interconnected community-based MGs are still in emerging and piloting phases of deployment.

MGs have some limitations such as high investment cost of RERs, optimal use of energy sources, control issues and lack of system protection and regulatory standards, and customer privacy. Due to high deployment of inherently intermittent RERs and increased integration of probabilistic controllable loads into MGs, researchers have focused on solving its energy management problems.

Energy management system (EMS) of an MG encompasses both supply and demand side management, while satisfying system constraints, to realize an economical, sustainable, and reliable operation of MG [10]. EMS provides many benefits from generation dispatch to energy savings, reactive power support to frequency regulation, reliability to loss cost-reduction, energy balance to reduced GHG emissions, and customer participation to customer privacy.

Several review papers addressed different aspects of MGs, as a survey on experimental MG systems installed in Europe, North America, and Asia regions [11], protection and control schemes for MG [12], and reactive power compensation techniques in MG [13]. They also addressed control methods for inverter-based MGs [14], droop control techniques [15], and control strategies for voltage and frequency regulation of MG [16]. They examined control strategies for DERs in MG [17], modeling, design, planning and architectures of hybrid renewable MGs [18], and a survey on AC and DC MGs [19]. The literature also provided reviews on homeostatic control-based energy efficient microgeneration systems [20], MG uncertainty quantification methods [21], and the survey on energy efficiency in buildings and MGs using network technologies [22]. Review papers related to energy management of MG are summarized by Table 1. Unlike these review papers, this paper presents a comprehensive and critical analysis of the MG EMSs. MG EMSs based on solution approaches like robust optimization, hierarchical control, homeostatic control, chance constrained programming, mesh adaptive direct search, and meta-heuristic approaches such as gravitational search, bacterial foraging, and many others have not been previously addressed. Moreover, the uncertainty quantification methods used in each MG EMSs are also highlighted. Furthermore, deployment cost, coverage range, and data rate-based graphical comparison on communication technologies selection is also discussed. Such comparison is necessary for the achievement of a secure, economical, and reliable communication network among MG components. It is also important for a smooth operation of centralized and, particularly, decentralized architecture of MG. Finally, insights into future directions and real world applications are also provided.

This review paper presents a comparative analysis on the proposed MG EMSs. Section 2 provides an overview on MG architectures and MG classification. Communication technologies used for effective coordination among MG components are discussed in Section 3. Section 4 provides a critical review on different MG EMS strategies based on various solution approaches used by authors and their main limitations. Section 5 discusses real world applications of MG EMSs followed by insights into future directions.

2. Microgrid architecture

An MG is composed of different DERs, responsive loads, and critical loads, as shown in Fig. 3. The MG is connected to the main grid through a point of common coupling (PCC) [29]. In both grid-connected and islanded modes, each DER is connected with PEI to achieve control, metering, and protection objectives together with an ability of a plug and play feature. During grid-connected mode, an MG reaps advantages of power trading with the main grid. However, in case of disturbances or failure in main grid, MG shifts its operation to islanded mode to ensure system stability. In this mode, it provide continuous supply to critical loads by efficient integrated operation of DERs, DR, and load shedding (LS). The entire MG operation is controlled and coordinated by MG central controller (MGCC) and local controllers (LCs) [30]. The effective management and coordination of DERs in MG results into improved system performance and sustainable development [31].

Due to the increased awareness of climate change, socio-economic development, and the need to mitigate GHG emissions, MGs mainly consist of sustainable energy systems, ase renewable energy systems and energy efficient systems that use local heat waste [32]. Optimization of these energy systems is achieved by MG EMS that solves decision making strategies. These strategies consider increased system energy efficiency, increased reliability, reduced energy consumption, decreased operational cost of DERs, reduced system losses, and mitigation of GHG emissions for sustainable development. Table 2 presents few examples of sustainable energy systems that are used in the literature for energy management operation of MG.

Apart from mode of operation, MGs are also classified with respect to power type, supervisory control, supply phase, and application as shown by Fig. 4.

3. Microgrid communication

Dispersed generation of DERs and active integration of DR requires a communication infrastructure to share information with each other and optimize their operation locally [59,60]. Therefore, an efficient data communication system is needed for continuous, fast, reliable, and accurate transfer of information among sensors, LCs and MGCC without any disturbances and disconnections. However, investment cost of such data communication systems can be much high, which depends upon the number of repeaters required to improve the quality of transmitted signals, while covering specific geographical area. Hence, it is vital to reduce installation cost, while maintaining reliable operation, by selecting suitable data communication technology for short and long distance applications [61,62].

In the literature, several wired and wireless communication technologies have been proposed for effective communication among different MG components. The selection of these communication technologies depends on the data rate, coverage area, quality of service,

Table 1
Existing reviews related to energy management of MG.

Ref.	Details
[23]	Modeling of RERs and ESSs are briefly explained. This review also discusses meta-heuristic optimization methods and software tools used for energy management and control of hybrid RERs, sizing objectives, ESS management, power quality, and energy dispatch related problems
[24]	Authors conducted a comprehensive review on energy management in MGs. The review topics are optimization objectives, constraints, algorithm types, and software tools
[25]	Authors conducted a comprehensive review on centralized EMSs of MG based on objectives such as power management, economic dispatch, and unit commitment using solution approaches of mixed integer linear and nonlinear programming methods, genetic algorithm, particle swarm algorithm, rule-based system, and artificial intelligent methods. Multi-agent system (MAS) is explained extensively for optimization of decentralized EMS of MG
[26]	Potential of multi-agent systems is discussed in detail in the context of energy management, operation, security and stability of MG system
[27]	Energy management strategies in the context of stand-alone and grid-connected hybrid RERs systems are reviewed. Energy management strategies based on linear programming and intelligent techniques are discussed
[28]	Authors presented a comprehensive review on MG planning. This review points out different computational optimization techniques applied to scheduling, reliability, environmental, sizing, and siting problems

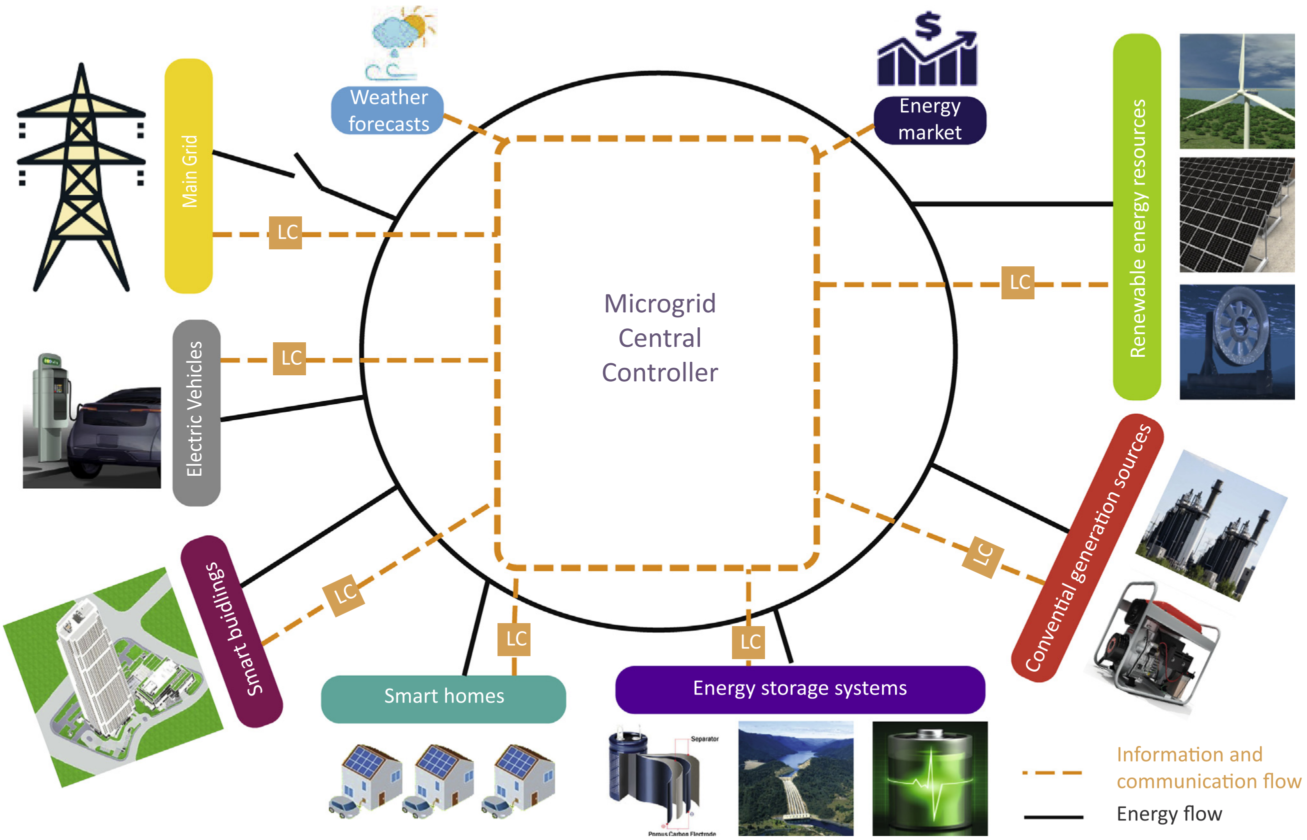

Fig. 3. MG architecture.

Table 2
Sustainable energy systems in MG.

Ref.	Solar	Wind	Fuel cell	Combined heat and power	Biomass	Hydro	Tidal
[33–36]	✓	✓					
[37]	✓					✓	
[38]	✓	✓		✓			
[39–41]	✓		✓				
[42]	✓		✓				✓
[43]		✓	✓				
[44–46]	✓	✓	✓				
[47]	✓	✓		✓			
[48]	✓				✓	✓	
[49]	✓	✓			✓		
[50]	✓	✓	✓	✓			
[51–54]	✓	✓	✓				
[55]	✓	✓		✓			
[56]		✓			✓		
[57]	✓	✓				✓	
[58]	✓		✓				✓

reliability, latency, and power consumption [63]. An overview of different communication technologies that can be used for MG operations, is shown in Fig. 5. Among these communication technologies, wired technologies, such as DSL, PLC, and fiber optics, have higher data transmission rate and reliability but at expense of high installation cost. On the contrary, wireless technologies, such as Zigbee, Z-wave, GSM, and wifi, etc., can be easily deployed with lesser installation cost, hence being better candidates for remote areas. However, they have low data transmission rate and signal interference problems. To conclude, with recent advancements in MGs installation, more sensors, meters, and LCs are needed to be integrated, monitored, and controlled regularly. Therefore, wireless technologies are, overall, better candidates as compared to wired ones due to their low deployment cost.

4. Microgrid energy management system

The International Electrotechnical Commission in the standard IEC 61970, related to EMS application program interface in power systems management, defines an EMS as "a computer system comprising a software platform providing basic support services and a set of applications providing the functionality needed for the effective operation of electrical generation and transmission facilities so as to assure adequate security of energy supply at minimum cost" [64]. An MG EMS, also having these same features, usually consists of modules to perform decision making strategies. Modules of DERs/load forecasting, Human Machine Interfaces (HMI), and supervisory, control and data acquisition (SCADA) among others ensure the efficient implementation of EMS decision making strategies by sending optimal decisions to each generation, storage, and load units [65]. An MG EMS performs variety of functions as monitoring, analyzing, and forecasting of power generation of DERs, load consumption, energy market prices, ancillary market prices, and meteorological factors as given by Fig. 6. These functions help EMS in optimizing MG operation, while satisfying the technical constraints.

The supervisory control architecture of MG EMS can be divided into two types, namely, centralized and decentralized EMSs. In centralized EMS, the central controller accumulates all the information such as power generation of DERs, cost-function, meteorological data, and energy consumption pattern of each consumer, etc. Then centralized EMS determines the optimal energy scheduling of MG and sends these decisions to all LCs. However, in decentralized EMS architecture, the MGCC sends and receives all the information to LCs in real-time. Each LC proposes a current and future demand or generation request to the MGCC. The MGCC determines the optimal scheduling and sends it back to the LC. The latter may disagree with the current operation and continue to bargain until the global and local objectives are achieved. With the integration of RERs, ESSs, EVs, and DR, the MG EMS strategies

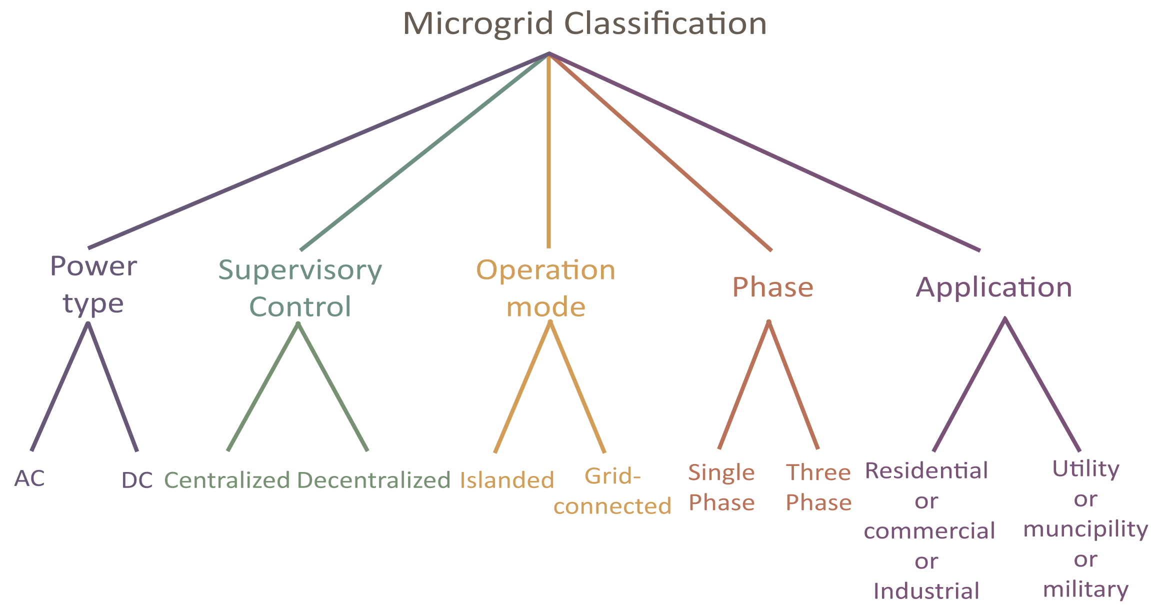

Fig. 4. MG classification.

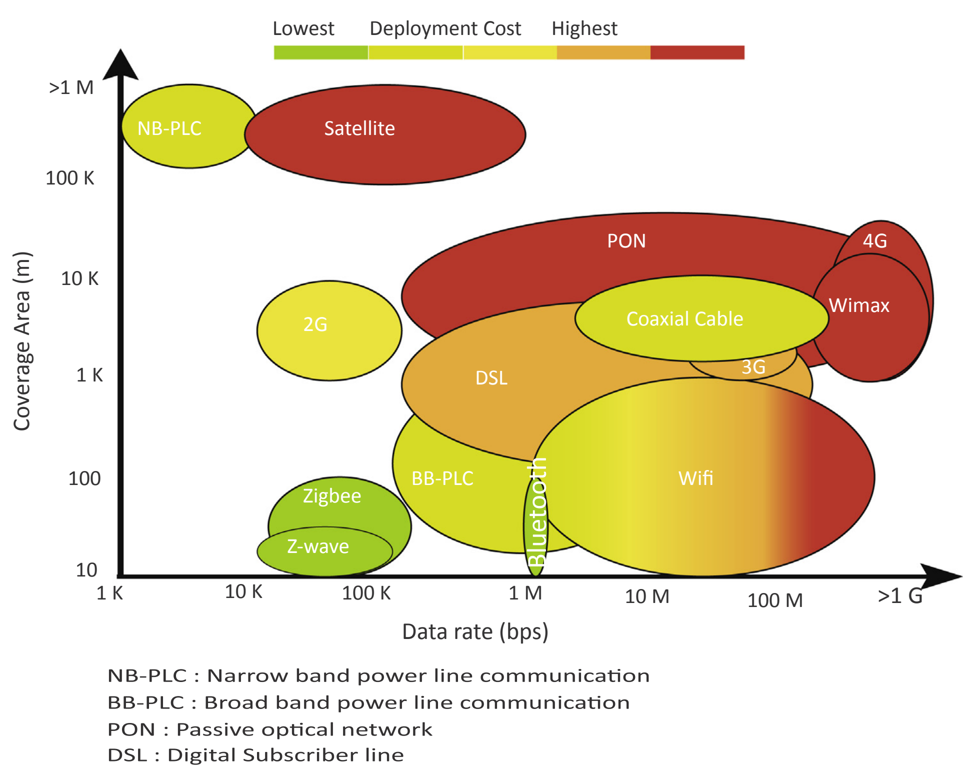

Fig. 5. Communication technologies for MG operation.

have been diversified from economic dispatch and unit commitment. The other strategies are scheduling of DERs and loads, minimization of system losses and outages, control of intermittency and volatility of RERs, and realization of economical, sustainable, and reliable operation of MG. These MG EMS strategies are shown in Fig. 7.

Many researchers have solved these energy management strategies using various solution approaches to achieve the optimal and efficient operation of MG. An extensive critical review of these strategies and solution approaches is described in the following subsections.

4.1. EMS based on classical methods

4.1.1. EMS based on linear and nonlinear programming methods

Sukumar et al. [39] proposed power sharing, continuous run, and on/off-based mixed mode MG EMS. The power sharing mode considers the power trading with the main grid, while fuel cell is bound to remain operational in continuous run mode. Both of these modes are solved by a linear programming (LP) optimization method. However, on/off mode is solved by a mixed integer linear programming (MILP) solution approach that optimizes the operation of MG with respect to on/off connection status of main grid, fuel cell, and ESS. The sizing of ESS is also computed considering MG operational requirements. A techno-

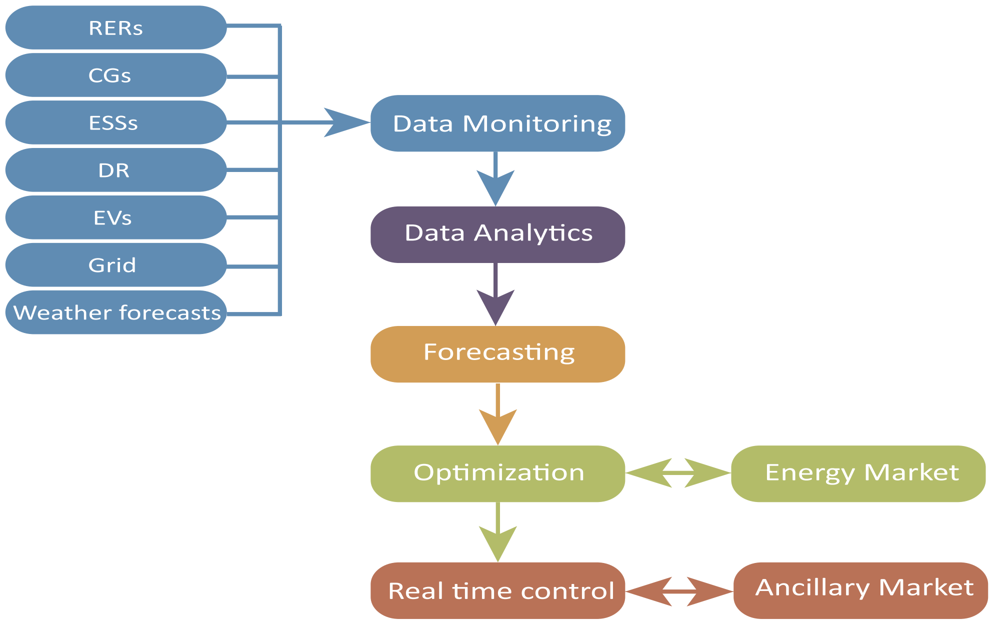

Fig. 6. MG EMS functions.

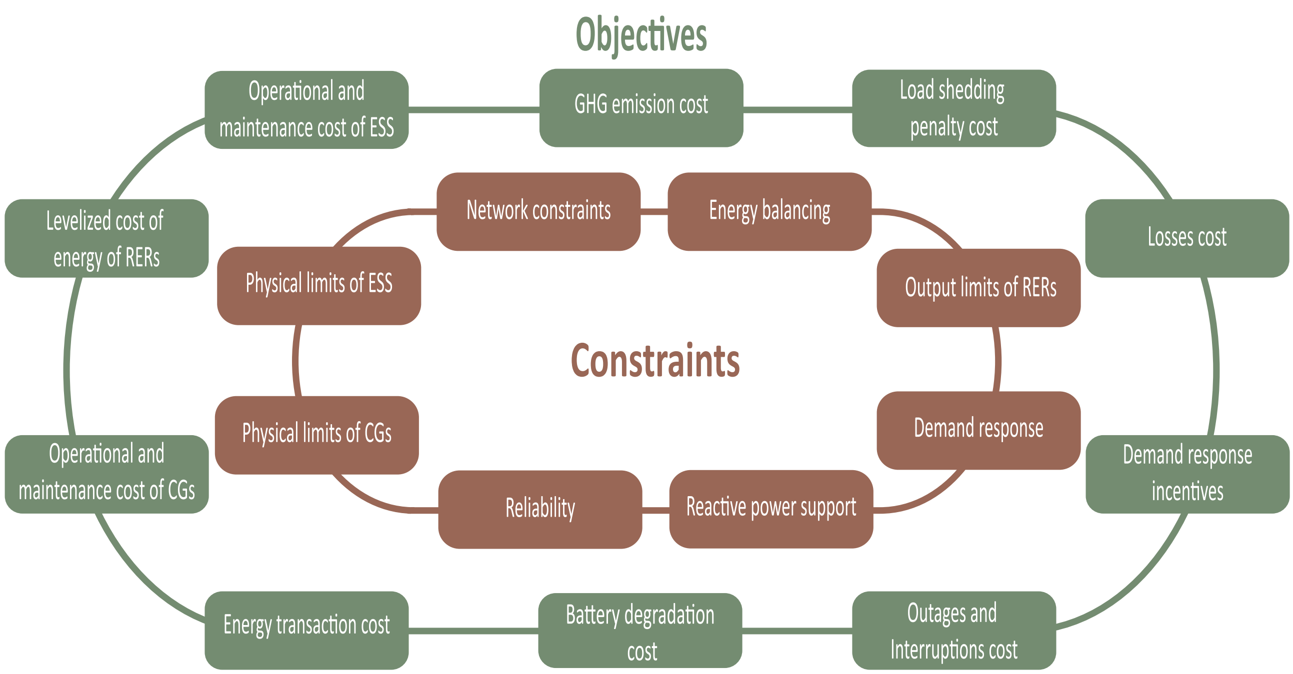

Fig. 7. Energy management strategies of MG.

economic MILP-based optimization model is proposed in [33] to compute energy consumption scheduling in MG EMS. The authors also presented advantages of DR program in handling intermittency and volatility effects of RERs, improving load factor, and reducing peak consumption. The capital, replacement, operational and maintenance (O&M), and residual costs-based MILP net present cost-optimization model is solved by GAMS software. HOMER simulation software is used for sizing optimization of MG.

Anglani et al. [66] proposed optimal EMS for remote military MG. The piecewise linear fuel consumption model of diesel generator is used as an objective function. The Rainflow counting method is also used to determine the battery sizing based on its lifecycle and depth of discharge to tradeoff between operational and capital costs of MG. The special order sets 1 and 2 based branch and bound solver tool solve the proposed semi-continuous optimization model for two scenarios. In scenario 1, only one generator operators, while in scenario 2, both generators are operating but only one will be used at a time. The effectiveness of the proposed optimal EMS model is also experimentally validated. Comodi et al. [67] presented a MILP energy trade profit model-based EMS for residential MG. Radial basis neural network (NN) method is used to forecast the power output of photovoltaic (PV) and solar thermal power systems. The profitable integration of thermal storage is realized by heat load management. However, the batteries are concluded to be economically unfeasible for integration in residential market due to their high investment and replacement costs.

For optimal energy management of residential MG, an operating cost-minimization model is proposed in [68]. It incorporates energy trading cost, penalty cost on adjustable load shedding, EVs batteries

Table 3
Critical analysis of of MG EMSs based on linear and nonlinear programming methods.

Ref.	Proposed approach	Contributions	Limitations	Supervisory control	Uncertainty handling approach
[39]	Linear and mixed integer linear programming	Power sharing, continuous run and on/off-based mixed mode EMS of MG is proposed.	Higher DOD of battery is selected that results in its fast degradation	Centralized	Forecasted
[33]	Mixed integer linear programming	Net present cost is determined and advantages of DR program are discussed with respect to load factor improvement and reduction in peak power consumption	No CG is considered for effective management of handling intermittency of RERs	Centralized	Forecasted
[66]	Mixed integer linear programming	Fuel cost minimization model using piecewise linear function of diesel generators and battery sizing problem are proposed	Uncertainties in PV power and load demand are not considered	Centralized	Forecasted
[67]	Mixed integer linear programming	Energy trading profit-based EMS model is proposed and the feasible integration of thermal storage is realized	Battery integration is discouraged. However, no alternative solution is proposed to deal with the intermittency of RERs	Centralized	Radial basis NN
[68]	Mixed integer linear programming	DR and range anxiety term of EVs are considered while optimizing daily energy resource scheduling of MG	Effects of plug and play feature of EVs on MG stability are not discussed	Centralized	Forecasted
[69]	Mixed integer linear programming	Utility grid peak shaving incentives are considered in optimal EMS model to maximize daily revenue of MG	Assuming load to be always more than generation results in considerable load shedding and consumer outrage during transmission lines congestion and grid disturbances	Centralized	Forecasted
[51]	Mixed integer linear programming	DR and penalty costs on load shedding are also included in optimal EMS model of MG	Battery degradation cost due to higher DOD is ignored	Centralized	Forecasted
[70]	Mixed integer linear programming	Outages constraint and load shedding cost are included in three-phase EMS power flow model that is linearized using approximation methods	DR and power losses are not taken into account	Centralized	Forecasted
[71]	Mixed integer linear programming	A comparative analysis is performed among the EMS models with perfect forecast and imperfect forecast, SOC-based EMS and EMS model with accurate information in respect of savings and computational time	Methods for predicting accurate information related to MG system are not described. DR is also not considered	Centralized	Forecasted
[72]	Mixed integer linear programming and nonlinear programming	An optimal MG energy management model of an isolated three-phase MG system is developed to minimize the fuel, start-up and shutdown costs of CGs and penalty cost on reactive power requirements	Complex formulation. DR and voltage regulation are not included	Centralized	Forecasted
[73]	Mixed integer nonlinear programming	The operating cost of CGs is minimized, while considering droop controlled active and reactive power dispatch of AC side CGs as a constraint	Emission cost of CGs and DR incentives are not considered	Centralized	Forecasted
[74]	Nonlinear programming	Market policies have been defined for MG participation in energy market on the basis of its profit and operational cost	No ESS is considered in EMS model of MG	Centralized	Forecasted
[41]	Nonlinear programming	Efficient MG EMS is proposed under Operation window of transformer nominal operation and voltage security. Three objective functions of customer benefits, network losses and load levelling are studied	Operational cost of DERs is not considered. Deep discharge battery with 100% DOD has reduced lifecycle time and increased investment and replacement costs	Centralized	Forecasted

wearing cost, the range anxiety term for electric vehicles (EVs). Three types of load are considered namely: critical, adjustable, and shiftable loads. The range anxiety of EVs is defined as the fear factor of running out of energy before reaching destination. Risk level-based three scenarios in range anxiety term are studied to analyze the tradeoff between operational cost of MG and average state of charge (SOC) of EVs battery. Shen et al. [69] proposed an optimal revenue maximization model of MG EMS together with main grid peak shaving application by introducing demand responsive loads. The authors assumed that the load demand of MG will always remain more than its generation supply. Two case studies of one bus and IEEE 14-bus MG systems are used to analyze the performance and effectiveness of the proposed MILP optimization model in CPLEX software. In [51], Tenfen and Finardi proposed an optimal energy management strategy to minimize the operational cost of MG together with incorporation of curtailable and shiftable loads in DR. The objective function includes the O&M costs, start-up and shutdown cost, energy trading cost with main grid, and load shedding cost.

Vergara et al. [70] proposed security constrained EMS for three-phase residential MG. The nonlinear optimization model is developed to minimize the operational cost of MG, while penalizing load shedding. The system outages are included as a constraint to ensure reliability of MG. The developed nonlinear model is converted into MILP model by linearizing the objective function, active and reactive power of generation sources, ESS model, and bus phase angles. Piecewise approximation, Taylor series, estimated operation points, and introduction of auxiliary variables-based methods are used for it. The performance and efficiency of MILP approximate model is compared with the three-phase nonlinear optimal power flow problem that results in an energy supply error below 2% with lesser computational time. Luna et al. [71] presented a real-time online MG EMS to minimize the operational and load shedding costs. Three case studies of perfect forecast, imperfect forecast, and accurate information are used in analyzing the developed model. A comparative analysis is performed among these three case studies in respect of savings and computational time.

A mixed integer nonlinear energy management model of an isolated three-phase unbalanced MG is proposed in [72]. It minimizes the fuel, start-up and shutdown costs of CGs, and penalty cost on reactive power requirements. The mathematical models and ABCD parameters of CG, ESS, transmission line, and transformer are formulated. The developed MINLP model is divided into two sequential stages of MILP-based unit commitment and nonlinear programming-based optimal power flow models. This decomposition solves the problems of intractability and non-convergence. Helal et al. [73] have proposed a mixed integer nonlinear EMS model for optimal operation of an islanded MG considering DR. The developed model includes operating cost of CGs as an objective function. Furthermore, droop controlled active and reactive power dispatch of AC side CGs, and operation of water desalination units are also included as a constraint in the proposed model.

Tsikalakis and Hatziargyriou [74] developed centralized architecture for energy management of a grid-connected MG. Two market policies are proposed to determine the price bids for MG participation in energy market. The objective of first policy is operational cost-minimization of MG, while second policy aims to maximize its profit considering energy transactions with main grid. Both of these optimal policies are solved using sequential quadratic programming method. Panwar et al. [41] introduced strategic EMS of a grid-connected MG, constrained by an operation window of transformer nominal operation and voltage security. The developed model minimizes MG operational cost using modified gradient descent solution method. The forward backward sweep algorithm determines power flow solution of MG. Three scenarios are considered in the objective function with respect to customer benefits, network losses, and load levelling.

The critical analysis of MG EMSs based on linear and nonlinear programming approaches is summarized in Table 3. Centralized supervisor control architecture is used in all these MG EMSs. The main contributions of the listed papers have been earlier discussed in this subsection, where most of the carried out researches were focused on energy resources optimization in MG. However, much emphasis is needed to consider the effects of depth of discharge (DOD) on battery performance, effects of GHG emissions of CGs on environment, customer privacy issues, integration of DR, and system reliability.

4.1.2. EMS based on dynamic programming and rule-based methods

Heymann et al. [75] proposed a Bellmans dynamic programming method for optimal energy management of a standalone MG. The proposed EMS model includes operational cost of CGs and load shedding cost in objective function. To reduce computational time of dynamic programming model, the Pontryagin maximum principle is used. It determines five optimal extreme points using continuous and concave properties of Hamiltonian instead of using all discretized control range. The performance and efficiency is compared with classical nonlinear programming and MILP models in terms of operational cost and computation time. The results show that the proposed approach is more effective than the aforementioned methods. In [76], an efficient EMS model is presented to optimize the operation of a grid-connected MG. The objective is to minimize the cash flow, which includes energy trading cost with main grid and battery ageing cost. Two cases of constant energy and dynamic energy prices are studied. The proposed dynamic programming approach performs better than the rule-based method.

Strelec and Berka [77] have presented an approximate dynamic programming approach to overcome the curse of dimensionality in the proposed EMS model of a grid-connected MG. Receptive field weight regression and lookup table are used to compute the approximate value of cost-function. Various scenarios of wind speed, load demand, and ambient temperature are generated to consider their uncertainty in the proposed model, which uses economic dispatch and unit commitment operations to optimize the energy scheduling of MG. The effectiveness of the proposed approach is compared with myopic optimization and dynamic programming methods. It gives better results in reducing operating cost, but with higher computational time, as compared to myopic optimization method. However, it achieves less computation time than dynamic programming method, but at the cost of higher objective function value.

A centralized rule-based energy management model is developed in [40] for both islanded and grid-connected modes of MG and simulated in PSCAD/EMTDC software. In the islanded mode, fuel cell operates only if SOC of battery is below 80%. While, in grid-connected mode, SOC of battery should remain more than 60% to have reliable operation in islanded mode. This rule-based control model ensures smooth transition between these two modes with respect to voltage and frequency stability of MG system. Kanchev et al. [78] proposed a concept of prosumers in an MG system. MG consists of prosumers and a microturbine. A prosumer is composed of PV system, battery, and ultra-capacitor. Two EMS models are considered for MG operation. Central EMS uses rule-based optimization method to control the energy operation of whole MG with an interval of half an hour, while a prosumer EMS manages the power balancing and primary frequency regulation in prosumer system. Merabet et al. [79] presented an online rule-based EMS to optimize the operation of MG in real-time by switching operations among battery charging mode, battery discharging mode, off-MPPT mode of PV system, and load shedding mode on the basis of load generation imbalance and SOC of battery.

Choudar et al. [80] presented a battery SOC-based hierarchical structure for MG EMS and proposed ultra-capacitors for power regulation and smooth operation of MG. The SOC of battery and energy level of ultra-capacitors determine the selection of four different operating modes, namely: normal mode, PV limitation mode, recovering mode, and disconnection mode, for efficient energy management of MG. A battery SOC-based EMS for a grid-connected residential MG is recommended in [81]. It uses persistence forecasting method for load demand prediction and Meteogalicias THREDDS server forecasted data for prediction of solar irradiance and wind speed. The central moving average strategy is used to reduce peaks and fluctuations within the energy exchange of MG with the main grid through the battery SOC management. Sechilariu et al. [82] proposed rule-based real-time EMS for building integrated MG. The rule-based power control algorithm is presented to switch operation among load shedding, battery charging and discharging, PV limitation, and grid supply modes. The operations are selected on the basis of load generation imbalance, time of use tariff, and battery SOC. To stabilize the DC bus voltage, the PI controller is used to calculate the load generation imbalance using PV power, load demand, and reference DC bus voltage as inputs. This power imbalance is compensated by battery supply and main grid.

The critical analysis of MG EMSs based on dynamic programming and rule-based approaches is summarized in Table 4. These MG EMSs are mainly focused on energy resources optimization and energy trading with main grid. However, a lot of work is still required on mitigation of environmental pollutants, consideration of DR, and inclusion of customer privacy issues for MG systems optimizations.

4.2. EMS based on meta-heuristic approaches

4.2.1. EMS based on genetic and swarm optimization

Elsied et al. [83] developed a multi-objective EMS using Zigbee-based reliable communication infrastructure. It optimizes the MG operation based on the objectives of minimization of operation cost, minimization of GHGs emission cost, and maximization of energy trade profit. Economic load dispatch and battery degradation cost-based multi-objective EMS of a remote MG is proposed in [84]. It performs both day-ahead and real-time operations using genetic algorithm (GA) and rule-based approach, respectively. The real time operation considers diesel generator supply, battery supply, and load shedding options in a sequential order to maintain load generation balance. Askarzadeh [38] proposed a memory-based GA for optimal power management of a grid-connected MG to minimize the operating cost of DERs. The performance of the proposed approach is better as compared to GA, particle swarm optimization (PSO) with inertia factor and PSO with constriction factor.

Chen et al. [65] proposed ESS economical model and matrix real coded GA-based smart EMS model for a grid-connected MG. An NN model is used to predict solar power. The ESS economical model maximizes the net present cost of ESS over its lifespan based on its capital, operation and maintenance costs, and energy arbitrage revenue. The smart EMS model incorporates generator bids, storage bids, and energy trading profit to minimize the operational cost of MG while satisfying energy balance constraint and physical constraints of DERs. Golshannavaz et al. [85] presented a GA-based EMS for optimal generation and reserve scheduling of a grid-connected MG. It models uncertainties of wind power and load demand by scenario generation and reduction method. The objective function includes the operating cost, energy purchase cost, reactive power support cost, active power reserve cost, demand responsive cost, switching cost of automatic controlled switches, and load shedding cost. Automatic controlled switches are used to enhance the techno-economic performance of MG. Radosavljevi et al. [86] proposed an optimal EMS for a grid-connected MG that considers uncertainties of RERs, load demand, and electricity price using point estimate method. The efficiency of PSO in finding best solution is shown to be better in comparison with GA, combinatorial PSO, fuzzy self-adaptive PSO, and adaptive modified PSO.

Li et al. [87] proposed a regrouping PSO-based optimal energy management strategy for industrial MG that can be operated islanded and grid-connected modes. In the islanded mode, the objective function aims to minimize the O&M costs of MG. However, for grid-connected mode, it also maximizes the energy trading profit with the main grid. The performance of the proposed approach is better as compared to GA in respect of global optimum solution and computation time. A novel

Table 4
Critical analysis of MG EMSs based on dynamic programming and rule-based methods.

Ref.	Proposed approach	Contributions	Limitations	Supervisory control	Uncertainty handling approach
[75]	Dynamic programming	Operational cost of CGs and penalty cost on load shedding are considered in objective function. To reduce computational time, the Pontryagin Maximum Principle is used	Higher DOD is selected that leads to fast degradation of battery. DR is not considered	Centralized	Forecasted
[76]	Dynamic programming	Cash flow, which includes energy trading cost with main grid and battery ageing cost, is minimized	Computational time complexity of proposed approach is not discussed	Centralized	Forecasted
[77]	Approximate dynamic programming	Approximate value of cost-function in economic dispatch and unit commitment operations is considered to optimize the daily energy scheduling of MG	DOD of battery for MG optimized operation with battery ageing status are not discussed	Centralized	Markov chain
[40]	Rule-based approach	In an islanded mode, fuel cell operates only if battery SOC is below 80%. In grid-connected mode, battery SOC remains more than 60% to ensure reliable operation in islanded mode	DR is not included. The model lacks the consideration of future availability of RERs	Centralized	Forecasted
[78]	Rule-based approach	Central EMS controls the energy operation of whole MG, while prosumer EMS manages the power imbalancing in prosumer system	GHG emissions cost and DR are not included	Centralized	Forecasted
[79]	Rule-based approach [79]	EMS switches operation among different modes on the basis of load generation imbalance and SOC of battery	No DR and knowledge of future availability profiles of RERs and load demand	Centralized	Forecasted
[80]	Battery SOC rule-based approach	A battery SOC-based hierarchical structure for MG EMS is proposed together with ultra-capacitors for power regulation and smooth operation of MG	No prior information of generation of RERs. DR and voltage regulation of MG system are not taken into consideration	Centralized	Forecasted
[81]	Battery SOC rule-based approach	Fluctuations in power transaction with the main grid are reduced	Higher DOD is selected that leads to fast degradation of battery	Centralized	Persistence forecasting method
[82]	Rule-based approach	Power balancing of building integrated MG is achieved. DC bus voltage stabilization is also ensured	Operation cost, energy transaction cost and DR are not considered	Centralized	Forecasted

Table 5
Critical analysis of MG EMSs based on genetic and swarm optimization.

Ref.	Proposed approach	Contributions	Limitations	Supervisory control	Uncertainty handling approach
[83]	Genetic Algorithm	A multi-objective EMS model considers operation cost, emission cost and energy trade profit as objectives for optimal operation of MG	DR and DOD of battery are not considered. The computational time complexity of the proposed approach is not determined	Centralized	Forecasted
[84]	Genetic algorithm	Battery degradation cost is considered to increase its lifecycle together with the operational cost model of MG	Emission cost of diesel generator is not taken into consideration	Centralized	Forecasted
[38]	Memory-based genetic algorithm	Quadratic cost-functions of DERs are considered in proposed EMS model to determine their optimal scheduling	No ESS is taken into consideration and computational time complexity is not calculated	Centralized	Forecasted
[65]	Matrix real coded genetic algorithm	DERs marginal price bids are proposed in smart EMS model to minimize the operational cost of MG	Emission cost of microturbine and DR are not taken into consideration	Centralized	Artificial NN
[85]	Genetic algorithm	Optimal scheduling of active and reactive power, and reserve power are determined. The cost related to load shedding and automatic controlled switches are also considered	Power losses and ESSs are not taken into consideration	Centralized	Scenario generation method
[86]	Particle swarm optimization	Operation cost of MG is minimized. The point estimated method is used to model uncertainties of RERs, load demand and electricity price	Emission cost of diesel generator and DR are not considered	Centralized	Point estimate method
[87]	Regrouping PSO	Global optimum solution is computed considering operational cost and energy trading cost of an industrial MG	DR and emission cost of diesel generators are not considered	Centralized	Forecasted
[35]	Guaranteed convergence PSO	A novel PSO variant is developed and implemented on 69-bus and 49-bus MG system to validate its performance in respect of optimal operation of MG	Authors have not considered emission cost of diesel generator and power losses of MG system	Centralized	Forecasted
[88]	Particle swarm optimization	Operation, emission and reliability costs of MG are optimized. Solar and wind powers uncertainties are modeled by point estimate method	Complex formulation of uncertainty modeling. Higher DOD leads to fast degradation of battery lifetime. Power losses are also not considered	Centralized	Point estimate method
[44]	self-adaptive modified θ-PSO	A novel optimization algorithm is proposed to minimize the operating cost of MG. The point estimated method is used to model MG uncertainties	Lifecycle cost of battery and DR are not considered	Centralized	Point estimate method
[89]	Multi-objective PSO	Grid operator-based operational value factor is defined for each objective function to maximize revenue of MG	Lifecycle cost of battery and emission cost of diesel generators are not scrutinized	Centralized	Forecasted
[52]	Adaptive modified PSO	A multi-objective operation model of MG is proposed to minimize its operational and emission costs	Computational time complexity of the proposed approach is not discussed. DR is not taken into consideration	Centralized	Forecasted
[90]	stochastic weight tradeoff PSO	The fuel cost, emission cost, load shedding cost, voltage deviation, active and reactive power mismatches, and energy trading cost with the main grid are minimized	Complex formulation. Power losses cost and reliability of MG system are not discussed. DR is also not taken into consideration	Centralized	Affine arithmetic

guaranteed convergence PSO with Gaussian mutation algorithm is proposed in [35] for optimal operation of a standalone MG. The objective function is composed of capital and O&M costs of MG. The proposed algorithm has been implemented on 69-bus and 94-bus isolated MG system that performs better than GA and PSO algorithms. Alavi et al. [88] developed an optimal EMS model to optimize the operation of MG. Beta and Weibull probability density functions are used in point estimated method to model the uncertainties of solar power and wind power, respectively. However, uncertainties in load demand are modeled by robust optimization approach. The objective of the developed EMS model is to minimize the O&M costs, emission cost, and reliability cost of MG.

Baziar and Kavousi-Fard [44] proposed a novel self-adaptive modified θ-PSO method to minimize the operating cost of MG. Point estimated method is used to model the uncertainties of RERs, load demand, and electricity price. Two scenarios are studied in context of availability of distributed generators and battery initial SOC. The proposed algorithm performance is better in comparison to GA, combinatorial PSO, fuzzy self-adaptive PSO, adaptive modified PSO and θ-PSO. Multi-objective PSO and advanced metering infrastructure-based EMS for an isolated AC/DC MG is presented in [89]. Operation value factor for each objective is introduced in the proposed optimal operation model of MG that has been defined by grid operators on the basis of day-ahead analysis. The objective function is composed of battery operation value, volt-var optimization, generation reduction, load shedding, and power transfer value between AC and DC MGs. The performance of the proposed solution is tested on 33-node MG system that shows the improved performance in achieving optimal solution.

Moghaddam et al. [52] proposed an adaptive modified PSO approach based on hybridization of chaotic PSO and fuzzy self-adaptive PSO to optimize the multi-objective EMS model of a grid-connected MG. The objectives is to minimize operational and emission costs of MG. The developed algorithm performs better than GA, PSO, chaotic PSO, and fuzzy self-adaptive PSO. Mohan et al. [90] proposed an energy and reserve management system for optimal operation of an MG. The objectives are to minimize the fuel cost, emission cost, load shedding cost, voltage deviation, active and reactive power mismatches, and energy trading cost with the main grid. The proposed approach is solved by affine arithmetic and stochastic weight tradeoff PSO-based perturbed optimal power flow method, and it performs better than interval arithmetic method.

Table 5 presents the critical analysis on MG EMSs that are solved by genetic and swarm optimization approaches. Many objectives deserve to be explored in detail such as the computational complexity of the proposed approaches, battery degradation cost, effects of GHG emissions of CGs on environment, and reliable and sustainable operation of MGs during islanded mode. Scenario generation and reduction method, point estimate method, and affine arithmetic methods are used to consider uncertainties within an MG system.

4.2.2. EMS based on other meta-heuristic approaches

In [91], a differential evolution approach is presented for optimal energy management of a grid-connected MG. The objectives are minimization of operational and emission costs of MG that have been optimized separately. Operational cost of MG includes bidding cost of DERs, DR incentives, and energy trading cost with main grid. The effects of DR in reducing peak shave demand and GHG emissions are also studied. The efficiency and efficacy of the proposed algorithm is better than PSO in terms of best solution and convergence speed. Yu et al. [92] proposed an optimal EMS model of a grid-connected MG, which determines the energy scheduling of MG with the objective of its optimal economic operation. The economical objectives are profit on selling energy to load end and main grid, energy purchasing cost with main grid, and battery ageing cost. The proposed approach is more efficient than rule-based method in achieving best economic operation of MG.

In [93], ant colony optimization-based two-layer EMS model for an islanded MG is proposed to minimize its operational cost. It includes bidding cost of RERs, CGs and battery, penalty cost on load shedding, and DR incentives in both day-ahead scheduling and 5 min interval real-time scheduling layers. Three scenarios of normal operation, sudden high requirement of load demand, and plug and play ability are studied with experimental validation. The proposed approach reduces operational cost of MG for almost 23% and 5% more than the modified conventional EMS and PSO-based EMS, respectively. Marzband et al. [94] introduced the gravitational search algorithm-based EMS model of an isolated MG that minimizes the operating cost of MG together with penalty cost on undelivered power. Three scenarios of normal operation, sudden high requirement of load demand, and plug and play feature are taken into consideration to evaluate the effectiveness of the proposed approach with experimental validation. The proposed algorithm performance is better as compared to PSO.

Niknam et al. [95] proposed a probabilistic EMS to minimize the operational cost of a grid-connected MG. The 2 m point estimate method is used to model MG uncertainties. The developed optimal approach is solved by self-adaptive gravitational search algorithm that performs better than GA, PSO, fuzzy self-adaptive PSO, and gravitational search algorithm. A modified bacterial foraging method-based multi-objective EMS model of a grid-connected MG is presented in [47]. It minimizes the objectives of operational and GHG emission costs. The sensitivity analysis on tradeoff between these two objectives is also studied using interactive fuzzy satisfactory method. The performance of the modified bacterial foraging method is shown to be better as compared to GA and PSO.

Motevasel and Seifi [96] proposed an expert EMS for optimal operation of a grid-connected MG that minimizes conflicting objectives of operation and emission costs. Artificial NN is used to forecast the wind speed. The proposed algorithm performs better than GA and PSO in respect of determining best solution. Marzband et al. [97] proposed multi-period artificial bee colony-based experimental two-layer EMS model for residential MG. It minimizes operational cost that includes linearized operating cost of RERs, CGs and battery, penalty cost on load shedding and incentives for controllable load in first layer of day-ahead scheduling. Similarly, second layer, 5 min interval real-time scheduling, considers operating cost of RERs, CGs and battery, penalty cost on load shedding, power imbalance, energy trading cost with main grid, and incentives for DR. The proposed solution approach is concluded to be more productive than mixed integer nonlinear programming algorithm. An EMS solution approach for an isolated MG is proposed in [98] to minimize its operational cost that includes operating cost of RERs, microturbine and battery, penalty cost on load shedding, and DR incentives. A hybrid NN and markov chain-based prediction method is used to forecast power generation of RERs and load demand. The proposed algorithm is more effective than PSO in respect of computation time and optimum solution.

Mohammadi et al. [99] presented a scenario-based EMS model for a grid-connected MG. It utilizes adaptive modified firefly algorithm to minimize operational cost considering uncertainties of RERs, load demand, and electricity price. Scenario generation and reduction method is used to determine these uncertainties by using their probability density functions. The performance of the proposed algorithm is better than PSO, fuzzy self-adaptive PSO, GA, firefly algorithm with respect to computational time, and finding best optimum solution. A multi-objective EMS of a grid-connected prosumer building MG, which is composed of PV system and battery, is presented in [100]. It aims to maximize MG profit by trading energy with main grid and neighboring building MGs. It also ensures that load demand is always met and PV produced power is not wasted.

Arefifar et al. [49] proposed a new probabilistic index, energy management success index, as an objective function to reduce the total operational cost of multi-MG system using tabu search method. The optimization model includes multi-state variable concept to consider the uncertainties of RERs and EVs. Selection of the number of states for

Table 6
Critical analysis of MG EMSs based on other meta-heuristic methods.

Ref.	Proposed approach	Contributions	Limitations	Supervisory control	Uncertainty handling approach
[91]	Differential Evolution	Operational and emission costs of MG are minimized separately, while considering DR	Battery degradation cost, in terms of DOD, is not considered	Centralized	Forecasted
[92]	Modified differential evolution	Economic operation of MG, which also considers battery ageing cost, is optimized	DR is not considered	Centralized	Forecasted
[93]	Ant colony optimization	Operational cost of MG, which includes bidding cost of DERs, penalty cost on load shedding and DR incentives, is minimized	Battery degradation cost and emission cost of CGs are not taken into consideration	Centralized	Forecasted
[94]	Gravitational search algorithm	Operating cost of an isolated MG is minimized considering three scenarios of normal operation, peak load demand, and plug and play ability	High DOD leads to fast degradation of battery lifetime. Emission cost of CG is not considered	Centralized	Forecasted
[95]	Self-adaptive gravitational search algorithm	An EMS strategy is developed to minimize operational cost of an MG together with 2 m point estimate method to model its uncertainties	Emission cost of microturbine and power losses of MG system are ignored	Centralized	Point estimate method
[47]	Modified bacterial foraging	A multi-objective intelligent EMS is proposed to minimize the operation and emission costs of MG	High computational time complexity. DR is not considered	Centralized	Forecasted
[96]	Modified bacterial foraging	An expert EMS is proposed to minimize the operation and emission costs of MG. Artificial NN is used to forecast wind speed	High computational time complexity. DR is not taken into consideration	Centralized	Artificial NN
[97]	Artificial bee colony	Operational cost of home MG is minimized based on two layer control model with experimental validation	Complex formulation. Emission cost of microturbine is ignored	Centralized	Forecasted
[98]	Modified artificial bee colony	DR and load shedding are also inspected together with operating costs of DERs to minimize operational cost of a standalone MG	Lifecycle cost of battery and emission cost of microturbine are not taken into consideration	Centralized	Forecasted
[99]	Adaptive modified firefly	A scenario-based EMS model for a grid-connected MG is introduced to minimize its operational cost considering MG uncertainties	Emission cost of microturbine and reliability cost in terms of undelivered power are not considered	Centralized	Scenario generation and reduction method
[100]	Modified simulated annealing	Energy trading profit with main grid and neighboring MGs is maximized and it is also ensured that load demand must be always satisfied and PV power must not be wasted	Selection of DOD of battery is not discussed. DR is not taken into consideration	Centralized	Forecasted
[49]	Tabu search	A new probabilistic index, energy management success index, is defined as an objective function to reduce the total operational cost and power losses of the MG system	Computational time complexity of proposed approach is not discussed	Centralized	Scenario generation method
[101]	Modified crow search algorithm	The operational cost of MG, which includes bidding cost of DERs and energy trading cost with main grid, is minimized	DR and emission costs of CGs are not considered	Centralized	Forecasted
[102]	Modified artificial fish school algorithm	The overall cost of MG, which includes operating cost of DERs and energy trading cost with main grid, is minimized to optimize its daily operation	Emission cost of CG is not considered	Centralized	Least square support vector machine
[103]	Imperialist competition algorithm	Operational cost of a standalone MG is minimized. A hybrid artificial NN and Markov chain method are used to forecast RERs and load demand	High DOD leads to fast degradation of battery lifetime. Emission cost of CG is not considered	Centralized	Forecasted

each uncertain variable depends on the requirements of processing time and improvement in optimum solution of developed optimization problem. The forward-backward-based probabilistic power flow method is used to determine the energy losses of the system. In [101], a modified crow search-based EMS model was presented to optimize the daily energy scheduling of a grid-connected MG. The objective is to minimize the operational cost of MG that includes bidding costs of DERs and energy trading cost with main grid. Three scenarios are studied with respect to operational status of distributed generators and value of battery initial SOC. The proposed approach is more efficient and effective than GA, PSO, fuzzy self-adaptive PSO, and crow search algorithm in respect of best solution and reduced computational time.

In [102], the overall operational cost of MG is minimized. It includes fuel cost of CGs, operating cost of DERs, energy trading cost with main grid. The least square support vector machine method is used to predict the power output of RERs. An EMS solution approach for a standalone MG based on imperialist competition algorithm is proposed in [103] to minimize the operational cost of MG together with penalty cost on undelivered power. A hybrid NN and Markov chain-based prediction method forecast power generation of RERs and load demand. Three scenarios of normal operation, sudden high requirement of load demand, and plug and play ability are taken into consideration. The effectiveness of the proposed approach is also validated experimentally. It is proven that the proposed algorithm performs better than PSO.

Table 6 summarizes the critical analysis on MG EMSs that are solved by meta-heuristic approaches, other than genetic and swarm optimization. In these approaches, a lot of work is still required on considering joint reduction of operational cost and environmental pollutants, reduction of MG systems losses, integration of DR, and reliability improvement. Centralized supervisor control architecture is used in all these MG EMSs. Few authors also used efficient uncertainty quantification methods such as scenario generation and reduction method, and point estimate method to take into account the effects of MG uncertainties in achieving a reliable and sustainable operation.

4.3. EMS based on artificial intelligent methods

4.3.1. EMS based on fuzzy logic and neural network

ArcosvAviles et al. [104] presented a fuzzy logic-based EMS to achieve smooth power profile of a grid-connected residential MG. The proposed model minimizes the fluctuations and power peaks in the energy exchange with the main grid. It also maintains the battery SOC level close to 75% of its rated capacity to improve its lifetime. The proposed approach performs better than SOC-based EMS. Chen et al. [105] introduced an efficient EMS model for a standalone DC MG using fuzzy logic control and Zigbee-based communication network. The proposed model ensures efficient utilization of RERs and improvement in lifetime of Li-ion battery. The efficacy and efficiency of the proposed approach is also experimentally validated. Kyriakarakos et al. [106] proposed a fuzzy logic-based EMS for an isolated MG that minimizes net present cost together with penalty cost on battery SOC, hydrogen, and water storages. The load demands are divided into three categories of electric load, water load, and transport load. The hydrogen is considered as a fuel for transport load. The decision inputs for the fuzzy logic system are battery SOC, water, and system frequency. The MG system simulation is performed for one year study on software platforms of Transys, Genopt, Matlab, and Trnopt.

Enrico et al. [107] introduced a fuzzy logic-based EMS of a grid-connected MG. The hierarchical genetic algorithm tunes Mamdani fuzzy inference systems to minimize the fuzzy rules of an EMS model. The improved MG model is realized by taking into account the realistic efficiency parameters of battery that replaces an ideal battery model. The developed approach optimizes the fuzzy rule base of an EMS for efficient energy flow and maximization of energy trading profit. The performance of the proposed approach appears to be better as compared to a classical fuzzy-GA method. Fuzzy-based MG economic dispatch and unit commitment is performed in [43] that considers two GAs to optimize its energy scheduling operation. First GA determines MG energy scheduling and fuzzy rules, while the second GA tunes fuzzy membership functions. Fuzzy expert system is also used to manage the power allocation of battery.

Chaouachi et al. [53] proposed an efficient multi-objective MG EMS to minimize the operational and emission costs of MG, which includes charging and discharging rates of battery determined by fuzzy expert system. The artificial NN ensemble method forecasts the power generation of RERs and load demand. The efficiency of the proposed approach is better compared to conventional multi-objective model that does not consider fuzzy expert system for battery scheduling. Wang et al. [108] presented a Lagrange programming NN approach for efficient MG EMS to minimize overall cost of MG that includes fuel cost, operation and maintenance costs, and emission cost of generation units. A radial basis NN forecasts power generation of RERs and load demand. Load is divided into four categories of critical load, controllable load, price sensitive load, and thermal load to consider DR. The proposed approach achieves the best solution more efficiently than PSO. Urias et al. [109] introduced a recurrent NN approach for efficient EMS of a grid-connected MG. It aims to minimize power import from main grid and maximize utilization of power output of RERs. DOD of battery is set to 60% to improve its lifetime. Load demand is divided into two categories namely: critical and ordinary loads. A hybrid wavelet functions and extended Kalman filter-based NN approach is adopted to forecast the load demand and power generation of RERs.

Venayagamoorthy et al. [110] proposed an intelligent adaptive dynamic EMS for a grid-connected MG. It maximizes the utilization of RERs and minimizes carbon emissions to achieve a reliable and self-sustainable system. It also improves battery lifetime. The proposed EMS is modeled using evolutionary adaptive dynamic programming and reinforcement learning concepts and solved by use of two NNs. An active NN is used to solve the proposed EMS strategy, while a critical NN checks its performance with respect to optimality. The new defined performance index evaluates the performance of dynamic EMS in terms of battery lifetime, utilization of renewable energy, and minimum curtailment of controllable load. The performance of the proposed approach is better as compared to decision tree approach-based dynamic EMS. Kuznetsova et al. [111] proposed a reinforcement learning-based MG EMS to achieve the maximum utilization of battery and wind energy resources, and the minimum dependence on energy purchase from main grid. In reinforcement learning, a Q-learning method is used to achieve the optimal operation of MG. To account wind speed uncertainties, Markov chain model is used to generate scenarios for forecasted wind speed. Two hours-ahead scenarios are considered only in optimization process to realize low computational cost of forecasting method.

Table 7 summarizes the critical overview on MG EMSs that are solved by fuzzy logic and NN methods. Centralized supervisory control architecture is used in all these MG EMSs. The uncertainties within an MG system are taken into account by using forecasted values. Most of the contributions are DERs operational cost in minimization, mitigation of environmental pollutants, and energy trading with main grid. However, computational complexity of the proposed approaches, customer privacy issues, DR, reliability of MG system, and losses cost of MG are not yet assessed in detail.

4.3.2. EMS based on multi-agent system

A MAS-based decentralized approach for optimal operation of a grid-connected MG is presented in [112]. All the consumers, storage units, generation units, and grid are considered as agents. In the decision making, the consumer consumption preference has been considered as an important factor. The multi-agent decentralized algorithm reduces the power imbalance cost while considering consumer consumption preference as an important factor in the decision making process. The authors concluded that the decision making time of the

Table 7
Critical analysis of MG EMSs based on fuzzy logic and neural network methods.

Ref.	Proposed approach	Contributions	Limitations	Supervisory control	Uncertainty handling approach
[104]	Fuzzy logic	Fluctuations and power peaks are minimized while exchanging energy with the main grid	Voltage and frequency regulation of MG system is not considered	Centralized	Forecasted
[105]	Fuzzy logic	Lifetime of Li-ion battery is improved. Zigbee is used for communication among MG components	It is difficult to meet load demand always due to no DR involvement and battery SOC level to be set 50% as a threshold	Centralized	Forecasted
[106]	Fuzzy logic	Penalty cost on battery SOC, water storage, and hydrogen storage are included in EMS model to minimize overall operational cost of MG	DR is not considered. The computation time complexity of the proposed approach is not discussed	Centralized	Forecasted
[107]	Fuzzy logic	A realistic battery parameters are included in MG model. Energy exchange profit is maximized	Complex formulation that results in higher computational time	Centralized	Forecasted
[43]	Fuzzy logic	Fuzzy-based EMS approach is proposed for MG scheduling and battery power management	Higher computational time complexity. Power losses are not considered	Centralized	Forecasted
[53]	Fuzzy logic	A multi-objective MG EMS minimizes the operation and emission costs of MG that utilizes charging and discharging rates of battery determined by fuzzy expert system	Computational time complexity of proposed approach is not discussed. DR is not taken into consideration	Centralized	Artificial NN ensemble
[108]	Neural network	Overall cost of MG is minimized, radial basis NN is used for prediction, and results are compared with PSO	Computational time complexity of proposed approach is not discussed. Operational cost of battery is not considered	Centralized	Radial basis NN
[109]	Recurrent neural network	Power import from main grid is discouraged to utilize maximum renewable power available within an MG system	Computational time complexity of proposed approach is not discussed. DR is not considered	Centralized	Extended Kalman filter-based NN
[110]	Neural Network	Maximum utilization of RERs and DR, improvement in battery lifetime, and reduction in carbon emissions are achieved	Complex formulation. Computational time complexity of the proposed approach is not discussed	Centralized	Forecasted
[111]	Reinforcement learning based-NN	MG operational performance is optimized by maximizing use of battery and RER, and minimizing energy purchase from main grid	Complex formulation. DR is not considered	Centralized	Markov chain

proposed approach is better than the centralized approach.

Bogaraj and Kanakaraj [45] presented a MAS-based approach to design an intelligent EMS and load shedding scheme for an islanded MG. It maintains energy balance through effective coordination among RERs, batteries, and loads. The agents are photovoltaic system, wind turbine, fuel cell, battery, and load. Fuel cell and battery bank are used as a backup. Load is divided into three groups based on priority. The power generation of RERs, loads, and atmospheric temperature, are forecasted using auto regressive moving average (ARMA) method. Two case studies of high wind and high irradiance, and low wind and low irradiance, are used to check the performance of the proposed approach. It also minimizes time delays in making decisions. STATCOM is used for reactive power compensation to reduce harmonics and improve voltage profile of MG system. Anvari-Moghaddam et al. [113] proposed an ontology driven MAS-based EMS for efficient operation of a grid-connected residential MG. The agents are categorized into central coordinator agent, building management agent, RER agent, battery agent, and service agent. The objectives of the proposed approach are to minimize operational cost and to satisfy consumers electrical and thermal comfort levels. Intra agent platform communication uses internal message transport protocol (IMTP), while inter agent platform communication uses hypertext transfer protocol (HTTP).

Nunna and Doolla [114] proposed an optimal MG EMS, considering DR and distributed storage, that aims to reduce peak demand and minimize electricity cost. Consumers are encouraged to participate in DR program by using an index-based incentive mechanism for them. The agents are generation agent, storage agent, load agent, DR agent, MG intelligent agent, and global intelligent agent. The MAS architecture is implemented on Java application development framework. Two case studies of two and four interconnected MGs are performed after each 15 min interval for day-ahead operation. Dou and Liu [115] proposed a multi-objective hierarchical MAS-based decentralized EMS for a grid-connected MG system to minimize its operational cost, emission cost, and line losses. The hierarchical MAS is divided into three levels. The upper level agent deals with the energy optimization of MG. The middle level agents are concerned with the coordination among control agents to switch operation modes using Petri-net model for voltage regulation. The lower level agents define *f/V* and *PQ*-based control strategies for unit agents to manage real-time operation of DERs.

A fuzzy cognitive maps-based MAS approach is proposed in [116] for decentralized EMS of an islanded MG. It minimizes system net present cost together with penalty cost on battery SOC, hydrogen storage, and water storage. Five intelligent agents are defined, which are RER agent, battery agent, desalination agent, fuel cell agent, and electrolyzer agent, respectively. The proposed MAS-based approach is simulated by interconnection of Transys, Matlab, Genopt and Trnopt software packages and is compared with fuzzy logic-based centralized EMS method in terms of economic benefits.

Table 8 summarizes the critical analysis on the contributions and main limitations of MG EMSs using multi-agents, together with the supervisory architectures. In this context, computational time complexity of the proposed approach, reduced GHG emissions, secure and reliable communication system for decentralized operation of MG, effects of selection of DOD on battery and MG performance, minimization of outages and interruptions, and use of efficient uncertainty quantification methods are not addressed. These potential areas should be assessed in detail to achieve energy efficient and environmental friendly operation of MG system.

4.3.3. EMS based on other artificial intelligent methods

Liu et al. [117] proposed stackelberg game theory approach for optimal energy management and energy sharing of PV prosumers-based grid-connected MG. It works on the principle of leader-follower model, where MG acts as a leader and all PV prosumers are followers. In the proposed model, the uncertainties of solar power and load demand are

Table 8
Critical analysis of MG EMSs based on multi-agent system.

Ref.	Proposed approach	Contributions	Limitations	Supervisory control	Uncertainty handling approach
[112]	Multi-agent system	Power imbalance cost is minimized, while considering consumer consumption preferences in the decision making process	Effects of charging and discharging cycles on batter lifetime are ignored	Decentralized	Forecasted
[45]	Multi-agent system	Load generation balance is achieved through battery scheduling and load shedding. STATCOM is used to improve power quality of MG	Operational cost of RERs and battery are ignored. Penalty cost on load shedding is also not considered	Decentralized	Auto regressive moving average
[113]	Multi-agent system	Multi-objective EMS is proposed to minimize operational cost of MG and to maximize consumers electrical and thermal comfort levels	Emission cost of microturbine is ignored. Operational cost of battery is also not considered	Decentralized	Forecasted
[114]	Multi-agent system	Peak demand and electricity cost are minimized using DR and distributed storage	Higher DOD is selected that leads to fast degradation of battery	Decentralized	Forecasted
[115]	Multi-agent system	Multi-objective formulation of EMS is proposed to minimize operational cost, emission cost, and line losses of MG	Complex formulation. Computation time complexity of proposed approach is not discussed	Decentralized	Forecasted
[116]	Multi-agent system	The net present cost of MG system and penalty cost on battery SOC, hydrogen storage, and water storage are minimized	DR is not considered. The computation time complexity of the proposed approach is not discussed	Decentralized	Forecasted

tackled by a billing mechanism approach. In this approach, the hourly deviation between scheduled and real power is compensated by regulating revenues or costs of PV prosumers with respect to their contributions in MG profit. The leader objective is global profit maximization, while follower objectives are maximum utilization of energy resources on prosumers level. However, a prosumer with higher preference parameter in consuming its energy has higher utilization level which, in turn, decreases profit. Therefore a tradeoff exists between utilization level and profit in reference to preference parameter.

Ma et al. [118] presented a leader follower-based game theoretic EMS for a grid-connected MG with DR mechanism in which MG and prosumers are considered leader and followers, respectively. The proposed approach aims to maximize the profits of MG and prosumers individually, while maintaining Stackelberg equilibrium to ensure fair share of profit distributed among them. The MG operator uses differential evolution and prosumers use nonlinear programing method to reach the Stackelberg equilibrium. The sensitivity analysis with respect to increasing number of PV prosumers shows upward trend in MG profit and good convergence rate of the proposed approach. It performs better than a centralized optimization model. In [119], a bi-level leader follower programming method is developed for optimal energy management of multi-MGs. The upper level deals with minimization of production cost of the whole system. Lower level is related to maximization of net profit of each MG. To reduce the effects of forecast errors of solar and wind powers, the proposed model is solved for a short duration, of the order of a few minutes to half an hour. The bi-level decentralized problem is converted into single level problem by using Karush-Kuhn-Tucker method for lower level problem, which is solved by LINDO-Global package in GAMS software.

A modified game theory-based multi-objective EMS of a grid-connected MG is proposed in [120] to minimize Pareto optimal objectives that include operation and emission costs of MG. In the proposed approach, the objective function is defined as the difference of Pareto objectives and supercriterion. Supercriterion is the normalized distance of the objective function from its worst value with 0 being best and 1 being worst. The developed multi-objective optimization model is compared in performance with multi-objective GA, multi-objective Sequential Quadratic Programming, and multi-objective Mesh Adaptive Direct Search. Lan et al. [121] introduced a rolling horizon Markov decision process-based EMS of a grid-connected MG. It minimizes electricity and natural gas costs considering wind power uncertainties modeled by Markov decision process. The greedy algorithm finds the feasible base policy and local optima for rollout algorithm that solves the developed EMS model to tackle large states of Markov decision process. The proposed approach is more efficient than scenario tree-based method in terms of both performance and computation time.

Jia et al. [122] presented an adaptive intelligence technique for the EMS of a grid-connected MG using hybrid ESS. It aims to maximize utilization of RERs and minimize load fluctuations considering dispatch power errors due to uncertainties in power generation of RERs and load demand. The smooth load profile is managed by joint operation of battery and ultra-capacitors, where sudden requirements of load demand are handled by ultra-capacitors. The hybrid ESS efficiency, ratio of energy discharge to the available energy, is higher in the proposed method as compared to PSO.

Table 9 summarizes the critical analysis on contributions and main limitations on MG EMSs based on other artificial intelligent techniques such as game theory and Markov decision process together with the supervisory architectures of these EMSs and uncertainty quantification methods. In these solution approaches, much emphasis is needed to consider communication system cost for decentralized operation of MG, mitigation of environmental pollutants, losses cost, EVs integration for DR, and system voltage and frequency regulation to ensure reliable and sustainable operation of MG. Computational time complexity of the proposed approaches have not been dealt with too.

Table 9
Critical analysis of MG EMSs based on other artificial intelligent methods.

Ref.	Proposed approach	Contributions	Limitations	Supervisory control	Uncertainty handling approach
[117]	Game theory	Objectives are to achieve maximum utilization on prosumers level and maximum profit on MG level. A billing mechanism is introduced to handle uncertainties of solar power and load demand	ESS is ignored, which can cause load shedding during islanded operation in case of disturbance in main grid because DR and PV cannot meet load demand always	Decentralized	Billing mechanism
[118]	Game theory	Objectives are to maximize MG and prosumers profits individually, while satisfying Stackelberg equilibrium	Emission cost of microturbine is not considered	Decentralized	Forecasted
[119]	Game theory	A bi-level problem is defined to minimize operational cost of MGs network in upper level and maximize net profit of each MG in lower level	Computational complexity is not discussed. No ESS is considered	Decentralized	Forecasted
[120]	Modified game theory	A multi-objective EMS of a grid-connected MG is proposed to minimize its operational and emission costs	Computational time complexity of the proposed approach is not discussed. DR is not considered	Centralized	Forecasted
[121]	Markov decision process	Electricity and natural gas costs are minimized considering wind power uncertainties to optimize the operation of MG	Higher DOD results in fast degradation of battery. Emission cost of CG is not considered	Centralized	Markov decision process
[122]	Adaptive intelligence technique	MG EMS is proposed to maximize utilization of RERs and minimize load fluctuations by managing operation of hybrid ESS	Neither MG profit nor selection of DOD of battery are discussed	Centralized	Markov chain Monte Carlo method

4.4. EMS based on stochastic and robust programming approaches

Ghasemi [123] proposed a grid-connected community MG architecture for agriculture purposes. The author introduced a stochastic coordination framework to minimize the cost of pumped storage unit and irrigation system, and energy trading cost with main grid. The point estimated method is used to model the uncertainties of wind power and wholesale electricity price. A probabilistic scenario-based optimal day-ahead economic operation of a grid-connected hybrid AC-DC MG is presented in [50]. It minimizes overall operation cost that includes energy trading cost with the main grid and operating cost of CGs. The forecasted values of electricity price, solar power, wind power, AC and DC loads are used. The scenarios with assigned probabilities are considered to deal with uncertainty in forecasted values of electricity price, solar power, wind power, AC and DC loads. A proportional-integral controller is used to control battery current that reduces fluctuations in DC bus voltage.

Cau et al. [124] presented a stochastic EMS for an isolated MG to minimize the utilization cost of battery and hydrogen storage system, and penalty cost on load shedding and dumped power. The utilization cost of ESS includes operation and maintenance costs, depreciation cost, and replacement cost. Scenario tree-based approach models the uncertainties of solar irradiance, wind speed, and load demand. Scenario reduction method limits these number of scenarios to reduce processing time of the proposed approach. For hydrogen storage operation, the electrolyzer converts the excess energy into hydrogen and stores it into H2 tanks. These H2 tanks feed a fuel cell for electricity generation in case of little or no availability of renewable generation to meet the load demand. The proposed approach is shown to be more efficient and effective than EMS with perfect forecast and SOC-based EMS in minimizing operational cost of MG. A two stage stochastic EMS is presented in [125] for efficient energy scheduling of a grid-connected MG. It aims to minimize the operating cost of CGs, battery degradation cost, and energy trading cost with the main grid. The two-stage model optimizes the day-ahead operation of MG in a first stage, and performs AC power flow, as a real-time operation, to compute power losses in a second one. Both these stages are solved iteratively until net change in power loss is within the specified limits. The effectiveness of the proposed model is tested on an IEEE 37-node system.

Rezaei et al. [54] introduced a stochastic frequency security constrained EMS for an isolated droop controlled MG. It minimizes frequency deviations during day-ahead MG operation and limits operational and emission costs of MG to a reasonable level. Operational cost of MG includes operating cost of CGs, RERs and reserves, load shedding cost, and DR incentives. Scenario generation and reduction method is used to model the uncertainties of RERs and load demand by using the probability density functions of their forecasted errors. CGs outages-based contingency analysis is also studied to test the robustness of the proposed approach. Shen et al. [126] presented a scenario-based stochastic EMS for a grid-connected MG using conditional value at risk methodology that aims to maximize the expected profit. The conditional value at risk is used to consider the risk level in computing the expected profit of MG. Latin hybercube sampling-based Monte Carlo simulation method generates scenarios of RERs, load demand, and electricity price. To reduce computational time, generated scenarios are reduced without the loss of accuracy of results. The sensitivity analysis of energy trade with the main grid is studied with respect to price standard deviation, price expected value, DR, and confidence level.

A two-stage stochastic programming model is presented in [127] to optimize operation of a grid-connected MG EMS considering uncertainties of RERs and load demand. First stage is related to optimization of investment cost of MG. Second stage deals with the energy management operation of MG. The effects of battery capacity on purchased power, sold power, and battery SOC are also studied for three cases, which are 50% uncertainty in load demand, 50% uncertainty in supply, and 50% uncertainty in both supply and load demand. Farzin

Table 10
Critical analysis of MG EMSs based on stochastic and robust programming methods.

Ref.	Proposed approach	Contributions	Limitations	Supervisory control	Uncertainty handling approach
[123]	Stochastic optimization	The overall cost of MG is minimized, including operational cost of pumped storage unit and irrigation system, and energy trading cost	The levelized cost of energy of wind and power losses cost are ignored. DR is not considered	Centralized	Two point estimate method
[50]	Scenario-based optimization	The overall cost of hybrid AC-DC MG is minimized, including energy trading cost with main grid and operating cost of CGs. A battery current controller is used to regulate the fluctuations in DC bus voltage	Emission cost of dispatch units and DR are not taken into consideration	Centralized	Scenario generation method
[124]	Stochastic optimization	The utilization cost of battery and hydrogen storage system, and penalty cost on load shedding and dumped power are minimized for efficient operation of MG	Computational time complexity is higher	Centralized	Scenario tree approach
[125]	Stochastic programming	The operating cost of CGs, battery degradation cost and energy trading cost with the main grid are minimized	Computational time complexity is not discussed. Higher DOD results in fast degradation of battery	Centralized	Monte Carlo simulation method
[54]	Stochastic optimization	The frequency management-based EMS is defined to control frequency deviations of an isolated MG while satisfying techno-economic and environmental constraints	Computational time complexity of proposed approach is not discussed	Centralized	Monte Carlo simulation and scenario reduction approaches
[126]	Stochastic programming	The expected profit and of MG is maximized considering risk management based on conditional value at risk factor	The levelized cost of energy of RERs and battery degradation cost are not considered	Centralized	Monte Carlo simulation and scenario reduction
[127]	Stochastic programming	Two-stage stochastic framework for MG EMS is proposed to minimize investment cost in first stage and operation cost in second stage	Emission cost of gas turbine and battery degradation cost are not considered	Centralized	Scenario tree approach
[128]	Stochastic optimization	Expected operational cost of MG is minimized for its optimal operation during unexpected islanding events	Computational time complexity is not discussed. DR is also not taken into consideration	Centralized	Monte Carlo simulation and backward reduction methods
[46]	Stochastic optimization	Multi-objective EMS model is proposed to minimize operational and emission costs of MG	Selection of higher DOD results in fast degradation of battery	Centralized	Scenario generation and reduction
[129]	Chance constrained programming	Two EMS models are represented for peak shaving and system protection, and frequency regulation, respectively	Complex formulation. Tradeoff between complexity and cost is ignored	Centralized	Probabilistic constraints
[130]	Robust optimization	MG performance in terms of imbalance cost and MG reliability in terms of loss of expected energy and loss of load expectation are realized	Complex formulation. DR in residential district is ignored	Decentralized	Bounded uncertainty
[131]	Robust optimization	Social benefit cost including operating cost of CG and battery, and energy trading cost is minimized while realizing worst case scenario for energy trading cost to account for the MG uncertainties	Emission cost of CG and DR are not taken into consideration. Higher DOD is selected that leads to fast degradation of battery	Centralized	Bounded uncertainty
[132]	Robust optimization	Two-stage EMS is proposed to perform day-ahead unit commitment operation in a first stage and real-time economic dispatch and energy trading operation in a second one	Computational time complexity of proposed approach is not discussed. Higher DOD decreases battery lifetime exponentially	Centralized	Bounded uncertainty
[133]	Robust optimization	Social cost of MG is minimized that includes operating cost of CGs and battery, DR incentives and worst case energy trading cost	Complex formulation. Computation time complexity of proposed method is also not discussed	Decentralized	Bounded uncertainty
[134]	Robust optimization	Operational cost of MG, which includes energy trading cost with the main grid, operating cost of combined cooling, heat and power unit and battery degradation cost, is minimized	DR application in handling uncertainties of MG system is not considered	Centralized	Bounded uncertainty
[55]	Robust optimization	Two-stage EMS model performs day-ahead unit commitment operation of CGs in first stage and real-time DR and energy trading operation in second stage considering MG islanding events	Levelized cost of energy of RERs is not considered. Computation time complexity of proposed method is also not discussed	Centralized	Bounded uncertainty

et al. [128] presented a stochastic EMS for optimal operation of an MG during unforeseen islanding periods. The scenarios of islanding durations and their corresponding probability of occurrence are estimated based on normal distribution function for each islanding event, which is caused by disturbances or failures in the main grid. Scenario generation and reduction methods is used to take into account the uncertainties of wind power and load demand during these estimated islanding intervals. The objective is to minimize the expected operational cost of MG, which includes operating cost of microturbine, wind power and battery, load shedding cost, potential revenue, and risk factor associated with the objective function value. The sensitivity analysis is also presented to study the impacts of islanding duration, risk factor, and battery operational cost.

A multi-objective stochastic EMS that considers portable RERs for DR application is presented in [46] to minimize operational and emission costs of a grid-connected MG. The operational cost of MG includes operating cost of dispatch units, RERs, ESSs, and energy trading cost. The portable RERs include small scale wind turbine and photovoltaic system. The developed multi-objective stochastic optimization model is solved by augmented epsilon constraint method in GAMS software. The impacts of electricity price, combined heat and power coefficient, initial energy states of ESSs, cut-in and cut-out wind speed, grid-tie line limit, and minimum reserves on operational and emission costs of MG are also studied. Liu et al. [129] proposed a chance constrained programming approach-based EMS for peak power shaving and frequency regulation of a grid-connected MG under uncertainties of RERs and load demand. The MG energy management operation is divided into two sub-problems of energy magnitude scheduling within the defined energy boundaries for system protection and real-time energy capacity deviation limit for frequency regulation. The proposed approach is more efficient than greedy planning, robust programming, and scenario-based optimization methods in terms of cost savings.

Kuznetsova et al. [130] proposed a decentralized EMS for a grid-connected MG using agent-based modeling and robust optimization approach to improve its performance and reliability. MG performance is determined in terms of imbalance cost associated with uncertainties of power output of RERs, load demand and electricity price. Moreover, MG reliability is improved by considering loss of expected energy and loss of load expectation parameters. The maximum deviations in power output of RERs, demand and electricity price forecasting are estimated by non-dominated Sorting GA trained NN. These maximum deviation ranges are used in formulating a robust optimization model for optimal operation of MG. Agent-based modeling is used to achieve the decision making of each agent to minimize expenses of train station and residential district. It also maximizes revenue of wind power unit at individual level. A scenario-based robust optimization approach is presented in [131] to optimize the worst case realization of energy scheduling of a grid-connected MG. The uncertainty sets of RERs and load demand are determined by interval prediction theory based on their forecast errors. Taguchi orthogonal array method uses these sets to generate limited number of scenarios. Scenarios with best statistical information are selected to reduce the processing time as compared to Monte Carlo simulation. Robust EMS model is developed to minimize social benefit cost of MG. It includes operating cost of CG and battery together with energy trading cost worst realization using search strategy based on Taguchi orthogonal array method.

Hu et al. [132] introduced a two-stage robust optimization-based grid-connected MG EMS model. It performs day-ahead unit commitment operation in a first stage, and real-time economic dispatch and energy trade operation in a second stage. The complexity of the proposed model is relaxed by using Lyapunov optimization method. The efficacy and efficiency of the proposed approach is better than greedy algorithm. Zhang et al. [133] introduced a robust decentralized EMS for a grid-connected MG to minimize its social cost. The objective function includes operational cost of CGs and battery, DR incentives and worst case energy trading cost. The developed optimization model is decomposed and solved iteratively by a distributed implementation of subgradient method. The authors also analyzed that the social cost of MG decreases with increase in proportion of selling energy price to buying energy price.

An optimal EMS of a grid-connected MG is presented in [134]. The nonlinear thermal and electric efficiency curve of microturbine is converted into piecewise linear approximations to make the problem tractable. The objective is to minimize the operational cost of MG that includes energy trading cost with the main grid, operating cost of combined cooling, heat and power unit, and battery degradation cost. The impacts of different budget of uncertainty values and efficiency curves on MG performance are also studied. Two-stage robust optimization approach for EMS of a grid-connected MG is presented in [55]. It performs day-ahead unit commitment operation of CGs in a first stage, and real-time DR and energy trading operation in a second stage. The proposed model takes into account the uncertainties of RERs and MG islanding events. The budget of uncertainty factor is introduced to avoid over-conservatism of the proposed approach, resulting in tradeoff between optimality and robustness. The developed two-stage model is transformed into a large scale MILP problem, which is solved by column and constraint generation algorithm-based decomposition approach. The comparison with stochastic programming method shows that the proposed approach is more effective in finding worst-case best solution. However, it is outperformed with respect to average case best solution.

The critical analysis of MG EMSs based on stochastic and robust programming approaches is summarized in Table 10. The main limitations of these approaches are complex problem formulation, higher computational time complexity, no mitigation mechanism for reducing GHG emissions, higher DOD selection of battery, and customer privacy issues.

4.5. EMS based on model predictive control

Solanki et al. [135] emphasized on use of smart load to perform an efficient EMS strategy based on a model predictive control (MPC) approach for an islanded MG. A supervised NN is used to estimate the residential controllable load. The objective function consists of operating cost of CGs and penalty cost on energy curtailment. The developed optimization model shows improved performance than decoupled EMS model, which decomposes the main problem into two sub-problems, namely: unit commitment and optimal power flow. It performs better in terms of best solution, less energy curtailed, reduced peak demand and improved load factor, but at the cost of higher computational time. The impacts of DR on objective function, less energy curtailment, load factor improvement, and peak demand reduction are also studied. Mendes et al. [136] proposed a hierarchical structure for optimal energy management of a grid-connected MG, together with vehicle-to-grid operation, to ensure its stability in a first level and its economic operation in a second one. The economic operation of MG includes energy trade with main grid, maximum use of RERs, and management of battery and EVs operation. The effectiveness of the proposed approach is also validated experimentally.

Minchala-Avila et al. [137] presented a nonlinear MPC approach for an islanded MG EMS model to ensure its stable operation. The voltage stability of MG system is secured by managing the control of battery SOC and load shedding scheme. An artificial NN is used for load demand prediction and an adaptive neuro-fuzzy inference system is used to forecast power output of CG based on load demand. Both of these predication methods are tested with the proposed approach and the latter shows better performance. An MPC-based EMS of a grid-connected MG is presented in [138] to minimize the energy trading cost with the main grid, and to ensure better utilization of battery during peak load demand. It also ensures maximum use of wind power to meet local demand. A fault-tolerant control scheme is introduced to have smooth operation of MG during sudden failures of wind turbines and power supply shortage. The efficacy and efficiency of the proposed approach is better than reinforcement learning algorithm in respect of best solution. A robust EMS for an isolated MG, located in a Chilean village, is proposed in [139]. The fuzzy prediction interval method determines the uncertainty set for wind energy. The uncertainty of solar power is not considered due to the low probability of solar irradiance variability. The objective is the efficient dispatch of MG sources at minimum operating cost. Two MPC optimizers are used to determine the upper and lower range of dispatch of MG units and the final output is obtained by a convex sum of these ranges with a defined weighting factor.

Luo et al. [140] introduce a two-stage coordinated approach for efficient EMS operation of a grid-connected MG. The piecewise linear approximations of thermal and electric efficiency curves of microturbine are considered in a first stage. It includes the operating cost of microturbine, battery degradation cost, and energy trading cost with the main grid in objective function. The first stage is related to economic dispatch operation of MG, while the second stage is an adjustment one. It deals in real-time with any load generation imbalance caused by uncertainties of power output of RERs and load demand. A sustainable EMS for an islanded MG is presented in [141] to optimize its energy scheduling considering multi-objective functions of its operation and emission costs. Different operational strategies have been considered with respect to minimization of operation and emission costs of MG. The impacts of DR on reduction in operation and emission costs are also studied.

Prodan et al. [142] proposed a fault-tolerant EMS for a grid-connected MG considering generator faults and uncertainties of RERs, load demand, and market price. The objective function includes the battery lifecycle cost, external grid cost, and load generation imbalance cost. The battery lifecycle cost is included in the objective function to consider its aging factor. Finally, a fault-tolerant strategy is introduced as a constraint to ensure the availability of sufficient resources of ESS to meet the load demand during generators fault.

Table 11 summarizes the contributions and main limitations of the proposed MG EMSs based on model predictive control. Centralized supervisory control architecture is used in all these MG EMSs. Moreover, forecasted data are mainly used to take into account uncertainties in these EMSs. However, a lot of work is still required to focus on computation time complexity, reduction of GHG emissions of CGs, outages and losses costs of MG system, efficient integration of DR and EVs, and customer privacy issues.

4.6. EMSs based on other approaches

Guo et al. [143] presented a real-time EMS of a standalone MG that uses rolling horizon optimization method to minimize the consumption of CG and to maximize utilization of wind energy. The GA-based back propagation NN method is used for an hour-ahead wind speed prediction. The resource scheduling of MG is divided into an hour-ahead scheduling and real-time dispatch. For real-time dispatch, the two operation modes are considered. In first mode, battery is used as a main source and *V/f* method controls its operation. While in second mode, CG is considered as a main source. Therefore, *V/f* and *PQ* methods are used to control the operations of CG and battery, respectively. In both of these modes, MPPT method is used for wind turbine. In [144], a two-stage hierarchical method based EMS is presented to minimize MG operational cost and fluctuations in energy exchanged at PCC. The proposed method consists of a day-ahead economic dispatch stage and a two-layer intra-hour adjustment stage. The latter stage is used to minimize the fluctuations in energy exchanged at PCC in both short term (15 min) and ultra-short term (1 min) intervals. Office building, modeled as a thermal ESS, and EVs are considered as flexible resources.

Akter et al. [145] proposed a hierarchical model for power sharing among residential prosumers in a grid-connected residential MG. Each house is equipped with a central EMS controller to share information

Table 11
Critical analysis of MG EMSs based on model predictive control.

Ref.	Proposed approach	Contributions	Limitations	Supervisory control	Uncertainty handling approach
[135]	Model predictive control	Operating cost of CGs and penalty cost on energy curtailment are minimized. Moreover, effects of DR on MG performance are also studied	Computation time of the proposed approach is higher. Emission cost of CGs is ignored	Centralized	Artificial NN
[136]	Model predictive control	An EMS is proposed to maintain MG stability in a first level and to optimize its economic operation in a second one	Fully discharged EVs result in exponential decrease of their batteries lifetime	Centralized	Forecasted
[137]	Model predictive control	The voltage stability of MG is achieved by controlling battery SOC and implementing load shedding scheme	Computational time complexity of proposed approach is not discussed	Centralized	Forecasted
[138]	Model predictive control	The energy trading cost with main grid is minimized as well as the maximum utilization of battery and wind power are achieved	Operational cost of wind turbine and battery are not taken into consideration	Centralized	Forecasted
[139]	Model predictive control	Operating cost of CG and penalty cost on load shedding are minimized. Wind power uncertainty is determined by fuzzy prediction interval method	Emission cost of CG and levelized cost of energy of wind turbine are not considered	Centralized	Fuzzy prediction interval method
[140]	Model predictive control	Two-stage EMS model is developed which performs economical scheduling operation in first stage and adjustment operation in second stage to deal with uncertainties of power output of RERs and load demand	Computational time complexity of proposed approach is not discussed. Emission cost of CG is not considered	Centralized	Forecasted
[141]	Model predictive control	The multi-objective function of operational cost and emission cost of MG system are minimized. Impacts of DR on proposed approach are also studied	Operational cost of battery is not taken into consideration	Centralized	Artificial NN
[142]	Model predictive control	Operational cost of MG, which includes battery lifecycle cost, energy trading cost with main grid and load generation imbalance cost, are minimized considering generator faults and uncertainties	Levelized cost of energy of RERs is not considered	Centralized	Bounded uncertainty

among residential prosumers. Three types of houses are considered, namely: traditional, proactive, and enthusiastic. Photovoltaic system is installed in both proactive and enthusiastic houses, while battery is installed in enthusiastic houses only. The objective is to maximize the energy sharing among houses in comparison with the main grid and minimize the investment cost. The authors concluded that the payback period is reduced due to power sharing among residential prosumers. Wang et al. [56] introduced a hierarchal control for a standalone MG EMS to improve the economical performance and reliability of MG. The economical objective includes penalty cost on starting new CGs, penalty cost on heavyvload and light-load operation of CGs, and operating cost of CGs and ESS. For system reliability, the battery SOC is used for voltage and frequency regulation to take into account uncertainties of wind speed and load demand in real-time.

Yanine et al. [146] presented homeostatic control-based energy and exergy management of a grid-connected MG that aims to achieve energy efficiency and thriftiness objectives. Homeostatic is a biologic term that refers to the process towards the state of equilibrium. Li-ion battery is used as an energy buffer to ensure effective implementation of MG demand response operation. In [147], the objective is to utilize the benefits of DR to deal with power mismatches that are caused by uncertainties of RERs. Predefined set of criteria are used to enhance the homeostatic regulation and control in energy consumption for sustainable operation of MG.

Shi et al. [148] proposed a predictor corrector proximal multiplier algorithm-based distributed EMS for a grid-connected MG to optimize its operation and to ensure customer privacy. The objective function includes operational cost of CGs, battery degradation cost, energy trading cost with main grid, load shedding cost, and power losses. The weights are introduced with each objective to have a tradeoff between operational cost and network losses minimizations of MG system. The nonconvexity of the developed model is solved by converting it into a relaxed optimal power flow problem. The authors concluded that the proposed approach is more efficient in minimizing network loss and operation cost of MG as compared to other existing methods in the literature.

Mohamed and Koiva [149] proposed an online EMS for a grid-connected MG, based on a mesh adaptive direct search method, to minimize its overall cost. The overall cost of MG includes operating cost of CGs, energy trading cost with main grid, and emission cost. In emission cost, the costs of nitrogen oxides, carbon oxides, and sulfur oxides are considered. The proposed approach is concluded to be more efficient than sequential quadratic programming approach in minimizing total cost of MG.

Table 12 summarizes the comparative analysis of the proposed MG EMS models based on other approaches such as rolling horizon, hierarchical control, homeostatic control, and many other. In these EMSs and solution approaches, an extensive work is required to focus on computational time complexity, algorithm convergence to optimal solution, reduction of GHG emission, integration of DR, MG reliability during islanded operation, minimization of power losses of MG system, and customer privacy issues.

5. Real world applications and discussion

An EMS is very important in utility, industry, commercial and residential sectors for energy efficient operation. It aims to optimize DERs scheduling, reduce energy consumption, and minimize GHG emissions. The integration of EMS with supervisory, control and data acquisition (SCADA), and human-to-machine interface (HMI) helps it in monitoring and analyzing data. It includes power output of generation sources, weather forecast, load demand, and real-time energy price. The EMS uses this data to optimize the system performance at generation, transmission, and distribution ends.

Most of the MG EMSs studied in the literature, as described in Section 4, have centralized supervisory control architecture. However,

Table 12
Critical analysis of MG EMSs based on other methods.

Ref.	Proposed approach	Contributions	Limitations	Supervisory control	Uncertainty handling approach
[143]	Rolling horizon optimization	Minimum consumption of DG and maximum utilization of wind energy are achieved. *V*/*f*, *PQ* and MPPT methods are used for real-time operation and control of CG and wind turbine	Operational cost of MG is not considered. Power losses of proposed MG system are also ignored	Centralized	GA-based back propagation NN
[144]	Hierarchical control	Operational cost of MG is minimized in first stage, while second stage is used to reduce fluctuations in energy exchanged at PCC	Computational time complexity of proposed approach is not discussed	Centralized	Forecasted
[145]	Hierarchical control	Objectives of minimization of investment cost of MG and maximization of energy sharing among houses are achieved	Battery operation is not discussed. Comfort level of users is also not considered	Centralized	Forecasted
[56]	Hierarchical control	Economical operation and reliability of MG is realized by minimization of operational cost, and regulation of system voltage and frequency, respectively	Levelized cost of energy of RERs is not considered	Centralized	Forecasted
[146]	Homeostatic control	Demand response, energy efficiency and thriftiness objectives are achieved in energy and exergy management of a grid-connected MG	Battery degradation cost is not taken into consideration	Centralized	Forecasted
[147]	Homeostatic control	The energy efficiency and thriftiness objectives are achieved by effective implementation of demand response in the residential sector	The benefits of DR in terms of mitigating GHG emissions and system reliability can also be realized	Centralized	Forecasted
[148]	Predictor corrector proximal multiplier algorithm	Optimal operation of MG is achieved by minimizing operational cost of CGs, battery degradation cost, energy trading cost with main grid, load shedding cost, and power losses	Computational time complexity of proposed approach is not discussed	Decentralized	Forecasted
[149]	Mesh adaptive direct search	Total cost of MG, which includes operating cost of CGs, energy trading cost and emission cost, is minimized	Levelized cost of energy of RERs and battery degradation cost are not taken into consideration	Centralized	Forecasted

due to the increased penetration of DERs in power system, centralized architecture faces problems of high computational time, less system scalability, and high instability in case of failures. Therefore, researchers are recently more focusing on a decentralized supervisory control architecture. However, it requires continuous availability of two-way communication link among MG components and their synchronization that results in increased system cost. Moreover, upgradation cost of these communication systems require to be optimized.

The operation of MG EMS is divided into two layers, namely: day-ahead dispatch layer and real-time dispatch layer. The day-ahead energy dispatch is further divided into subvhourly dispatch to take into account the forecast errors. The reference values are sent to LCs in real-time using communication links. For rural, residential, and remote areas MGs, the selection of communication technologies mainly depends on the deployment cost and data rate. Zigbee, z-wave, wifi, and Bluetooth are better options for such MGs. However for municipality and utility microgrids, the coverage range and data rate are most important, and passive optical network, 3G and 4G are better options. At DERs and load end, routers use these communication technologies to share information among LCs and MGCC. The LCs can be implemented by using low cost embedded systems, such as Aurdinos and Rasberry PI. They are designed to collect data from monitoring sensors and smart meters and perform control actions locally to ensure customer privacy. The MGCC performs energy management operations with the help of SCADA, HMI and information received from LCs. The solution approaches for these energy management operations are mainly selected on computational time complexity and convergence to optimum solution based merits. The experimental implementation of microgrid energy management systems are also validated using various solution approaches such as linear programming [66,71], meta-heuristic methods [93,94,97,103], artificial intelligent [105], and model predictive control [136]. Moreover, microgrid energy management systems are currently being developed and deployed by energy companies as Schneider Electric [150], ABB [151], General Electric [152], Siemens [153], Alstom, Tesla, and so forth.

6. Conclusion and future trends

Microgrids are generally composed of distributed energy resources, demand response, electric vehicles, local controllers, microgrid energy management system-based central controller, and communication devices. This paper has presented a comprehensive and critical review on the developed microgrid energy management strategies and solution approaches. The main objectives of the energy management system are to optimize the operation, energy scheduling, and system reliability in both islanded and grid-connected microgrids for sustainable development. Hence, microgrid energy management system is a multi-objective topic that deals with technical, economical, and environmental issues.

This extensive review addresses solutions, opportunities, and prospects to achieve the energy management objectives using various efficient methods. These methods are selected based on their suitability, practicability, and tractability, for optimal operation of microgrids. The objective types of MG EMS depend on its operation mode, its centralized or decentralized operation, economical aspects, and the intermittent and volatile nature of renewable energy sources. They also consider environmental issues of conventional generators, health status of batteries, active DR integration, system losses and reliability, and customer privacy. Many research studies have been conducted on some of these objective types. However, an extensive is still required to manage the customer privacy issues, secure and reliable communication system cost management, particularly for decentralized operation. Furthermore, microgrid systems reliability analysis is not studied in detail for islanding and remote applications. These potential areas need to be addressed in detail to achieve optimal energy efficient operation of microgrids.

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