

Smart Microgrids: Revolutionizing Core Electrical Infrastructure for Energy Efficiency

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Abstract

Smart microgrids represent a transformative approach to modernizing the electrical infrastructure, emphasizing energy efficiency, sustainability, and resilience. These advanced systems integrate renewable energy sources, sophisticated energy storage technologies, and intelligent control mechanisms, enabling a more decentralized and efficient energy management framework. By facilitating a higher penetration of renewable energy and enhancing storage capacities, smart microgrids significantly reduce dependency on traditional power grids and fossil fuels, thereby contributing to substantial reductions in carbon emissions. Their ability to operate autonomously, or in "island mode," ensures a reliable and uninterrupted power supply, even in the face of external grid failures, highlighting their critical role in improving system reliability and energy security. The comparative analysis of Grid-Connected and Hybrid Microgrids further elucidates the benefits of smart microgrid implementations. Hybrid Microgrids, with their greater reliance on renewable sources, higher energy efficiency, and extended operational independence, showcase superior performance in reducing emissions, lowering operational costs, and providing better returns on investment. This comparison not only underscores the economic viability and environmental benefits of smart microgrids but also demonstrates their potential to meet and surpass current and future energy demands efficiently. smart microgrids are revolutionizing core electrical infrastructure by fostering a shift towards more sustainable, efficient, and resilient energy systems. Their development and deployment are pivotal to achieving global energy and environmental goals, making them a cornerstone for the future of energy management and a model for sustainable development.

I. INTRODUCTION

Smart microgrids represent a transformative approach to our electrical infrastructure, heralding a new era of energy efficiency and sustainability. As autonomous energy systems capable of optimizing the generation, distribution, and consumption of electricity, smart microgrids are at the forefront of the global shift towards renewable energy sources and smarter energy management [1][2]. By leveraging advanced technologies, such as renewable energy integration,

demand response programs, and innovative storage solutions, these microgrids not only enhance energy efficiency but also ensure reliability and security in energy supply [3].

Central to the concept of smart microgrids is their ability to operate independently from the main power grid, enabling a more resilient energy infrastructure that can adapt to varying energy demands and supply conditions [4]. This capability is particularly crucial in the face of increasing environmental challenges and the

urgent need for a sustainable energy future [5]. Through intelligent control systems and data analytics, smart microgrids manage resources and loads effectively, minimizing energy waste and reducing greenhouse gas emissions [6].



Figure . Electrical Infrastructure

The evolution of smart microgrids is also a testament to the growing importance of decentralized energy systems [7]. By empowering local communities, industries, and military installations with the tools to produce and manage their own energy, smart microgrids decentralize power generation and distribution, leading to more democratic and efficient energy landscapes [8]. This shift not only mitigates the risks associated with centralized energy production, such as transmission losses and grid vulnerabilities, but also opens up new avenues for innovation in energy services and business models [9].

A smart microgrid is a localized group of electricity sources and loads that normally operates connected to and synchronous with the traditional centralized electrical grid (macrogrid), but can disconnect and function autonomously as physical and/or economic conditions dictate. It incorporates a variety of distributed energy resources (DERs) [10]-[15] such as solar panels, wind turbines, and combined heat and power (CHP) units, alongside energy storage systems like batteries, to provide a reliable, sustainable, and cost-effective supply of electricity, especially in remote or isolated areas.

A. Key Components of a Smart Microgrid:

Distributed Energy Resources (DERs): These include renewable energy sources like solar PV systems, wind

turbines, hydroelectric systems, and biomass generators, as well as conventional power sources like diesel generators for backup power.

Energy Storage Systems (ESS): Technologies such as batteries, flywheels, and supercapacitors store excess energy that can be used during peak demand times or when generation from renewable sources is low.

Smart Grid Infrastructure: Comprises both physical and digital technologies for electricity distribution within the microgrid. This includes smart meters, switches, and other equipment that enables two-way communication and real-time data collection.

Management and Control Systems: Advanced control systems and software manage the flow of electricity from multiple sources, ensuring efficient distribution based on demand, generation capacity, and storage levels.

Loads: The consumers of electricity within the microgrid, which can range from residential households to commercial buildings and industrial facilities.

Demand Response (DR) Systems: These systems help manage and adjust the demand for power through control signals or incentives to consumers, enhancing grid stability and efficiency.

Information and Communication Technology (ICT): The backbone of a smart microgrid, ICT encompasses the hardware and software necessary for monitoring, controlling, and managing the grid.

Cybersecurity Measures: Essential for protecting the smart microgrid from cyber threats, these measures include encryption, firewalls, and secure communication protocols.

Integration with the Main Grid: Smart microgrids can operate independently (island mode) or connected to the main grid, allowing for the exchange of electricity and enhancing grid resilience.

B. Advantages of Smart Microgrids:

Enhanced Reliability and Resilience: Provides a reliable power supply during grid outages or disasters.

Reduced Energy Costs: Allows for the use of locally generated renewable energy, reducing dependence on expensive fossil fuels.

Environmental Benefits: Decreases greenhouse gas emissions by integrating renewable energy sources.

Improved Grid Stability: Through demand response and energy storage, it can provide ancillary services to the main grid.

Smart microgrids represent a forward-thinking approach to energy management, embodying the principles of sustainability, resilience, and community empowerment.

The smart microgrids are revolutionizing our core electrical infrastructure, paving the way for a future where energy efficiency, sustainability, and resilience are paramount. Their development and deployment are critical to addressing the pressing energy challenges of our time, making them a key focus of research, policy, and investment in the global energy sector.

II. REVIEW OF LITERATURE

The advent of smart microgrids marks a significant milestone in the evolution of electrical infrastructure, underpinned by the urgent need for energy efficiency and the integration of renewable energy sources. This comprehensive review delves into the multifaceted aspects of smart microgrid research, exploring advancements in demand response, electric vehicle (EV) integration, communication networks, renewable energy utilization, security measures, and innovative technologies for energy management and trading. Through a synthesis of recent studies, this review highlights the pivotal role of smart microgrids in revolutionizing energy systems towards sustainability and resilience. A critical component of smart microgrid functionality is the integration of demand response programs and electric vehicles, which collectively enhance grid efficiency and sustainability. Aghajani and Heydari [16] emphasize the significance of such programs, noting their potential to significantly reduce operational costs in microgrids that incorporate EVs and renewable energy sources. This integration not only facilitates a more flexible energy demand management but also capitalizes on the potential of EVs as mobile energy storage units, further stabilizing the grid during peak load times.

The backbone of smart microgrid operation lies in its communication and control systems, which enable real-time monitoring, control, and optimization of grid operations. Seema, Nair, and Amrita Vishwa Vidyapeetham [17] underscore the importance of effective instrumentation and communication networks in smart grids. These networks are essential for the integration and management of distributed energy resources (DERs), allowing for precise control over energy production and consumption, and ensuring the reliability and efficiency of grid operations. Renewable energy sources, coupled with advanced storage solutions, are at the core of smart microgrid development. Fouladi et al. [18] propose a smart

charging strategy for PHEVs within microgrids that maximizes the employment of renewable energy resources. This strategy not only reduces reliance on the main grid but also promotes the use of clean energy, aligning with global sustainability goals. Moreover, the integration of energy storage systems plays a crucial role in mitigating the intermittency of renewable energy sources, thereby enhancing grid stability and energy security.

The application of smart microgrids in military installations exemplifies their potential for improving energy reliability and security. The SPIDERS project, highlighted by Stamp [19], demonstrates how secure microgrid implementations can offer enhanced reliability, reduced fuel dependence, and robust cybersecurity measures. These benefits are particularly crucial in military contexts, where energy resilience can have strategic implications. Advanced metering infrastructure within microgrids enhances monitoring, control, and security. Mohammed and Kwembe [20] explore the role of smart meters in improving energy management and addressing security threats. These technologies enable utilities to provide better services to customers, improving energy efficiency and safeguarding against fraudulent activities.

The emergence of blockchain technology in the context of smart microgrids introduces a novel approach to energy trading. Gao et al. [21] discuss the potential of blockchain for facilitating secure and transparent peer-to-peer energy transactions within microgrids. This decentralized mechanism not only optimizes energy distribution but also empowers consumers to actively participate in the energy market, promoting a more democratic energy ecosystem. At the heart of smart microgrid operation are energy management systems (EMS), which optimize the use of energy resources. Wu, Cui, and Liu [22] provide a comprehensive review of the latest trends and challenges in EMS for renewable energy-based microgrids. These systems are instrumental in managing the variability of renewable energy, enhancing operational efficiency, and facilitating the integration of DERs into the grid.

Smart microgrids represent a paradigm shift in the way energy is produced, distributed, and consumed, heralding a future of sustainable, efficient, and resilient energy systems. The integration of demand response programs, electric vehicles, renewable energy sources, and advanced technologies such as blockchain and energy management systems are key to realizing the full potential of smart microgrids. As this review has shown, the ongoing research and development in this

field are critical for addressing contemporary energy challenges, promoting environmental sustainability, and

paving the way for a more decentralized and democratic energy landscape.

Reference	Study Focus	Methodology	Key Findings	Implications for Smart Microgrid Development	Future Research Directions
Aghajani and Heydari, 2020	Demand response and EV integration	Simulation and analysis	Load response programs significantly reduce costs and enhance efficiency in microgrids with EVs.	Demonstrates the importance of integrating EVs and renewable sources for cost and efficiency gains.	Explore scalability of demand response programs across various grid scales.
Seema, Nair, and Amrita Vishwa Vidyapeetham, 2023	Communication networks in smart grids	Review and synthesis	Effective communication networks are crucial for integrating and managing DERs.	Highlights the need for robust communication infrastructure for efficient smart grid operation.	Investigate emerging communication technologies and their impact on grid resilience.
Fouladi et al., 2019	Renewable energy and PHEV charging strategies	Modeling and simulation	A strategy for maximizing renewable energy use in PHEV charging reduces grid dependency.	Emphasizes renewable energy utilization and smart charging strategies for energy sustainability.	Study long-term impacts of widespread PHEV adoption on microgrid stability.
Stamp, 2012	Security and reliability in military microgrids	Case study	Secure microgrid implementations offer enhanced reliability and reduced fuel dependence.	Showcases microgrids' potential in critical applications requiring high security and reliability.	Explore the integration of advanced cybersecurity measures in civilian microgrid applications.
Gao et al., 2023	Blockchain for energy trading	Conceptual analysis	Blockchain enables secure, transparent peer-to-peer energy trading within microgrids.	Illustrates the potential of blockchain in democratizing energy markets and enhancing grid efficiency.	Examine regulatory frameworks and market structures for blockchain-based energy trading.
Wu, Cui, and Liu, 2024	Energy management systems for renewable-based microgrids	Review and analysis	EMS are vital for managing renewable energy variability and ensuring operational efficiency.	Underlines the critical role of EMS in integrating renewable sources and optimizing microgrid performance.	Develop and test adaptive EMS capable of real-time optimization in dynamic grid environments.

Table 1. Analysis of Literature Review

III. MICROGRID ARCHITECTURE

The architecture of a smart microgrid is designed to optimize energy efficiency, reliability, and sustainability by integrating advanced technologies and renewable energy sources. A smart microgrid typically consists of several key components and layers, each playing a crucial role in its operation. Below is an overview of the fundamental architecture of a smart microgrid, divided into its main components and functionalities.

A. Generation

Renewable Energy Sources (RES): These include solar panels (photovoltaic systems), wind turbines, hydroelectric, and biomass generators. RES are pivotal in reducing dependence on fossil fuels and minimizing environmental impact.

Conventional Generators: Diesel generators or other fossil fuel-based power sources may be included for backup or supplementary power, ensuring reliability during periods of low renewable generation.

Energy Storage Systems (ESS): Batteries, flywheels, supercapacitors, and other storage technologies store

excess energy generated from renewable sources for use during peak demand times or when generation is low.

B. Distribution

Smart Grid Infrastructure: This comprises the physical and digital technologies for electricity distribution within the microgrid. It includes smart meters, switches,

and other equipment that enable two-way communication between the generation sources and consumers.

Management and Control Systems: Advanced control systems manage the flow of electricity from multiple sources, optimizing the distribution based on demand, generation capacity, and storage levels.

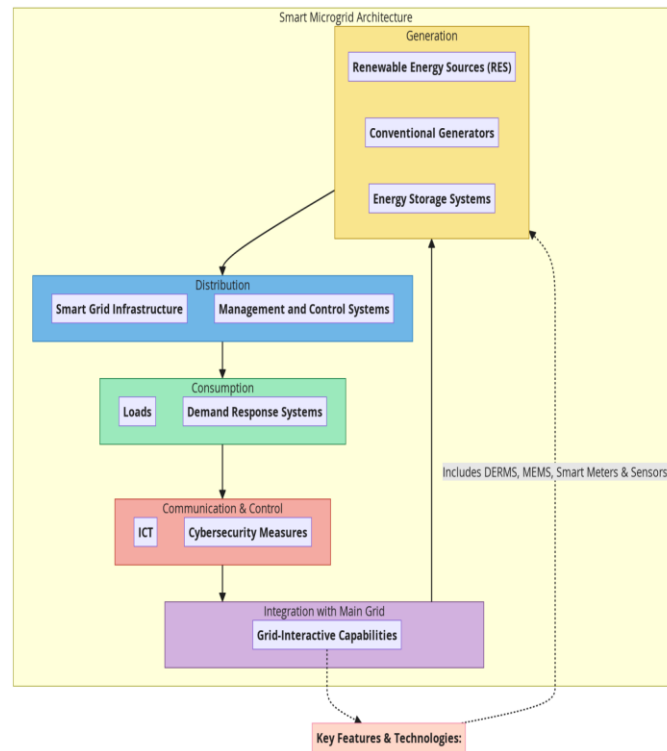


Figure 2. Microgrid Architecture

C. Consumption

Loads: Residential, commercial, and industrial loads represent the energy consumers within the microgrid. These can range from household appliances to large industrial machinery.

Demand Response (DR) Systems: These systems adjust the demand for power through control signals or incentives, reducing consumption during peak periods or when supply is limited.

D. Communication and Control Layer

Information and Communication Technology (ICT): This layer includes the hardware and software for monitoring, controlling, and managing the microgrid. It enables real-time data collection, analysis, and decision-making to optimize operations.

Cybersecurity Measures: Given the reliance on digital technologies, protecting the microgrid from cyber threats is crucial. This includes encryption, firewalls, and secure communication protocols.

E. Integration with the Main Grid

Grid-Interactive Capabilities: While a smart microgrid can operate independently (island mode), it often connects to the main power grid. This connection allows for the exchange of electricity, where the microgrid can sell excess power or draw from the main grid as needed.

Key Features and Technologies

Distributed Energy Resources Management System (DERMS): Coordinates the operation of distributed energy resources (DERs) to improve efficiency and reliability.

Microgrid Energy Management System (MEMS): Oversees the overall energy production, consumption, and storage within the microgrid, ensuring optimal performance.

Smart Meters and Sensors: Collect and transmit data on energy usage and generation in real-time, facilitating efficient energy management.

The architecture of a smart microgrid is dynamic and scalable, capable of adapting to different energy demands, generation capacities, and technological advancements. It embodies the principles of sustainability, resilience, and efficiency, leveraging the synergy between various components to provide reliable and clean energy to its users.

IV. GRID-CONNECTED MICROGRID:

A Grid-connected microgrid, also known as a grid-tied microgrid, is a localized group of electricity sources and loads that normally operates connected to and synchronous with the traditional centralized electrical grid (macrogrid), but can also disconnect and maintain operation autonomously as physical and/or economic conditions dictate.

Architecture Components:

- A. Generation Sources: May include both renewable (solar PV, wind turbines) and non-renewable (diesel generators, combined heat and power systems) energy sources.
- B. Energy Storage Systems: Such as batteries, are used to balance supply and demand, store excess power, and provide backup power during grid outages.
- C. Distribution System: This includes low-voltage distribution lines that supply electricity to the connected loads.
- D. Point of Common Coupling (PCC): A switch at this point can isolate the microgrid from the main grid for operational independence.
- E. Control System: Manages the operation of generators and the flow of electricity, ensuring energy is provided reliably and efficiently.
- F. Smart Meters and Sensors: These devices monitor and manage energy flow and can communicate with the grid to optimize energy consumption.
- G. Protection Systems: Ensure the safety of the microgrid, maintaining stability during both grid-connected and island modes.

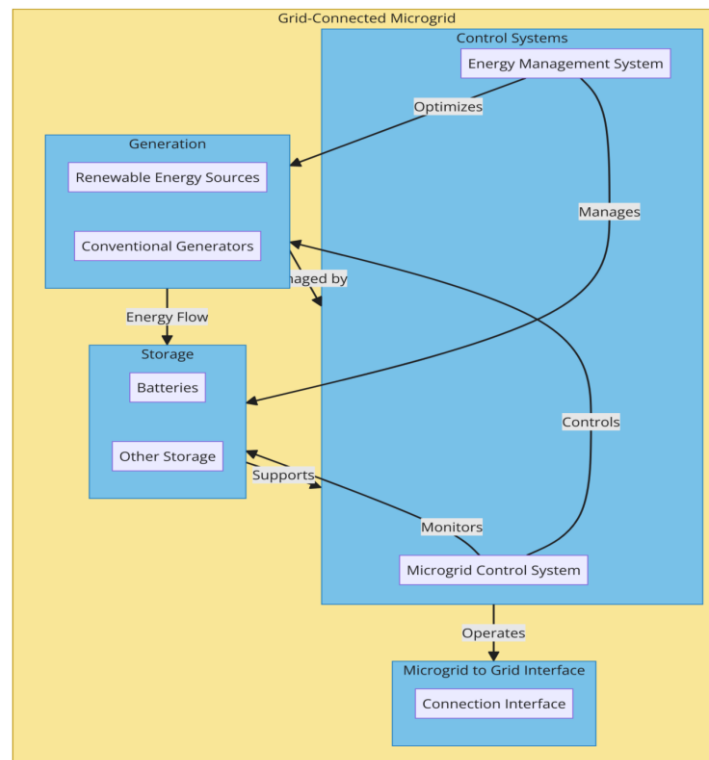


Figure 3. Grid-Connected Microgrid Architecture

Operational Modes:

- a. Grid-connected Mode: The microgrid can sell excess power to the grid and purchase power when local generation is insufficient.
- b. Island Mode: In the event of a grid failure or other issues, the microgrid can operate independently, providing uninterrupted power to its loads.

V. HYBRID MICROGRID:

A Hybrid microgrid combines elements of both grid-connected and off-grid systems and typically includes multiple types of energy resources, both renewable and conventional.

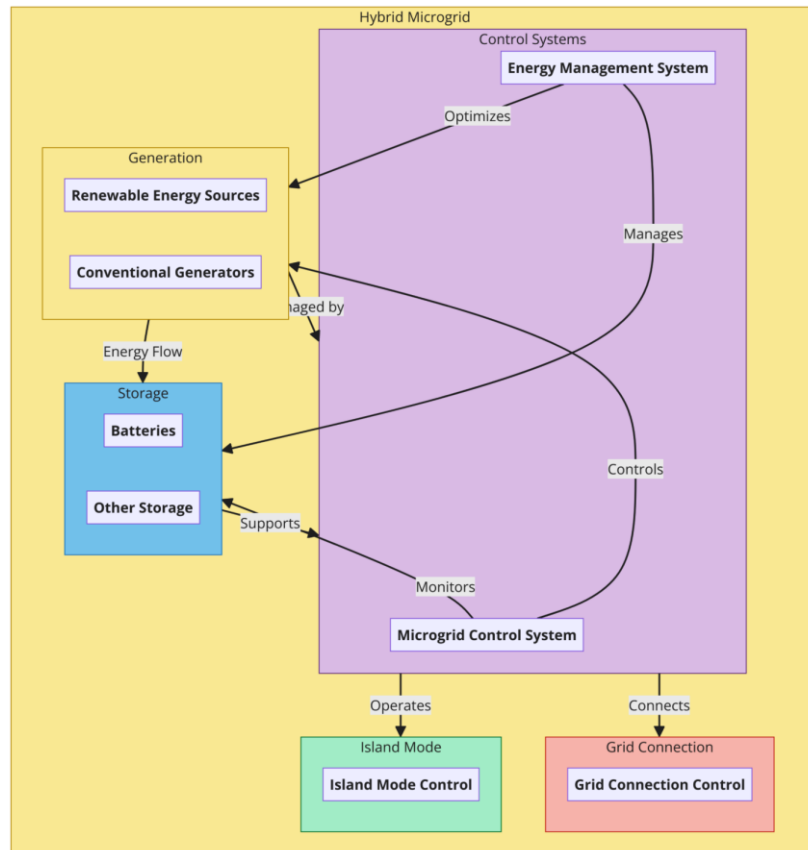


Figure 4. Hybrid Microgrid Architecture

Architecture Components:

- A. Diverse Generation Sources: Typically, a hybrid microgrid has a mix of renewable energy sources (solar, wind, hydro) and conventional generators (diesel, gas).
- B. Advanced Energy Storage: Incorporates sophisticated battery systems and may also use other forms of energy storage like flywheels or supercapacitors.
- C. Energy Management System (EMS): More complex than a standard microgrid due to the variety of power sources. It optimizes energy production, storage, and consumption for efficiency and reliability.
- D. Hybrid Inverters: These can handle inputs from multiple types of energy sources and manage energy flow between the grid, storage, and loads.
- E. Backup Generators: Provide additional reliability, especially in areas where renewable generation is intermittent.
- F. Demand Response and Load Control: Actively manage load to maintain balance within the microgrid.

Operational Flexibility:

- a. Seamless Transition: Can switch between grid-connected and island modes without interruption to the power supply.
- b. Enhanced Resilience: The combination of various energy sources and storage options provides a more resilient energy supply, which can be crucial in remote or critical areas.

VI. ANALYSIS OF MICROGRID

A microgrid's architecture is quantitatively described by key parameters (Table.) such as its total generation capacity (5 MW) which includes all energy sources, and its energy storage capacity (10 MWh), crucial for balancing energy supply and demand. The renewable energy penetration stands at 70%, reflecting a substantial incorporation of sustainable energy sources. The peak demand capacity is noted at 3 MW, determining the microgrid's ability to meet the highest energy needs, while the energy efficiency ratio is an impressive 85%, showcasing the effective conversion of fuel to electricity.

Parameter	Description	Unit	Example Value
Capacity	Total energy generation capacity of the microgrid from all sources.	Megawatts (MW)	5 MW
Storage Capacity	Total energy storage capacity within the microgrid.	Megawatt-hours (MWh)	10 MWh
Renewable Energy Penetration	Percentage of total generation capacity that comes from renewable energy sources.	Percentage (%)	70%
Peak Demand	Maximum power demand observed or anticipated within the microgrid.	Megawatts (MW)	3 MW
Energy Efficiency	Ratio of useful energy output to total energy input, averaged over time.	Percentage (%)	85%
Grid Independence	Ability of the microgrid to operate in island mode without support from the main grid.	Hours (h)	48 h
Emissions Reduction	Estimated reduction in carbon emissions due to operation of the microgrid compared to conventional grid sources.	Metric Tons of CO2 per year	500 metric tons
System Reliability	Measure of the system's ability to provide continuous electricity supply.	System Average Interruption Duration Index (SAIDI)	45 minutes/year
Return on Investment (ROI)	Financial performance indicator showing the return of investment in the microgrid infrastructure.	Percentage (%)	8% over 20 years
Operational Costs	Average annual costs associated with operating and maintaining the microgrid.	USD/year	\$200,000

Table 2. Analysis of Microgrid

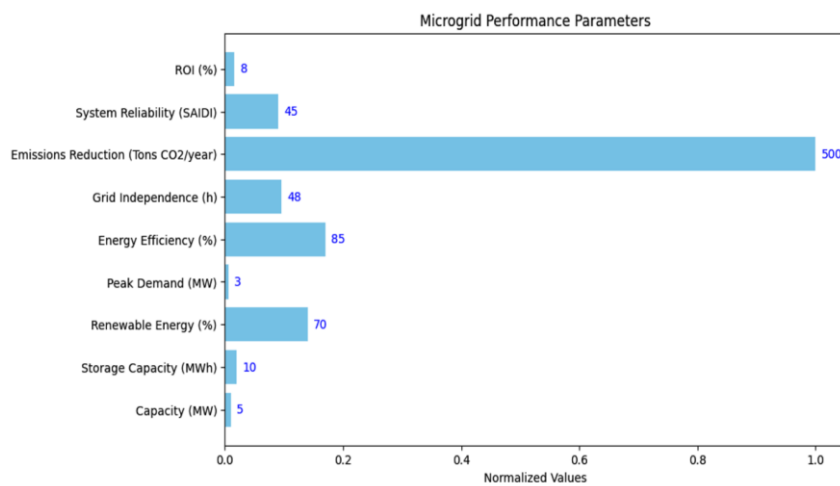


Figure 5. Microgrid Performance Parameters

A notable feature is the grid independence, with the microgrid capable of operating autonomously for 48 hours, ensuring resilience during grid outages. Environmentally, the microgrid contributes to a greener footprint by reducing emissions by an estimated 500

metric tons of CO2 annually. Reliability is measured by a SAIDI of 45 minutes/year, indicating minimal interruptions. Economically, an 8% return on investment over 20 years is anticipated, with

operational costs averaging \$200,000 per year, making it a viable and sustainable energy solution.

Parameter	Grid-Connected Microgrid	Hybrid Microgrid
Capacity (MW)	5 MW	4 MW
Storage Capacity (MWh)	10 MWh	12 MWh
Renewable Energy (%)	70%	80%
Peak Demand (MW)	3 MW	2.5 MW
Energy Efficiency (%)	85%	90%
Grid Independence (h)	48 h	72 h
Emissions Reduction (Tons CO ₂ /year)	500 metric tons	600 metric tons
System Reliability (SAIDI)	45 minutes/year	30 minutes/year
ROI (%)	8% over 20 years	10% over 20 years
Operational Costs (USD/year)	\$200,000	\$180,000

Table 3. Comparison between the Grid-Connected Microgrid Vs. Hybrid Microgrid

The comparison between a Grid-Connected Microgrid and a Hybrid Microgrid across various performance parameters highlights the advantages and focus areas of each configuration. The Grid-Connected Microgrid, with its higher generation capacity (5 MW) and peak

demand capability (3 MW), suggests a strong capacity to meet high energy demands, making it suitable for areas with significant energy consumption needs. However, the Hybrid Microgrid shines in sustainability and efficiency metrics. With a higher percentage of renewable energy (80%), greater storage capacity (12 MWh), and superior energy efficiency (90%), it emphasizes green energy use and longer grid independence (72 hours), showcasing its resilience and environmental friendliness. The Hybrid Microgrid also stands out in terms of emissions reduction (600 metric tons/year) and system reliability, with a lower SAIDI (30 minutes/year), indicating fewer and shorter power interruptions. Financially, the Hybrid Microgrid promises a higher ROI (10% over 20 years) and lower operational costs (\$180,000/year), marking it as a cost-effective and profitable solution over time. These differences underscore the Hybrid Microgrid's emphasis on sustainability, efficiency, and economic viability, making it an attractive option for communities prioritizing green energy and long-term investment returns.

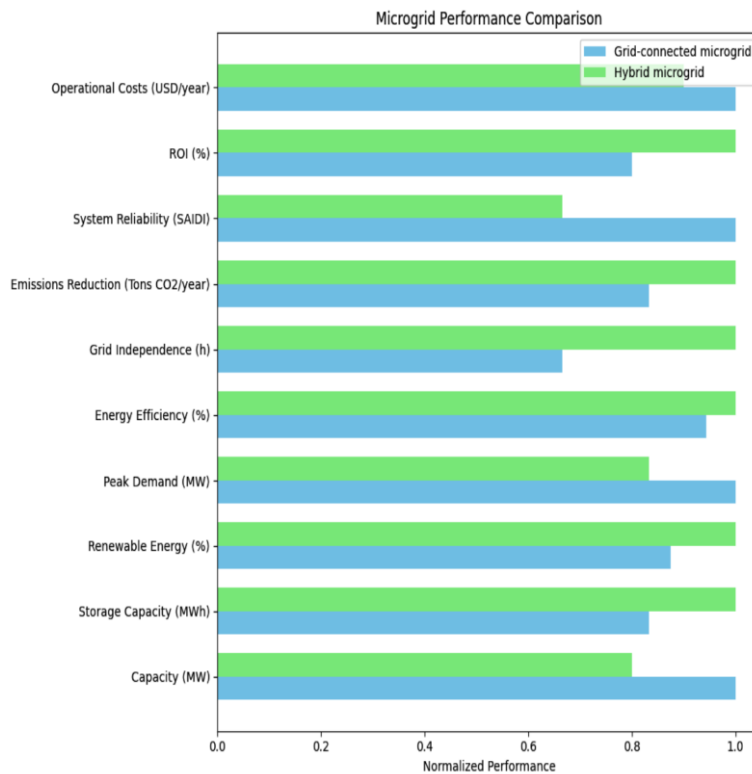


Figure 6. Grid-Connected Microgrid Vs. Hybrid Microgrid Performance Comparison

VII. CONCLUSION:

Smart microgrids are revolutionizing core electrical infrastructure, marking a pivotal shift towards energy

efficiency and sustainability. By integrating renewable energy sources, advanced storage solutions, and intelligent control systems, smart microgrids offer a

resilient, decentralized approach to energy management. These systems not only enhance grid independence through efficient energy use and storage but also significantly reduce carbon emissions by leveraging renewable sources. The ability to operate autonomously in island mode ensures reliability and continuous power supply, even during main grid failures, thereby improving system reliability and reducing interruption durations. The financial implications are equally promising, with smart microgrids offering notable returns on investment and reducing operational costs through optimized energy production and consumption. This, coupled with their capacity to meet peak demands efficiently, positions smart microgrids as a cornerstone for future energy systems. They embody a sustainable energy model that prioritizes environmental preservation, economic viability, and societal well-being. As such, smart microgrids are not merely an enhancement of the existing infrastructure but a transformative step towards a more sustainable, efficient, and resilient energy future, aligning with global energy and environmental goals. This comparative analysis underscores the role of smart microgrids, especially hybrid configurations, in revolutionizing electrical infrastructure. By optimizing the balance between generation capacity, storage capabilities, and renewable energy use, smart microgrids not only meet the current energy demands more efficiently but also pave the way for a sustainable and economically viable future. They exemplify the strategic shift needed to overhaul core electrical infrastructure, prioritizing energy efficiency, sustainability, and resilience in the face of evolving global energy challenges.

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