



Energy-Efficient Storage System Optimization and Recent Trends in Enhancing Energy Management and Access Microgrid: A Review

Al Smadi Takialddin¹, Al sawalha Ayman², Binod Kumar Pattanayak³, Al Smadi Khalid⁴, Habboush Ahmad Khader⁵

¹Member IEEE, Faculty of Engineering, Jerash University, Jordan.

²Faculty of Science, Jerash University, Jordan,

³Department of Computer Science & Engineering

⁴Computer Science, Jadara University, Irbid, Jordan.

⁵Faculty of Information Technology, Jerash University, Jerash, Jordan.

* Corresponding author's Email: dsmaaditakialddin@gmail.com

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A B S T R A C T

This study explores energy storage systems, focusing on environmentally sustainable alternatives like batteries, flywheels, thermal storage, and pumped hydro storage. It highlights case examples like vanadium redox flow batteries in maritime hybrid propulsion systems and portable hydrogen energy storage devices. The results suggest these technologies can replace traditional fuel sources, especially in isolated areas. The study also explores the integration options for energy storage in microgrid, examining models, assessment indices, and optimization methods used in designing systems. It also examines the capabilities of software in determining optimal system sizes and uncertainty analysis in modeling energy storage devices. The study introduces state-of-the-art technology to demonstrate the effectiveness of energy storage systems in microgrid, providing crucial data for future industry progress.

1. Introduction

Energy systems are the backbone of modern society, extracting energy from diverse sources and transforming it into various forms for use in the utility, industrial, building, and transportation sectors. While fossil fuels have traditionally met customer demand, the need for sustainable alternatives like solar and wind energy, which must be collected during their availability and stored for future use, is becoming increasingly urgent. This is where energy storage comes in, offering many benefits for energy systems, including higher integration of renewable energy and improved economic viability [1, 2]. Numerous types of energy storage systems can be classified in multiple ways. The Ragone plot is an illustrative tool commonly used to analyze the properties of different electrochemical energy storage types. This plot allows for the comparison of the specific energy and specific power of each storage type, enabling the identification of their potentials and the contrast between them. It is particularly useful for applications requiring different energy storage capacities and extraction rates [3, 4, 5]. Storage energy density refers to the amount of energy stored in a given space or mass, while power density refers to the rate at which energy is transferred in a given volume or mass. High-energy density devices are necessary when there is a prolonged absence of generated energy [6, 7, 8, 9]. In contrast, high-power density devices are required for devices that experience frequent charge and discharge variations within a short period. Energy storage devices can also be categorized according to their duration of storage. Short-term energy storage often entails storing energy for hours to days, whereas long-term storage pertains to storing energy for a period ranging from a few months to a season (3-6 months) [10,11]. For example, a prolonged thermal energy storage system preserves thermal energy in the ground during the

summer to be utilized during the winter. Several reviews have comprehensively assessed energy storage systems, including extensive classifications, characteristics, advantages, environmental consequences, potential implementation, and application opportunities. Conducting comprehensive assessments encompassing all types of energy storage is crucial for understanding their distinctions, prospective integration possibilities, and necessary policy advancements. This study examines various methods of energy storage, with a specific emphasis on their operational theories and technological coattention. By examining and contrasting their respective uses, this paper provides a comprehensive and up-to-date examination of each form of storage classification [12–15].

Techniques of energy storage

Due to recent advancements in the Electric Vehicle industry and the economy's transition towards more environmentally friendly energy sources, the demand for Energy Storage Systems (ESS) has significantly increased. It is anticipated that the demand for energy storage will triple by the year 2030 [16]. In response to the high demand, researchers have been compelled to create innovative techniques for energy storage that are both more efficient and capable of providing reliable and regulated electricity as required.

During monopoly periods, power plants frequently relied on locally sourced fuel or gasoline saved in advance as their primary energy storage source [17, 18, and 19]. The authority required coal-fired power stations to maintain a fuel reserve that could sustain them for a maximum of 20 days in case of a fuel supply disruption. This ensured that the plants could continue producing energy while rectifying the issue. The on-demand nature of

electrical power distribution often facilitated overcapacity in both generation and the network. A central governing body regulated the timetables for power generation and adjusted them according to the day of the week, the season, and the time of day [20]. The most established and mature storage technology, with the greatest installed capacity of any company in the world at 153 GW. 8It provides time-shifting, peak-opping, valley-filling, and seasonal energy production and consumption control. However, it is costly, restricted in terms of location, and subject to delays due to environmental licenses [21]. Castle-Aided Energy Storage (CAES) is a technology with a restricted geographic reach, but its reaction time is too slow to offer necessary supplementary services. Second-generation CAES technology allows compressed air to be stored in an above-ground structure, potentially threatening the battery sector. Flywheel technology, used for commercial energy storage in the US and UK, can inertia, reserve, regulate frequency, and respond to frequency. Recent developments in materials, magnetic bearings, and power electronics have made flywheel technology a viable choice for energy storage [22.23.24]. Battery energy storage systems have become increasingly popular for supplementing intermittent renewable energy sources like solar photovoltaics (PV) and wind power. Lithium-ion battery technology has emerged as the clear frontrunner for portable devices and energy storage due to its high energy density, low self-discharge, lightweight design, adaptability, and low maintenance needs. However, the high initial investment required to implement extensive use of battery energy storage systems is the main barrier to their general adoption [25]. The demand for

lithium-ion batteries is predicted to quadruple between 2015 and 2020 due to the increasing popularity of electric automobiles and portable battery devices. Lithium's primary source of raw materials is pegmatite-type solid granite or underground Salt Lake in liquid form, with 50% of the world's lithium deposits in Chile, Bolivia, and Argentina. However, higher raw material costs have not significantly influenced battery costs, which are still declining [26.27]. China has taken the lead in this industry, and its plans to combat climate change via increased renewable energy generation should keep it at the forefront for the foreseeable future. Battery usage in portable devices and for energy storage is expanding, driving up global demand for batteries. Australia has the most electrical capacity in the world, mainly made up of a single 100 MW battery. The United States has the greatest available power, with 431 MWh, and California leads in the number of behind-the-meter solar energy storage (BES) installations [28-30]. Community batteries combined with PV and BES provide operational benefits and cost savings, such as optimizing Time of Use pricing, accessing frequency management, avoiding distribution and transmission-related failures, and delaying network growth. Commercial BES systems are transportable, flexible, and straightforward to deploy, but there are obstacles to deployments, such as high costs, current network operator practices, and limited rates [31]. Electrical energy storage (EES) is a technique that stores electricity produced during low-demand, low-generation-cost hours or from intermittent power sources for use during peak demand and high-generation-cost periods [32].

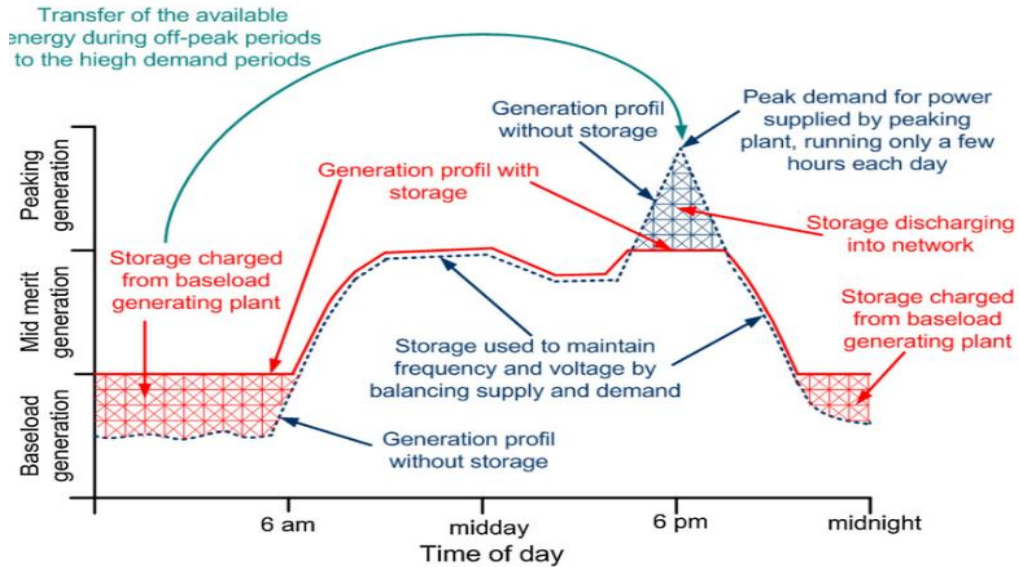


Figure 1: The basic concept of energy storage [9]

Solar Energy Storage System

Power grid operators and aggregators have looked at energy storage as a possible solution to the variability of renewable supply. Extensive research has been conducted on energy storage control and assessment of its role in renewable generation, power balancing with fixed or flexible load management and phase balancing. A study has been done on residential energy storage systems, both with and without the integration of renewable energy sources, to determine which of these two approaches could be more effective in lowering the cost of power. The only subject of discussion in these assessments was the acquisition of energy. Instead, the authors propose offline storage control methods for dynamic systems considering load prediction and day-ahead scheduling. Since historical data on load and renewable generation is readily available, and the cost of using batteries is ignored [33]. Battery storage systems have emerged due to the need for electrical power and energy applications. It is becoming more common to install solar photovoltaic (PV) systems in homes with battery storage, which allows the homeowner

to save any extra energy produced by the PV system during the day and utilize it later when the sun goes down. System owners will have a better chance at realizing the financial benefits of combining solar PV with storage systems if a sustainable and affordable battery market is fully developed. Both lead-acid and lithium-ion batteries are now the most common choices for use in solar photovoltaic (PV) systems that need rechargeable batteries. However, lead-acid batteries have lower starting and operating expenses (O&M) than lithium-ion batteries, even though lead-acid batteries have a bigger negative impact on the environment. However, lead-acid batteries are not the best option for energy management due to their relatively low energy densities (30-50 Wh/kg) and limited cycle life. Lead-acid batteries are extensively utilized as backup power (200-1000 cycles). However, lithium-ion batteries have been steadily developed and used in solar PV applications for utility-scale solar farms and solar roofs due to their better energy density (up to 300 Wh/kg) and life cycle (up to 10,000 cycles). Despite their many advantages, the higher cost of lithium-ion batteries might be attributed to their specialized packaging needs and built-in

overcharge protection mechanisms. Due to factors including material, operating mode, management system, and geography, the size and cost of battery storage systems for residential-scale applications might vary considerably worldwide. Values for capacity vary from 1.2 to 100 kWh, with prices per kWh sitting between 400 to 1100 USD. We looked at websites based in Jordan and the USA to understand prices and dimensions. A lead-acid battery storage system has been integrated with off-grid solar photovoltaic installations for homes. Regulations and support for energy storage systems in Thailand are primarily oriented at R&D efforts as part of the country's Smart Grid Master Plan [34, 35, and 36]. Battery and solar PV cell prices continue to drop. Because of variables like weather, location, and time, the availability of renewable energy sources like wind and solar may be erratic. If energy storage devices are deployed, they may help mitigate these swings and store energy for later use. As more nations invest heavily in increasing their usage of renewable energy, demand for battery management systems (BMS) is anticipated to increase. One estimate puts the worldwide BMS market at \$12.23 billion by 2025; Grand View Research Inc. released that figure in their June 2019 report. A home microgrid is a household that has its electrical grid and maximizes energy efficiency by combining photovoltaic (PV) systems, energy storage, and intelligent energy management. Therefore, increasing the percentage of photovoltaic

energy in the electrical microgrid seems to have 41 benefits in lowering emissions, raising environmental awareness, and having a minimal environmental effect. Still, new energy management systems are required to save costs and guarantee a reliable energy supply. Today's academics and engineers seem concerned with energy storage and the most efficient solar microgrid management. In the past and the future, researchers will use a wide range of sophisticated and elementary optimization techniques [37,38].

Types of Energy Storage Systems Used in Micro grids and Energy Hubs

In general, Energy Storage Systems (ESS) utilized in microgrids (MGs) can be categorized into three groups based on their energy storage type, nominal power, energy ratings, and applications, as seen in Figure 6. Energy Storage Systems (ESS) can store energy in various ways: chemically, mechanically, electrically, and electro-chemically. Examples of chemical energy storage systems include hydrogen-based energy storage systems (HBS). Pumped hydro storage systems (PHS), compressed air energy storage systems (CAES), and flywheel energy storage systems (FWES) are examples of mechanical energy storage systems. Supercapacitor energy storage systems (SCES) and super-magnetic energy storage systems (SMES) are examples of electrical [39].

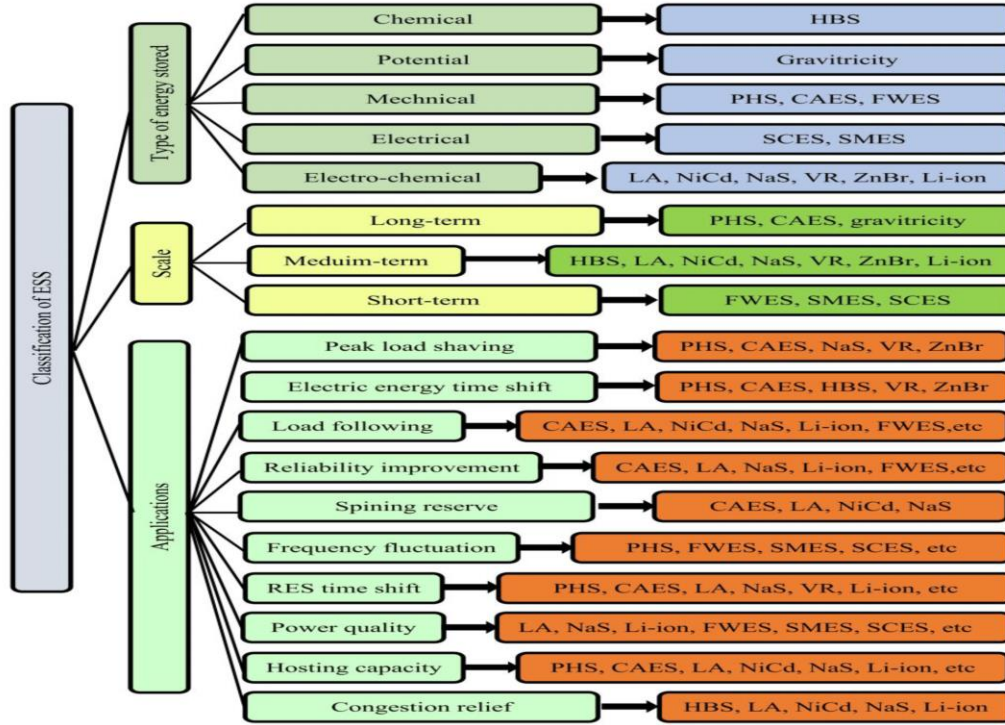


Figure 2. Classifications of ESSs according to energy store type, nominal power and energy ratings, and applications^[1]

ESSs in Microgrids: Integration Strategies and Models

Integration Strategies

Free-standing or grid-connected photovoltaic systems are only two examples of how this technology might be used. Its modular design makes it easy to adjust its size from miniature (portable) to massive (solar field scale). Energy derived from this source does not contribute to global warming since no greenhouse gases are released during

production or usage (production, transformation, or consumption). Load management and energy storage systems working together might decrease the price of PV and increase its efficiency [40]. State-of-the-art, current, applications, trends, and progress in household solar energy storage systems are summarized in this review research. Integrating photovoltaics (PV) with energy storage in intelligent buildings; furthermore, the significance of solar energy storage in light of possible future storage options.



Figure 3. Configurations of ESSs in MGs^[2]

It is critical to find ways to reduce electricity costs (such as by using depreciated wind power plants that are no longer receiving subsidies) and to increase full-load hours (such as by using only a portion of the production profile of wind power plants with no peaks and a high number of total load hours). You need both of these to put storage technology to use in the real world. New storage options will only make sense if constructed parallel with grid expansions and if new excess production, particularly from variable RES, becomes likely. Only under these conditions will its implementation be cost-effective^[41]. In general, even though energy storage systems have gotten a considerable amount of attention, the design of these systems still has to be improved before this technology can be used in a domestic context. Because of this, research opportunities exist regarding storage strategies and systems. Because of its dependability and low overall cost, short-run sensible heat storage will continue to be the industry standard until additional advancements are realized ^[42].

Integration Models

A study was conducted to assess the efficiency of an optimal sizing method for a two-layer battery in a grid-connected microgrid (MG) with a photovoltaic (PV) system, energy storage system (ESS), and electrical loads.

^[46]. introduced a model-based optimization approach to minimize the overall cost and optimize the scale of a grid-connected microgrid (MG) that includes a combined Li-ion battery system, a wind turbine, a photovoltaic (PV) unit, a fuel cell, and a micro-turbine ^[47]. examined twelve proposed setups of a microgrid (MG) in the rural community of India, both with and without a grid-tied system. The simulations demonstrated that the hybrid structure of a utility grid-tied network, which combines photovoltaic, wind, and hydropower sources, was the most economically advantageous ^[48]. Examined the issue of reducing fluctuations in a grid-connected microgrid that includes a wind turbine and a battery energy storage system (ESS).

Microgrid control

The unpredictable and sporadic generation of renewable energy sources (RESs) adds to the intricacy of effectively managing microgrids (MG). Hence, it is crucial to implement an effective control system to provide a consistent and uninterrupted power supply. The MG Central Controller (MGCC) oversees and administers the MG. MGCC can be placed at a local control center or a distribution substation ^[49, 50]. The Local Distributed Generation (DG) units and distributed Energy Storage System (ESS) devices are regulated by

the Microgrid Control and Communication (MGCC) system, which interacts with controllers at lower hierarchical levels. MGs

can also be controlled utilizing decentralized techniques such as droop control and agent systems.

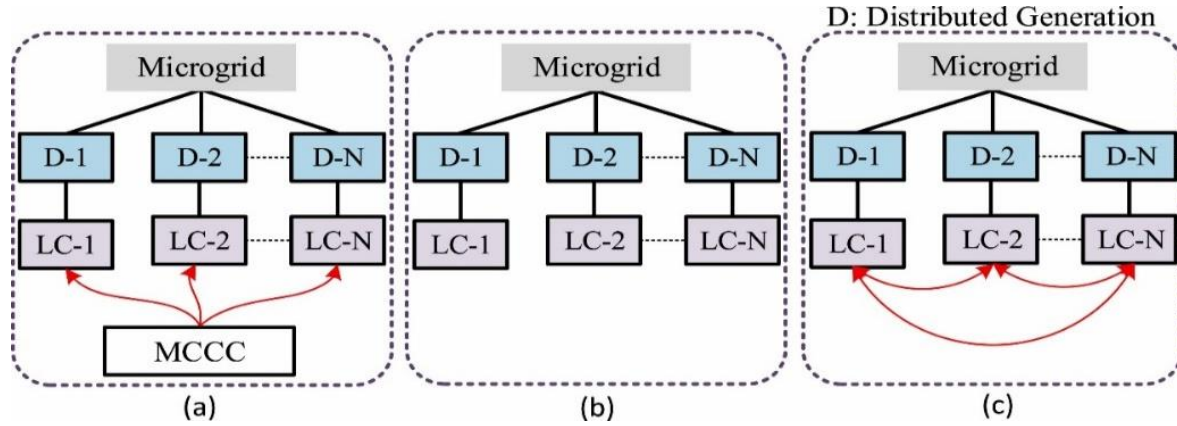


Fig. 3. MG control structures: (a) centralized, (b) decentralized, and (c) distributed. [1]

Centralized control management is efficient and provides real-time system monitoring, with a chief controller overseeing various DG units. Modern computational technologies enable CC to monitor and analyze data in real time. Decentralized control aims to maximize the autonomy of micro sources and loads in MGs, ensuring stability, cost-effectiveness, and reliability. It requires minimal local connections and no high-performance computer units. However, global optimum solutions for the entire MG system cannot be guaranteed.

Artificial Intelligence EMS-Based Methods

Artificial neural networks (ANN), fuzzy logic systems (FLS), and ANFIS are widely used to manage multiple MG energy. Recent AI-based techniques include a strategy for intelligent

multi-MG energy management using deep neural networks and model-free reinforcement learning techniques. This aims to reduce the demand-side peak-to-average ratio and maximize energy sales profits. A model-free Monte Carlo reinforcement learning method is used to improve pricing strategy. A non-intrusive load monitoring-based EMS for residential MGs uses smart meter data and consumer appliance data to evaluate energy consumption behaviors. Simulations show the proposed EMS achieves higher operation cost/customer satisfaction than conventional methods[51].

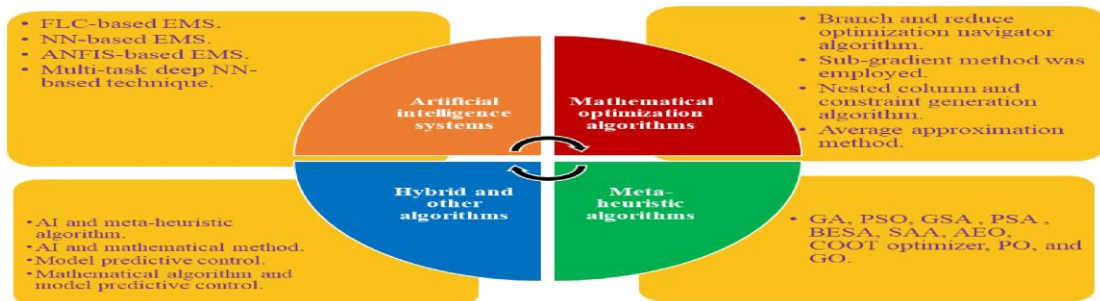


Figure 4. Classification of commonly used types of algorithms in energy management [2]

The study explores various energy management systems based on artificial neural networks (ANNs) for regulating power in hybrid AC and DC distribution networks. The ANN-based EMS determines the optimal operating mode by gathering data on distributed generation power, load demand, and the battery's charge (SOC) state. Experiments were conducted to validate the proposed EMS operating algorithm by building a small-scale microgrid EMS and monitoring system in a laboratory unit. The study also employs an ANN to manage multiple microgrid, employing an ANN-based backtracking search algorithm and an ANN-based binary PSO as scheduling control approaches. The efficacy of both algorithms was proven in limiting fuel consumption, decreasing CO₂ emissions, and boosting system efficiency in the direction of grid decarbonization [52]. Applied a microgrid EMS and proposed a demand-side response function-based distributed energy, real-time management model. The model satisfies application conditions and represents a particular application of bounded rationality approaching complete rationality in the electricity market, suggesting an optimized FLS energy management system for an isolated MG using a low-complexity FLS with only 25 base rules. Dong et al. provided an adaptive, optimal FLS-based EMS for real-time energy dispatch using a novel offline metaheuristic optimization technique [53]. Created an intelligent EMS for a smart DC-MG by combining FLS and fractional-order proportional-integral-derivative controller approaches.

Hybrid EMS-Based Methods

Recent studies have shown the superiority of hybrid energy management strategies over individual ones. Hybrid algorithms can be classified into AI and meta-heuristics-based EMS, AI and mathematically-based EMS, and mathematical algorithms and model

predictive control-based EMS. Yuan et al. proposed an EMS for hybrid AC/DC MGs using advanced machine learning, consisting of forecasting and scheduling. Rocha et al. proposed a new methodology to solve smart homes' energy management planning problem, considering electricity price fluctuations, the importance of each intelligent home equipment, operating cycles, and an ESS. Samuel et al. proposed an EMS that turns an infinite number of MGs into a coherent system without affecting the perspectives and goals of each MG [54]. Different strategies for synthesizing a fuzzy inference system-based EMS were investigated, using a hierarchical GA to reduce the EMS rule-based system's complexity and boost the energy exchange profits with the grid.

Presented a developed predictive control-based EMS for urban MGs using the day-ahead optimal power flow strategy, considering the ancillary flexibility services of DGs [59]. A novel EMS for minimizing an MG operating cost and maximizing the RES self-consumption during the day by optimally defining the setting for a central ESS. A hybrid approach for short-term demand forecasting is proposed, combining wavelet packet transform and Harris Hawks optimization-based feed-forward NN [55].

Simulation case study

This study examines the performance of an isolated campus microgrid (MG) as a case study for peak shaving-based energy management (EM). The MG has two traditional gas turbine generators (GTG) and battery storage to store excess energy. The MG has time-changing loads, with the GTG having a maximum power output of 4.2 MW and the BESS having a maximum power output of 400 kW. The results show that the capacity factor of the MG falls within the industry's recommended range of 50% to 80%. However, the average plant utilization factor is 75.04%,

indicating an unfavorable ratio between actual and expected energy production. The average load factor is 60.35%, below the industry benchmark of 80% or above. The maximum utilization factor (UF) is 67.65%, consistently

falling short of the optimum benchmark of 80%. The study suggests that battery storage-based energy management systems can significantly enhance the performance of MGs in real-world scenarios.

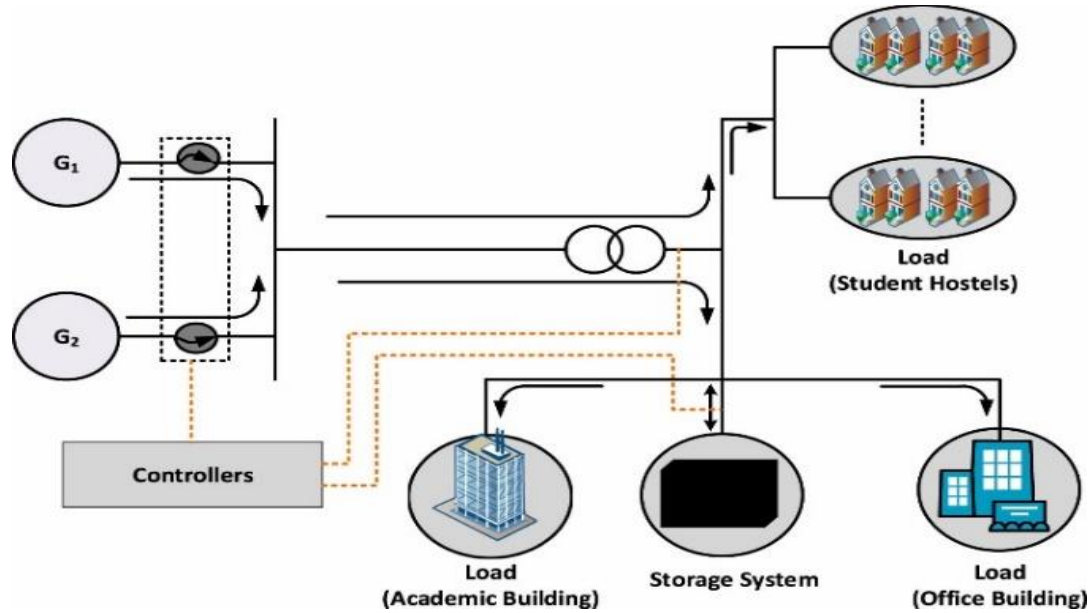


Fig. 5. Proposed structure of test MG

Fig 5. The test microgrid (MG) has two peaks during a typical working day, with the evening peak exceeding the optimal capacity. The battery energy control system accurately sustains the instantaneous power equilibrium, enabling the BESS to assimilate energy from the gas turbine generation system during low demand and reserve it for future use during high demand. This enhances the dynamic performance of the campus MG. The BESS can provide more economically efficient functioning for generators, reducing energy

production expenses and minimizing the use of conventional generators. The simulation findings show that the BESS adheres to the energy management technique, providing power during low-demand periods and capturing power after discharge. To avoid excessive charging and insufficient discharging, it is optimal to maintain a battery storage level of 20% and 90%. The simulation findings confirm that the BESS functioned according to the intended specifications.

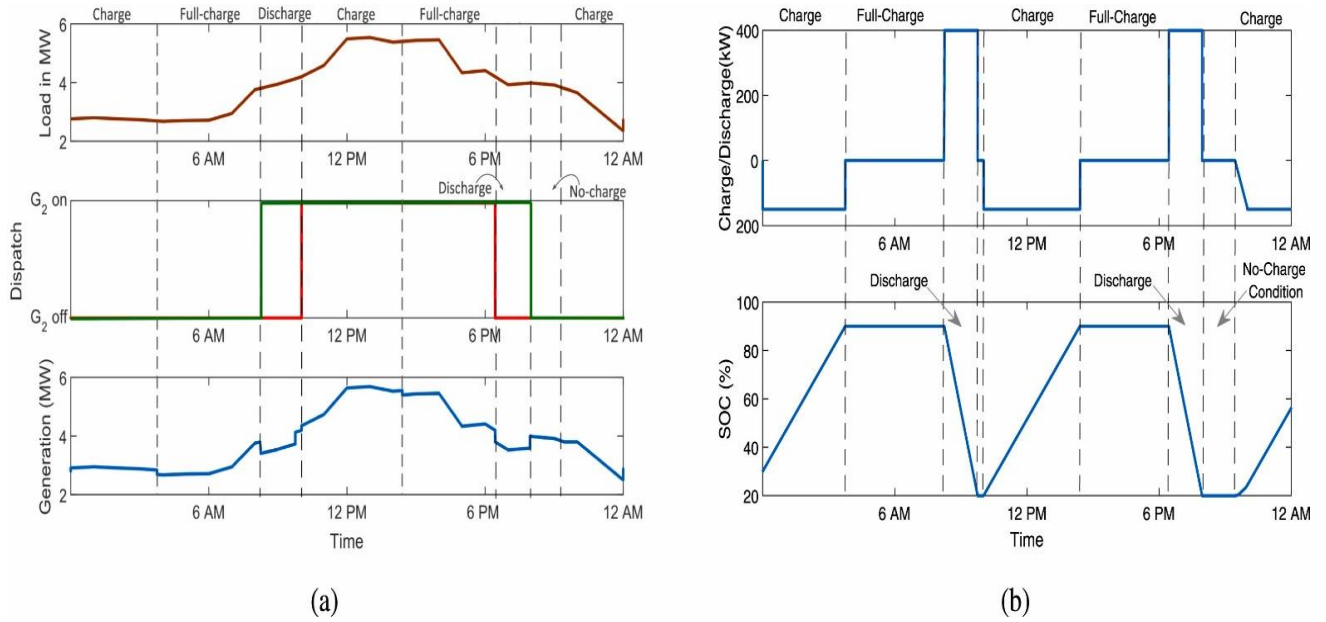


Fig 6. Simulation results for case MG: (a) EM results (power) with dispatch of generator G_2 , and (b) charge-discharge (kW) behavior of BESS and SOC.

Conclusion

Researchers are now investigating novel energy storage technologies, including flow batteries, thermal storage, and hydrogen storage, that have the potential to offer superior performance and efficiency compared to current methods. The purpose of this paper was to provide a comprehensive overview of MGs. This survey investigates the fundamental technologies employed in MGs, recognizing their potential significance. This analysis categorizes MGs into seven classes based on their applications, infrastructure, and end-user requirements. Additionally, this text examines MG control strategies to offer a deeper understanding of these techniques. The advent of MGs undoubtedly paves the way

for a more ecologically sustainable future and improved power supply services. Nevertheless, there remain several specific and noteworthy areas that require development. Several research concerns and challenges have been highlighted for MGs. Future research areas have been highlighted to address the concerns and challenges. This review presents the most advanced and up-to-date information on MGs, likely to capture the interest of investigators, professionals, and researchers. However, this work does not address the communication systems for implementing MG. Hence, additional investigation could be undertaken to emphasize the present state of the MG communications study.

NOMENCLATURE	
ANN	Artificial neural networks
CAES	Compressed air energy storage systems
CV	Capacity value
DR	Demand response
ESS	Energy storage system

ESVT	Energy Storage Valuation Tool
EMS	Energy management system
HBS	Hydrogen-based energy storage
LA	Lead-acid batteries
MG	Microgrid
NBR	Net benefit ratio
NG	Nano grid
NPV	Net present value
PV	Photovoltaic
SOC	State of charge
RV	Resiliency value
WO	Whale optimization
CAES	Castle-Aided Energy
EES	Electrical energy storage
SMES	super-magnetic energy storage systems
HBS	hydrogen-based energy storage systems
FLS	fuzzy logic systems

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