

Review Article

Microgrids, Renewable Energy Sources and Storage Systems: The Future of Energy Production

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Abstract - There is a significant change in the global energy landscape due to concerns about climate change, technological progress, and the need for energy security. Microgrids that use renewable energy sources represent a shift in paradigm from centralized fossil fuel power generation to distributed, sustainable energy systems. This review examines the technology behind microgrids, their operational features, economic aspects, and future possibilities. The combination of falling renewable energy costs, improvements in energy storage, and advanced control systems makes microgrids a key part of future energy infrastructure. They provide resilience, sustainability, and accessibility for both developed and developing regions.

Keywords - Microgrids, Renewable Energy Sources, Energy Storage Systems, Energy Production.

1. Introduction

The world faces a major energy challenge in terms of meeting rising global electricity demand while significantly cutting greenhouse gas emissions. Traditional centralized power systems, largely based on fossil fuels, are increasingly seen as insufficient for addressing these challenges. The mode of operations in the traditional energy landscape is such that power is generated at large, centralized plants and transmitted over long distances. This poses the challenge of transmission of energy, thereby leading to situations where power cannot be easily transmitted to remote areas. Existing grid infrastructure in developed nations has been installed for decades, and as such, they face infrastructure aging and deterioration. In view of this, the components of the grids are operating beyond their intended lifespan.

This aging infrastructure led to challenges such as Increased failure rates (older equipment is more likely to break down unexpectedly), reduced efficiency (degraded components waste more energy through resistive losses), higher maintenance costs (older assets require more frequent and costly repairs), and safety concerns (deteriorating equipment raises risks of fire and electrocution). Further, traditional grids are subjected to limited modernization or updated technologies. These grids still use the electromechanical protection devices, manual switching equipment, and limited sensing capabilities, thereby facing the challenge of real-time monitoring and diagnostic capabilities, automated fault detection and isolation systems, advanced communication networks for coordinated control, and integration capabilities for modern energy technologies [1-3].

Also, the challenge of vulnerability to climate change in the events of extreme weather conditions still remains an issue with the traditional grids, thereby causing unexpected power outages. Hurricanes and tropical storms cause damage to transmission towers, distribution poles, and substations, while wildfires can cause the transmission lines to spark fire. Also, in the events of ice storms and flooding, there may be an accumulation of ice on the transmission lines, which can lead to conductor breakage and tower collapse, and the water floods can damage underground equipment and substation components.

In essence, there is a need for a shift in paradigm of energy production from the traditional grids to a flexible system of production that guarantees non-depletion of resources and promotes equity in energy consumption with less financial constraints on the transmission system. The implementation or installation of microgrids can provide some level of flexibility in the generation and distribution of power. The demanded flexibility in the power generation and distribution requires a decentralized system of generation with renewable capabilities that can mitigate depletion of natural resources and an adaptable system for peak load demand, which are the features of the microgrid that make it suitable for flexible production and distribution of power [4-6].

A microgrid is a local energy system that can work as a standalone unit (Islanded mode of operation) or together with the main power grid (grid-connected mode of operation). They have emerged as a potential solution, particularly when combined with renewable energy sources such as solar



Photovoltaics (PV), wind turbines, and energy storage systems, microgrids offer a route toward cleaner, more resilient, and accessible energy production [7]. They are a group of connected loads and distributed renewable energy resources that can operate as a single unit with respect to the grid. It can connect and disconnect from the grid to work in both grid-connected and islanded modes, thus making its operation a hybrid mode. The main features of microgrids that makes it suitable for sustainable production of power are; autonomy (the ability to function independently from the main grid during outages or disruptions), controllability (advanced energy management systems that optimize generation, storage, and consumption), flexibility (the ability to integrate various energy sources and types of loads), and scalability (ability to enable additional units that are usable from single-building setups to community-wide networks). The microgrid is self-sufficient because it can supply energy to specific geographic regions or important facilities within the system. These facilities which are meant to be operated without power failure such as hospitals, military intelligence systems, university campuses and research institutes requires the operation of microgrids because the once there is a storm or interruption of power supply from the traditional grid, the microgrid's controller disconnects from the traditional grid thereby shifting automatically to islanded mode using its own energy sources thus, providing resilience in power generation [8-10].

1.1. Microgrids

Microgrids integrate distributed energy resources at the point of consumption, in contrast to traditional grid systems that depend on sizable, centralized power plants and substantial transmission infrastructure. Typically, these systems include wind turbines, solar photovoltaic arrays, combined heat and power units, and increasingly, energy storage systems that function as the network's operational backbone. The main components of a typical microgrid are the energy generation unit, the energy storage unit, the control system, and the power distribution systems. The generation unit is a subsystem in the microgrid where the energy to be converted to power is generated.

In microgrids, the integration of several sources of energy is possible, which is one of the key features of the microgrid over traditional grids. In view of this, several renewable and non-renewable sources are harnessed. However, considering the challenge of environmental pollution due to the combustion of non-renewable sources of energy, the microgrids use several renewable energy sources. A major drawback with the use of renewable energy sources is the challenge of their intermittency. For instance, the solar photovoltaic panels cannot harness the sun at night, while the wind turbines cannot function effectively in the absence of wind. Hence, the microgrid generation unit is complemented by dispatchable resources, such as natural gas generators, fuel cells, and biogas systems. However, recent research has

shown that hybridizing two or more renewable sources can optimize the performance of the generating unit, thereby addressing the challenge of intermittency through the inclusion of integrated energy storage systems [11, 12].

The energy storage system is another major component of the microgrid. They serve as buffer storage systems to store the energy received from the renewable energy sources, thereby addressing the intermittency of the renewable sources and providing a constant supply of energy. There are different types of storage systems, such as chemical storage systems, mechanical, thermal, and electrochemical storage systems. The function of the energy storage system in the microgrid cannot be overemphasized because it serves as an energy bank between the intermittent generation and variable demand by storing excess energy during the peak periods of high energy production of the renewable energy sources and discharging the energy during the peak demand or when the output of the renewable sources is low. The advanced energy management system is another component of the microgrid that serves as the intelligence system by using sensors, communication networks, and control algorithms to coordinate the operations of other components effectively. The connection of the microgrid to the traditional grid and disengaging to operate in islanded mode is achieved by the point of common coupling, which provides a seamless transition or switching [13, 14].

Microgrids show great versatility in different applications and locations. In remote and island communities where the development of traditional grid infrastructure is too costly, microgrids offer affordable ways to provide electricity. Islands that once relied on diesel generators have made the switch to solar-powered microgrids with storage. This change significantly lowers fuel costs, reduces supply chain issues, and reduces carbon emissions while enhancing service reliability. Critical facilities such as hospitals, emergency response centers, military bases, and data centers use microgrids to ensure continuous power during outages. Losing power at these places can lead to compromised patient care, disrupted emergency services, or loss of data, and as such, making the investment in better resilience is worthwhile. Schools and corporate campuses are increasingly adopting microgrids to meet sustainability goals, lower energy costs, and act as testing grounds for energy innovation. Most importantly, microgrids are providing electricity access for hundreds of millions of people in developing areas without connection to centralized grids. Solar microgrids in rural communities are driving economic growth, enhancing educational outcomes with reliable lighting, allowing refrigeration for medicines and food, and avoiding the heavy carbon footprints associated with traditional electrification methods [15].

The benefits of microgrids are extensive. Resilience is one of the strongest advantages that enables microgrids to continue supplying power during hurricanes, wildfires,

cyberattacks, or equipment failures that take down the main grid. During recent severe weather events, communities with microgrids maintained essential services while surrounding areas faced long blackouts, showcasing the real value of local energy independence. Environmental gains align closely with global climate goals. By incorporating high levels of renewable energy with storage systems for effective use, microgrids greatly cut greenhouse gas emissions compared to fossil fuels.

Reduced transmission losses from local generation further enhance environmental performance while boosting overall efficiency. The economic benefits are becoming clearer as the costs of renewable energy and battery storage have fallen sharply. In many areas, renewable-based microgrids now compete financially with both diesel generation and extending the grid. Beyond immediate energy savings, microgrids offer valuable services to the larger grid, such as reducing peak demand, supporting voltage, and regulating frequency. They delay costly investments in transmission and distribution infrastructure while creating local jobs in installation, operation, and maintenance [16, 17].

The improvements in power quality and reliability that microgrids provide benefit sensitive operations in industrial settings, semiconductor manufacturing, and data centers, where even brief power interruptions can lead to significant financial losses. With precise control over voltage and frequency and rapid responses to disturbances, microgrids often offer better power quality than traditional grid services in many areas. However, microgrids face several technical hurdles that require ongoing innovation. Managing the unpredictability of renewable energy requires accurate forecasting, sufficient energy storage, and smart control strategies. New machine learning methods are enhancing prediction accuracy for solar and wind energy, and as battery prices keep falling, longer-duration storage is becoming more financially viable. Ensuring power quality and grid stability in systems that heavily rely on inverter-based renewable sources is fundamentally different from conventional operations with synchronous generators.

Modern inverters equipped with grid-forming capabilities and synthetic inertia are tackling these issues, allowing fully renewable microgrids to function without backup fossil fuel sources. Protection and safety systems need careful design to ensure proper response modes in both connected and standalone situations, while also keeping personnel and equipment safe under all operating conditions. Integration with the main grid also brings technical and regulatory challenges. Microgrids must not disrupt grid stability or affect neighboring customers, which requires advanced control and communication systems. Many regulations are not keeping pace with technological developments, causing barriers to interconnection, unclear liability, and limitations in business models, which can slow down deployment [18, 19].

The economics surrounding microgrids have greatly improved as technology costs have dropped and value recognition has increased. The cost of solar photovoltaic systems has fallen by about 90% over the past ten years, while battery prices have similarly decreased, fundamentally changing project economics. Creative financing options such as third-party ownership, energy-as-a-service contracts, and green bonds help lower upfront costs. Supportive policies can speed up deployment. Feed-in tariffs, renewable energy credits, investment tax credits, and accelerated depreciation enhance financial returns.

Net metering rules that allow microgrids to sell excess power back to utilities at retail rates boost project viability. On the other hand, regulatory obstacles such as complicated interconnection processes, utility models threatened by distributed generation, and poor valuation of resilience and environmental benefits can hinder adoption in some areas. Progressive regions are changing regulations to make microgrid deployment easier by simplifying interconnection procedures, creating tariff structures that fairly value distributed energy resources, and developing planning processes that recognize microgrids as alternatives to traditional infrastructure investments [20, 21].

2. Methodology

The methodology adopted in this article involves a structured approach. Firstly, different renewable energy technologies were reviewed, followed by energy storage systems and their technologies. Further, the control and management strategies for these renewable energy and storage systems were also reviewed.

2.1. Renewable Energy Technologies in Microgrids

Renewable energy technologies are essential for modern sustainable microgrids. They change the way localized power systems generate, store, and distribute electricity. By integrating solar, wind, biomass, hydro, and new renewable sources with control systems and energy storage, microgrids can achieve high levels of renewable energy while keeping reliability and power quality intact. The various renewable technologies used in microgrids, their technical features, integration challenges, and effective combinations are presented in this section of the article [22].

2.1.1. Solar Photovoltaic Systems

Solar Photovoltaic (PV) technology turns sunlight into electricity through the photovoltaic effect. When photons hit semiconductor materials, they create electron-hole pairs that generate an electric current. Most PV cells use silicon, available in three types: monocrystalline (18-22% efficiency), polycrystalline (15-17% efficiency), and thin-film versions (10-12% efficiency for most). The cost of solar PV has dropped significantly—about 90% from 2010 to 2021—making it one of the most affordable sources of electricity worldwide. Current costs for utility-scale installations average \$0.048/kWh, but microgrid applications, which are on a

smaller scale and require more components, typically face higher costs [23]. The solar PV is highly adaptable for microgrid applications. Its modular design allows for systems ranging from kilowatts to megawatts, making it suitable for everything from single buildings to entire communities. Rooftop installations on commercial and residential buildings maximize space without needing extra land, which is especially important in urban areas. Ground-mounted arrays are used in larger microgrids and often include tracking systems that follow the sun's path, boosting energy capture by 20-35% compared to fixed installations. Floating solar panels on water bodies are becoming popular as they help cool the panels, improving their efficiency by 5-10% while also reducing water evaporation and algae growth [24].

Building-integrated photovoltaics are an emerging area where solar cells are built into building materials like windows, facades, and roofing tiles. Although BIPV tends to be pricier than regular installations, it eliminates separate mounting costs and serves dual purposes: architecture and energy generation. Recent innovations in solar PV continue to improve performance and usability. Bifacial solar panels capture light reflected from their rear surfaces, increasing energy yield by 5-30%, depending on ground type and mounting configuration.

Perovskite solar cells, which can be used alone or with silicon, have reached lab efficiencies above 30% and may lower costs further, although there are still challenges with durability and scaling. Half-cut cell technology enhances shade tolerance and reduces resistive losses by splitting cells into smaller units that carry less current. Multi-junction cells, which use different semiconductor materials to capture various wavelengths, are nearing theoretical efficiency limits; however, high costs limit their use to specialized applications like space and concentrated photovoltaics [25].

However, the main challenge of integrating solar PV is its intermittent nature—cloud cover can cause output to drop by 50-70% in seconds, and daily generation patterns lead to sharp increases at sunrise and decreases at sunset. Improving forecasting using satellite imagery, machine learning, and local weather data helps manage microgrid operations. Short-term forecasts (minutes to hours ahead) inform real-time dispatch, while longer-term predictions help with scheduling and maintenance. Energy storage systems, especially batteries, are crucial for bridging gaps between variable solar generation and steady demand.

Typically, battery systems store energy for 2-6 hours, balancing cost and operational needs. Adjusting ramp rates through inverter settings can smooth out quick output changes, preventing voltage swings and reducing stress on other microgrid parts. Modern inverters with advanced grid support features allow solar PV to enhance microgrid stability beyond just supplying energy. These inverters can regulate voltage,

assist with frequency through power adjustments, and keep connections during disturbances [26].

2.1.2. Wind Energy Systems

Wind turbines convert the kinetic energy of moving air into rotational energy, which is then turned into electricity by generators. Most installations use modern horizontal-axis wind turbines. These consist of rotor blades, a nacelle housing the generator and power electronics, a tower supporting everything, and a foundation anchoring the structure. The small wind turbines (1-100 kW) are suitable for distributed microgrid applications, while medium-sized turbines (100 kW - 1 MW) are suitable for larger community microgrids or industrial facilities. Although Vertical-Axis Wind Turbines (VAWTs) are less efficient than horizontal-axis designs, they can operate in any direction, produce less noise, and pose fewer risks to birds, making them useful for urban settings despite being more expensive and less available. Wind energy shows specific patterns that complement solar generation in many areas. Wind speeds often increase in the evening and at night when solar output is lower. Seasonal variations typically feature more wind resources in winter, balancing the lower solar output during that time and providing diversity for hybrid systems [27].

Also, the wind power output depends on the wind speed's cube, meaning small changes in speed can lead to large variations in generation. Doubling the wind speed can increase power output by eight times within operational limits, resulting in significant variability that needs careful management. Wind forecasting has improved significantly with weather prediction models and machine learning, achieving errors of less than 10% for next-hour forecasts in wind farms. In order to integrate wind successfully into microgrids, a comprehensive site assessment is necessary. This includes evaluating wind resources and the impacts of terrain, obstacles, and turbulence. Optimizing the placement of turbines can maximize energy capture and minimize wake effects when multiple turbines are close together.

Tower heights are crucial—doubling the height can raise power output by 20-50% in many areas by accessing stronger winds and reducing turbulence. Noise limits the siting of wind turbines near homes. Though modern turbine designs reduce sound, regulations generally require turbines to be at least 300-500 meters from occupied buildings. Visual impacts and community acceptance are also important non-technical factors influencing deployment.

Modern variable-speed turbines use power electronic converters for optimal operation under various wind conditions. These systems provide grid support functions like voltage regulation, power factor correction, and low-voltage ride-through. However, since these inverter-based systems decrease overall inertia, careful control coordination is needed with other microgrid resources to maintain stability [27, 22].

2.1.3. Biomass and Biogas Systems

Biomass energy systems turn organic matter into usable energy through combustion, gasification, anaerobic digestion, or biochemical processes. Unlike solar and wind, biomass offers dispatchable generation that can operate on demand, filling in gaps when other renewables are not enough. This capability makes biomass especially valuable for maintaining microgrid reliability with high levels of renewable energy. Direct combustion of solid biomass, such as wood chips or agricultural waste, generates steam that powers turbines. Combined Heat and Power (CHP) systems can produce both electricity and useful thermal energy, achieving system efficiencies of over 80%, compared to 30-40% for systems generating electricity alone. Gasification converts solid biomass into synthetic gas (mostly hydrogen and carbon monoxide), which can fuel engines or turbines. Anaerobic digestion breaks down organic matter in environments without oxygen, creating biogas (60-70% methane and 30-40% carbon dioxide) for electricity generation, heating, or conversion to pipeline-quality renewable natural gas. Common feedstocks include animal manure, food waste, wastewater sludge, and dedicated energy crops. Biomass systems are mostly deployed in agricultural communities with plenty of organic waste, which benefit greatly from biomass systems. They turn waste into valuable energy while solving disposal issues. Dairy farms use [26]

2.1.4. Geothermal Energy

Enhanced geothermal systems and improved binary cycle technologies are expanding geothermal energy beyond traditional high-temperature volcanic areas. These systems can provide continuous power generation or adjustable operation, supporting intermittent renewables. Small-scale geothermal systems (below 5 MW) are increasingly found in microgrids with suitable geological conditions. They offer very high-capacity factors (85-95%) and require little land. Binary cycle plants that operate using lower-temperature resources (100-180°C) accessed through deeper drilling (2-5 km) in various locations show promise for distributed generation. Although drilling costs are still high, advancements such as directional drilling and hydraulic stimulation techniques from the oil and gas industries are driving down expenses [22].

2.1.5. Fuel Cells and Hydrogen

Fuel cells convert hydrogen into electricity through electrochemical reactions, providing zero-emission and adjustable power generation. Green hydrogen, produced through electrolysis using renewable energy, allows for seasonal energy storage. This addresses the variability of renewables over multi-day or multi-month periods, which exceeds practical battery storage limits. The round-trip efficiency (typically 35-45%) is lower than that of batteries. However, hydrogen storage offers scales and durations not feasible with batteries. Reversible fuel cell systems that combine electrolysis and fuel cell functions in a single unit

reduce costs for systems needing both hydrogen production and consumption. Emerging solid oxide fuel cells can work on various fuels, including hydrogen, natural gas, and biogas. They also provide high-quality waste heat for combined heat and power (CHP) applications, achieving combined efficiencies of over 80% [22].

2.1.6. Hydroelectric Source of Energy

Hydroelectric power is one of the oldest and reliable sources of renewable energy generation, with unique characteristics making it exceptionally valuable for microgrid applications. Unlike intermittent solar and wind resources, hydroelectric systems provide predictable, dispatchable generation with exceptional operational flexibility and longevity. Small-scale hydroelectric installations that range from Pico hydroelectric systems to hydro level systems offer sustainable energy solutions for remote communities, industrial facilities, and distributed energy networks without the environmental and social impacts associated with large dam projects. The hydroelectric power depends equally on two key parameters; these are the flow rate (volume of water per unit time) and the vertical distance to waterfalls. A site with a high head can generate substantial power with modest flow rates, while low-head sites require larger water volumes to produce equivalent output. Hydroelectric systems provide exceptional value in microgrids through reliable baseload generation that operates continuously with minimal variation, unlike intermittent solar and wind resources.

This stability reduces energy storage requirements and provides a foundation for integrating more variable renewable sources. During periods when solar and wind output meet or exceed demand, hydroelectric generation can be reduced or temporarily stopped, banking water in upstream reaches for later use, which is a natural form of energy storage. Flow regulation through turbine guide vanes or nozzle controls enables responsive dispatch matching generation to demand in real-time. Response times of seconds to minutes allow hydroelectric units to follow load changes, absorb sudden demand increases, or compensate for cloud-induced solar output reductions. This flexibility proves particularly valuable in smaller microgrids where load variations represent larger proportions of total capacity. The control power management system adjusts hydroelectric output to match demand variations, maintaining system frequency without requiring battery discharge. Sophisticated algorithms balance competing objectives, including frequency regulation, voltage support, water conservation, equipment wear minimization, and economic optimization [28, 29].

2.1.7. Hybrid Renewable Energy Sources

Combining two or several sources of renewable energy, such as hydroelectric generation with solar, wind, and solar with wind, creates a highly reliable hybrid renewable energy source that enables the microgrids to leverage the complementary characteristics of the renewable sources. One

of these complements is the seasonal complementarity which occurs in many regions that experience summer solar peaks coinciding with reduced stream flows, while spring snowmelt or fall/winter precipitation increases hydroelectric output when solar production declines. Also, the daylight patterns are another issue: solar generation peaks during midday, when many microgrids experience modest loads, while hydroelectric can be dispatched to meet morning and evening demand peaks. Water accumulating during high-solar periods becomes available for afternoon and evening generation. Also, in terms of response, the hydroelectric generation responds quickly to solar intermittency from cloud passage, reducing battery discharge cycles and extending storage system life.

The combination of fast-responding hydro and energy storage creates a robust capability to manage renewable variability. Also, sources like hydroelectric power can assist in the reduction of storage requirements because the dispatchable hydroelectric generation significantly reduces battery capacity needs compared to solar-wind systems, lowering capital costs and avoiding battery replacement expenses. Economic analyses frequently show that hybrid hydro-solar-battery systems achieve lower lifecycle costs than solar-battery systems alone at sites with adequate water resources [30, 31].

Combining solar and wind resources takes advantage of their complementary nature, leading to reduced overall system variability and lower storage needs compared to single-resource systems. Solar generation peaks in the morning and midday, while wind typically adds energy in the afternoon and evening, creating steadier daily production. Many areas see summer solar and winter wind peaks, further enhancing their synergy. Using shared infrastructure, such as inverters, control systems, transmission connections, and maintenance facilities, can lower total system costs in hybrid setups. An optimally sized solar-wind combination can achieve capacity factors of 40-50% or higher, surpassing the performance of typical single-resource systems while keeping costs reasonable [27, 32].

Modern microgrid control systems coordinate hydroelectric generation with other resources through hierarchical architectures. Local controllers manage individual turbine-generator units, regulating speed, voltage, and power output based on setpoints from central energy management systems. Communication protocols enable real-time data exchange and coordinate dispatch. Predictive control algorithms incorporating solar and wind forecasts, demand projections, and water availability optimize dispatch schedules hours or days ahead. During high-solar production, hydroelectric output can be reduced to minimum flows or temporarily stopped, allowing water storage in upstream reaches. As solar output declines or demand increases, hydro generation ramps up using stored water, effectively converting natural stream into zero-cost energy storage [33].

3. Energy Storage System

The microgrid operates on distributed architectures that emphasize resilience, sustainability, and local control, and are replacing centralized generation in the evolution of electrical power systems. Microgrids are made possible by energy storage systems, which provide the flexibility required to balance variable loads and intermittent renewable generation while guaranteeing continuous power availability during grid outages or islanded operation. In microgrid ecosystems, energy storage serves several vital purposes. Above all, by separating the timing of energy production from consumption, it offers temporal flexibility. While consumption usually peaks in the early evening after the sun has set, solar panels generate electricity during the day, frequently reaching their peak output during midday when local demand may be moderate. By storing excess generation during times of abundance and releasing it during times of scarcity, energy storage fills this temporal gap. Intermittent renewable resources from supplemental contributors are converted into reliable, dispatchable power sources that can meet baseload requirements thanks to this load-shifting capability [13].

Energy storage systems are not just the means by which energy can be shifted in time, but they also play an important role in providing essential services to the grid that help in keeping the power quality and system stability at a good level. In fact, they react to frequency changes within only a few milliseconds, and thus they can help the system by either providing or absorbing power, thereby keeping the system at the normal frequency of 50 or 60 Hertz, which is the standard most commonly used for thermal or electronic machinery. The energy storage units are able to sustain voltage through reactive power control, and by this, they prevent the occurrence of voltage sags and swells that can cause the wear and tear of the most delicate components of electronics. When local grid, connected operation is changed to an islanded one, energy storage systems are still there to ensure that the transition is smoothly and without any loss of continuity of service, as they take over the responsibility of frequency and voltage regulation in the area which has been disconnected from the main grid, be it a purposeful disconnection or a fault that has occurred upstream [34].

3.1. Electrochemical Storage Systems

Lithium-ion batteries have become the primary energy storage solution for microgrid applications. This transition is largely attributed to high cost, saving measures, and performance enhancements that arose from the electric vehicle sector. In general, these electrochemical devices exhibit high energy density and achieve excellent efficiencies, usually above 90 percent. Furthermore, they can be easily scaled down to kilowatt or up to megawatt-hour capacities. The lithium-ion units have different chemistries, such as lithium-ion phosphate, which is safer and more durable, and nickel manganese cobalt compounds that have the highest energy density. The features of lithium-ion batteries make them a

perfect fit for microgrid systems that are heavily used and require fast reaction. One of the features is the capability of going from a full discharge to a full charge within a matter of hours, responding to control signals within milliseconds, and performing even at different temperatures, though their efficiency may vary somewhat. Also, the cycle life has been improved greatly, such that it is possible to have several thousand full-depth discharge cycles before the capacity decreases significantly, which in turn means life spans of ten to fifteen years can be realized if the batteries are operated under the correct conditions [35].

The flow battery is another energy storage system that uses liquid electrolytes stored in external tanks and circulated through electrochemical cells. Among such batteries, vanadium redox flow batteries have reached the highest level of commercial maturity. The main benefit of the flow battery architecture is the independent scaling of power and energy in larger tanks, enabling longer storage duration without the need for additional power-conversion equipment. In this regard, flow batteries are extremely suitable for applications requiring storage for a duration of four to ten hours. Moreover, they can retain extended cycle life with a very small degradation since the active materials are dissolved in the solution and do not undergo solid-state phase transformations. However, their lower energy density and higher upfront costs have hindered their deployment to some extent in comparison with lithium-ion systems. Considering the issues of upfront cost, lead-acid batteries are still used in some microgrid settings, especially where initial capital costs are the main concern or where existing infrastructure can be utilized. Advanced designs, such as absorbed glass mat and gel formulations, provide better performance than flooded lead-acid configurations. However, acid batteries suffer from limited cycle life, low round-trip efficiency, and have environmental issues associated with lead, which have resulted in the replacement of lead-acid batteries by lithium-ion in most new installations [31, 36].

Also, the sodium-sulfur batteries function at high temperatures of approximately 300 degrees Celsius, where both electrodes are in a molten state and are separated by a solid ceramic electrolyte. These devices provide high energy density and have exhibited long lifespans on the scale of the grid. The elevated temperature has benefits and drawbacks. one of the drawbacks is that self-heating during the charge and discharge operations lessens the necessity of an external thermal management system, but a certain amount of energy is still needed to keep the battery at the operating temperature during the rest period, thereby lowering the total efficiency of the system if it is infrequently cycled [37].

3.2. Mechanical Storage Systems

A type of mechanical storage system is the pumped hydro storage, which is typically associated with utility-scale facilities, and can be adapted to microgrid scale where appropriate topography exists. The principle is simple in

operation as excess electricity drives pumps that elevate water to an upper reservoir, with this gravitational potential energy later recovered by allowing the water to descend through turbines. Efficiency typically ranges from 70 to 80 percent, accounting for pumping losses, evaporation, and generation inefficiencies. The technology offers essentially unlimited cycling capability, with operational lifespans measured in decades. However, geographic requirements, including suitable elevation differences, available water resources, and appropriate geology, significantly constrain potential deployment locations [38].

Compressed air energy storage systems are another type of mechanical storage that utilizes off-peak or excess electricity to compress air into underground caverns, depleted natural gas reservoirs, or purpose-built pressure vessels. During discharge, the compressed air is heated and expanded through turbines to generate electricity. Adiabatic systems capture and store the heat of compression for later reuse, significantly improving round-trip efficiency and potentially exceeding 70 percent, compared to conventional systems that may achieve only 40 to 50 percent. The scalability of compressed air storage makes it potentially attractive for community-scale microgrids, though geological requirements for underground storage limit the widespread deployment of the compressed air energy system [38].

Further, the flywheel energy storage system is a type of mechanical storage that employs a large rotor to store energy in the form of rotational kinetic energy. The rotor is usually suspended by magnetic bearings in a vacuum enclosure to minimize friction losses. The latest flywheels made of carbon fiber composites can rotate at very high speeds, thereby storing a lot of energy in relatively small volumes. The main advantage of flywheel systems is their outstanding power density and the ability to endure hundreds of thousands of charging and discharge cycles with very little degradation. They are very good at providing short-duration, high-power services such as frequency regulation and power quality improvement. On the other hand, the continuous energy losses resulting from bearing friction and aerodynamic drag limit their use for storage of longer durations beyond minutes to hours [39].

3.3. Thermal Storage Systems

Thermal energy storage stores excess electricity as heat or cold for use at a later time, and this is particularly relevant to microgrids that serve facilities with substantial heating and cooling loads. Sensible heat storage in such materials as water, molten salts, or concrete is simple and straightforward. Latent heat storage using phase change materials can achieve higher energy density by making use of the very large amount of energy that is absorbed or released during the solid-liquid transition. When microgrids have combined heat and power systems or concentrating solar thermal generation, thermal storage makes it possible to decouple the thermal and

electrical generation temporally, thus increasing the overall system efficiency. In solar power microgrids, molten salt thermal storage enables continuity of power output into night hours, effectively decoupling generation from demand. The salts are heated to high temperatures by sunlight in the daytime, and in the absence of solar radiation, the heat is transferred from the salts to a steam cycle to produce electricity. Also, seasonal storage of low-grade thermal energy in aquifers or boreholes can leverage periods of ambient thermal surplus or deficit to balance the demand. The integration of thermal storage into microgrids can enhance resilience and lower costs [14].

3.4. Chemical Storage Systems

Hydrogen production through electrolysis powered by excess renewable resources presents a long-duration storage medium with the potential for a variety of microgrid applications, including backup power, building heating, and mobility. The hydrogen can be compressed, liquefied, or converted into ammonia for storage and transportation, although hydrogen remains quite challenging in terms of volumetric energy density and materials compatibility. The efficiency from solar to hydrogen to power is modest at best; however, the dense energy carrier characteristic and the versatility of end-use sectors combine to give hydrogen a very low long-term cost of storage and a high value proposition. In addition to green hydrogen, other carbon-neutral and low-carbon pathways under investigation might further diversify the future energy storage landscape of microgrids. The choice and integration of alternatives to lithium-ion batteries open up a much larger solution space in the design of microgrids aimed at long-term sustainability and cost-effectiveness. The broad spectrum and heterogeneity of these emerging and mature technologies provide a deep strategic deferral of resource risks and costs beyond the horizon of the lifespan of any single technology. Operators and planners should develop in-depth, scenario-based understandings of these options at a system, technology, and policy level to effectively leverage them for mitigation and opportunity. This holistic perspective can guide progressive and adaptive deployment of complementary assets, thereby turning the challenge of spatially differentiated, temporally evolving, and multidimensional storage requirements into a dynamic advantage [14, 37].

4. Microgrid Control, Management, and Integration Systems

The intelligence of microgrids comes from the system control and management systems of energy, which coordinate the distributed energy resources, storage assets, and controllable loads. The control of these components is required to achieve operational objectives and meet constraints. Hierarchical control architectures like this generally have multiple stratifications, with different timescales and the level of centralization generally varying. Modern microgrids generally use three-level hierarchical

control systems. Primary control manages power sharing among distributed generators and keeps voltage and frequency stable through droop control or virtual synchronous machine algorithms. Secondary control adjusts voltage and frequency to standard levels and manages power flow to and from the main grid. Tertiary control optimizes economic dispatch, handles energy storage, and coordinates with utility systems and energy markets [10].

At the lowest level, local controllers embedded within each asset respond to conditions present in the environment in milliseconds by providing critical services, such as frequency and voltage regulation, through autonomous control loops that need not communicate with higher-level systems. One common local control approach is droop control, where each generator or storage system automatically adjusts its output in response to frequency deviations; the amount of adjustment by each component is predetermined by the droop setting. Also, a supervisory control system operating at the microgrid level assists in the optimization of energy flows from minutes through to hours, dispatching resources to minimize their operating cost, maximize renewable utilization, or for other operational purposes.

The supervisory control system process forecasts of solar and wind generation, load predictions, electricity price signals, and storage state-of-charge information to develop optimal charging and discharging schemes. They define the problem in terms of time horizons through a model predictive control that assists in decision making, considering new information available and previous forecasts that have been refined. Traditional optimization approaches are increasingly integrated with machine learning algorithms to learn patterns in generation and consumption, thereby enhancing forecasting and, consequently, improving operational decisions. Historical neural network training can predict solar energy generation using weather forecasting and learned patterns of cloud movement, forecast building loads based on occupancy patterns, weather conditions, and day-of-week effects, and even predict battery degradation based on operational history to optimize lifetime value rather than merely short-term economics [40].

The power electronics, which precisely link the storage devices operating at a voltage level to the alternating current electrical system serving the loads, are an important component in the effectiveness of energy storage in microgrids. Essential for this conversion operation is a bidirectional inverter that converts direct current supplied by batteries or other storage systems into an alternating current compatible with the grid for discharge, and vice versa for charging. Modern power electronics offer conversion efficiencies of more than 97 percent, which reduces the amount of energy losses sustained in every transformation. Advanced inverter functionalities go beyond just energy conversion. Grid-forming inverters, which “form” and

maintain a voltage and frequency reference during islanded operation, create the grid rather than merely tracking the parameters established by substantial synchronous generators. This is absolutely essential for microgrid operation during outages or intentional disconnection from the main grid. Grid-following inverters, on the other hand, synchronize to the existing references for voltage and frequency and then are injected or absorbed by higher-level control systems while maintaining power quality standards [41, 42].

Further, battery management systems play a crucial role in monitoring and controlling safety aspects of energy storage at the individual cell and module level, ensuring that energy storage systems remain within safe voltage, current, and temperature ranges. Most modern computerized battery management systems equalize charge among the series-connected cells so that no individual cell will be overcharged or over-discharged compared to others in the string, a condition that could otherwise hasten degradation and maybe generate safety hazards. Temperature monitoring and thermal management systems help ensure optimal operating conditions, as performance and life of batteries are highly temperature dependent. Also, careful consideration is given to all aspects of the integration of the physical architecture of energy storage, which are: electrical protection, fire safety, and thermal management. Modern battery systems comprise secured weatherproof casings that are suitable for outdoor installation. For large systems, cells, battery management electronics, power electronics, fire suppression systems, and environmental controls are integrated into turnkey systems that reduce on-site installation and construction requirements, but this may result in some optimization loss compared with custom-designed installations [43].

The communications infrastructure that links the control layers together provides reliable connectivity and security in an increasingly threatened environment. The ideal solution is dedicated fiber optic networks, but they may prove impractical from a cost perspective for geographically dispersed assets. Alternatively, cellular networks, private radio systems, and the new wave of low-power wide-area networks may provide the basis for a wireless connection that ultimately involves trade-offs among bandwidth, latency, coverage, and price. In order to avoid energy theft, cybersecurity considerations ensure in-depth defense, such as network segmentation, encrypted communications, authentication and authorization systems, and continuous monitoring for indication of intrusion into the system [21, 44].

5. Conclusion

Microgrids integrated with renewable energy sources and

energy storage offer a transformative approach to electricity generation and distribution. This approach will address issues of climate, reliability, and electricity access. Significant cost reductions in renewable technologies, improvements in energy storage and control systems, and an increased understanding of resilience value can make microgrids operating on renewable energy sources more competitive in comparison to traditional centralized generation. Also, the energy storage systems can be perceived as a critical component that facilitates the resilience of microgrids, giving them the flexibility to make intermittent renewable generation capable of reliably serving variable loads, sustaining power quality, and enabling islanded operation. Great advances in performance and cost in the last decade, in particular lithium-ion batteries, have shown that the concept of microgrid is economically viable. The existence of several technologies complements one another, offering advantages for various specific applications, indicating that future microgrids would use various storage options optimized for their specific operational demands, resources, and economic conditions.

Further, the evolution of microgrid, renewable energy sources, and storage systems will depend on the sustained innovation of integrated technologies, considering electrochemistry, power electronics, control systems, and business models. This innovation can be sustained by regulatory frameworks to appreciate the whole value proposition of clean energy generation and storage. There will be a need for workforce development to provide technical skills for installation and maintenance. Also, a framework or model network for financing the investment that comes with huge upfront costs is necessary. A consideration of these innovations will assist the technology in becoming a leading protagonist in facilitating the paradigm shift towards a more distributed, renewable, and resilient electrical system for energy security and climate change.

However, the successful deployment of microgrids will require technological innovation, supportive policies and regulations, creative financing methods, and attention to equity and environmental concerns. As the global energy transition speeds up, renewable energy microgrids will be crucial in building sustainable, resilient, and accessible energy systems for all communities. The blend of economic, technological, and policy factors indicates that distributed renewable energy systems will increasingly complement and often replace centralized fossil fuel infrastructure. This transition is not just a simple technological change; it is a complete rethinking of energy systems to become more sustainable and resilient, thereby addressing the challenges of the 21st century.

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