Energy Reports 9 (2023) 5565–5591

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Review article

A comprehensive review on energy management strategy of microgrids

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A R T I C L E I N F O

Article history:
Received 6 November 2022
Received in revised form 11 April 2023
Accepted 23 April 2023
Available online xxxx

Keywords:
Demand response
Distributed energy resources
Energy management
Microgrids
Optimization

A B S T R A C T

Renewable energy resources are a one-stop solution for major issues that include drastic climate change, environmental pollution, and the depletion of fossil fuels. Renewable energy resources, their allied storage devices, load supplied, non-renewable sources, along with the electrical and control devices involved, form the entity called microgrids. Energy management systems are essential in microgrids with more than one energy resource and storage system for optimal power sharing between each component in the microgrid for efficient, reliable and economic operation. A critical review on energy management for hybrid systems of different configurations, the diverse techniques used, forecasting methods, control strategies, uncertainty consideration, tariffs set for financial benefits, etc. are reviewed in this paper. The novelty of reformer based fuel cells, which generates hydrogen on demand, thereby eliminating the requirement of hydrogen storage and lowest carbon footprint is discussed for the first time in this paper. The topics requiring extended research and the existing gap in literature in the field of energy management studies are presented in the authors' perspective, which will be helpful for researchers working in the same specialization. Papers are segregated based on multiple aspects such as the configuration, in particular, grid-tied, islanded, multi microgrids, the control strategies adopted besides the identification of limitations/factors not considered in each work. Moreover, at the end of each section, the literature gap related to each category of segregated group is identified and presented.

Contents

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https://doi.org/10.1016/j.egyr.2023.04.360

Nomenclature

RER	Renewable Energy resource
DER	Distributed Energy resource
EMS	Energy management system/strategy
MG	Microgrid
DGS	Distributed generator systems
CCHP	Combined cooling heating power system
DRP	Demand response program
PSO	Particle Swarm Optimization
SOC	State of Charge
CVaR	Conditional value at risk
EV	Electric vehicle
MILP	Mixed-integer linear programming
FC	Fuel cell
MMG	Multi microgrids
MPC	Model predictive control
ELM	Extreme learning machine
MT	Micro turbine
IPI	Independence Performance Index
ENS	Energy not supplied
GHG	Greenhouse gas
BESS	Battery energy storage system
CDG	Controllable distributed generator
WT	Wind turbine
P2G	Power to gas
TT	Tidal turbine
CPV	Concentrated photovoltaic panels
SST	Solar steam turbine
CHP	Combined heat and power
ESS	Energy storage system
ARMA	Autoregressive moving average
SMC	State machine control
MPPT	Maximum power point tracking
SOH	State of health
DG	Diesel generator
LCOE	Levelized cost of energy
LP	Linear Programming
RTH	Rolling time horizon
TOU	Time-of-use
OC	Operations cost
MICP	Mixed-integer convex programming
ADMM	Alternating direction method of multipliers
HEMS	Home energy management systems
PCC	Point of common coupling
HOMER	Hybrid optimization of multiple energy resources
ECMS	Equivalent consumption minimization strategy
GLPK	GNU linear programming kit
ESS	Energy storage system
MOGSO	Multi-objective group search optimization
ED	Economic dispatch
BSS	Battery storage system
SC	Super capacitor
VSI	Voltage source inverter
DE	Diesel engine
GAMS	General algebraic modelling system
MINLP	Mixed-integer nonlinear program
HIL	Hardware in loop
GA	Genetic Algorithm
PHS	Pumped hydro storage
HPU	Hydrogen production unit
CHP	Combined heat and Power
NPC	Net Present Cost
MPSO	Modified particle swarm optimization
HEMS	Home Energy Management System
DoD	Depth of Discharge
NSGA	Non-Dominated Sorting Genetic Algorithm
PHS	Pumped hydro storage

1. Introduction

Distributed generation is the integration of Renewable Energy Resources (RERs) along with their storage devices to the mainstream power grid for the additional generation of cleaner energy, reduced emissions, and meeting the growing demand for electricity. A classification of the energy generation and storage units is presented in Fig. 1. Energy generation is either from dispatchable sources, in which the generation is controllable depending on the demand and non-dispatchable sources in which the generation cannot be controlled, hence cannot guarantee to meet the varying demands. Storage units are devices, which support the energy management of the system in non-dispatchable systems, by storing the unused energy during surplus generation, which can later be used to meet the demand. Considering dispatchable sources, the main disadvantage is the emissions and heat which are harmful for the environment. Hence, the priority for selection of dispatchable sources is the one with least emissions. Fuel cells are promising in this aspect, but common fuel cells need provision for hydrogen storage, which increases the cost. Recent technological advance in this field is the reformer based fuel cell, which generates hydrogen on demand, without the need for hydrogen storage and minimum emissions. The choice of non-dispatchable sources depends mainly on the geographic features of the location, which decides the availability of natural resources such as solar irradiation, wind, biomass, etc. Under the context of storage devices, battery is the most widely used due to the high energy density and diminishing costs. However, batteries are disadvantageous due to the adverse effects on the environment during its disposal. Pumped hydro storage is suitable in locations where the geographic features permit, but the investment cost could be high compared the other storage methods. Compared to batteries, super capacitors have higher power density, fast charge/discharge, long cycle life and environmental protection (Zhong et al., 2022). Comparing the different methods of energy storage, super capacitor and flywheels are the best options in terms of energy density and environmental impact.

The stochastic nature of RERs causes reliability issues; a penetration level of about 20%–30% of total generation can cause adverse effects to the entire grid due to the stochasticity of RERs (Atwa and El-Saadany, 2010). This necessitates additional control circuits to attain stable power supply, which can replicate the mainstream grid in operation and performance. Microgrids (MGs) are local clusters consisting of distributed generator units, energy storage systems, loads and electric devices, which incorporate the RERs to the distribution network to meet customer demand (Jin et al., 2017b). According to the U.S. Department of Energy, MGs are "a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid" (Ton and Smith, 2012). Microgrids have two modes of operation: the islanded mode and grid connected mode. Islanded mode is preferred in either locations where the geographic features makes it impractical for extension of the main grid or secluded locations faraway from main grid where the economic viability of grid extension is limited. In areas with available mainstream power grid, MGs can be either grid-tied to reduce the operation cost or islanded to improve the reliability in case of grid power outage.

The main bus in the MG connects the DG units to the main grid and the Point of Common Coupling (PCC) connects the MG with the upstream power grid (Zacharia et al., 2019). MGs can work in AC/DC or radial(ring) mode (Mohanty and Pradhan, 2017; Lasseter, 2002) and sell/buy energy in case of the shortage of energy from the utility grid (Katiraei et al., 2008). Local Controller(LC) and Central Controller(CC) transfers data and information using efficient communication technologies in MGs with this technology selected based on coverage area, data rate and deployment cost (Zia et al., 2018). Smart grid incorporates the RERs, the energy management strategy and the distribution system (Wang et al., 2018a), and uses modern Information and Communication Technology (ICT) for efficient grid management and maintaining demand–supply balance (Jaramillo and Weidlich, 2016) with improved energy efficiency, security and reduced power loss.

The main difference between the main grid and the MG is that, while, in the main grid, the load is uncontrollable and optimal scheduling can be considered only for the generation side, in MG the generation units and load can be considered as a single entity for economic dispatching (Husted et al., 2018). The stability of the main grid should be unaffected on addition of the MG. MG optimization is necessary to reduce fuel cost, Energy Not Served (ENS), power loss and Greenhouse Gas (GHG) emissions (Petrollese et al., 2016).

A good number of research papers published in the context of microgrids is mainly focussed on two factors, i.e. cost and reliability. The cost factor is considered in grid tied systems while reliability is the main factor considered in off-grid microgrids. An extensive review on the methods used for energy management, factors considered and the limitations are presented in this review. The main contributions of this paper are:

- Extensive review covering almost all topics of energy management of microgrids
- Classification based on the techniques of control with the limitations of each paper, along with the research gap under each classification.

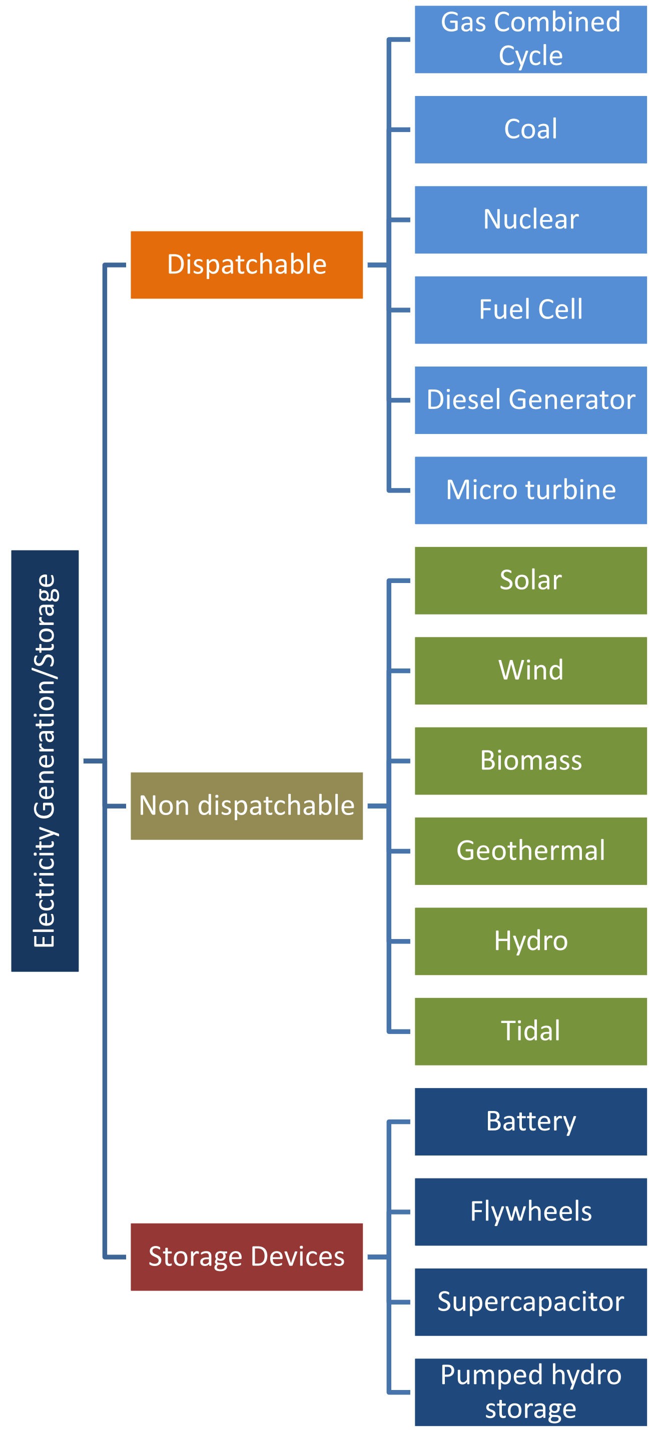

Fig. 1. Significant elements of distributed generation units with classification.

- Reformer based fuel cell, which eliminates the need for hydrogen storage and minimum emissions is introduced for the first time in this paper.

The remainder of the paper is organized as follows. Section 2 is the literature review covering almost all the topics in energy management of microgrids, with details summarized in tables. Section 3 gives an understanding on the topic of energy management systems, the classification, optimization techniques along with the pros and cons of each technique. Section 4 gives an analytical comparison between the different methods used in energy management, Section 5 details the 'Understanding' of the topic based on the authors' perspective and Section 6 is the conclusion.

2. Literature review

Research on the EM of MGs is classified based on the whether a single MG or microgrid community is considered. Studies on single MGs are classified based on whether the MG is grid-tied or standalone, or AC/DC MG. Very few studies consider both grid-tied and standalone modes simultaneously, and fewer papers consider the EM of storage devices. A comprehensive review of literature papers in the context of energy management systems are categorized based on multiple facets, investigated in depth and rendered in the following section.

2.1. Multi-Microgrids (MMGs)

In order to serve the electrical load of a community with multiple consumers and varying load demand, a community MG is required to ensure reliable operation. A microgrid community consists of more than one MG connected to the grid working together to meet the load demand of a community. EM in multi microgrid(MMG) involves control of individual MGs as well as a group of MGs as a whole, which makes it more intricate to control. Hence, a more coordinated approach for optimal power flow between the individual units in each MG, as well as between individual MGs, is essential. A summary of studies considering EM of MMDs is presented in Fig. 2. The figure describes the objectives, methodology adopted, the outcome and shortcomings of each paper, which will serve for better understanding by the readers.

The EMS of MMG system with five MGs based on characteristics of each unit in the DG system is presented in He et al. (2019) using Lagrange function for solving and distributed neurodynamic algorithm for optimization combining DRP. Factors for effective DR participation are considered and Multi Resolution Analysis (MRA) is adopted to forecast the wind speed. Demand–supply balance is achieved even in case of communication link failure with minimized operation-cost. The EMS of community MG involving critical loads and several generators from different owners is presented by a business model in Li et al. (2016) using a bi-level strategy to model the interaction between community MG operator and numerous owners. Under emergency conditions, a centralized EMS deals with shortage in meeting the critical loads by coordinating operation of multiple parties to utilize the shiftable capabilities of their flexible loads. Case study conducted in a practical MG community showed improved financial benefits in grid-tied mode and reduction of non-critical load shedding by 6.2%. The EMS of Smart Grid (SG) integrated with MMGs is proposed in Rahim et al. (2019) using IoT environment for bidirectional flow of data and power. The EMS is based on convex optimization and a Sub Gradient Based Distributed Algorithm (SBDA) is adopted to convert a complex optimization problem into simple, manageable and independent sub-problems. Results verified convexity with reduced computation time and equilibrium of power exchange between Smart Grid and MG. IoT (Internet of things) is a term used to specify the connectivity of various entities irrespective of the place, time or entity, by means of globally networked internet. The term entity refers to the unit, which interacts with the internet, which could represent either a person or any other unit, which needs interaction with any other unit, by data exchange over the internet. A detailed study on why IoT is required in smart grids, how IoT can be applied to smart grids, the technologies involved and architectures is presented in Ghasempour (2019) along with the challenges and possibilities of future research.

A cooperative EMS based on the Distributed Model Predictive Control (DMPC) for MMG with three MGs consisting of a PV/wind/battery system is proposed in Xing et al. (2019). The MMG is virtualized in two levels to simplify internal interactions among subsystems considering only critical loads which resulted in pareto optimal solution close to centralized MPC, minimized operations cost and higher computation speed. Nevertheless only critical loads are considered, while flexible loads need to be addressed. Optimal energy scheduling for MMGs based on multi-objective stochastic compromise programming and with/without DR strategy is proposed in Karimi and Jadid (2020) by optimizing the Independence Performance Index (IPI) along with the MMG cost. Results showed an increase of Independence performance index (IPI) by 17%, reduction of ENS by 2.3% and significant reduction of GHG emissions.

EMS of MMG with surplus power from RERs based on hierarchy is proposed in Jiang et al. (2019) with DRP in two levels. The first level is of the individual MG to maximize the energy consumption of RERs, and the second level is for maximizing the utilization ratio in the MMG system. Renewable energy rate was shown to increase by 12.32% besides reduction of total operations cost. Similar studies based on hierarchy are presented in Wang et al. (2018b) and Bazmohammadi et al. (2019). In Wang et al. (2018b), the first level decides the optimal power scheduling in the community level, and the second stage accounts for the dynamic fluctuations involved using rolling horizon optimization. In Bazmohammadi et al. (2019), the first control tier coordinates the overall operation of the MG by controlling the power flow among the MGs and between the MGs and upstream power grid; the lower control layer coordinates the operation of individual MGs. Chance-constrained model predictive control is used to account for uncertainties in RERs, loads and power exchanged between the MGs. Results proved improved independence of MGs, improved real time power deviation and considerable reduction of system cost.

Energy management based on alternating direction method of multipliers(ADMM) algorithm is proposed in Rajaei et al. (2021) with robust optimization technique to adapt to the stochasticity of RERs. An additional control parameter is incorporated to improve the robustness. The coordinated operations of MGs is achieved by transactive signals under ADMM, which eliminates the need for central controller. An enhanced tube model predictive control(MPC) based decentralized energy management for microgrid community comprising of four microgrids is presented in Xie et al. (2021) adopting online platform, considering battery degradation and the uncertainties of RERs and load demand. The uncertainties is accounted by min–max robust optimization along with rolling horizon MPC and privacy is enhanced by adopting advanced ADMM algorithm. Results proved the plausibility of applying the proposed method in practical systems. Frequency variation in microgrids due to the various objectives for optimal energy management and the control strategies used is considered in Giraldo et al. (2022) adopting strategies for frequency regulation. Greedy algorithm is adopted for minimization of operations cost while cooperative algorithm is adopted for maximizing the

Aspect	Sub Aspect	References
Objectives	Minimize cost	[14], [15], [16], [18], [22], [23], [24], [25]
	Meet Demand	[14], [15]
	Minimize transmission losses	[16]
	Minimize emissions	[16], [19]
	Mitigate intraday uncertainties	[21]
	Max. exploitation of RERs	[18], [20], [24]
	Improve MG Independence	[19]
	Reduce ENS	[19]
	Maximize energy reserves	[25]
Factors considered	Stochasticity	[14], [19], [20], [22], [23]
	Power Quality	[16]
	End user comfort	[16]
	Grid Security	[16]
	High RE penetration	[21]
Software/Platform	CPLEX	[15], [20]
	IoT	[16]
	MATLAB	[18], [20], [24]
	HIL	[18]
	IEEE Bus Network	[23], [25]
	Python/Gurobi	[25]

Aspect	Sub Aspect	References
Control Strategy	Centralized	[15], [19]
	Decentralized	[15], [16], [25]
	Distributed	[14],[18],[23],[24]
	Demand Response	[14], [15], [19], [20]
	Hierarchy	[20], [21], [22]
Factors not considered	Emission Reduction	[14], [15], [18], [21], [22], [23], [25]
	Dynamic variations in load	[14], [15], [19], [20], [23]
	Real-time variations in market prices	[14], [19], [20]
	Stochasticity of RERs	[15], [16], [19]
	Failures in communication lines	[14], [15], [16],[18], [19], [20], [21], [22], [23], [24] [25]
	Network Congestion	[14], [15], [16],[18], [19], [20], [21], [22], [23], [24] [25]

Fig. 2. Summary of energy management in multi microgrids.

energy reserve and rolling horizon method to consider the uncertainties. Compared to greedy algorithm, cooperative algorithm was found to be more substantial in maintaining the frequency limits.

The security of the communication link in community MGs is essential, as any failure in the communication lines can lead to the collapse of the entire MMG. However, none of the papers reviewed considered failure in communication lines. The available literature has not considered grid resilience and risk assessment, which are important factors for effective operation in MMGs, and very few papers have considered the dynamic nature of RERs, load and market prices. EM in multi-microgrids is more intricate compared to single microgrids, as it is required to control individual MGs as well as coordinate the operation of a cluster of MGs. As the popularity of MMGs is expected to increase in the coming years, there is the extensive possibility for research related to energy management techniques, which can ease the control strategy for stable, efficient, reliable and economic operation by adopting effectual control algorithms and optimization techniques. The computation time in MMGs is high due to the presence of multiple control elements, which can be reduced by adopting hybrid optimization techniques. This topic requires enormous research, as MMGs are more complex and computation speed is an important criterion, which marks the efficiency and performance of the related energy management system. In case of failures in communication lines and power, neighbourhood community clusters can be considered as a backup to meet the emergency loads, which is never considered in any of the published works.

The following sections consider single MGs under various classifications. Under each section, charts are included which summarizes the content of each paper. The chart incorporates the hybrid energy system, which includes the DERs and storage methods adopted in each paper, the methodology adopted along with the limitations. These charts are introduced for better and easier understanding of the entire content of each literature considered.

2.2. Grid-tied single MGs

Energy management is essential in grid-tied MGs to ensure a reliable supply for the load and increased benefits considering several factors that include uncertainties in RERs, grid constraints, minimizing emissions, in addition to other factors. A large number of papers on EM focus on grid-tied MG (summarized in Fig. 3), using several techniques and a variety of factors, which is presented in the following section.

2.2.1. EM based on demand response programs

Demand response based EM is applicable in countries which promote the same by the introduction of various types of tariffs to reduce peak consumption by utilizing the features of flexible loads. Consumer participation in reducing the peak consumption is encouraged by incentives offered by the electricity distribution companies.

In Mansour-lakouraj and Shahabi (2019), EM based on hierarchy/DR is proposed using the AutoRegressive Moving Average (ARMA) model to consider uncertainties. CVaR is used for risk assessment and MILP is used for formulation, which incorporates linearized AC grid constraints for high computing efficiency. An extra interconnection point serves to acquire power from neighbouring MGs under emergency conditions. Increasing capacity of storage devices resulted in improved resilience with economic operation under emergency conditions. Considering risk factor greatly affected the participation of MG in electricity market and additional interconnection point reduced load shedding. In Wang et al. (2018a), MG with flexible load is considered using three different DR strategies, namely, fixed, Real-Time-Pricing (RTP) and Time-of-Use(ToU) tariffs, to analyse the factors influencing operation-cost under different strategies. Optimization is solved using genetic algorithm (GA) and validated using MG setup in China. Results proved reduced operations cost without disturbance for consumers besides improved utilization rate of RERs. Three different DRPs including the influence of natural gas price in the DR strategy were considered, which showed that DR strategy is adversely affected with increase in price of natural gas.

A hybrid predication based EMS is proposed in Yuan et al. (2019) for MG with three kinds of loads to prevent the collapse of centralized EMS caused due to data interruption. The advantages of Model-Predictive-Control (MPC) and Extreme-Learning-Machine (ELM) techniques are combined for improved prediction accuracy and prospect vulnerability assessment is used to select a neighbouring device to predict the interrupted data. An improved PSO is used for optimization considering DR for fixed, flexible and interruptible loads, which increased computation speed and improved accuracy, besides reduction of prediction error and optimized cost by 40% and 55% respectively. In Shahryari et al. (2019), incentive-based DRP is considered with two load patterns using the MOGSO (Multi-Objective-Group-Search-Optimization) algorithm adopting the hybrid copula-scenario method to model uncertainties. A fuzzy decision-making technique is adopted to find the best solution for each Pareto-front, and neural network is used for computing the predicted uncertain parameters. Considering intra-day market resulted in precise pattern of load consumption with reduction in total cost and emission cost. In Chaudhary and Rizwan (2018), MG with surplus PV generation incorporating DRP is presented. A hybrid model consisting of neural networks and wavelet transform is used to forecast PV energy and validated using a small-scale PV system considering four cases of DRPs. Performance based on root-mean-square-error (RMSE) and Mean- absolute-error (MAE) were found to be satisfactory.

Information gap decision theory (IGDT) to obtain bidding strategy for day-ahead market is used for EM in Mehdizadeh et al. (2018), incorporating ToU based DRP. The robustness and opportunity functions are modelled using Mixed-Integer-Nonlinear-Programming (MINLP) in IGDT. Two case studies were considered with and without DRP, which showed 4.6% lesser operations cost considering DRP.

The optimal dispatch of large-scale MG with flexible loads, along with DRP on a district level, is presented in Jin et al. (2017a). District level heating and cooling is considered in which the MG for a cluster of buildings meets the thermal/electrical energy required, adopting MILP for modelling and tested in a campus prototype. Two dispatch strategies, the day-ahead and adaptive dispatch are considered, which showed peak load reduction of 18% and improved benefits of 9%. A PV/battery based office building MG incorporating DR and Mixed-Integer-Linear Programming (MILP) is presented in Thomas et al. (2018). PV smart-meter data of 2 years is used to consider uncertainty, and the results are compared with their deterministic counterpart. Six different scenarios were considered, which showed that considering uncertainties resulted in reduction of 370% operation-cost per day.

In Tabar et al. (2019), a MG with electrical and thermal loads is presented with real-time DR, internal power market and shiftable loads. Stochastic linear-programming is proposed in which costs of MG, emission and demand are considered which showed increase in MG revenue by 10.5%, reduction of pollution cost by 1.5% and reduction of demand cost by 0.5%. Similar work is presented in Moghaddas-Tafreshi et al. (2019) that adopts Multi-Agent System (MAS) using day-ahead forecasting to estimate the RERs and loads. The stochasticity of RERs and loads are considered using Monte Carlo, PSO algorithm to minimize operations cost, and real-time based DRP is incorporated to shift flexible loads, which reduced the operations cost besides reduced computational effort. A residential MG with surplus RE generation is presented in Farmani et al. (2018) which adopts DR under deterministic and stochastic approaches. The uncertainties are accounted by using the Monte Carlo method, and the correlation between uncertain parameters are investigated which showed a decrease in the expected value and variance of operation-cost when correlation between historic data is considered. Besides, the

Aspect	Sub Aspect	References
Hybrid Energy System	PV	[3],[10],[11],[13], [27],[28],[29],[30],[31], [32],[33], [35],[37],[38],[39],[40],[41],[42],[43],[44],[45],[46], [47],[48],[49], [50], [51], [52],[53], [54], [55], [56], [57], [58], [59], [60], [61]
	Wind Turbine	[26],[27],[28], [30],[33],[34],[36],[38], [39],[44],[45],[46],[62],[48], [49], [50],[63],[51],[52],[54],[55],[58],[59],[60]
	Fuel Cell	[11],[13],[27],[28], [32], [35],[38], [39],[40], [45],[62],[48],[63],[54],[55],[59]
	Micro Turbine	[27],[28],[30],[33],[34],[35],[38],[45],[62], [48],[63],[51],[54],[59]
	Diesel Generator	[39],[44],[51],[54],[55],[56],[61]
	Battery	[10],[13],[27],[30],[31],[32],[34],[35],[36], [37],[38], [39], [40],[41], [42],[43],[44], [46],[47], [49],[50],[63],[51],[53],[54],[55],[57], [59],[60],[61]
	ESS	[26], [28],[33],[62],[52]
	Ultra capacitor	[42],[43],[57]
	PHS	[29]
	EV	[3],[45],[64],[51]
	Home EMS	[65],[64]
Objectives	Minimize Cost	[3],[10],[11],[13],[28],[30],[31],[34],[35], [36],[38],[39],[46],[47],[62],[48],[64],[49], [50],[63],[52],[53],[54],[56],[58],[59],[61]
	Max. exploitation of RERs	[10],[40],[65],[47], [50],[63],[53],[54], [59],[61]
	Minimize emissions	[11],[28],[33],[38],[62],[50],[63],[52],[53], [55],[58],[61]
	Peak load reduction	[11],[64]
	Grid stability	[13], [60]
	Prevent collapse of central EMS	[27]
	Grid resilience	[26],[31],

Fig. 3. Summary of EM in grid tied MGs.

correlation between uncertain parameters are investigated, with results showing improved benefits for the MG residents while adopting Smart EMS (SEMS).

In Tavakoli et al. (2018b), the EM of a commercial building MG based on hierarchy/DR and Model-Predictive-Control (MPC) using 100 plug-in-electric-vehicles (PEVs) is presented using Conditional-Value-at-Risk (CVaR) to consider the stochasticity of electricity price. First, the WTs and PEVs are coordinated for power balance between demand and supply, then, based on aggregated power of PEVs, the PEV controller optimally schedules the power for the charging/discharging of individual PEVs and the process is repeated with updated values for optimization after measuring the actual values of the system. The Seasonal-Autoregressive-Moving-Average (SARIMA) model is used to predict the uncertain parameters. Operational cost reduced between 32% and 38% for different values of confident levels. In Zhang and Tang (2019), a residential MG is presented considering DR, which is solved using GA, implemented in an embedded platform and verified in residential MG. Compared to government recommended policy, the annual benefits in ToU tariff was shown to increase by 17.5% besides improvement in daily household incomes. A Multi-Objective-PSO (MOPSO) involving fuzzy logic to select the best optima is used in the EM of MG in Aghajani et al. (2015) which considers six different cases on a test MG. Compared to the Non-Dominated Sorting Genetic Algorithm (NSGA-II) algorithm, the MOPSO algorithm was found to be better in performance. Considering operation-cost and polluting emissions simultaneously along with DRPs resulted in reduction of operations cost and emissions by 24% and 16% respectively.

With the increased popularity of Plug-in Electric Vehicles (PEVs), utilizing the batteries of PEVs to participate in DRPs considering the stochasticity of the PEVs' driving patterns while also considering the uncertainties of RERs, load and electricity price, is an area which needs extensive research. Utilizing the

Aspect	Sub Aspect	References
Objectives	Smoothen power exchange at PCC	[3]
	Mitigate uncertainties in PV	[29],[57]
	Study possibility of bidirectional energy flow between EV and grid	[32]
	Maximize financial benefit	[33],[37],[65],[44],[45],[51],[53]
	Preserve data privacy	[46]
	Model multi vector energy system to control individual units in MG	[55]
	Avoid Overvoltage	[60]
	Improve grid quality	[60]
Factors considered	Stochasticity of RERs	[3],[13],[26],[30],[31],[32],[33],[34],[35],[38],[39],[49],[51],[52],[56],[58]
	Uncertainties in demand	[3],[13],[26],[30],[33],[34],[35],[39],[44],[49],[51],[52]
	High penetration of RERs	[13],[31], [35],[52]
	Real time changes in electricity market prices	[26], [28],[30],[31],[33],[35],[39],[59]
	Forecast error	[39],[60]
	Spinning reserve	[39]
	Data Interruption	[27]
	Unexpected emergency conditions	[26],[43],[56]
	Uncertainties in EVs driving schedule	[32]
	Maintain stability	[40],[41]
	Protection of system units and improve efficiency	[40]
	Maintain power balance	[42],[43],[60]
	Network flexibility	[45]
	Battery degradation	[54]

Fig. 3. (*continued*).

batteries of PEVs is economical as the batteries serve dual purposes: powering the vehicle as well as participating in DRPs. Nevertheless, batteries are expensive components in MGs, which require periodic replacement. Hence, a correlation study considering battery degradation and participation of PEV batteries in DRPs, optimality analysis and the related economic feasibility study is an open area for research, which is never considered in any research works.

2.2.2. EM based on hierarchy

In hierarchy based EM, the control is attained in different layers with each level assigned to meet one objective at the device level and system level. In Jin et al. (2017b), a PV based office building MG is considered in which the building is modelled as a steady-state model of Virtual Energy Storage System (VESS). Optimal dispatch is attained in two levels. The first level uses a day-ahead scheduling to minimize the daily operations cost, and the second level has a two-layer intra-hour adjustment methodology for smooth power exchange at the PCC. In addition, a Vehicle-to-Building (V2B) control strategy is adopted to utilize EVs as a flexible resource. Case study in a low voltage office building showed decrease of about 14% in the daily operations cost with smoothened fluctuations at the PCC. Stochastic-MPC (SMPC) based EM considering fixed, shiftable and curtailable loads is presented in Zhang et al. (2018) that adopts the Monte Carlo method to consider uncertainties. The proposed method, which combines the advantages of MPC and the stochastic approach, is formulated using Mixed-Integer-Quadratic Programming (MIQP). SMPC was shown to provide lowest operations cost but faces problem of longer computational time and limitation of extensibility if applied in large-scale optimization problems.

Aspect	Sub Aspect	References
Control Strategy	Centralized	[11],[27],[29],[31],[33],[35],[38],[49],[50],[63],[52],[53],[54],[55],[56],[57],[59],[60],[61]
	Decentralized	[13],[34],[65],[47],[62],[48],[64],[51],[58]
	Distributed	[44],[45],[46]
	Hierarchy	[3],[26],[36],[40],[41],[42],[43],[47]
	Demand Response	[10],[26],[27],[28],[29],[30],[32],[33],[34],[35],[36],[37],[38]
	Real Time/Online	[39],[49],[50],[63]
Software/Platform	MATLAB	[11],[13],[28],[29],[37],[46],[47],[49],[63],[53],[54],[56]
	CPLEX	[26],[33],[35],[45],[54],[59]
	GAMS	[30],[45],[62],[59]
	Gurobi/Python	[31]
	PetriNets	[42]
	IEEE MG Test System	[48],[56]
	dSpace	[63]
Factors not considered	Battery degradation	[3],[11],[13],[27],[28],[30],[31],[32],[34],[35],[36],[37],[38],[39],[40],[41],[42],[43],[44],[46],[47],[49],[50],[63],[51],[55],[57],[59],[60],[61]
	Grid Resilience	[10],[33],[45],[50],[52],[53]
	Stochasticity in RERs	[10],[11],[27],[37],[40],[65],[45],[46],[47],[62],[48],[64],[53],[55],[61]
	Uncertainties in demand	[10],[11],[27],[31],[37],[38],[40],[65],[45],[46],[47],[62],[48],[53],[55],[58],[61]
	Real time changes in electricity market prices	[10],[11],[27]

Aspect	Sub Aspect	References
Factors not considered	Fuel cell aging	[11],[13],[27],[28],[38],[39],[40],[62],[63],[54],[55],[59]
	Emissions	[11],[13], [27],[28],[32],[35],[38],[39],[40],[44],[62],[48],[54],[56],[59]
	Economic feasibility of adopting PHS	[29]
	Network disturbance caused due to EVs	[32]
	Uncertainties in EVs driving schedule	[36],[45],[64],[51]
	Operations cost	[40],[41],[42],[43],[57],[60]

Fig. 3. (*continued*).

In Han et al. (2019a), a DC MG is considered for increased reliability and minimized hydrogen consumption. Control is attained in two levels; the system level and device level using Equivalent-Consumption-Minimum-Strategy (ECMS). The results are validated in lab scale DC MG setup that proved improved stability, efficient utilization of RERs and minimum hydrogen consumption, compared to classical PI or machine control methods. EMS using model-predictive-control (MPC) combining voltage and power control for interconnection of converter isproposed in Hu et al. (2018) which adopts State of Charge(SoC) feedback and real-time power allocation related charging for battery to smoothen PV output. Control is achieved in two levels for stable operation considering flexible reactive power flow in the grid-tied mode, which is real-time controlled by the power converter, with results proving efficient stability maintenance of voltage and power under grid-tied and islanded modes with variable loads and generation.

Lu et al. (2010) presents EMS to supply real and reactive power corresponding to the power references of the grid using Petri nets. A general control strategy is developed using Petrinets considering three different operating modes, with the mode of operation at any time depending on the availability of PV energy, stored energy and the grid requirement. Choudar et al. (2015) presents EMS considering three different operating modes based on the battery SoC, energy level of ultra-capacitors, the power generated and demand, with due importance given for the power limitation in case of extra generation. Smoother operation was achieved with quick dynamic compensation and optimal use of storage devices.

2.2.3. EMS based on decentralized control

A two-level control strategy for MG with high penetration of RERs considering short/long term planning is presented in Petrollese et al. (2016). Two controllers, optimal generation scheduling (OGS), aimed to minimize the operation-cost, and MPC, aimed to attain stability, work simultaneously in real-time application, which is validated in a lab-scale setup. The results of proposed strategy, compared with SoC based EMS and MPC alone strategy showed better integration between storage devices and reduced operation-cost. EMS for smart homes MG with home EMS (HEMS) is presented in Carli and Dotoli (2019) with optimal planning of controllable loads by end-user. Mixed-integer-convex-programming (MICP) incorporating the Alternating Direction Method of Multipliers (ADMM) is adopted for optimization. Potential of DER energy exchange was shown to be fully utilized to minimize energy consumption costs while satisfying customer need. A distributed structure for EM is presented in Silani and Yazdanpanah (2018) adopting stochastic modelling. Control is achieved in two levels: the local controller (LC) to optimize the cost function and the MG centralized controller accepts optimal schedule from the LC to optimize the total cost function. Algorithms with/without stochastic load were considered which showed that EMS considering uncertainty of load offers more financial benefits for customers and is sturdy to communication failure in grid-tied and islanded modes. Ref. Ahmadi et al. (2022) proposed a decentralized EMS for PV/wind/micro turbine based networked multi energy systems considering the stochasticity of the RERs, demand and energy cost for improved network flexibility. Plug-in vehicles are considered for storage along with thermal and hydrogen storage with provision for power to hydrogen (P2H) and hydrogen to power (H2P) conversion. Optimization is based on progressive hedging algorithm with the objective is to maximize the profit over a duration of 24 h with results proving improved profits besides being configurable to be adopted for adding new agents.

A blockchain based decentralized EMS for a residential MG with flexible and fixed loads adopting virtual power plant(VPP) for management of DERs is proposed in Yang et al. (2021). In this approach, besides the traditional way of trading energy with the grid, the users can interact among each other for energy trading besides the added benefits of demand response programmes, while preserving the data privacy. Primal–dual method is adopted for optimization and the use of a central coordinator is eliminated, as blockchain is a computing machine, which is reliable. Results were validated with real data, which showed cost reduction of prosumers by 38.6% and reduction of overall system cost by 11.2%. A similar study adopting a hierarchical and decentralized approach with interaction of users among themselves is presented in Elkazaz et al. (2021) for further reduction of prosumers' cost considering battery degradation. The EMS is based on coordination between the distributed home battery systems and the flexible loads of each house considering day-ahead scheduling and uncertainties of RERs and load. A sensitivity analysis is performed for varied sizes of loads, battery size and efficiency and PV size. The system was shown to be computationally efficient and reliable, with improved battery lifetime besides being flexible to be adopted in large-scale communities.

Energy management of a multi energy system considering the uncertainties in RERs and demand is presented in Faghiri et al. (2022). Long short-term neural network method is adopted to consider the uncertainties of demand. The quadratic cost function is linearized using the piecewise linear method to reduce the computational cost and time. Operations cost was reduced by 34% with reduced complexity and computation time. A blockchain based energy management of AC/DC microgrid is presented in Wang et al. (2022), adopting Whale Optimization Algorithm(WOA) for optimization and Unscented Transformation(UT) to consider the stochasticity. The results with four different metaheuristic algorithms specifically genetic algorithm, particle swarm optimization, mixed integer linear programming(MILP) and WOA are presented, which showed minimum operations cost with Whale optimization algorithm(WOA) considering/not considering stochasticity.

A decentralized home EMS adopting electric vehicles for additional energy storage is presented in Du et al. (2022) considering a scenario of 100 households with actual data of ToU tariff. Instead of adopting minimum cost method, which can result in increased uncertainty and peak, minimum variance method is adopted to avoid the same that resulted in reduction of electricity cost, peak demand and uncertainty by 12%, 30% and 50% respectively.

2.2.4. Real-time EMS

A Bayesian optimal algorithm based data driven framework is applied for online EMS of residential MG in Ref. Dong and Chen (2018). Two algorithms are presented and compared: the online model, which is based on the greedy-algorithm, and an offline-algorithm, which is implemented in MATLAB. Flexible and long-term optimization was achieved with best performance for the online algorithm, but requires a wide range of information and accurate objective function. A similar study using deep learning adaptive-dynamic-optimization algorithm based on closed-loop control is presented in Wu and Wang (2018) with real-time control decision making according to changes of energy. Compared to offline management algorithm, the proposed algorithm have online self-learning ability, simple structure, more accurate closed-loop control and better online characteristics to meet real-time EM. A real-time EMS is presented in Elsied et al. (2016) using GA to solve and ZigBee for effective communication. The control system is based on Advanced Lead-Lag Compensator, and the load forecasting data is based on hourly load data of 4 years. Validation in experimental MG setup proved the economic and environmental benefits but the communication network is inflexible to accommodate notable increment in peak-load.

Energy-Internet oriented architecture for EM with a real case study of a MG in Beijing is presented in Hong et al. (2018) which models uncertainties in two stages that are solved using column and constraints generation (C&CG) algorithm. Smart charging of electric vehicles and selling surplus energy to the grid resulted in increased revenues.

2.2.5. EM based on centralized control

Stochastic EM considering high penetration of RERs and surplus power generation problem is presented in Tabar and Abbasi (2019) by converting and storing the surplus power in the form of hydrogen using P2G (power-to-gas) technology and transferring to upstream power grid when required. Results showed that an increase of 10% in hydrogen generation resulted in about 45% increase in revenue and considering stochasticity of RERs and load improved the robustness but with reduced revenue. Dynamic programming (DP) is combined with grid input/output(I/O) strategy for EM of MG in Guo et al. (2019) considering two different weather conditions (sunny/cloudy) with measured and forecasted PV power profiles and compared with a rule based (RB) algorithm. The study recommends the use of storage batteries in regions with sunshine throughout the year and battery storage is not recommended for more cloudy/rainy areas based on economic viability. In Nemati et al. (2018), two optimizers — MILP based and GA based EMS are presented considering five different operation policies and validated in a test MG. Adaptive continuous penalty method in GA resulted in global optima with high computational speed. Considering complete economic model of battery reduced costs of aging and MG costs up to 84% and 4% respectively.

A novel method for modelling the components of MG with multiple stochastic loads based on state-space modelling approach is presented in Giaouris et al. (2018) using data from actual MG setup in Greece. The developed model is capable of considering several EMS, DR and forecasting realizations simultaneously. Multi-criteria assessment approach is adopted to analyse the performance of 20 different EM methods including DR strategy. The system proved to describe any hybrid system and its operation easily with improved performance. In Sardou et al. (2018), PSO and the Primal–Dual Interior-Point (PDIP) method are combined for optimal energy flow. The model is validated using the MCVM method, which is based on a Monte Carlo simulation considering two cases. Compared to probabilistic and stochastic approach, the proposed method is proved to be robust with reduced operations cost and simpler computation. A heuristic rule-based algorithm for EM is proposed in Aktas et al. (2018). High energy and power density for hybrid ESS with flexibility to interface several ESS to the DC link is achieved considering various loads and irradiance levels. Besides, bidirectional power flow with stable voltage and flexibility for interfacing multiple ESS with DC link is achieved which is verified experimentally using dSPACE.

MILP based EMS for MG with fixed load and EV as flexible load is presented in Jaramillo and Weidlich (2016). The model is validated in MG setup with five cases. Results stresses the importance of energy storage to reduce peak consumption from the upstream grid and peak-demand minimization using flexible loads. In Rabiee et al. (2016), PSO based EMS using the concurrent scheduling of Battery-Electric-Vehicles (BEVs) and responsive loads is presented. The expected operation-cost of MG is obtained using a two-stage model, in which the costs of production and reserve power are minimized at the first stage while costs related to uncertainties of RERs based on a scenario-approach are minimized in the second stage. Three different cases are considered with/without BEVs and responsive loads. Participation of 10% consumers in DRPs resulted in reduced operations cost and emissions.

In Mostafa et al. (2020), EM using stochastic optimization to consider the uncertainty in market-price adopting Information Gap Decision Theory (IGDT) to model load uncertainty is presented. The problem is formulated in MILP with four cases with/without battery storage and various initial charges for battery. Compared to other optimization techniques, GAMS provided the lowest operation-cost. The use of sodium sulphide (NaS) batteries and adopting stochastic optimization resulted in 21.6% and 3.6% reduction in operations cost respectively.

EMS of home MG is presented in Pascual et al. (2015) using a central-moving-average-strategy for better utilization of the battery considering both forecasting error as well the battery SoC resulting in minimum occurrence of fluctuations in the grid. The results are validated in a practical MG, which proved better utilization of the battery considering both forecasting error as well the battery SoC besides minimum occurrence of fluctuations in the grid. EM aimed to reduce the electricity cost of a ship is presented in Tang et al. (2018) while meeting the port regulations on emissions.

2.3. EMS based on fuzzy logic in grid-tied MGs

Fuzzy logic is adopted in studies (summarized in Fig. 4) related to EM due to simplicity of implementation and ease of understanding the reason for a particular decision being taken or prediction undergone. Moreover, it is capable of precisely estimating the unstable parameters of the MG (Sedaghati and Shakarami, 2019).

Adaptive Fractional Fuzzy Sliding Mode Control (AFFSMC) based EM is proposed in Sedaghati and Shakarami (2019) in which the controller is capable of following the pre-set instructions accurately and rapidly. MPPT controller maximizes utilization of PV energy, and fuzzy sets gauge the uncertain grid parameters accurately considering dynamic model with varied loads and faults. Reliable power supply was achieved with excellent dynamic response and quick tracking performance. In Tavakoli et al. (2018a), EM using linear-programming incorporating conditional-value-at-risk (CVaR) to consider stochasticity is presented. Optimality between grid resilience and operational cost are considered, which showed that the grid resilience of commercial building improved remarkably by increased independence of MG from main grid, with slight increase in the operations cost.

EM based on Fuzzy Inference Systems (FIS) using hierarchical GA with four different optimization techniques is proposed in Leonori et al. (2020). An Eco-State-Network (ESN) based Rolling Time Horizon (RTH) strategy is used for in depth comparison of results. Near optimal solution in terms of overall profit was attained with reduced computational cost and run time.

Multi-Objective-PSO (MOPSO) is used for EM in Aghajani and Ghadimi (2018) adopting fuzzy logic. The proposed model is validated using the NSGA-II algorithm and tested in three scenarios: under normal operation of the grid, working at the maximum capacity of RERs, and unlimited power exchange between LV and MV networks. The second case resulted in an approximately 10% reduction in pollution but with increased operation-cost. Unlimited power exchange between LV and MV was proved to be the best option with about 23% reduction in pollution and 5% reduction in operations cost. A similar study based on MOPSO is adopted for EM for reliable supply under fifteen different scenarios in Indragandhi et al. (2018). A PSO based algorithm, which is robust, flexible, versatile, and easy to control, controls the converter. Battery SoC is computed by a coulomb counting method and fuzzy based control is used to control charging/discharging based on SoC. Least cost was attained for energy exchanged between AC/DC MGs besides improved electrical energy utilization in rural areas.

A fuzzy control based EMS is proposed in Chen et al. (2012) with FC as back up to meet the base-load under system failure adopting ZigBee and RS-485 for communication interface, which resulted in maintenance of battery SoC within desired limits, leading to extended battery life and power balance.

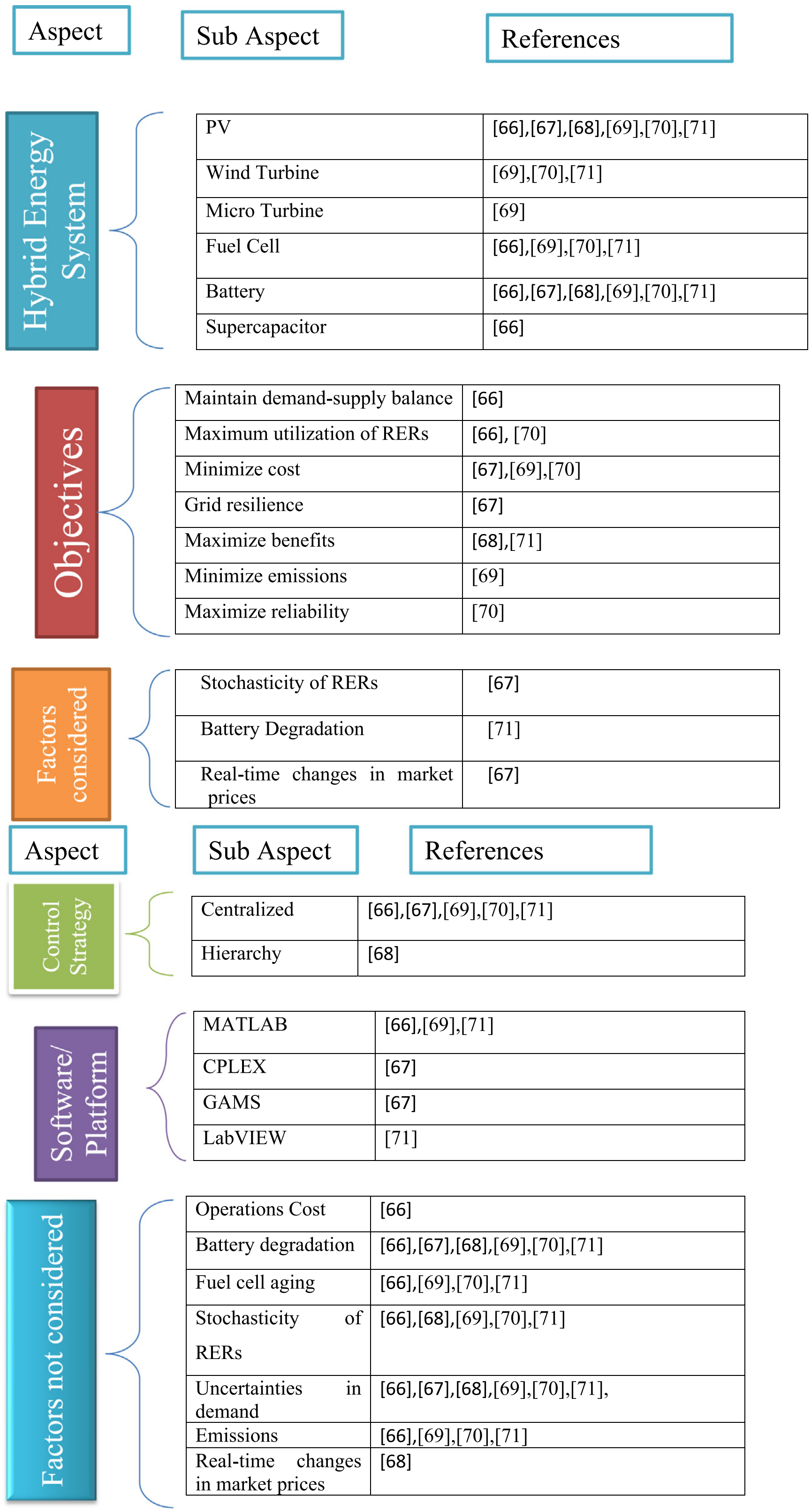

Fig. 4. Summary of EM adopting fuzzy logic.

2.4. EMS of islanded MGs

EM is essential in the islanded mode of MGs for the system to work with maximum efficiency, stability and reliability. In studies related to EM in islanded MGs (summarized in Fig. 5), the priority is to coordinate the different units to meet the load demand without interruption while maintaining voltage and frequency within limits. Power balance is required to prevent system oscillation or system failure by maintaining appropriate real-time power flow. MGs operate in islanded mode either when there

Aspect	Sub Aspect	References
Hybrid Energy System	PV	[72],[73],[74],[75],[76],[77],[78],[79], [80],[81],[82],[83], [84],[85],[86],[87],[88],[89],[90],[91]
	Concentrated PV	[92]
	Wind Turbine	[76],[79],[92],[82],[83],[84],[85],[93],[91]
	Fuel Cell	[72],[73],[76],[80],[82],[83],[86],[88]
	Micro Turbine	[82]
	Tidal Turbine	[77]
	Biomass	[75]
	Geothermal	[75]
	Diesel Generator	[77],[80],[81],[82],[84],[85],[87],[90],[93]
	Solar steam turbine	[92]
	Hydro	[90]
	Electric Vehicle	[91]
	Battery	[72],[73],[74],[75],[76],[77],[78],[79], [92],[80],[81],[82],[84],[85],[86],[87], [88],[89],[90], [91], [93]
	Ultra capacitor	[82],[84],[89]
Objectives	Minimize cost	[72],[76],[77],[78],[92],[81],[83],[85], [86],[87],[91]
	Improve Robustness	[73]
	Improve reliability	[72],[76],[88],[89]
	Maintain power balance	[74]
	Build MG emulator for testing various EMS	[75]
	Build simulation model to imitate the RERs adaptable to changes in MG	[75]

Fig. 5. Summary of review on energy management in islanded microgrids.

is an interruption of supply from the main grid or in locations where extension of the main grid is practically impossible due to distance or geographic constraints.

2.4.1. EM based on hierarchy

Hierarchical EM for economic operation of MG is proposed in Pu et al. (2019) by combining minimum-utilization-cost-theory with a state-machine-control (SMC) method. Control is achieved in two levels; the upper level provides reference output for each device depending on its working state and load requirement and the lower level controls each micro-source based on the instructions sent by the upper layer considering the battery SoC and SoH stability. Utilization cost reduced, efficiency of hydrogen storage system increased and more stability in battery SOC and SOH values were obtained with the proposed approach. A similar study for DC MG is presented in Han et al. (2019b). The control is achieved in two levels: the local level in which each unit is controlled based on their inherent operating characteristics, and the system level using an equivalent-consumption-minimization-strategy in which the power flow between battery and FC is allocated. The results were verified using HIL platform, which proved maximum exploitation of PV energy, stabilized bus voltage and smoothened output of FC.

In Jayachandran and Ravi (2019), model predictive voltage control (MPVC) based EMS is presented in which a prediction based PV, battery and hierarchical controller is developed. Control is achieved in two stages, the DC–DC converter control to maintain power balance within the hybrid system, and VSI control for optimal power flow (active/reactive) between the hybrid system and the MG. Results proved that the DC link voltage, SoC balance and PCC voltages were maintained constant under fluctuating RE outputs and loads. In Petreus et al. (2019), a geothermal/PV/biomass/battery based MG is presented using hardware-in-loop (HIL) emulators for geothermal and biomass resources. The system is controlled in two levels. The first level is for voltage and frequency control by controlling the reactive

Aspect	Sub Aspect	References
Objectives	Minimize emissions	[77],[78],[80],[82],[85],[90],[93],
	Meet demand	[92],[81],[85]
	Maximum exploitation of RERs	[92],[80],[82],[90],[93]
	Increase fossil fuel replacement rate	[92]
	Avoid energy losses and overload	[92]
	Reduce LCoE	[80]
	Regulate frequency	[83]
	Prevent system oscillation and failure	[84]
	Reduce energy from fossil fuel	[86]
	Reduce system size	[86]
	Protect communication lines	[88]
	Efficient and stable operation of MG	[90]
	Maximize number of chargeable EVs	[91]
Factors considered	Active and reactive power flow	[74]
	LCoE	[77]
	Battery degradation	[72],[77],[81]
	Forecast error	[79]
	Cost of energy storage	[92]
	Stochasticity in RERs	[82],[85]
	Uncertainties in load	[82],

Fig. 5. (*continued*).

and active power respectively, and the second level is the EM algorithm adopting cycle-charging algorithm, based on the balance between energy generated by RERs, battery SoC and load demand. Results were experimentally validated in lab scale MG for four cases, which proved to be predictive and cost effective control algorithm. Besides, emulators are cheap and can run under different scenarios and control methods compared to other complex emulators. In Rullo et al. (2019), a two-level optimization framework for integration of sizing and EMS is presented. Optimal sizing is performed in the outer-loop using Genetic Algorithms (GAs) and EM is based on an Economic-Model-Predictive-Control (EMPC) and performed by the inner-loop using rolling horizon Mixed-Integer-Linear-Programming (MILP). Capital cost, operations cost and capacities of PV and battery were shown to be reduced besides improving the disturbance rejection capacity.

2.4.2. EM based on DR

In Zia et al. (2019), EMS incorporating DR is proposed using integer free Second Order Cone Programming (SOCP) for convex global or near global optima. SOCP is used to convexify the non-convex constraints with the advantage of simpler computation and is tested in 7-bus islanded MG, which reduced the optimality gap to less than 1% with reduced computation cost. EM based on a multi-agent approach, μGIM (Microgrid intelligent management) software, which is designed to run in raspberry pi 3 and light weighted, is presented in Gomes et al. (2020) using a GNU linear-programming kit (GLPK) for optimization. The proposed architecture, which is implemented in a single-board computer and deployed in an office building, is focused on end-users aiding to monitor, manage, control the RERs and actively transact energy in response to DRPs in the smart grid intelligently. The developed μGIM platform with single board computer for intelligent and efficient EM was proved to be highly efficient without issues on practical implementation. A detailed study on smart grid and its structure is presented in Ghasempour and Lou (2017). In Solanki et al. (2017), EM using MPC for considering errors in forecasting is presented. Based on the emission characteristics and fuel consumption of the components in the DG unit, equivalent CO_2 emission models are developed and, to consider the impact of DRP, demand-shifting load models are developed which are then incorporated in the unit-commitment model. Five different cases are considered to investigate the optimal dispatch of Distributed Generator Units (DGUs) and the effect of DRPs on the emission and cost of the system using MILQ and MINLP for modelling. Results proved that dependence of CO_2 emissions on DR strategy

Aspect	Sub Aspect	References
Control Strategy	Centralized	[78],[92],[80],[81],[82],[84],[86],[87],[93]
	Decentralized	[83],[88],[89],[90],[91]
	Hierarchy	[72],[73],[74],[75],[76]
	Demand Response	[77],[78],[79],[85]
	Online/Real-time	[85],[90],[93]
Software/Platform	MATLAB	[72],[82],[83],[87],[89],[91]
	RTLAB	[72],[88]
	HOMER	[73]
	HIL	[73],[93]
	ANSI-C	[75]
	PSIM	[75]
	JAVA	[78]
	GAMS	[79],[82]
	DICOPT	[79]
	CIGRE	[79]
	Bocop	[81]
	CPLEX	[79],[82],[85]
	Gurobi/Julia	[87]
	RTDS	[90],[93]
	OpenDSS	[91]
	TRNSYS	[91]

Aspect	Sub Aspect	References
Factors not considered	Stochasticity in RERs	[72],[73],[77],[78],[92],[80],[81],[83],[84],[85],[89],[90],[91]
	Uncertainties in load	[72],[73],[77],[79],[92],[80],[81],[83],[84],[85],[89],[90]
	Battery degradation	[72],[73],[74],[75],[76],[78],[79],[92],[80],[82],[84],[85],[86],[87],[88],[89],[90],[93],[91]
	Aging of fuel cell	[72],[73],[76],[80],[82],[83],[86],[88]
	Emissions	[72],[83],[84],[86],[87],[88]
	Operations cost	[73],[74],[84],[89],[93]
	Underutilization of RERs by curtailment	[76]

Fig. 5. (*continued*).

depends on the type of operating strategy and the operating strategy corresponding to Pareto optimal of operating and emission cost is the best strategy.

2.4.3. EM based on centralized control

EMS, along with optimal design for MG in Morocco, is presented in Mellouk et al. (2019) using parallel-hybrid GA-PSO. The developed parallel GA-PSO algorithm was proved to be superior to GA and PSO in terms of speed of convergence, solution quality and convergence success rate. The energy cost was close to fossil fuel cost and more than 50% fossil fuel replacement rate was achieved. In Khawaja et al. (2019), finite automata is adopted to generate numerous EMS and works in three steps: Firstly, the hybrid system is sized based on the initial EMS; secondly, finite automata is used to compare several EMSs with the obtained size and to find the best EMS among them; finally, the selected EMS is upgraded by extracting the recommended conditions. PV size reduced by 57%, operating-time of diesel generator and FC reduced by 35% and 83% respectively, levelized cost of energy(LCoE) reduced by 40%,fuel cost reduced by 23% and PV utilization increased to 98%.

In Heymann et al. (2018), EM using nonlinear, continuous-time, rolling horizon formulation is presented. Deterministic optimal control problem is used for formulation which is solved using three optimization methods – MILP, a direct method, and Bellman's Dynamic Programming Principle (DPP) – and validated in MG located in the Atacama desert, which proved to produce global optima with reduced computation time.

In Moradi et al. (2018), EM by employing a single-objective optimization method for modelling and advanced dynamic programming method for solving is presented. A probabilistic programming method is used to consider uncertainties in RERs and load. Two scenarios, with/without storage devices were considered, which showed that the presence of ESS reduced operations cost with maximum utilization of RERs. In Hassan et al. (2018), the net power of a MG is split into high and low frequency components. The ultra-capacitor suppresses the high-frequency part while the low-frequency part is compensated by the DG. Three cases were considered and the system with ultracapacitor was proved to be the best storage option for power-balance and system stability.

In Bruni et al. (2016), three types of model predictive control (MPC) - ideal MPC, Deterministic MPC (DMPC), and stochastic MPC (SMPC) - are used for EM in residential MGs using real weather forecast as input. The influence of EMS on the efficiency of the MG and a compromise between thermal comfort and energy savings is investigated. Proposed algorithms were compared with rule-based algorithm, with case study in home MG, which proved better performance in terms of smoother operation and possibility of reduction in system sizing. Best performance in stability was achieved for deterministic model predictive control algorithm due to the best quality of weather forecast data.

An islanded MG supplying a village with 600 houses is considered in Mazzola et al. (2017) adopting MILP. The influence of the quality of forecasting on operations cost is studied with Non-Predictive (NPS) and Predictive-Strategies (PS) for more accurate assessment of practical implementation of each strategy and a quantitative comparison between the two strategies is presented. Real data of a complete year is used and the prediction at each time step corresponds to the average data of the same time during the previous year. Reduced operations cost was obtained for higher number of clustered houses and with significant size of PV, and forecast error less than 20%, predictive strategies was shown to improve savings between 4%–8%.

2.4.4. EM based on decentralized control

A decentralized virtual impedance control is proposed for EM in Wen et al. (2018) using pre-set values for battery SoC limits to avoid damage due to overcharge/over-discharge. Over-discharge of battery is avoided by load shedding. Battery SoC limits were maintained within range besides improving battery life, which was validated under normal and faulty conditions. In Yu et al. (2019), a MISO fuzzy controller incorporating load frequency control is adopted for EM with dynamic models for RERs. The performance of the controller is improved using modified-PSO (MPSO) for tuning the controller parameters and simulated for radially distributed single line MG, under several scenarios. Four cases were considered which showed reduction of generation costs up to 30% besides regulating frequency. EM considering the electrical characteristics of the system components is presented in Zhang and Wei (2020) using a battery controller to maintain the bus frequency. The factors considered in EM for each component are SoC and instantaneous working power for battery, P-f droop control for PV system, efficiency of energy conversion in HPU, and maximum-power-point in FC to coordinate the power flow between the various units, considering battery protection. Experimental verification using RTLAB proved that the communication lines were saved besides improving reliability.

A multi-agent system based multi-time scale EMS is proposed for a practical MG under construction at high altitude (Zhao et al., 2015). Virtual bidding and model predictive control (MPC) are adopted to achieve Optimal Dispatch (OD) and OD in real-time respectively. Proposed EMS is simulated on a real-time digital simulator (RTDS) - PXI and tested in a practical MG considering real-time operation as well as seven possible cases of emergency, which validates the proposed EMS. A fuzzy logic based decentralized energy management of an islanded MG incorporating fuzzy cognitive maps is presented in Boglou et al. (2022) for optimal charging of electric vehicles and minimization of NPC adopting particle swarm optimization. Considering a duration of 20 years, the increase in NPC caused due to high penetration of EVs in islanded microgrids was reduced by 8.8%, peak load and load variation reduced by 17 and 29% respectively besides increase in number of chargeable EVs by 99%.

2.4.5. Online/real-time based EMS

Online EMS incorporating demand side management (DSM) for isolated village MG in the Atacama desert with provision for SCADA is presented in Palma-Behnke et al. (2013), with additional management for water supply system. EMS is modelled in mixed-integer-programming (MIP) combining unit-commitment with a rolling horizon strategy (UC-RH) which reduces the adverse effect of uncertainties. Neural network based prediction is adopted for load prediction. Two cases, with/without wind turbine were considered which showed reduction of about 15% operation-cost considering WT and rolling horizon strategy. A similar study is presented in Guo et al. (2014) adopting real-time EMS based on a rolling horizon strategy for a desalination plant. Two operating modes with/without the DG are presented, using SCADA to supply real-time data. Instead of using back propagation (BP) neural network for wind forecast, genetic algorithm-BP (GA-BP) is used to reduce computation time, which resulted in forecast error less than 10% with minimized use of diesel generator.

The factors to be addressed for EM studies in islanded MGs are reliability, stability, cost and emissions. While most of the related works consider a probabilistic or prediction based approach, more studies considering the dynamic fluctuations of load and RERs are essential, as this replicates the case of practical MGs. Storage devices play an important role in islanded MGs, and the commonly used storage device is the battery, while supercapacitor and other storage devices are considered in very few cases. Degradation of battery and fuel cell are factors needed to be addressed in storage devices. The economic analysis of considering the degradation of storage devices has not been presented in any of the works. This is essential as consideration of degradation in storage devices may result in increased energy cost due to reduced usage of storage. Hence, an economic analysis is vital in this field. Economic feasibility of adopting diverse storage techniques such as P2H storage, super capacitor and pumped hydro storage(PHS) is never presented in literature.

Resilience is one important factor that is least considered in any of the existing literature related to EM in islanded MGs. More attention is required in this matter, as the system should be able to restore to normal in case of adverse events.

2.5. EMS considering both grid-tied and islanded modes

While most of the studies related to EM considers either standalone or islanded modes, very few papers (summarized in Fig. 6) consider both the modes simultaneously with the additional objective to smoothen the transition between the two modes.

Power gradient limitation and optimal power flow (OPF) based EM using the ϵ-constraint method is presented in Agnoletto et al. (2019) which is validated experimentally using two scenarios. The first scenario is with dispatchable and non-dispatchable source and the second with dispatchable source and storage device, which showed improvement of battery lifetime due to the smoothening of the fast transitions during the charging and discharging of batteries. In Tummuru et al. (2019), a Small-Signal-Average (SSA) method is adopted to study the stability under various conditions and the second harmonic Phase-Locked-Loop (PLL) for effective synchronization/resynchronization under emergency situations. The frequency and voltage magnitude at the PCC was regulated besides seamless transition between grid-tied and islanded modes.

EMS for both grid connected and islanded modes in MG based on Flexible-Time-Frame (FTF) DER schedule combined with single-time interval Optimal-Power-Flow (OPF) is presented in Yang et al. (2019). Instead of a day-ahead schedule, the FTF-DER schedule uses the latest forecasts in RERs and load, which is formulated in MILP. OPF based economic-dispatch (ED) is formulated as a quadratic programming problem to integrate real-time constraints. Using latest forecasts resulted in economic benefits and improved system security with reduced computational effort and the method is capable to be extended for large MG with more than tens of distributed generator units.

MILP based EM is presented in Zacharia et al. (2019) implementing two optimization algorithms. In case of emergency transition from a grid-tied to islanded mode, the day-ahead planning is re-scheduled. The developed novel optimization algorithm updates the optimal scheduling for smooth transition between the two modes and economic operation of the MG. Optimal and smooth operation was achieved during transition between the two modes.

MILP based double-level control consisting of a schedule layer and dispatch layer is used for EM in Jiang et al. (2013) in which the error between the forecasted and real-time data is corrected by coordinated control of the two layers. The schedule layer is responsible for maximizing the benefits by sequencing the controllable units optimally, and the dispatch layer ensures safe/stable operation by adjusting power of the controllable units, which resulted in improved revenues of about 61% in grid-tied mode. Load was satisfied with minimum operations cost in islanded mode. In Li and Xu (2018), MILP based EM for multi-energy PV/WT/battery/CCHP/FC/electric chiller (EC)/electric-boiler (EB)/ice-storage tank (IST) based MG is proposed. The resilience and operating efficiency is improved by coordination of different DG units and storage devices incorporating DRP. Case study for three cases in MG test system proved improved operational efficiency and flexibility besides reducing the net operation-cost.

Switching MGs between islanded and grid-tied modes can cause stability issues and harmonics and the smooth transition between these modes is essential in related studies on EM. More research is open considering resilience, degradation of storage devices, emission reduction and harmonics elimination in related works.

2.6. EMS in storage devices

EM is essential for storage devices to improve utilization and lifetime for economic benefits. In the literature, only very few papers (summarized in Fig. 7) consider the EM of storage devices.

An economical storage management system based on the capacity of ESS in a grid-tied MG by timely participation in the electricity market is presented in Nayak et al. (2019) for fixed-time-independent load and variable load. The operation-cost and technical parameters of five different types of battery are compared with the real-time hourly energy price to assess the competence of the ESS to obtain maximum economic benefit. Smooth transitions between the grid-tied and standalone modes with optimal scheduling was achieved. Besides, lead acid battery with carbon-enhanced electrodes were proved to be more beneficial. Two different EMSs, the external energy maximization strategy (EEMS) and equivalent consumption minimization strategy(ECMS) for storage devices in emergency power unit (EPU) of electric aircraft with FC/battery/SC, and a comparison of nine different metaheuristic algorithms are presented in Zhao et al. (2019). The algorithms are compared based on hydrogen consumption, total system efficiency, and alterations of SoC with importance to different energy sources. Among the different algorithms compared, moth swarm algorithm (MSA) was proved to be the best based on overall performance.

DR based EMS for a grid-tied MG is presented in Fang et al. (2018). The dispatch strategy of transferable load is proposed using an adjacent-period method and solved using improved PSO. Day-ahead optimal scheduling is implemented based on forecasted values of RERs and loads. Proposed method is proved to be stable, practicable, secure and reliable. EM for storage devices in standalone MGs is presented in Cau et al. (2014) adopting a scenario tree approach to consider the uncertainties of RERs and load. Case studies are conducted for different seasons and the proposed method is compared with SoC based EMS and EMS based on perfect forecast. Operations cost reduced was by 15% compared to SoC based EMS with improved system performance. Storage devices play a very important role in the operation of MGs. Although a variety of storage devices are available, the majority of the related works consider the battery as the main storage device and other storage devices are considered in very few papers. Flywheels for energy storage are never considered. Extensive research on energy management, which compares storage devices based on their performance, efficiency, cost per unit of energy storage, and eco waste is necessary to investigate the possibilities of adopting in actual MGs.

Based on enormous analysis of research papers under the topic of energy management, the perception of authors is depicted in the following section.

3. Energy management systems

The presence of various distributed generator units and loads with stochastic nature in MGs necessitates additional control algorithms, i.e. energy management systems for optimal power flow between each component of the MG to achieve stable and economic operation. An energy management system (EMS) is essential in DG systems with more than one source and storage device for setting the operating point of each unit in the MG to coordinate and monitor energy flow between the various units for efficient, reliable and economic operation resulting in demand–supply balance (Zhou et al., 2016; Khan et al., 2019; He et al., 2019). EMS manages in real-time the energy flow within the MG components as well as between the MG and main grid based on the previously set strategies (Leonori et al., 2020). Energy Management(EM) should first ensure that the load is met, thereafter

Aspect	Sub Aspect	References
Hybrid Energy System	PV	[5],[95],[96],[97],[98],[99]
	Wind Turbine	[97],[98],[99]
	Micro Turbine	[98]
	Fuel Cell	[98],[99]
	Diesel generator	[5],[97],[98]
	Battery	[5],[95],[96],[98],[99]
	Ultracapacitor	[96]
	ESS	[97]
Objectives	Maximize profit under grid tied mo	[5],[98]
	Maximize utilization of storage devices in islanded mode	[5]
	Prevent battery degradation	[95]
	Reduce power loss	[95]
	Minimize generation cost	[95]
	Meet load demand with smooth transition between islanded and grid tied modes	[96]
	Minimize stochasticity of RERs	[97]
	Maximize utilization of RERs	[97]

Fig. 6. Energy management studies considering grid-tied and islanded modes.

to maximize efficiency and minimize operation-cost (Yu et al., 2019). The EMS of MGs in the literature consider single MGs, in islanded and grid-tied modes in addition to multi-microgrids (MMGs) in which EM is considered for a MG community. The different strategies used in energy management is studied and compared in this work. The basic objective for comparing the different strategies for energy management is to investigate the pros and cons of each method, the centralized, decentralized, distributed and hybrid while applied to different configurations of microgrid i.e. single MG, multi MG and home EMS. This will help to decide the strategy to be adopted for any system, depending on the system configuration and the amount of data exchange. Few important terminologies to be understood in energy management, specifically, classification based on various aspects, comparison of optimization techniques used in energy management, classification of loads adopted and demand response programmes are described in the following sub sections.

3.1. Classification of EMS

The EMS in MGs can be classified based on the power type, the connection with the main grid, the control strategy, configuration, solving technique and the method of parameter selection. Fig. 8 shows classification of energy management systems which is widely used in literature. The control strategies used in EM of MGs are broadly classified as centralized, decentralized, distributed and hybrid control. In centralized control, a Central Control Unit (CCU) sends the command signals for control and protection to local control units and breakers which are dedicated to individual units. The CCU incorporates algorithms based on requirement to find the optimal operating point considering several factors such as cost, emission, grid availability, reliability, resilience, etc. A comparison between centralized and decentralized control is presented in Table 1.

In interconnected power systems extending to a wide area, it is difficult to implement a centralized approach due to the requirement of vast communication and computation needs. The decentralized approach requires a high level of coordination, which becomes problematic due to the availability of only local data considering extended MGs. Hence, a hierarchical approach, instead of using a fully centralized or fully decentralized approach, is recommended in such systems. This consists of three levels: the primary, secondary and tertiary controls. Control of power electronic converters, islanding detection, droop control, etc. come under primary control. EM comes under secondary control to ensure reliable, secure and economical operation in MGs, and tertiary control coordinates operation of multiple MGs (Olivares et al., 2014). Hybrid EM combines the advantages of centralized and decentralized control in terms of being flexible compared to the centralized approach and reduced operation-cost

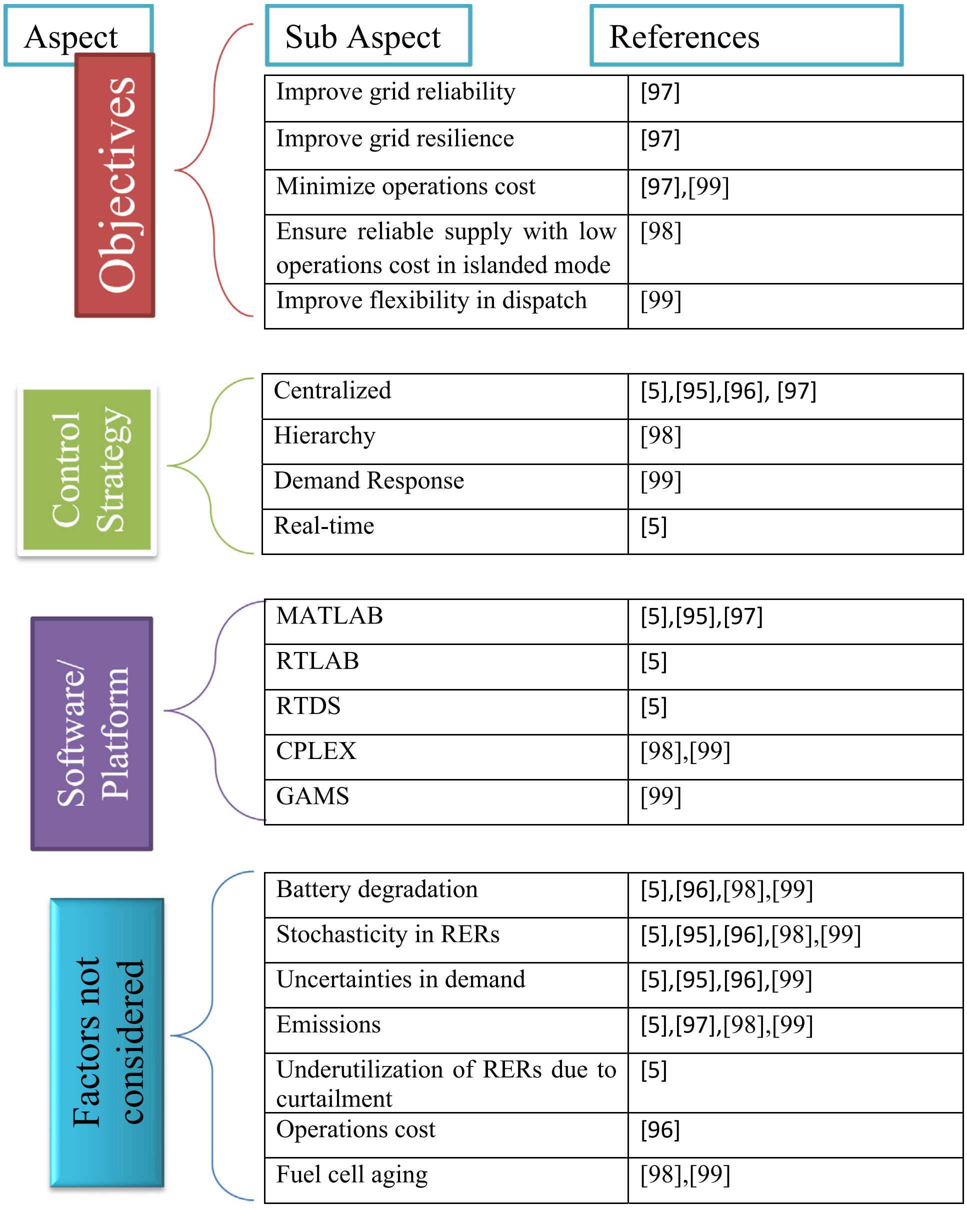

Fig. 6. (*continued*).

Table 1
Summary of centralized and decentralized approaches.

Centralized	Decentralized
Central controller with capability of bulk data handling is responsible for decision making based on data availability attained by communication between the controller and the MG components (Olivares et al., 2014)	Individual controllers for each unit, with data available for each unit (Ilic-Spong et al., 1988) resulting in self-scheduled system by interaction among themselves (Li et al., 2016)
Promotes optimal overall operation in terms of voltage and current and minimum requirements to run optimization algorithm but can cause low efficiency and delays if the data communication link between the control unit and management unit is improper (Agnoletto et al., 2019)	Advantages of being robust, reliable, less computational time, data accuracy in information exchange, preserve data privacy and improved security of network (Rahim et al., 2019)

compared to the decentralized approach (Wang et al., 2018b). Distributed control requires minimal communication network and essential information from other units, with the advantages of privacy protection, lower computational effort and ease of extension (Xing et al., 2019; Shi et al., 2014). The difference between decentralized and distributed control is the presence of a central control agent in distributed control, which collects optimized results from distributed agents and sends them to the controller to implement. This is absent in decentralized control (Fontenot and Dong, 2019).

Based on grid connection status, energy management studies can be classified as grid-tied systems, which can obtain energy

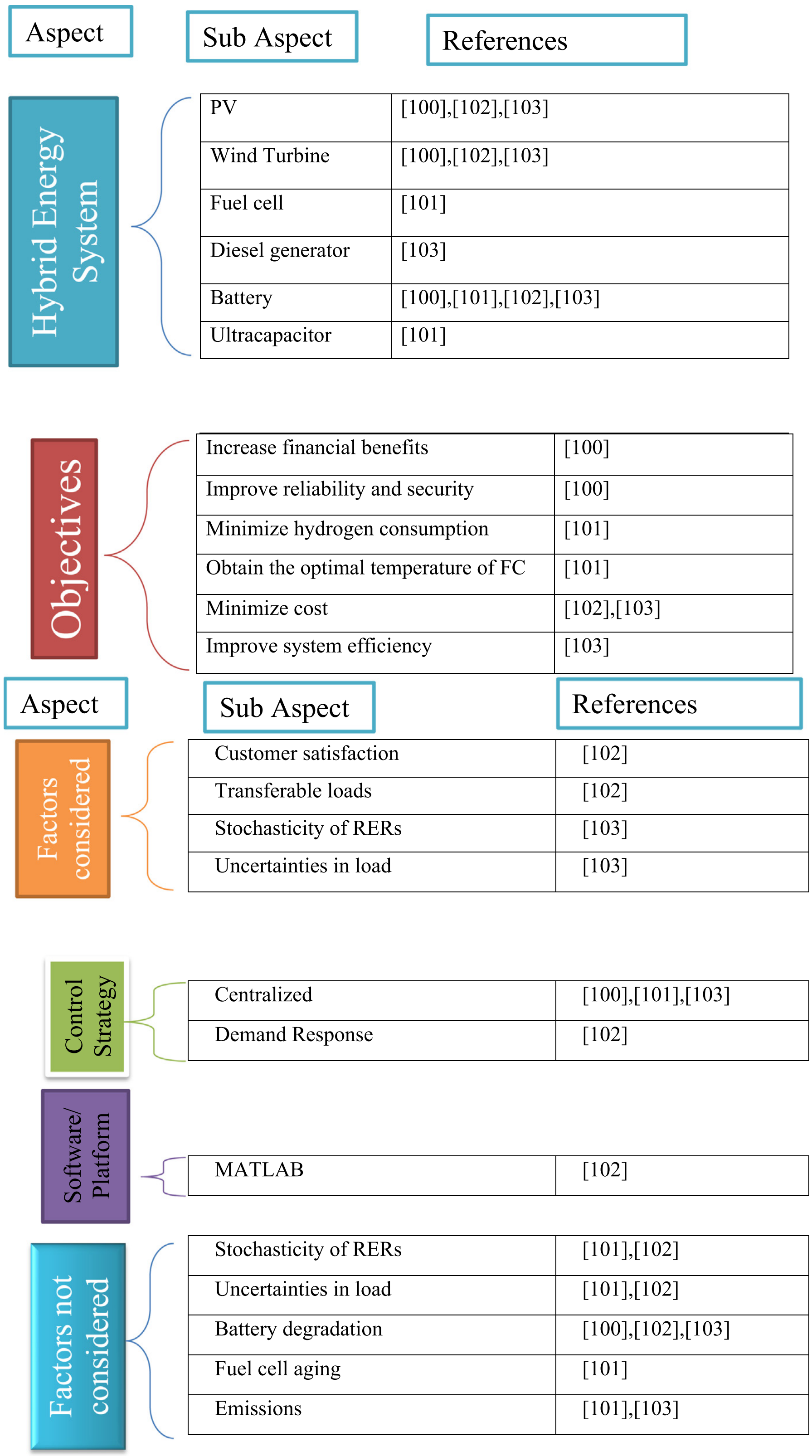

Fig. 7. Energy management in storage devices — Summarized.

from the grid in case of shortage of energy supplied from DERs and off-grid systems which solely depend on the energy from DERs. Based on the configuration, it can be classified as single MG and multi microgrid(MMG) systems. Multi microgrids are community microgrids in which a group of MGs serve to meet the demand of a community.

A few other classifications are based on the signal type, solving platform and other factors which are listed below. Based on the type of power, MGs are classified as AC and DC MGs. Platforms used in solving EM problems are of two types: the offline and online (Wu and Wang, 2018) approach. The majority of research work on EM is based on an offline approach due to the complexity and high cost involved in the online approach. Offline methods are mostly centralized, and are incapable of addressing the real-time changes in the system which can be overcome using online methods (Dong and Chen, 2018). Online methods can deal with real-time changes leading to a more efficient system, but are expensive compared to offline methods. Based on the method of parameter consideration, EMS are classified as deterministic and stochastic methods in which the RE generation, load and electricity price are considered as known parameters with forecasted parameters being considered to be perfect in the deterministic approach, whereas uncertainties in forecasting are considered in the stochastic approach (Zhang et al., 2018). Simulation techniques used in energy management are of two categories: real-time simulation and non-real time simulation. In real time simulation, the simulator executes the event in exactly the same time as the actual event occurs. Non-real time simulation is the traditional technique in which the behaviour of the system is calculated either slower or faster than the actual occurrence of the event, depending on system complexity.

3.2. Optimization methods in MGs

Optimization techniques used in MGs are deterministic, analytical, heuristic, stochastic, and hybrid based models. Linear Programming (LP), non-linear programming, dynamic programming, Mixed Integer Linear Programming (MILP), greedy algorithms, Lagrange relaxation (Ahmad et al., 2018), interior-point method (Granville, 1994), and dynamic programming are methods used under the deterministic approach (Leonori et al., 2020). Genetic Algorithms (GAs) (Bora et al., 2019), Artificial Bee Colony Algorithm (ABCA) (Karaboga et al., 2014), Ant Lion Optimizer (Kamboj et al., 2017), Particle Swarm Optimization (PSO), grey wolf optimization, cuckoo search, mine blast algorithm, the whale optimization algorithm, the moth swarm algorithm, the harmony search, electromagnetic field optimization and Intelligent Flower pollination algorithm (Zhao et al., 2019), all come under the heuristic/metaheuristic approach. Metaheuristic algorithms are based on natural processes which reaches the optimum value by continuous iterations (Shaheen et al., 2021). Some other metaheuristic algorithms seen in literature are Tree–Seed algorithm(TSA) (El-Fergany and Hasanien, 2018), Sine–Cosine algorithm(SCA) (Attia et al., 2018), Salp-Swarm algorithm(SSA) (El-Fergany and Hasanien, 2020), Sunflower optimization (Hussien et al., 2021), Cuttlefish optimization (Hussien et al., 2020), Mean Variance Mapping optimization(MVMO) (Rueda and Erlich, 2013; Erlich et al., 2014) and Hunger Games Search algorithm (Shaheen et al., 2021). Optimization problems in power in optimal power flow and energy management problems are solved using variations or modified versions of the above-mentioned algorithms e.g. Shaheen et al. (2021), Marcelino et al. (2021) and Nemati et al. (2015). A hybrid system e.g. Kim et al. (2020) uses a combination of any of the two methods, but it has the drawback of longer computation time (Mellouk et al., 2019) which can be rectified by parallelism. The pros and cons of widely used optimization techniques/algorithms are presented in Table 2.

In problems with several mutually opposing objective functions, multi-objective optimization yields a set of optimal values instead of a single optima while satisfying a number of equality and inequality constraints (Aghajani and Ghadimi, 2018). The Rolling Time Horizon (RTH) strategy is a combination of any optimization algorithm mentioned above along with prediction algorithms to incorporate the uncertainties involved in DERs.

3.3. Demand Response Program (DRP)

According to the U.S Department of Energy, Demand Response Program (DRP) is a tariff set up to encourage pattern change in electricity consumption either responding to varied electricity prices over time or to incentives offered to reduce electricity consumption during periods of high market-price or when grid reliability is at risk (Qdr, 2006). It is a technique used for EM to increase benefits to both suppliers and consumers by adjusting the load curve using flexible and interruptible loads (Yuan et al., 2019).

DRPs are of two types: incentive-based (Shahryari et al., 2019) and price-based. Incentive-based programmes are further classified as interruptible/curtailable, and capacity market programmes (Mansour-lakouraj and Shahabi, 2019). The incentive-based programme encourages customers to participate in MG scheduling by offering financial benefits and, in the interruptible/curtailable programme, customers reduce consumption for incentive benefits. In the price-based scheme, the customer curtails demand in response to increasing market-prices (Chaudhary and Rizwan, 2018). Time-Of-Use (ToU), Critical Peak Pricing (CPP) and Real-Time Pricing (RTP) are the types of price response in DRPs where the electricity price is previously determined in ToU and CPP but changes hourly in RTP (Zhao et al., 2013). In ToU type of DR, MGs can participate in DR programmes by reducing the peak-load and flattening the load curve by shifting a part of the load from peak period when energy cost is high to off-peak period with lower energy price resulting in reduced operation-cost (Mehdizadeh et al., 2018). The total load remains the same but the operation time is shifted to reduce peak-load.

3.4. Load classification in MGs

Load classification in MGs is shown in Fig. 9. Loads in MGs are broadly classified as static (fixed) and flexible loads. Static loads are non-manageable and the power demand should be met at any point of time, e.g. hospital ICU, data centres. Flexible (responsive/adjustable/time-shiftable/non-vital) loads can assist in DRPs by responding to price signals (Karimi and Jadid, 2020) and are classified as curtailable and shiftable (deferred) loads, which can respond to economic incentives (Parhizi et al., 2015). In curtailable loads, the ability to shift the usage time is limited, but can be traded off with satisfaction of end-user based on DRP (Jin et al., 2017a). In shiftable loads, the operation time can be adjusted even though it consumes a certain amount of energy during the scheduled period (Jiang et al., 2019). Shiftable loads can be classified as interruptible (elastic) loads and non-interruptible loads. In elastic loads, operational time and power rating can be controlled by end-users depending on the required comfort level, and non-interruptible loads are flexible in terms of operational time, but cannot be interrupted during operation (Rahim et al., 2019).

4. Analytical comparison of techniques used in energy management

The appropriate strategy for energy management for any system depends on the system configuration, which decides the amount of data exchange involved.

Considering single MGs, in Zia et al. (2018), centralized and decentralized methods are compared with regard to the high penetration of RERs. Under this context the centralized approach can cause instability issues with reduced computational speed and less scalability. The decentralized approach is more applicable, but can result in increased system cost. Refs. Yuan et al. (2019) and García Vera et al. (2019) considers the data interruption, in

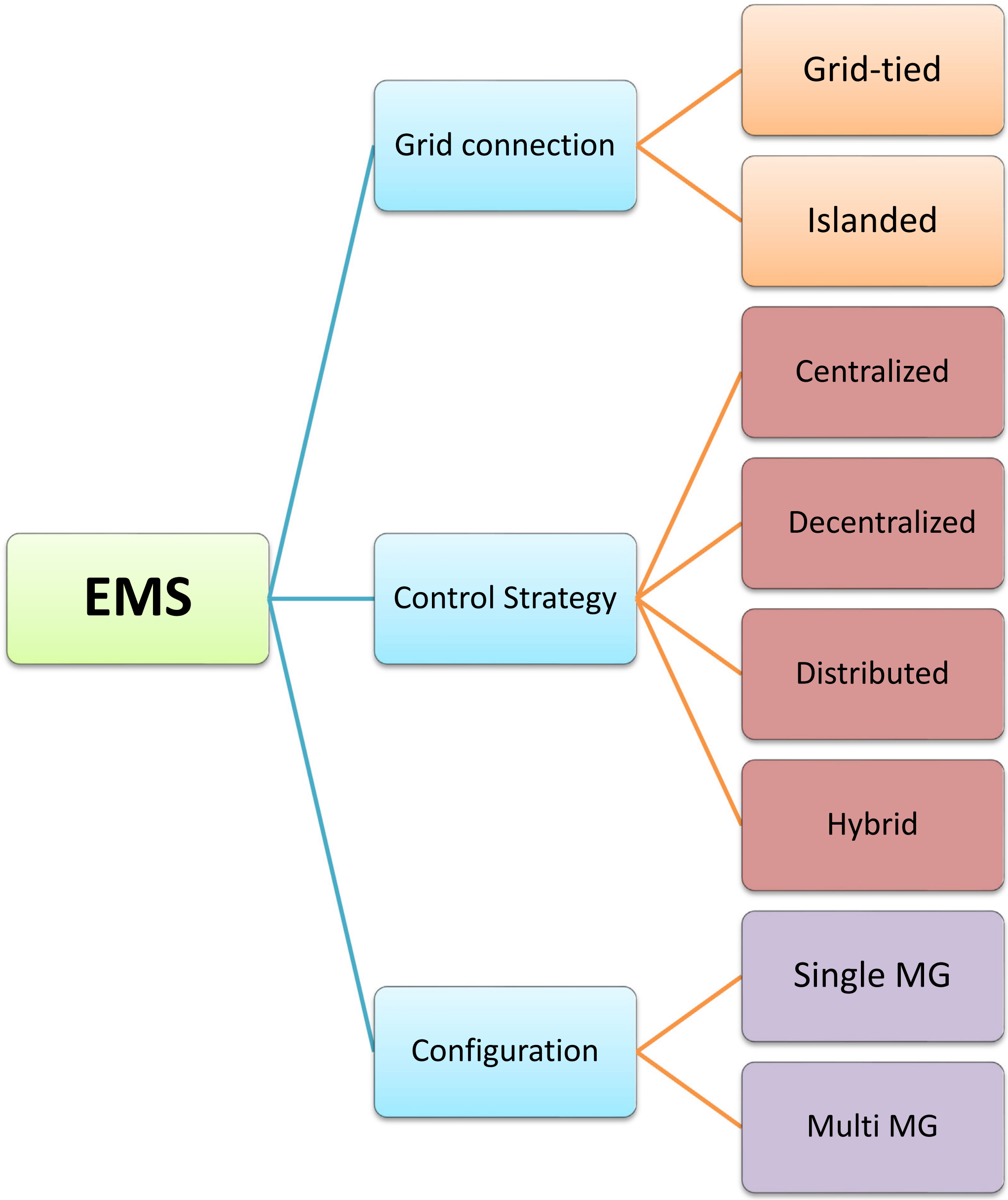

Fig. 8. Classification of energy management systems.

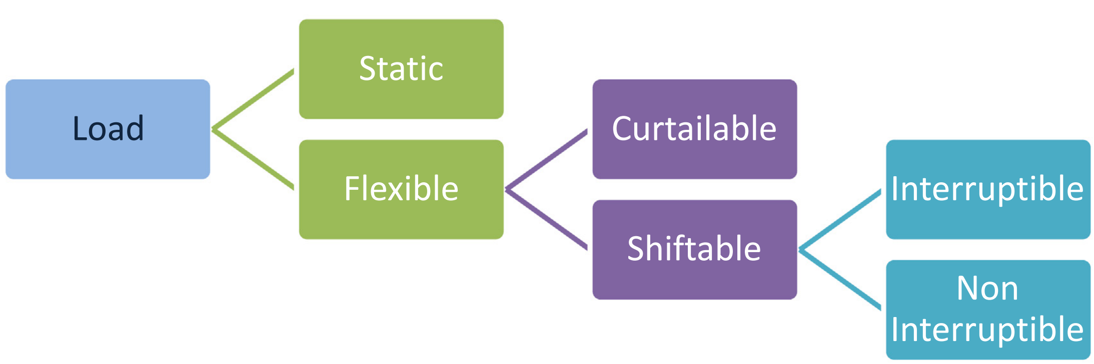

Fig. 9. Load classification in MG.

small MGs with less computational data, but data interruption can cause collapse of the entire MG. Moreover, the computational cost increases due to the presence of a single central controller which has to effectively handle bulk data. Application of centralized approach in multi objective systems is feasible, but tends to become complicated, expensive and bulky. Hybrid

Table 2
Comparison of widely used optimization algorithms.

Algorithm	Strength	Weakness
Linear programming	Computational reliability and speed	Most of the real world problems are nonlinear, which can result in substantial losses when it is developed as linear model (Geem et al., 2001)
Mixed integer linear programming	Guaranteed convergence of the solution with global optimum values (Urbanucci, 2018) Fast and effective solvers available commercially	Optimum solution cannot be obtained if the constraints are contradictory (Urbanucci, 2018) and nonlinear effects cannot be accounted
Nonlinear programming	Results are more reliable as the model exactly replicates the nonlinear characteristics of the system under study	Optimal results cannot be obtained if the functions used in computation are not differentiable. Requirement for feasible starting point to obtain global optima (Geem et al., 2001). Complicated algorithms and not feasible for post-optimal sensitivity analysis (Stott and Marinho, 1979)
Dynamic programming	The sensitivity analysis can be inferred from problem solution (Nelson and Levy, 1968), formulation can be done based on initial value problems (Bellman and Kalaba, 1965)	Increase in the number of variables increases exponentially with increasing number of functions requiring more memory space (Geem et al., 2001)
Heuristic approach	Optimum solution obtained with reasonable computation time and memory space while preserving the nonlinear characteristics (Geem et al., 2001), efficient and upgradable (Mistry and Desai, 2015)	Some hidden solution may result in local optima instead of the global optima (Mistry and Desai, 2015)
Greedy algorithm	Assured solution with high speed and ease of use. Results are independent of the tolerance which is the only adjustable factor (Wolters, 2009)	Only sub-optimal values are obtained and objective functions are not considered directly (Wolters, 2009)
Lagrange relaxation	Can handle general constraints for both sequencing and routing problems (Chen et al., 1998). More suitable bounds evaluated in short computational period (Fabri et al., 2019)	Optimality is not guaranteed (Chen et al., 1998) and identical solutions can cause oscillations (Guan et al., 2002)
Interior point Method	Better convergence characteristics besides being less sensitive to initial values (Verma et al., 2017), parameter tuning is not necessary (Madrigal and Quintana, 1999)	Even after reaching the maximum number of iterations, the solution may still be far from optimal value (Vargas et al., 1993)
Genetic algorithm	Robust with globally optimum results and applicable to multi-modal and large scale optimization problems (Sivanandam and Deepa, 2008)	Substantial number of fitness functions are to be evaluated and can result in premature convergence (Sivanandam and Deepa, 2008)
Artificial bee colony algorithm	Applicable to wide range of functions, flexible, low risk of premature convergence and results are global optimum values (Gerhardt and Gomes, 2012)	Higher cost of computation and requires more time and memory space (Gerhardt and Gomes, 2012)
Particle swarm optimization	Simple in coding, less sensitive to the nature of objective function and initial points, short computation period (Lee and Park, 2006)	Not feasible for real time applications and difficult to find the optimal design parameters (Lee and Park, 2006)
Artificial bee colony algorithm(ABCA)	Fewer control parameters required (Karaboga and Akay, 2009), great convergence, robust	Often fails to find global optima (Guo et al., 2011), premature convergence (Jadon et al., 2015)
Ant lion optimizer	Scalable, flexible, easy, good balance maintained between exploration and exploitation (Assiri et al., 2020), superior performance (Guo et al., 2020)	Slow and premature convergence (Wu et al., 2017; Abualigah et al., 2021)

approach reduces the complexity, whereas in hybrid approach data complexity is reduced and failures are easily mitigated (Khan et al., 2019). Distributed approach provides lesser operations cost and distributes the computational burden (Moghaddas-Tafreshi et al., 2019). Centralized controller requires to collect all the data regarding individual units thereby increasing the computational burden especially in large scale power grids whereas distributed offers best performance in terms of flexibility, robustness, computation time and cost (Chang et al., 2021).

Considering multi microgrids, compared to centralized method, the flexibility and scalability of decentralized method is better (Bazmohammadi et al., 2019).

Under the context of home EMS, in centralized approach, huge investment is required for information and technology sector to meet the load and grid constraints compared to decentralized method, which has less computational stress (Du et al., 2022). Hybrid EMS has better flexibility compared to centralized method and reduced operations cost compared to decentralized method (Wang et al., 2018b).

Taking into account the parameters considered in energy management, considering uncertainties in the RERs and loads results in better management of resources with considerable reduction of operations cost as in Thomas et al. (2018), and robust against communication failure (Silani and Yazdanpanah, 2018), but with computational complexity. With reference to modelling of system components, accurate modelling by considering the characteristics of the units in detail can produce results, which is practically feasible to be adopted in MGs. Considering the effect of grid resilience on operations cost, grid resilience improved with slight increase in operations cost (Tavakoli et al., 2018a). Choice of appropriate battery technology along with stochastic optimization can result in reduced operations cost (Mostafa et al., 2020)

With reference to the studies on energy management on microgrids, it can be understood that for small systems centralized method is more relevant, due to its simplicity, as only less data is involved, which reduces the computational time and effort. But it not preferable in larger systems with higher number of distributed energy resources and storage devices, due to the huge data that is to be handled by the central controller which makes it cumbersome leading to increased cost, less efficiency and increased computation time. Under such circumstances, distributed or method is preferable, as the effort for managing multiple number of RERs, storage devices and load can be distributed for sub units which act as controllers, which in turn reduce the computational effort, time and cost. In the distributed method, a central controller collects the optimized results from distributed agents for energy management. Decentralized method is the same as distributed method except the absence of central controller. This gives an understanding that distributed and decentralized methods is more applicable to multi-microgrid systems or any system which require huge exchange of data for energy management.

5. Understanding

Energy management (EM) is essential in microgrids for the efficient and smooth flow of energy among the various energy resources and storage devices for stable, economic, resilient and economic operation. The intermittency of renewable energy resources calls for sufficient energy storage and multiple energy resources to ensure secure and reliable power supply, leading to high costs. Energy management is essential in microgrids with combinations of renewable energy resources, dispatchable sources, storage systems and loads to ensure optimal power flow between the individual units for the system to work with maximum reliability and minimum cost. A broad category of papers adopting a variety of algorithms and methods is available in EM studies which are mostly simulation based, but more studies are crucial to validate the practicability of implementing the proposed methods in actual microgrids. Even though multiple methods are adopted in EM studies, the authors feel that simulation based on real time systems can provide more reliable results for practical implementation, as the results exactly replicates the behaviour of the actual system. With regard to validation of the results, more studies adopting hardware in loop (HIL) to test the feasibility of practical implementation are vital.

Operation cost, stability, emission reduction, reliability and resilience are the important factors to be considered in microgrid operation. Most of the papers consider one or two of these important factors while compromising the others. In order to exploit renewable energy to the maximum level, renewable energy resources and storage devices are to be selected based on the availability and geographic features of the specific location. PV and wind energy are the most widely studied topics, while doors are open for more research based on alternative renewable energy resources. Batteries are widely used as storage devices in microgrids with few studies considering supercapacitors, but the possibility of adopting micro turbine with hydrogen storage in microgrids is a promising solution, which requires more research and can minimize the eco waste resulting from batteries. Battery swapping is another method of exploiting the battery storage used in electric vehicles necessitating extended research.

Fuel cells requiring hydrogen storage are considered in a limited way in the research work related to energy management as these require space and facility for hydrogen storage, and the work considering fuel cells often ignores the details of hydrogen storage due the complexity involved. Fuel cells incorporating reformer coils are a recent technological progress in this field as they eliminate the requirement for hydrogen storage. The integrated fuel reformer technology enables it to generate hydrogen based on demand and operates on HydroPlus (methanol+water) liquid fuel with a reduced footprint and more energy density. This type of fuel cell is applicable for backup, requiring run times of days instead of hours between refuelling, and it is capable of generating several times more energy than compressed hydrogen of the same volume. It is a promising solution, as currently available storage devices like batteries and compressed hydrogen fuel cells are applicable only for a limited number of hours.

The degradation of battery and fuel cells are other factors to be accounted in studies related to energy management. Again, when degradation is considered, the device may not be subjected to work with its full capability, which can increase the energy cost, while on the other hand, maximum use of the device may result in exhaustion requiring replacement of the unit. Hence, research is open to investigate the optimum point for the storage devices to work with minimum cost.

6. Conclusion

A broad survey of literature pertaining to numerous facets to be understood under the topic of energy management systems is investigated in this paper. The initial part of the paper covers the general topics related to energy management, followed by a critical review of the research works in energy management which are segregated based on multitude of aspects, in particular the systems adopting energy management systems, the configuration of the distributed generation units and the methods of control. Energy management is a comprehensive topic requiring extended research, as it is required for hybrid renewable energy units to work in an economic, reliable and competent manner. The configurations of distributed generator units adopting energy management, the control strategies, the optimization techniques adopted, more importantly, the limitations/factors not accounted in each work is presented in tabular form for prompt understanding. Papers are categorized based on the microgrid configuration and the approach used for control with the limitation of each paper pointed individually, besides specifying the shortcomings of the research works in each categorized group. Varied configurations of microgrids, community microgrid, single microgrid islanded and grid-tied, are considered together and separately and energy management in storage devices is analysed in depth. The state-of-the art technology in fuel cell, specifically, reformer based fuel cell without the need for hydrogen storage facility and lowest emissions is introduced for the first time in this paper. Due to the requirement of storage facility for hydrogen which involves additional space and cost constraints, fuel cells are generally less preferred in microgrids. The reformer based technology makes it attractive to be adopted in microgrids as it consumes less space and uses hydroplus liquid as fuel. With regard to the factors considered in energy management, deterministic approach tends to be less challenging in terms of modelling and implementation whereas stochastic approach is likely to be more challenging but generates more realistic results, to be implemented in actual microgrids. Stochastic approach with real time simulation systems is hardly seen in any work being complicated and expensive, but adopting the same in research works can produce results, which can exactly replicate the actual system. The eco waste resulting from batteries is a subject matter to be emphasized, as battery is the commonly used storage device. Storage alternatives are to be diversified to options with minimum eco waste and carbon footprint for more ecofriendly microgrids. Diverse topics of importance which requires more attention in the field of energy management is identified and pointed out in this paper.

Future works on energy management should consider more robust optimization algorithms, which could be hybrid algorithms for more reliability and minimized cost. Especially in real time systems where the status of individual unit varies depending on the availability of natural resources, the results may not be optimal if robust algorithm is not adopted. The algorithm should be robust enough to accommodate the real time variations. Validating the results of simulation by hardware-in-loop techniques is crucial as this can be implemented in practical systems, which is the real need of the world today, where problems related to climate change, geopolitics and fossil fuels are of big concern. Data privacy is another important factor to be addressed, as the privacy of data exchanged over networked microgrids can be at stake.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgment

The authors acknowledge the support received from Sultan Qaboos University and the Sustainable Energy Research Center, SQU.

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