

MICROGRIDS INTEGRATED WITH DIVERSE ENERGY STORAGE TECHNOLOGIES, ITS CHALLENGES AND OPTIMIZED APPLICATIONS: A REVIEW

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Abstract

Microgrid development is strongly influenced by improved energy storage system (ESS), which holds a vital key to stabilizing the grid. A hybrid energy storage system combines various storage technologies to further synchronize frequency, reducing fluctuations and intermittency problems created by renewable energy sources. The main focus of this research is the advantages and obstacles of incorporating next-generation long-duration energy storage in clustered microgrids with flexibly generated electricity from renewable energy sources like solar, wind, and energy-from-waste units. The key challenges of the research area in focus are the management and control of power, quality of power, economic viability, reliability, and environmental issues such as carbon traces. A thorough review of popular optimization methods and tools is performed, discussing ways to tackle these issues in accordance with industry standards and operational settings. This study offers important insights into enhancing the efficiency, scalability, and sustainability of microgrid-integrated storage systems, facilitating the worldwide shift towards decentralized energy systems.

Keywords: Energy from waste; Energy storage; Flexible generation; Microgrid cluster; Optimization; Renewable energy

Introduction

According to IRENA's study, renewable energy will account for more than 90% of the world's emissions reductions to remain within the 1.5°C climate limit. Of these solutions, hydrogen and its products will be the leading alternatives, contributing 12% of the world's energy consumption. In order to achieve this target, the electrolyzer capacity to generate dedicated hydrogen will need to rise from 0.3 GW currently to 5 TW by 2050. Among which 2/3rd of total hydrogen generation uses renewable

electricity, and the rest with natural gas and carbon capture and storage (CCS), including emergency power supply, electrification, and energy efficiency (Gielen *et al.*, 2021). These sources not only contribute their share towards fulfilling the energy demand but are also helpful in the reduction of carbon emissions. The waste-to-energy process can add a new milestone in power generation and waste minimization. About 1026 million, which is 13% of the world's population, mainly remote villages and

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islands face scarcity of the direct supply of electricity from the grid to maintain a minimum threshold of 250 kilowatt-hours (kWh) per year for rural and 500 kWh for urban households (Ritchie *et al.*, 2020). The opportunities in implementing sustainable energy technologies such as solar, wind, tidal, and waste-energy-based sources are much promising at the community level not only in terms of direct economic benefits as prosumers but also reliability and resiliency of power systems, diminishing the emission of greenhouse gases (Tucho and Nonhebel, 2017; Barik and Das, 2018). A microgrid/hybrid microgrids (μ G)/(h μ Gs), comprising renewable energy sources (solar, wind, biomass, and geothermal), conventional generating units (steam/gas turbines, micro-turbines, and fuel cells) with energy storage systems as backup is expected to fulfill the energy demand in such areas. (Sedghi *et al.*, 2015). Several articles have made efforts to address the challenges μ Gs/h μ Gs in view of power quality, islanding, variable energy generation, control, integration, etc (Das *et al.*, 2011; Akinyele *et al.*, 2018; Hirsch *et al.*, 2018; Carpintero-Rentería *et al.*, 2019). The brief review of existing literature related to RES-based microgrids equipped with flexible generation and categorization of diverse ESS technologies have been investigated here. The structure of the paper is:

- Section 2: briefs the literature review on RES-based microgrid
- Section 3: lists the technical characteristics of diverse ESS technologies
- Section 4: reviews the new-generation energy Storage technologies and its integration in clustered microgrids
- Section 5: the concluding section highlights the challenges and remedies for grid integration of ESS in existing literature

Literature Review on RES-Based Microgrid Equipped with Flexible Generation

As discussed, the μ G is a flexible structure developed by employing renewable energy sources and conventional generating units which is capable of catering to the energy demand not only in the rural part of the world but also the metropolitan cities Mahto and Mukherjee (2017), albeit the intermittent behavior of the power output of the renewable energy units may lead to power imbalance and reliability issues. In most of the μ Gs (Das *et al.*, 2011; El-Fergany and El-Hameed,

2017), the diesel engine generator (DEG) used as a backup generating unit has certain disadvantages, e.g., DEG uses fossil fuel, and emits greenhouse gases raising environmental concerns (IEA, 2020).

The global average of per-capita CO₂ emissions is around 4.4 tonnes, and in India, the value is about 1.6 tonnes which is 6.4% of global emissions (Zhao and Wang, 2014). So, the goal of the reduction in harmful gases can be achieved by the use of bio-energy-based generators instead of using traditional fossil fuel-based generators. The bio-fuel like bio-gas/bio-diesel could be the possible alternatives. The bio-diesel has similar properties as same as diesel with less sulfur content and causes less harmful emissions (Barik and Das, 2020). The fuel makes the bio-diesel engine generator (BDEG) preferable to the traditional DEG. Another advantage is that it has a high flash-point and is eco-friendly. Like bio-diesel, bio-gas is also eco-friendly, though it has been produced from the anaerobic digestion of bio-degradable wastes. The biogas can be utilized directly for cooking/heating purposes or can be used as fuel for the bio-gas turbine generator (BGTG).

In addition to solar PV, solar thermal, and wind, there are specific other clean energy options available μ Gs. The sewage water, rainwater, and water coming from the community's houses are flowing directly to the lake/pond/river, etc. That can be utilized to form a small water reservoir from which the energy can be generated with the help of a micro-hydro turbine generator (MHTG). The MHTG can be installed directly in the channel without disturbing water flow, and wastewater can be diverted for irrigation. Un-treatable and non-degradable wastes can be used to generate power and heat in biomass-fired combined heat and power (BCHP) plants, and the residual can be used for landfills.

Renewable energy sources can be combined with clean generating units to provide backup power e.g., BDEG, would provide backup power (Zhou *et al.*, 2019). However, uncertainty like the unavailability of RESs for a very short period, the backup unit may not be able to cater because of its slow response. Under such circumstances, energy storage devices may be useful (Shankar and Mukherjee, 2016). There are several storage devices; can be battery energy storage system (BESS), superconducting magnetic energy storage (SMES), capacitive energy storage (CES), flywheel energy storage system (FESS), fuel cell (FC), or other available storage systems according to the cost and feasibility (Das *et al.*, 2012a, 2014; Arya and Kumar, 2016; Yoo *et al.*, 2017; Mu *et al.*, 2019). As conventional fossil fuel generators have a hazardous

impact on the environment, so, non-fossil fuel (bio-fuel) based generating unit is an advantage. Based on the load requirement, the pool members in such μ Gs can communicate as prosumers with each other at some stage of their operation in emergencies (Zou *et al.*, 2019; Chaudhary *et al.*, 2021). Figure 1, illustrates the benefits of two or multi-area interconnected μ Gs because of reliability, resiliency, and accessibility.

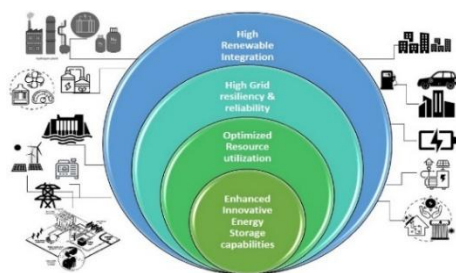


Figure 1. Benefits of Energy storage systems on Renewable based microgrids

Diverse ESS Technologies and Their Technical Characteristics

Research in energy storage has increased dramatically, the impact energy storage can have on the current and future sustainable energy grid is substantial. With almost 60% of the additions coming from China and the US, the total installed battery storage capacity expanded at a compound annual growth rate of 95% to reach 17 gigawatts. Globally, there were 11 projects being built in addition to around 1,363 operational energy storage projects. Among these 40% of operational projects are located in the U.S. after adding 1,665 MW of resources in the first three quarters of 2021, the details of the announced projects as per the distribution of ESSs types are shown in Figure 2 (Ropp, 2020). Energy storage developers plan to

install more than roughly 5.3 GW of power storage capacity between 2020 and 2025 in the scale-up of alternatives to pumped hydroelectric storage to achieve net-zero emissions (Conover *et al.*, 2014).

A collection of “best practices” for categorizing energy storage systems (ESSs), measuring and reporting their performance is aimed at uniform assessment and reporting efficacy of ESSs. It is being used to evaluate how an ESS will perform in terms of specific performance attributes pertinent to a diverse range of applications. ESS consists of storage device, battery management system, and power conversion systems. A collection of “best practices” for categorizing energy storage systems (ESSs), measuring and reporting their performance is aimed at uniform assessment and reporting efficacy of ESSs. It is being used to evaluate how an ESS will perform in terms of specific performance attributes pertinent to a diverse range of applications. ESS consists of storage device, battery management system, and power conversion systems. (Lee and Jung, 2016). Different performance indices adapted in determining the technical suitability or choice of an ESS during power asset integration and planning as per the study based on listed 50 papers are listed below in Table 1.

A comprehensive study of the major energy storage devices employed in power system is conducted in R-studio platform based on co-occurrence mapping analysis of 1484 papers ranging between 2005-2025 of Scopus database is shown in Figure 3 (Aria and Cuccurullo, 2017). It depicts the major topics of interests of researchers worldwide. Here, it clearly shows certain storage devices do hold influential coverage of work over the rest, including the co-linked area of focus like microgrid, energy management, energy efficiency, virtual storage with solar, fuel cells. Lithium-ion batteries, super-capacitors etc.

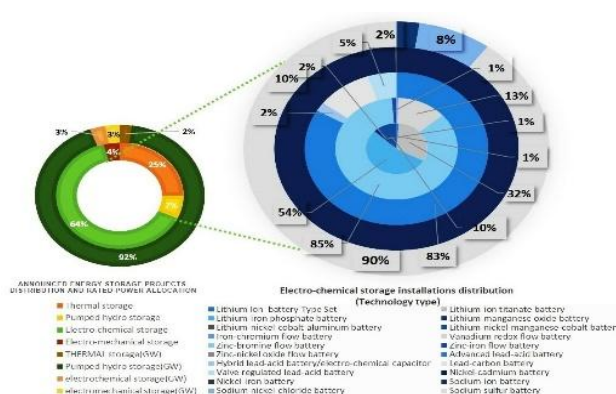
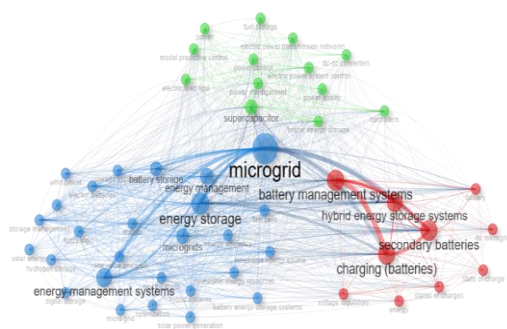


Figure 2. U.S. Energy Storage Projects by Technology Type in 2021

Table 1. List of references for parameter ranges of all ESS types

	Round-Trip Efficiency	Operating Temp. (°C)	Critical Voltage (V)	Recharge Time	Response Time	Spatial Requirement Cycles	Life In Years	MRL	TRL	Typical Power Range	Power Density W/Kg	Typical Energy Range	Energy Density	Recyclability	Eco-Friendly	Advantages	Disadvantages
Sodium-Sulphur Battery	[30]	[75,36]	[50,51]	[42]	[3,36]	[45]	[31]	[27]	[75,36,42]	[30]	[36]	[30]	[36]	[33]	[75,40]	[57]	[57]
Li-Ion Battery	[79,80,39]	[36,38]	[43-46]	[38]	[36,38]	[45]	[77,,34]	[80,40]	[33,79]	[38]	[36]	[38]	[38]	[41]	[33,54]	[57]	[57]
Sodium Metal Halide	[33]	[36,49]	[52]	[52]	[36,51]	[45]	[41]	[36]	[36]	[30]	[36]	[30]	[40]	[40]	[42]	[57]	[57]
Lead Acid	[79,36,44]	[36,42]	[43,45]	[30]	[36,43]	[45]	[30]	[75,36]	[33,36]	[31]	[36]	[31]	[31]	[79,33]	[40]	[57]	[57]
Ni-Cd Battery	[31]	[1,,36]	[31]	[30]	[36,43]	[45]	[30]	[36]	[36]	[30]	[36]	[30]	[38]	[40,33,54]	[40]	[57]	[57]
Zinc-Hybrid Cathode	[39]	[75,,36,53]	[31]	[53]	[27]	[45]	[79,53]	[53]	[33,,]	[30]	[36]	[30]	[40]	[40]	[40]	[57]	[57]
Redox Flow Battery	[79]	[41]	[47,48]	[30]	[41]	[45]	[40]	[40]	[75,36,42]	[30]	[36]	[30]	[40]	-	[40]	[57]	[57]
PSH	[79,36]	[38,41]	-	[36]	[38,41]	[45]	[79,40]	[59,60]	[33,42]	[35]	[36]	[40]	[36]	-	[40]	[57]	[57]
CAES	[79,44]	[41]	-	[49]	[41]	[45]	[40]	-	-	[35]	[36]	[40]	[36]	[65]	[42]	[63]	[57]
Flywheel	[30]	[42]	-	[30]	[42]	[45]	[40]	[61]	[33,36]	[40]	[36]	[36]	[36]	-	[40]	[57]	[57]
Ultracapacitor	[62]	[62]	-	[62]	[62]	[62]	[64]	[64]	[64]	[62]	[62]	[62]	[62]	[62]	[62]	[64]	[64]
SMES	[37]	[38,42]	-	[30]	[75,,38,42]	[45]	[40]	[40]	[33,36]	[40,35]	[36]	[40]	[36]	-	[42]	[57,63]	[57]
Combustion Turbine	[51]	[65]	-	[65]	[51]	[65]	[51]	[51]	[51]	[65]	[65]	[65]	[66]	[66]	[66]	[51,66]	[51,66]
FC-HES	[56,57]	[58]	-	[58]	[57]	[58]	[57]	[59,62]	1,12,42,59	-	[58]	[58]	[56,57]	[58]	[58]	[57]	[57]
LT-TES	[67]	[67]	-	[67]	[67]	[69]	[67]	68,69	68,69	[67]	-	-	-	[68]	[67]	[68]	[68]
HT-TES	[67]	[67]	-	[67]	[67]	[67]	[67]	68,69	68,69	[67]	-	-	-	[68]	[67]	[68]	[68]



stationary storage refers to grid resilience and commercial applications such as ancillary services and energy leveling that serve as an alternative to transmission/distribution network upgrade requirements. (Lazarewicz and Judson, 2011; Nazaripouya *et al.*, 2018). Grid-related issues can be mitigated through commercial and industrial energy storage and EV charging infrastructure, while batteries are in high demand for long-term energy storage and backup power. (Sudworth, 2001; Linden, 2004; Park *et al.*, 2016; Mekhmonov *et al.*, 2024). Emerging energy storage technologies are being used in different industrial applications such as air conditioning, refrigeration, hydrogen refuelling stations, and motive forklifts. (Chatzivasileiadi *et al.*, 2022). These technologies are also being considered for use in the military sector, where efficient and dependable energy storage is of utmost importance. Of these new technologies, advanced aluminium (Al) battery technology is emerging as a strong candidate, especially in marine use. This is because it has a much larger energy capacity, estimated to be four times the capacity of traditional lithium-ion batteries. (Zucker and Hinchliffe, 2014; Jannesar *et al.*, 2018). With these benefits, the Al-battery technology market is anticipated to see significant growth, with estimates predicting a market value of USD 812 million by 2025 (ESMAP, 2020; IRENA, 2020).

Integration of ESSs in clustered microgrids

Recent trends in research proposes clustered Microgrid as a self-healing reconfiguring technique to improve the reliability of existing power grids with high renewable integration. Based on the topology of clustering studied so far, they are identified in two categories subjected to controllability: (a) topology 1, in which optimization relies on the relocation of existing DERs, while (b) another topology introduces optimization of new microgrids in addition to the existing network (Wang *et al.*, 2015; Li *et al.*, 2018a). This cluster can be further disintegrated into AC/DC/hybrid type microgrids interconnected via line technologies like dual H-bridge converter with a high-frequency transformer for DC/DC type microgrid subjected to power control; Voltage source converters in AC/DC type for voltage control (Choobineh *et al.*, 2018). Classification of such structure-wise Microgrid clusters is presented in Figure 4. Listed along with the classification of microgrids cluster as parallel, ring, mesh or nested type network. However, ongoing studies in this direction do not benchmark these systems as their performances are still in the research stage subjected to scalability, reliability, protection, and stability.

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A substantial number of renewable hydrogen projects are now in the experimental stage, and the technologies, methods, and processes employed are novel. Regional large-scale supply and consumption centres are not established yet. (Ibrahim, 2008; Kim *et al.*, 2012). Aiming to increase energy efficiency and cost-effectiveness as research in this field continues, with the expectancy to witness more breakthroughs and innovations making renewable energy more practical and cost-effective. (Hubert *et al.*, 2003; Chatzivasileiadi, 2013; Enescu *et al.*, 2020; Murdock 2023). According to the application, ESS is classified as both stationary and mobile. Whereas mobile storage refers to battery or plug-in hybrid electric/hydrogen-based fuel cell vehicles (EVs/FCEVs), lighting and ignition batteries in boats, ships, cars, and other modes of transportation,

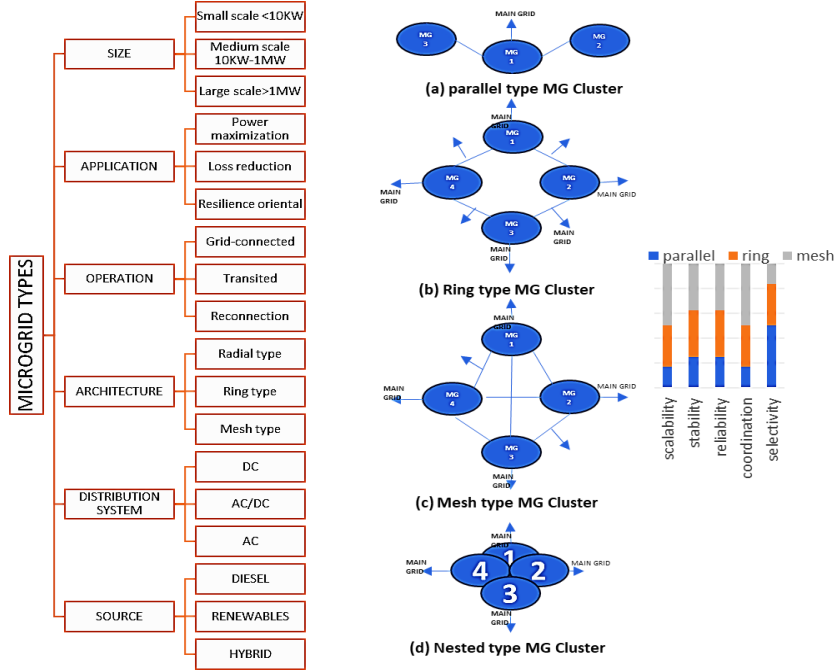


Figure 4. Classification of Microgrids and performance chart of different microgrid-cluster types (a-d)

In this paper, an in-depth investigation is done to identify the suitable control strategies and optimization techniques for microgrid operation i.e., grid-connected or islanded mode.

In islanded mode of operation: reactive power management is evident due to the nonexistence of infinite bus leading to active power imbalance, voltage and frequency mismatch which is regulated by application of a Static transfer switch or optimum shunt capacitor placement with a proper optimization algorithm (Shahgholian, 2021).

In interconnected mode of operation: Under normal operating condition, where microgrid is connected to the distribution grid while injecting the required amount of power and/or partially supplied from the main grid. The distributed generators operating in 'PQ mode' with the control system is called "PQ inverter control". In such case microgrids are operating in centralized control which in case of fault or any other compromising events tend to switch in islanded mode from main grid to ensure onsite protection of equipment (Sharma and Sood, 2020).

A stratified design framework is proposed to ensure reliability on flexible generation by storage devices for sizing microgrid clusters, which maximises placement of distributed energy resources (DERs) with respect to economic advantages (Bekele *et al.*, 2024). Other recent works focus on the design strategy that leverages a hybrid microgrid clusters model featuring self-built and

leased energy storage model that dynamically balances investment and operational costs while ensuring robust performance through tailored planning (Wang *et al.*, 2024a). The current trend for optimising planning capabilities of microgrid clusters is evolving with enhanced chaotic mapping and dynamic opposition-based learning techniques (Dey *et al.*, 2024). A stochastic control approach for optimising battery storage capacity and power-sharing strategies in interacting microgrids establishes a design principle for optimal energy management (Li *et al.*, 2024). In addition to the above, the expandability of the existing microgrid network with a wide range of storage technologies in the cluster, the challenges and advantages arising from their different system dynamics are discussed in the next section.

Review of Applied Optimization Tools and Their Application

The emerging trend of energy storage technologies is not limited to traditional approaches as DEG, BESS, FC & AE have been considered by Das *et al.* (2012b) in addition to that ultracapacitor (UC)/CES has been also considered in (Sabihuddin *et al.*, 2014). PHEV unit is in (Chen *et al.*, 2009). (Widera, 2019) have proposed a new type of storage unit named pumped thermal energy storage (PTES) which can produce both heat and electricity by using

the compressed heat energy storage (CHEST) principle. (Ruiz-Cortes *et al.*, 2018) have proposed a scheme for charging and discharging storage units (especially Li-ion batteries), with the help of GA to make the system performance better. To stabilize the system frequency, Mi *et al.* (2019) have used FC, AE, BESS & FESS as storage units for the performance improvement of the system. A combination of BESS & SMES units for storage purpose has been considered by (Redondo *et al.*, 2009; Rastler, 2009, 2010; Naish *et al.*, 2008; Inage, 2011). FC, BESS, and FESS have been taken under consideration as storage units for an isolated μ G by

Baldi *et al.* (Baldi *et al.*, 2019; Petrovic and Hossain, 2020; Beaudin *et al.*, 2010). The storage units decide the system cost and reliability, to overcome these issues is reported by Mi *et al.* (2019). Li *et al.* (2018b) have proposed a sliding mode algorithm (SMA), which will help to reduce the BESS capacity in the stabilization of the multi-area microgrid. A combined effect of ESS and DC-link has been studied in (Hassenzahl *et al.*, 2004). (Prakash *et al.*, 2020) have modeled static synchronous series compensator (SSSC) for LFC study. (Xu *et al.*, 2018) have proposed a new type of pumped hydropower energy storage (PHES) technique for

Table 2. Review of applied optimization tools and their application in grid-connected and isolated RES-based hybrid energy storage microgrid

References	ESS Type	Application Description		Applied Optimization Techniques/Tools
		Pros.	Cons.	
Grid-connected microgrid				
(Sharma and Sood, 2020)	Lead acid, redox flow, sodium sulfur batteries	Location-based energy and Expense Minimization	PQ and reliability are underestimated	GA with LP solver
(Prakash <i>et al.</i> , 2020)	Zinc halide batteries	Location, capacity, and the power rating of batteries considered for ESS and total cost minimization and peak shaving reducing technical violation	low cycle efficiency limitations	Hybrid Tabu Search PSO approach
(Lei and Gong, 2017)	Variable redox flow batteries	Energy arbitrage, emission, losses, fee, maintenance costs of BESS resulting in reduced emissions and mitigating RE intermittence	Complicated BESS Optimal charging/discharging	Dig SILENT
(Gabielli <i>et al.</i> , 2020).	Lead-acid and Li-ion batteries	Efficiency, PV data-based charging-discharging, and energy cost factors considered for time-shifting and energy arbitrage	Computational complexity of incentive mechanism	GAMS model and CPLEX solver
(Trebilcock <i>et al.</i> , 2020)	Li-ion batteries	real-time measurement with significant ESS losses reduction	lowered PQ level with an increase in nonlinear effects and risk factor	Multi-period AC OPF, MPC, MILP, and CPLEX
(Martínez <i>et al.</i> , 2017)	Variable redox flow batteries	Uncertainty of fuel and load, ESS cost is optimized, VRB is reasonable for application	Unresolved PQ issues	DP optimization algorithm
(Xu <i>et al.</i> 2020)	Hydrogen storage	a larger share of battery storage resulting in a significant reduction in CO ₂ emission	Large storage space requirement	MILP
(Widera, 2019)	CHEST	Enhanced flexible energy storage coupled to a Smart heating system with higher round-trip efficiency	Sensitive to latent and sensible heat energy system sizing	TRNSYS simulation Environment-based laboratory-scale prototype
(Shankar and Mukherjee, 2016)	Photovoltaic (PV), micro turbine (MT), Fuel cell	Significant reduction in annual cost and CO ₂ emission	immediate located DG in peak hour line overloading	Harmony Search algorithm in a low voltage microgrid
Isolated microgrid				
(Lei and Gong, 2017)	Variable redox flow batteries	ESS and RE uncertainties and conventional power and load	optimal sizing attained	hybrid optimization model with meta-heuristic algorithm
(Fortenbacher <i>et al.</i> , 2017)	Ni-Cd and Li-ion	Investment and operational costs minimized	The limited solution in local optima	Autoregressive stochastic optimal ESS model sizing
(Awad <i>et al.</i> , 2014)	Lead-acid	Good cycle control and enhanced ESS life expectancy	multiple constraints leading to computational complexity	Non-dominated sorting Genetic algorithm
(Zhang <i>et al.</i> , 2016)	PHS	Curtailement rate, High wind penetration is considered for a reduction in levelized cost	Overlooked ecological impacts	Multi-objective PSO
(Wang <i>et al.</i> , 2024b)	Sodium Sulphur batteries, lithium-ion	wind power uncertainty, energy error, the Lower investment cost of NaS	Reliability, Network Security issues unresolved	Improvised Grey Wolf Optimizer
(Anastasiadis <i>et al.</i> , 2017)	Solar/FC electric vehicles (EVs)	stabilizing services via vehicle-to-grid, community-friendly	multi-time-scale characteristic challenging control	The multi-dimensional, multi-physics models implementation
(Martínez <i>et al.</i> , 2017)	Open water power battery	effective energy and water resources usage, as well as microgrid sizing, cybersecurity, and self-healing	Challenging inrush currents in compressor lacking (V,f) control and thermal loading	PID controller control loops based Human Machine Interface

the LFC study. So, $\mu\text{G}/\text{h}\mu\text{G}$ storage may help to maintain the frequency up to a certain extent. Table 2 Represents a brief review of trending optimization tools for the application of ESS as per the suitability of different types of microgrids. (Denholm *et al.*, 2010; Alanen *et al.*, 2012; Simbolotti and Kempener, 2012; Garche *et al.*, 2013; Subburaj *et al.*, 2015).

Integration of Ess in Microgrid: Challenges and Remedies

Microgrids in the presence of renewable energy and storage devices have been considered as the sustainable means to wipe out the energy poverty of nonelectrified areas of the world, combat the global temperature rise, and arrest the burning of fossil fuels at the same time. The technologies pertaining to energy storage/advanced energy storage along with new renewable generation are evolving at a faster rate. (Yamamura *et al.*, 2011; Buchmann, 2018; Lourenssen *et al.*, 2019). At the same time, challenges related to monitoring, control, and management of microgrids and their operation are rising and need to be addressed appropriately. (Silva-Monroy and Loose, 2012). The hybrid system combines fuel cells, batteries, and solar PV to effectively handle DC load power and minimize battery bank capacity. It employs maximum power point tracking (MPPT) and supercapacitors to maximize battery capacity and increase cycle life (Abd el Motaleb *et al.*, 2016; Zhang *et al.*, 2016). The iterative Monte Carlo Simulation and Nonlinear Programming have been used to solve the multi-objective problem of energy loss and voltage deviation in wind turbine and PV integrated microgrid involving probabilistic modelling of EV demand (Xu *et al.*, 2020). Utilizing Grey Wolf Optimization (GWO) to optimize secondary frequency control in an autonomous microgrid system, considering fitness function, control variables, gains, and integral time absolute error, comparing results with past controllers (Miao and Hossain, 2020). The performance evaluation of a 3DOF-PID controller using the water cycle algorithm, comparing it to other control schemes, using sensitivity analysis and Thyristor controlled series compensator territorial scheme for sufficient electricity generation in developing nations leads to load shedding and unplanned power outages, necessitating standby power supplies, home microgrids, solar energy, and electric vehicle batteries (Daw *et al.*, 2018; Robledo *et al.*, 2018).

For example, Iran's Kiyalo based a hybrid renewable energy system (HRES) combines solar, wind, and diesel power, aiming for reliability,

affordability, and environmental friendliness using NREL's HOMER software (Kumar *et al.*, 2018). The study suggests using ANFIS scheduled fractional ordered PID control to mitigate frequency excursions in AC microgrids, demonstrates its efficacy against random load perturbations and system nonlinearities (Sankar *et al.*, 2019), Solving automatic generation control problems using the TLBO algorithm with multi-type-multi-area loading (Singh *et al.*, 2023). The papers presents a sliding mode controller for superconducting magnetic energy storage in a wind-diesel power system, based on an adaptive RBF neural network, ensuring power exchange during power imbalances and enhancing performance in load and wind power fluctuations (Shafaati *et al.*, 2017). In a deregulated environment, Automatic Generation Control (AGC) for a two-area power system is covered in the paper. The study delves into nonlinearities such as communication delay and suggests a new kind of cascade controller with, a novel Quasi Opposition Lion Optimization Algorithm (QOLOA) is proposed. A sensitivity analysis shows how resilient the controller is to changes in the system's parameters in a range of deregulation scenarios (Kalyan *et al.*, 2023). Few article examines the transient performance of a home microgrid in three configurations: distributed, decentralized, and centralized, using MATLAB/Simulink for simulation and evaluating voltage, frequency, and harmonic distortion (Fathi *et al.*, 2019). Cluster microgrid research explores various frequency control techniques, including demand response plans, energy storage, optimization, prosumer effects, smart homes, shiftable loads, emergency protocols, and heating and ventilation systems (Singh and Suhag, 2023). Demand Side Management (DSM) and Dynamic Economic Emission Dispatch (DEED) are combined to maximize load factor and power utilization. In spite of the uncertainties surrounding renewable energy sources, an energy management algorithm (EMA) is suggested to balance load demand with generated energy. In order to increase load factor, reduce operating costs, and maximize profit for all electricity market contenders, a machine learning technique based on random forest regression is utilized to forecast load demand, wind, and solar power for a 24-hour period (Kumar and Shankar, 2021; Kumar *et al.*, 2023; Thoker and Lone, 2023).

Reliability of the power supply affects customer satisfaction and, in turn, supplier preference. New devices, methods, and models for evaluating the reliability of power system networks are being researched and developed at a faster pace (Moradian *et al.*, 2019; Singh and Suhag, 2019; Mongird *et al.*, 2020; Roy and Das, 2023).

In addition to the cons mentioned in the sub-sections, summing up the challenges of microgrid implementation are:

1. Maintaining the balance between stochastic generation and continuously varying load demand is an essential criterion to maintain the stability of the microgrid in all possible operating modes. As such development of a widely acceptable control strategy for microgrid operation needs to be explored.
2. Maintaining microgrid flexibility in adopting all new/ advanced storage devices as well as energy sources in the face of continued technological change is also an issue.
3. Necessary standard and operational configurations for the interconnection of new/advanced energy storage devices are to be developed.
4. Challenges related to cybersecurity and the continuous development of standards to combat the same.
5. Issues with the adoption of low-capacity energy systems and related changes in the system impacts.
6. Development of a proper metering system to address issues with proper billing in a microgrid.

Scientists and engineers all over the world are striving hard to find appropriate solutions to these challenges. The most recent technological advancements, including Internet of Things (IoT), artificial intelligence (AI), and information and communication technologies (ICT), as well as the development or modification of existing standards for the communication of distributed energy resources, may be beneficial in resolving these problems. The development of an appropriate control strategy in maintaining the balance between the generation and load demand is the need of the hour to ensure an efficient and reliable energy supply from the microgrid

Conclusions

The combination of different energy storage systems in microgrids enormously increases energy efficiency, reliability, and sustainability. Some of the important findings state that hybrid energy storage systems like battery-supercapacitor and hydrogen storage improve load management and grid stability. Sophisticated energy management strategies like AI-optimized, IoT-based monitoring, and multi-agent control even optimize system performance. Nonetheless, the increasing complexity of modern power networks highlights the necessity to diversify energy storage options to

meet each unique operating demand. Storage devices have varied strengths based on reaction speed, energy capacity, and scalability. For example, while lithium-ion batteries remain the preferred choice due to their great efficiency, sodium-ion batteries are a more sustainable and cost-effective option. Hydrogen storage systems enable long-duration energy requirements and sector integration, while supercapacitors provide ultra-fast response for frequency regulation. Pumped hydro storage and thermal energy storage also play important roles in large-scale energy balancing. Notwithstanding these developments, a number of significant challenges remain. Ensuring grid stability in the face of stochastic renewable generation and dynamic load fluctuations requires the formulation of strong, broadly accepted control strategies. Providing microgrid flexibility to support future storage technologies and energy sources continues to be a critical issue. Uniform interconnection standards for future energy storage systems need to be developed, as well as countermeasures to cybersecurity attacks and secure energy transactions. In addition, the implementation of low-capacity energy systems poses integration problems, while the lack of proper metering and billing mechanisms makes energy trading and management within microgrid systems challenging. The most recent technological breakthroughs, such as IoT, AI, blockchain, and ICT, provide potential solutions to these challenges. Microgrid monitoring via IoT may enhance real-time decision-making, energy optimization via AI can improve demand response planning, and blockchain-based smart contracts can enable secure and transparent peer-to-peer energy trading. Furthermore, adaptive control systems are critical for synchronizing energy usage and generation, increasing grid flexibility, and removing transmission bottlenecks. In the future, research should focus on developing dynamic energy management systems, improving cybersecurity resilience, and adapting microgrids to new energy storage technologies. Microgrid-integrated storage, when combined with a variety of energy storage devices, can allow a more robust, adaptable, and sustainable power infrastructure as decentralized energy systems become more prevalent.

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