

Review

DC Microgrid Deployments and Challenges: A Comprehensive Review of Academic and Corporate Implementations

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Abstract: DC microgrids are revolutionizing energy systems by offering efficient, reliable, and sustainable solutions to modern power grid challenges. By directly integrating renewable energy sources and eliminating the inefficiencies of AC-DC conversion, these systems simplify energy distribution and enhance performance in critical applications such as data centers, electric vehicle charging, and telecommunications. This review paper comprehensively examines the design, implementation, and performance of DC microgrids in real-world settings. Key components, including distributed energy resources (DERs), energy storage systems (ESSs), and control strategies, are analyzed to highlight their roles in ensuring reliability and operational efficiency. This review also explores the challenges facing DC microgrids, such as stability issues, protection mechanisms, and high initial costs, while offering insights into advanced control strategies and modular designs to overcome these obstacles. Through an evaluation of global case studies, this article bridges the gap between theoretical research and practical deployment and also demonstrates how DC microgrids can enhance energy efficiency, support sustainable power generation, and provide resilience in various applications. The findings highlight the potential of DC microgrids as a cornerstone of future energy systems, enabling clean, reliable, and decentralized energy solutions.



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Keywords: DC microgrids; renewable energy integration; distributed energy resources (DERs); energy storage systems (ESSs); energy efficiency; sustainable power systems; decentralized energy solution

1. Introduction

Microgrids have become a transformative solution for addressing modern energy challenges, offering enhanced reliability, efficiency, and sustainability [1]. These systems integrate distributed energy resources (DERs), energy storage systems (ESSs), and power electronic converters with controllable loads to ensure secure and efficient energy distribution while reducing dependency on centralized grids [1,2].

DC microgrids, in particular, have gained significant attention due to their distinct advantages over traditional AC counterparts. While AC microgrids have advanced significantly, components such as laptops, mobile phones, electric vehicles (EVs), and renewable energy sources predominantly operate in DC mode. In conventional AC power microgrids, supplying these devices requires AC-DC conversions, leading to energy losses and reduced system efficiency [3–7]. DC microgrids eliminate these conversion stages, directly supplying power to DC-powered loads and improving overall system performance [8,9]. This

efficiency advantage, combined with their ability to simplify the integration of renewable energy sources such as photovoltaic systems (PVs) and fuel cells, makes DC microgrids appealing [6,10].

Unlike AC systems, DC microgrids eliminate the need for frequency synchronization and reactive power management, thereby simplifying their operation. Additionally, ESSs operate on DC power and integrate seamlessly with DC microgrids, reducing overall system costs and enhancing reliability [6,11]. These advantages have driven the adoption of DC microgrids in applications requiring high efficiency and reliability, such as data centers, telecommunications, EV charging infrastructure, and zero-net-energy buildings [7,12,13].

Despite these advantages, DC microgrids face challenges such as stability issues, complexities in bidirectional power flow, and low system inertia. To address these challenges, robust control strategies are essential for ensuring voltage regulation, load sharing, and system stability. However, even these strategies encounter limitations, such as sluggish dynamic responses and trade-offs in achieving optimal voltage regulation [7].

The growing demand for renewable energy solutions positions DC microgrids as a compelling alternative to traditional AC microgrids. By simplifying system architecture and minimizing the need for multiple voltage conversion stages, DC microgrids' construction costs and streamline control implementations could be decreased and be more appealing [4,5,11]. Researchers continue to explore ways to enhance performance, reduce costs, and maximize renewable energy utilization, solidifying DC microgrids as a vital component of future energy systems [14,15]. Table 1 shows a comparison between AC and DC microgrids based on some key indicators.

Table 1. AC and DC microgrid comparison.

Key Indicators	AC Microgrid	DC Microgrid
Power Conversion	Requires multiple AC-DC and DC-AC conversions, leading to higher energy losses.	Direct power transfer with minimal conversion, reducing energy losses.
Energy Efficiency	Lower efficiency due to conversion losses and reactive power requirements.	Higher efficiency due to the elimination of multiple conversion stages.
System Complexity	More complex due to synchronization, frequency control, and reactive power.	Simpler as it does not require frequency and reactive power management.
Integration with Renewables	Less efficient due to frequent AC-DC conversions.	More efficient integration, particularly for PV systems and battery storage.
Voltage Stability	Stability depends on frequency control and reactive power balance.	More stable as it is unaffected by frequency fluctuations.
Protection and Fault Management	Simpler fault detection using zero-crossing points.	More complex due to the absence of zero-crossing points.
Applications	Common in traditional power grids, industrial setups, and residential areas.	Ideal for data centers, EV charging, remote/off-grid areas, and modern DC-powered appliances.
Installation And Maintenance Cost	Lower initial cost but higher operational expenses due to conversion losses.	Higher initial cost but lower operational expenses due to improved efficiency.

Survey Methodology

To ensure a comprehensive and objective review of the existing literature on DC microgrids, a structured literature search strategy was adopted. Several scholarly databases, including Google Scholar, Web of Science, IEEE Xplore, ScienceDirect, ResearchGate, and Scopus, were utilized to identify relevant studies. The search process focused on retrieving publications that discuss implemented DC microgrid projects, their control systems, operational modes, and communication networks. To achieve this, a combination of specific keywords was employed, including “DC Microgrid”, “implemented DC microgrid”, “DC Microgrid Project”, and “Control system”, along with their possible variations and combinations. The search was not limited to a specific timeframe; however, studies from the last 10 to 12 years were prioritized to ensure the inclusion of recent advancements in DC microgrid technology.

The selection process involved multiple screening stages to ensure relevance and quality. Initially, the titles and abstracts of retrieved articles were examined to determine their alignment with this study’s scope. Articles that focused exclusively on AC microgrids were excluded. Furthermore, simulated DC microgrid studies and DC microgrid projects lacking technical details were omitted to maintain the review’s practical relevance. The final selection included only peer-reviewed journal articles, conference papers, and authoritative reports that provided detailed insights into DC microgrid components, operational modes, communication networks, challenges, and research gaps. Through this filtering process, the total number of selected articles was reduced to approximately 96, ensuring a focused and high-quality dataset for analysis.

Following the initial filtering, full-text evaluations were conducted to extract and synthesize key insights from the selected studies. The extracted data included information on control methodologies, communication technologies, system architectures, and operational challenges. The final dataset was carefully curated to ensure a balanced representation of existing research, providing a solid foundation for identifying trends, challenges, and potential areas for future research in DC microgrid development.

This review paper explores the real-world implementation of DC microgrids, highlighting their practical applications, the technical factors contributing to their effectiveness, and the challenges they encounter. Through an examination of case studies, it aims to bridge the gap between theoretical research and practical deployment, providing valuable insights for researchers, policymakers, and industry practitioners.

The structure of this paper is organized as follows: Section 2 discusses the key components of DC microgrids, including DERs, ESSs, and control strategies. Section 3 explores the operation of DC microgrids in both grid-connected and islanded modes. Section 4 examines real-world implementations, testbeds, and distribution systems. Finally, Section 5 addresses the challenges faced by DC microgrids and provides perspectives on their future development.

2. Key Components of DC Microgrids

DC microgrids are composed of several key components that work together to ensure reliable and efficient energy generation and distribution [16]. These key components include distributed energy resources, energy storage systems, and controllable loads, all managed by advanced control strategies. Figure 1 shows the layout of a typical DC microgrid.

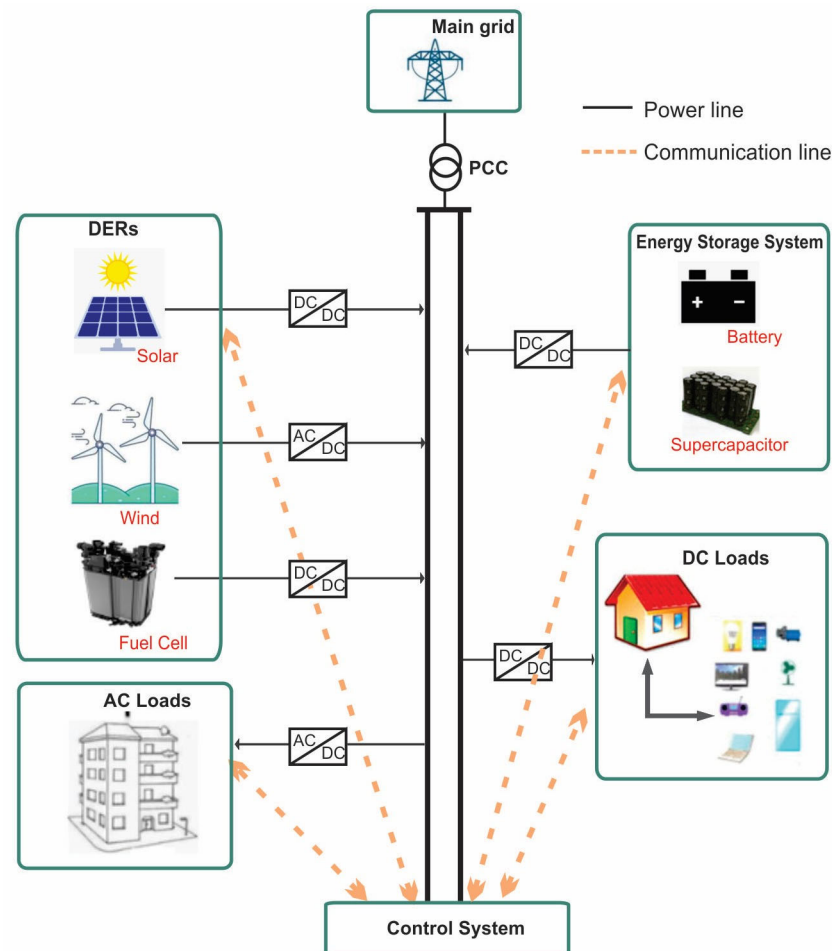


Figure 1. Illustration of DC microgrid layout.

2.1. Distributed Energy Resources (DERs)

DERs serve as the primary sources of power in DC microgrids. These include renewable energy sources, such as PVs, wind turbines, and fuel cells, as well as traditional sources like diesel generators. Positioned close to the point of consumption, DERs provide greater flexibility and reduce dependence on centralized grids [17–19]. They play a critical role in modern power systems by enabling decentralized and sustainable energy generation. Among these, solar PV and wind are particularly favored for their efficiency and renewable nature [20].

Integrating DERs into DC microgrids offers several advantages. They can directly supply DC-powered electronic loads without the need for rectifiers, thereby reducing energy conversion losses and improving overall efficiency [21]. Additionally, DERs integrate seamlessly into DC systems, avoiding the need for multiple power conversion stages [10,20]. Unlike AC microgrids, DC microgrids do not require the synchronization of distributed generators, significantly simplifying their operation. Additionally, they enhance reliability, as faults in one line are less likely to propagate and cause system-wide failures [20–23]. DERs play a crucial role in improving the reliability, sustainability, and efficiency of DC microgrids by enabling the seamless integration of renewable energy sources and enhancing energy delivery.

2.2. Energy Storage Systems (ESSs)

ESSs play a vital role in DC microgrids by providing backup power, balancing loads, and enabling effective energy management. ESSs encompass various technologies, in-

cluding batteries, supercapacitors, and flywheels [18,24,25]. Among these, batteries and supercapacitors have gained significant attention due to their unique capabilities.

Battery technologies, such as lithium-ion, lead–acid, and flow batteries, are highly valued for their high energy density and ability to store large amounts of energy for extended durations. These batteries support critical functions such as load balancing, peak shaving, and energy storage, thereby enhancing the overall efficiency and reliability of microgrids [26]. On the other hand, supercapacitors, also known as ultracapacitors, are characterized by their high power density, rapid charging and discharging capabilities, and long cycle life. They are especially suited for applications requiring quick response times, such as voltage regulation or providing ancillary services [2].

The integration of ESSs into DC microgrids addresses the intermittency challenges associated with renewable energy sources, ensuring smoother power delivery and improved grid stability. This integration enhances DC microgrid performance and expands their applicability to critical infrastructure and renewable energy systems.

2.3. Loads and Demand-Side Management (DMS)

Understanding and managing the electrical loads within a DC microgrid are critical for ensuring efficient operation. Loads in microgrids are generally categorized into critical and non-critical types. Critical loads, such as those in hospitals, data centers, and other essential services, demand an uninterrupted power supply. In contrast, non-critical loads can tolerate temporary power disruptions or adapt to flexible consumption patterns [27,28].

Demand-side management (DSM) could help in optimizing energy consumption patterns and improving overall energy efficiency in DC microgrids. DSM focuses on shifting energy demand from peak to off-peak hours, effectively balancing supply and demand to reduce costs and improve system performance. Techniques such as load scheduling, peak clipping, valley filling, and load shifting are employed to optimize energy usage without requiring additional generation infrastructure [28–30].

Integrating DSM into DC microgrids offers several advantages. It reduces energy storage requirements, extends battery life, and lowers overall system costs by improving the utilization of renewable energy sources. Additionally, DSM defers the need for costly infrastructure upgrades by reducing peak loads, ultimately lowering electricity costs [31,32].

2.4. Communication Networks and Protocols for DC Microgrids

Communication links are enabled by networks and governed by protocols, which together provide fast, reliable, and secure data exchange in DC microgrids. Typically, networks can be divided into wired and wireless categories. Wired networks, such as Ethernet, Power Line Communication (PLC), or fiber optics, often deliver higher data rates and lower latency but come with higher installation costs and less deployment flexibility. Wireless options, such as ZigBee, LoRa, Wi-Fi, and cellular technologies, can be more economical and easier to install, especially in areas where new cables are difficult to place. However, they may face interference and bandwidth limitations in noisy or congested environments. Whether wired or wireless, the choice depends on data requirements, reliability needs, and overall system scale [33–36].

Various communication protocols have been adopted for DC microgrids to coordinate control actions and share operational data efficiently. Widely employed industrial protocols include Modbus, which offers simplicity for controller-to-device communication, and IEC 61850, valued for its interoperability across different equipment [34]. Distributed Network Protocol 3 (DNP3) can be used in supervisory control and data acquisition (SCADA) systems to enhance reliability, while Message Queuing Telemetry Transport (MQTT) or TCP/UDP-based protocols often appear in Internet of Things (IoT)-driven solutions. These

protocols help central or distributed controllers exchange status updates, control signals, and safety parameters in near real time. Selecting a protocol typically depends on factors such as latency tolerance, available bandwidth, cybersecurity requirements, and integration complexity with existing hardware [33,36,37].

A robust monitoring system is crucial for real-time oversight, fault detection, and energy optimization in DC microgrids. Monitoring applications rely on sensor measurements, such as voltage, current, and state-of-charge for batteries, that are transmitted over the chosen network infrastructure to local or cloud-based platforms. Advanced data analytics, often supported by IoT and edge computing frameworks, can detect anomalies, forecast demand, and optimize resource allocation. Many modern microgrids also incorporate SCADA or web-based dashboards, enabling operators to track performance indicators and issue commands remotely. By unifying sensing devices, communication links, and control algorithms, the monitoring system ensures reliable operation and efficient coordination among distributed resources, ultimately enhancing the resilience and stability of DC microgrids [35–38].

2.5. Control Systems

The control system serves as the control center of a microgrid, orchestrating the coordination of various components, including DERs, ESSs, and loads, to maintain stable and efficient operation. It operates through a hierarchical structure comprising three levels: primary, secondary, and tertiary control [39,40].

- Primary Control

Primary control operates at the local level and is responsible for immediate, fast-response tasks such as voltage regulation, power balancing, and load sharing. It relies entirely on local measurements and does not require communication links, making it highly reliable and responsive. Primary control is often implemented through droop control methods, which adjust the output of distributed energy resources based on voltage variations at the DC bus. This approach ensures stability and proportional load sharing among the DERs [6,41].

- Secondary Control

Secondary control is a higher-level mechanism designed to address system-wide issues, such as voltage restoration and power quality regulation. It ensures the secure, safe, and economical operation of the DC microgrid, whether operating in grid-connected or islanded mode. Secondary control also facilitates the coordination of distributed generators (DGs) and prepares the system for smooth reconnection to the main grid when required. Communication links are typically used at this level to collect data and provide system-wide adjustments [6,41].

- Tertiary Control

Tertiary control provides the most advanced level of oversight in a DC microgrid. Its primary focus is on optimization, energy management, and overall system regulation. It integrates requests and demands from the main utility grid, coordinating the operation of multiple interconnected microgrids within the system. Tertiary control plays a critical role in optimizing power flows, ensuring energy efficiency, and maintaining economic operation across the microgrid network [6,41].

Further discussions on hierarchical control systems can be found in the literature such as [7,42–44].

Moreover, three main control strategies are employed in DC microgrids: centralized, decentralized, and distributed control [22,45–48].

- **Centralized Control**

In centralized control, a single controller oversees all DERs within the DC microgrid. It collects and processes data on power generation, energy storage, and load demand, then dispatches commands to individual components to maintain system stability. The central controller can optimize power flow, manage critical and non-critical loads, and handle real-time adjustments through digital communication links (DCLs) [42,49,50]. This strategy offers advantages such as strong supervision, centralized decision-making, and simplified monitoring of system performance. However, centralized control has significant limitations, such as vulnerability to single-point failures, reduced scalability, and reliance on extensive communication networks. As a result, it is best suited for small-scale microgrids with limited data requirements [49,51,52].

- **Decentralized Control**

Decentralized control relies on local controllers at individual units, such as DERs and energy storage systems, to manage operations independently without external communication links. Each controller processes locally measured data, such as voltage and current levels, to regulate its corresponding device. A prominent example of this approach is the droop control method, which balances voltage regulation and power sharing among distributed units [51,53,54]. This strategy offers enhanced reliability and simplicity, as it eliminates the dependency on centralized communication systems. However, its limitations include reduced accuracy in load sharing and potential performance issues due to a lack of information exchange among units. To address these challenges, the careful tuning of control parameters, such as droop coefficients, is essential to balance precision and stability [54–56].

- **Distributed Control**

Distributed control combines the strengths of centralized and decentralized approaches. Each unit in the microgrid operates with a local controller, which communicates only with neighboring units via DCLs. This peer-to-peer exchange enables collaborative decision-making without relying on a central controller, ensuring resilience and scalability [57,58]. The key advantages of distributed control include improved fault tolerance, as the system remains functional even with partial communication failures, and proportional load sharing with effective voltage restoration. These features make distributed control suitable for larger and more complex microgrids, where centralized methods may face challenges in scalability and reliability [59–62].

2.6. Point of Common Coupling (PCC)

The Point of Common Coupling (PCC) is the interface between the microgrid and the main utility grid, enabling power exchange and integration with the broader electrical network [63,64]. It ensures the smooth and reliable operation of a DC microgrid, allowing for power transfer, synchronization, and adherence to grid codes and standards [22]. Unlike AC microgrids, DC microgrids have unique operational requirements that demand adaptations in control methods and protection systems. The PCC in a DC microgrid must account for the specific characteristics of DC power, such as the absence of frequency and reactive power, which are important in AC systems [10,20].

The design of the PCC involves several key considerations, including the selection of appropriate switchgear, power electronics, and control algorithms. It must also coordinate multiple renewable energy sources connected to the microgrid, managing their simultaneous power injection into the main grid while ensuring compliance with relevant standards [10,22]. Furthermore, the integration of multiple renewable energy sources in a DC microgrid, connected to the main utility grid, emphasizes the importance of maintain-

ing power quality at the PCC. The proper management of power quality at this interface is essential to the reliable and efficient operation of the overall system [65]. The PCC is, therefore, a critical component in DC microgrids that requires careful design and consideration to support stable and efficient system performance.

3. DC Microgrids' Modes of Operation

DC microgrids are versatile systems designed to adapt to varying operational scenarios through two primary modes of operation: grid-connected and islanded modes. These modes enable the microgrid to maintain energy stability and optimize resource utilization under different conditions [20].

3.1. Grid-Connected Mode

In the grid-connected mode, the DC microgrid operates while connected to the main utility grid, allowing for bidirectional power flow through a voltage source converter (VSC). This mode facilitates the efficient integration of renewable energy sources and enables the sale of surplus power back to the grid, contributing to overall energy efficiency [66]. Additionally, this mode provides a reliable backup power source for the microgrid and supports the stability of the main grid by balancing supply and demand [67].

3.2. Islanded Mode

In islanded mode, the DC microgrid functions independently from the main grid, ensuring power continuity during outages or in remote areas where grid access is unavailable. This mode requires the microgrid to regulate its own voltage and power balance, maintaining stability and power quality for critical loads [65,66]. Power management algorithms are used to balance generation and load on the common DC bus. Taking advantage of hybrid energy storage systems is essential for effective operation in the islanded mode. For instance, batteries provide long-term steady power, while supercapacitors handle short-term high-power demands, ensuring reliable performance [68–71]. The use of decentralized control strategies, such as droop control, allows distributed energy resources to share loads and coordinate efficiently without requiring extensive communication systems [65,72].

An important feature of DC microgrids is their ability to transition seamlessly between grid-connected and islanded modes. This flexibility is supported by distributed control approaches, which enables each component to manage its own energy flow and contributions dynamically. This adaptability makes DC microgrids a reliable solution for diverse applications, from rural electrification to enhancing urban energy resilience [20,72].

4. A Review of the Existing DC Microgrids, Distribution Systems, and Testbeds Across the Globe

The growing interest in DC microgrids has transitioned from theoretical research to real-world applications, demonstrating their potential in addressing modern energy challenges. Across the globe, numerous projects and testbeds have successfully implemented DC microgrids and distribution systems, showcasing their practicality, efficiency, and adaptability in diverse applications. From powering advanced data centers with 380 V DC systems to enabling resilient renewable energy integration in remote areas, these case studies highlight the transformative impact of DC microgrids on energy systems. This section explores the most notable implementations of DC microgrids, offering insights into their design, operation, and contributions to the energy transition.

4.1. DC Microgrid at Xiamen University, China

The DC microgrid at Xiamen University is located in the engineering building on the Xiang'an Campus in China [73]. As the first operational DC microgrid for a commercial building in the country, it represents a milestone in sustainable energy systems. Developed by the School of Energy Research at Xiamen University in collaboration with companies such as Nextek, PeoplePower, and Intel, the primary objective of this system is to showcase the efficiency and practicality of DC microgrids in real-world applications.

The microgrid is powered by a 150 kWp rooftop PV system, serving as its primary energy source. A 200 Ah, 336 V lead–acid battery provides energy storage, ensuring stable operation. The microgrid operates on a 380 V DC bus, which supports various loads directly. The key loads include DC LED lighting, air conditioning, and electric vehicle (EV) charging station. The lighting system has a capacity of 20 kW, providing illumination for offices and laboratories through input that support both 24 V and 380 V DC. The air conditioning system consists of 30 kW DC-powered units capable of both heating and cooling functions. Additionally, the microgrid supports a 40 kW DC fast charger station for EVs [73,74]. The structure of this microgrid is illustrated in Figure 2.

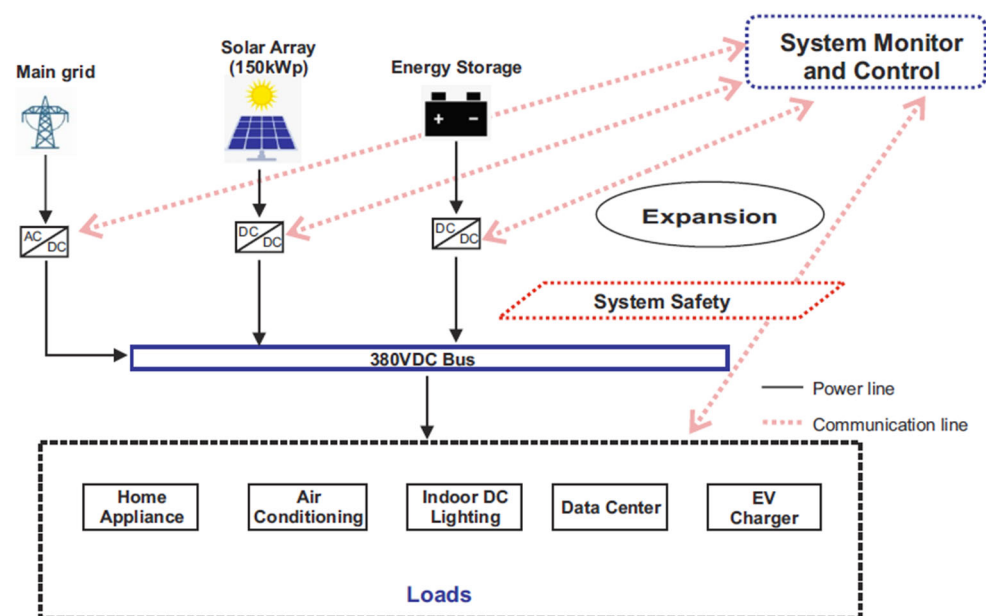


Figure 2. Structure of DC microgrid at Xiamen University.

This microgrid incorporates a cloud-based energy management system to monitor and control operations in real time, ensuring efficient performance and enabling rapid adjustments to energy usage. It is designed to primarily rely on solar PV as the main energy source, with backup support provided by grid-connected AC/DC inverters. By utilizing DC power, the system minimizes the need for energy conversions, thereby enhancing overall efficiency.

This microgrid has demonstrated significant efficiency improvements over traditional AC systems. For instance, lighting systems achieve an efficiency of 92% compared to 78% for AC systems, while electric vehicle charging reaches 94% efficiency versus 76% for AC chargers. Similarly, data centers powered by it operate with an efficiency of 78%, outperforming the 64% efficiency of their AC systems. Additionally, the system has proven to be highly reliable, maintaining stable operation with bus voltage fluctuations kept within $\pm 5\%$ range.

The microgrid's installation cost was approximately USD 2.2 per watt, with a projected payback period of 5.5 years when factoring in incentives. The rooftop solar panels

further reduce the building's reliance on the central grid and lower carbon emissions. For instance, the panels generate sufficient power to operate LED lighting for buildings as tall as 16 stories.

This project faced several challenges, including the following:

- The need for additional energy sources to support heavy loads like air conditioning and EV charging.
- Managing unbalanced loads caused by intermittent EV charger usage.

These challenges highlight the need for hybrid DC/AC microgrids or incorporating additional renewable energy sources, such as parking lot PV systems, to meet higher energy demands. While the project demonstrated that rooftop solar panels are sufficient to meet the lighting requirements of large buildings, heavy loads like air conditioning and EV charging necessitate supplementary energy resources. At this stage, a hybrid DC/AC system appeared to be a more practical solution for commercial applications.

4.2. Burlington DC Microgrid at Etratech Inc. Ontario Canada

The Burlington DC microgrid is located at the headquarters of Etratech Inc., in Ontario, Canada [75]. It was developed by ARDA Power as a demonstration project to showcase the potential of a modular and scalable DC bus-based microgrid for industrial applications. Its purpose was to explore efficient energy solutions for industrial facilities by combining renewable energy, energy storage, and advanced control systems. The block diagram of the microgrid is shown in Figure 3.

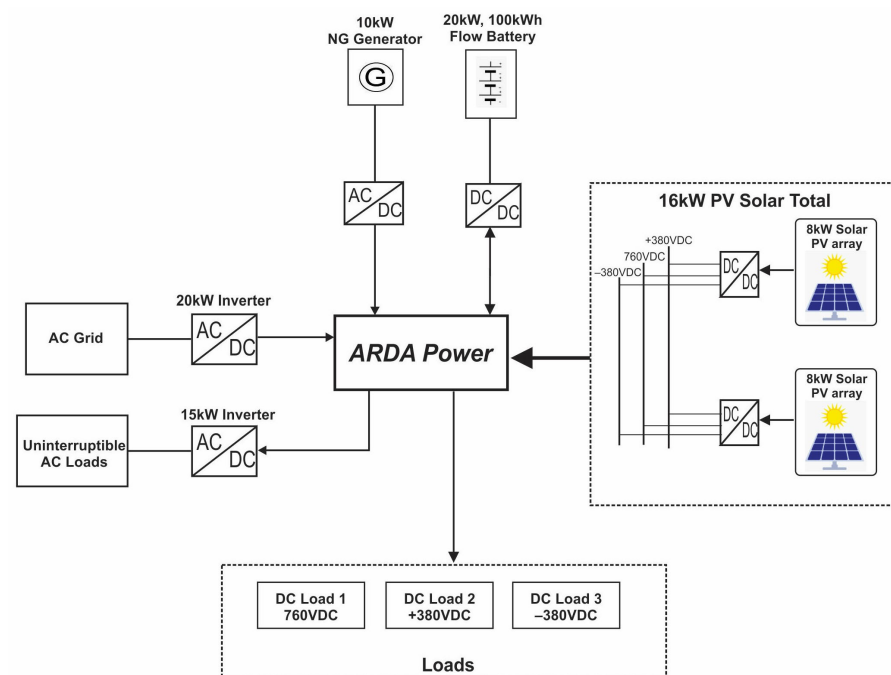


Figure 3. Block diagram of Burlington DC Microgrid.

This microgrid operates on a bipolar ± 380 V DC bus and integrates two 8 kW solar PV arrays as its primary energy source. These arrays are connected through ARDA Power unidirectional DC/DC converters to the DC bus. A vanadium redox flow battery system with a capacity of 20 kW/100 kWh provides storage, ensuring stable operation and supporting voltage regulation. In addition, a 10 kW natural gas generator serves as a backup energy source, adding resilience during periods of low solar production. The microgrid powers various loads, including high-efficiency LED lighting, which replaced traditional 400 W metal halide fixtures. The LED fixtures consume only 230 W, delivering energy

savings and improved lighting quality. Other DC loads include air conditioning unit rated at 18,000 BTU and mini fridge, both operating at 48 V DC.

The microgrid's control system operates in a decentralized architecture, with the battery serving as the primary voltage regulator. A programmable logic controller (PLC) located in the central distribution hub manages critical functions, such as load shedding and dimming, to optimize energy usage. The system supports both grid-connected and off-grid modes, with grid-connected inverters ensuring seamless transitions between the two. Bidirectional DC/DC converters enable efficient energy transfer and maintain load balancing across the DC bus, contributing to the system's stability and operational efficiency.

The Burlington DC microgrid has exhibited substantial performance improvements. Replacing traditional lighting with dimmable LED fixtures resulted in energy savings exceeding 40%. Furthermore, the integration of advanced features such as ground and arc fault detection enhances system reliability, ensuring stable operation even in the presence of minor electrical faults.

Despite its successes, the project encountered challenges, including balancing loads across the ± 380 V DC bus and managing transient power fluctuations caused by variable solar generation and dynamic load demands. Additionally, the high initial cost of advanced energy storage systems and modular converters posed economic barriers. However, the modular design approach mitigated these challenges by reducing site-specific engineering costs and enhancing scalability, making the microgrid a practical and cost-effective solution for industrial applications.

The project at Etratech Inc. highlights the benefits of modular and scalable microgrid systems. It demonstrated how centralized distribution hubs could simplify fault management and improve system reliability. The transition from traditional lighting to LEDs improved energy efficiency and significantly reduced long-term maintenance costs. These findings provided valuable insights for the design and implementation of similar microgrid systems in other industrial applications.

4.3. Bosch DC Microgrid, California

The Bosch Direct Current Building-Scale Microgrid Platform (DCBMP) was installed at the Honda Distribution Facility in Chino, California [76], with the primary goals of enhancing energy reliability, reducing operational costs, and maximizing the utilization of solar energy. Developed as part of California's EPIC program, it was notable for being the only fully DC architecture-based microgrid within its award group. Designed to operate continuously in a commercial setting, the microgrid primarily powered DC lighting and ventilation loads, ensuring 24/7 functionality.

The microgrid featured a 286 kW rooftop PV system, delivering renewable energy directly to the system. Energy storage was facilitated by a 180 kW lithium-ion battery, which stabilized operations and supported load leveling. The system operated on a 380 V DC bus, connecting the solar panels, battery, and various loads. Bosch's energy management system optimized energy flow, ensuring seamless integration and efficient operation of all components. Key loads powered by the microgrid included DC LED high capacity lighting, ventilation systems, and industrial fan [76,77]. The diagram of the microgrid is shown in Figure 4.

The DCBMP achieved significant improvements in energy efficiency. For DC loads, efficiency increased by 2% to 6%, while solar utilization efficiency improved by 7% to 10%. Additionally, the project substantially reduced building maintenance requirements, as the DC LED lighting system offered superior illumination, brighter and more efficient, compared to traditional lighting solutions. Maintenance costs for the lighting system

were reduced by 45% to 50%, showing the long-term value of DC technologies. These enhancements enabled the facility to meet Title 24 energy efficiency standards.

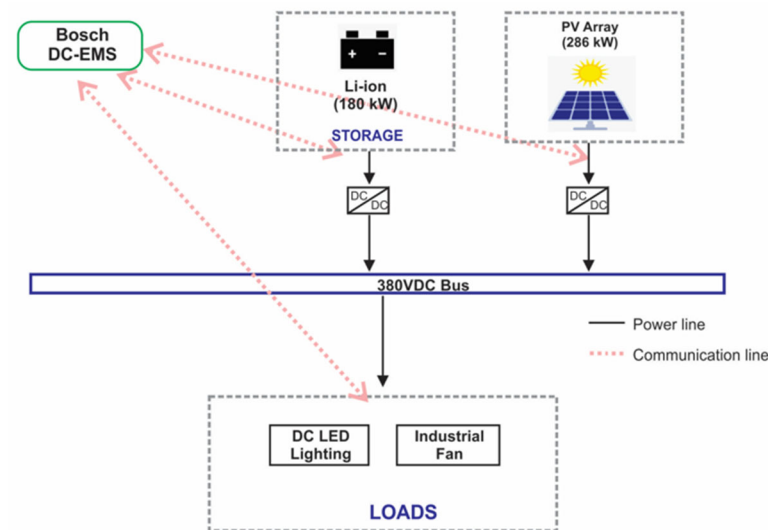


Figure 4. Diagram of Bosch DC Microgrid.

From a broader perspective, the project demonstrated significant economic benefits, reducing the total cost of ownership by approximately 30% compared to AC microgrids. These savings were achieved through lower energy consumption and reduced maintenance costs, highlighting the operational advantages of DC microgrid systems.

Despite its successes, the project encountered several challenges. Certification of DC equipment, including compliance with UL specifications, caused delays. Modifications to the utility interconnection process and operational changes at the warehouse further impacted the timeline. Additionally, complications arose from the failure of a battery vendor, introducing additional setbacks. Although the project was decommissioned after the grant period due to external factors, it successfully demonstrated the potential of DC microgrids in commercial facilities. Key recommendations included extending data collection periods and enhancing outreach efforts to educate stakeholders about the benefits and operation of DC systems.

4.4. DC Microgrid at the Obihiro Sanitation Center, Hokkaido Japan

A DC microgrid was constructed within the existing facilities at the Obihiro Sanitation Center in Obihiro City, Hokkaido, Japan [78]. This microgrid was part of a research project funded under the “Development and Demonstrative Research on Technology to Counter Global Warming” initiative. Designed as a self-sustaining energy solution for an office building, the microgrid aimed to reduce CO₂ emissions and enhance energy efficiency. Additionally, it was engineered to operate independently during natural disasters, ensuring reliable power supply for the community.

The microgrid included several key components. Two PV systems, each rated at 10 kW, served as the primary energy source, supported with rectified 30 kW from the main grid. Energy storage was provided by 25 kWh lithium-ion batteries with bidirectional charging and discharging capabilities. EVs were also integrated into the system, functioning as additional energy storage units. The entire system operated on a 360–400 V DC bus, efficiently distributing power to various DC loads, including LED lighting, a refrigerator, a TV, a Blu-ray player, notebook computers, and the EVs themselves. Additionally, the system could draw power from the commercial grid through a rectifier when needed. Figure 5 illustrates the complete system configuration of the microgrid.

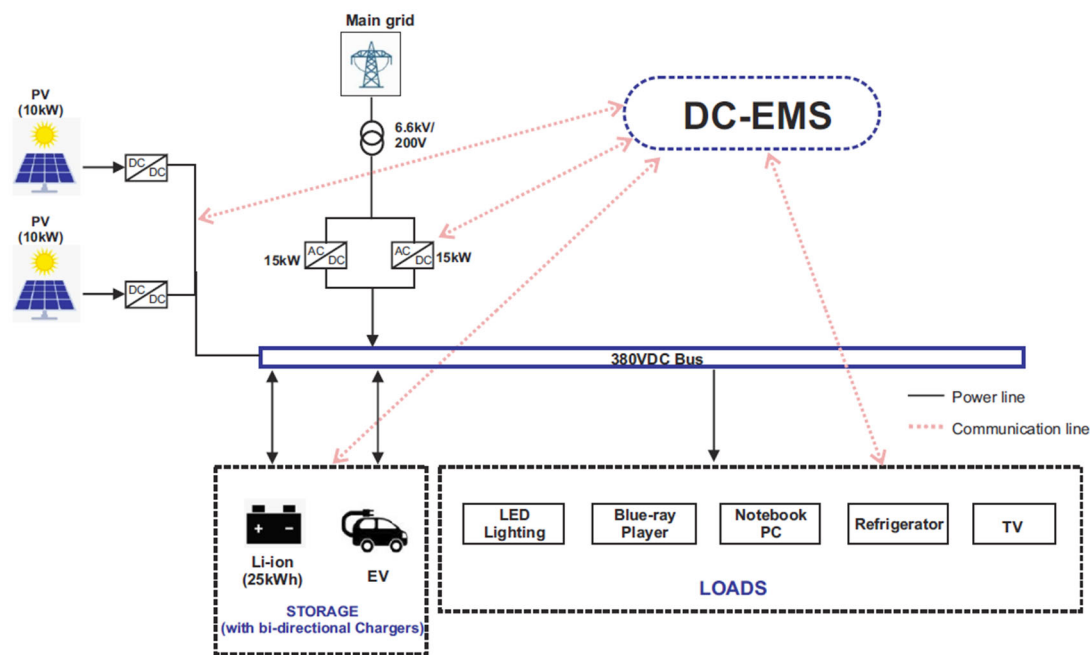


Figure 5. System configuration of DC microgrid at Obihiro Sanitation Center.

The developed energy management system (EMS) played a central role in the microgrid's operation. It prioritized the utilization of renewable energy from the solar PV panels and managed the batteries and EVs to maximize energy efficiency. The EMS also incorporated weather forecasts, EV driving schedules, and load data to optimize power distribution and minimize CO₂ emissions. During peak load periods, the EMS first drew power from the batteries and EVs before resorting to the commercial grid, ensuring efficient and sustainable energy management.

The microgrid demonstrated impressive performance metrics. The lithium-ion chargers operated with an efficiency of 96.0%, while the LED lighting achieved 93.3% efficiency, significantly surpassing the performance of traditional AC systems. Additionally, the microgrid reduced CO₂ emissions by 10%, with further variations observed across different seasons. The EMS enhanced these reductions, contributing an additional 16% decrease in emissions by optimizing system operations.

The project demonstrated several key benefits. Environmentally, it showcased the potential of DC microgrids to significantly reduce CO₂ emissions. Economically, the findings indicated that similar systems could be deployed in office and community settings to enhance sustainability and reduce energy costs. The study underscored the transformative potential of DC microgrids in managing and utilizing energy in commercial buildings, delivering both reliability and environmental advantages.

4.5. Nushima Island DC Microgrid

The DC microgrid on Nushima Island, Hyogo, Japan, was developed as part of an initiative to establish decentralized and sustainable energy systems for isolated regions [79]. Supported by the Ministry of Environment, Japan, under the "Technology Development Projects for Prevention of Global Warming" program, the project ran from 2012 to 2014. Its primary goal was to demonstrate how renewable energy and DC power systems could efficiently meet the energy needs of remote areas while minimizing environmental impact.

The microgrid was powered by a combination of renewable energy sources, including an 8 kW rooftop PV system and a 1 kW wind turbine. Energy storage was facilitated by a 46 kWh stationary lithium-ion battery system with bidirectional charging capabilities. Additional flexibility was provided by mobile batteries integrated into electric vehicles

and plug-in hybrid boats, enabling stored energy to be transported and utilized in other locations as needed. Operating on a 360 V DC bus, the microgrid efficiently distributed power to both DC and AC appliances. Key DC loads included LED lighting, refrigerators, air conditioners, and TVs, while critical AC loads, such as satellite phones and business refrigerators, were powered via a DC/AC converter [79,80].

The system's operation was supported by an advanced power flow management system. A bidirectional DC-DC converter played a key role in maintaining the batteries' balanced state-of-charge (SOC) while regulating energy flow between sources and loads. The system seamlessly transitioned between grid-connected and islanded modes, ensuring uninterrupted operation during emergencies. Additionally, an energy management system optimized demand-side energy usage through dynamic pricing strategies, effectively reducing overall energy demand and enhancing efficiency. Figure 6 illustrates the block diagram of the microgrid.

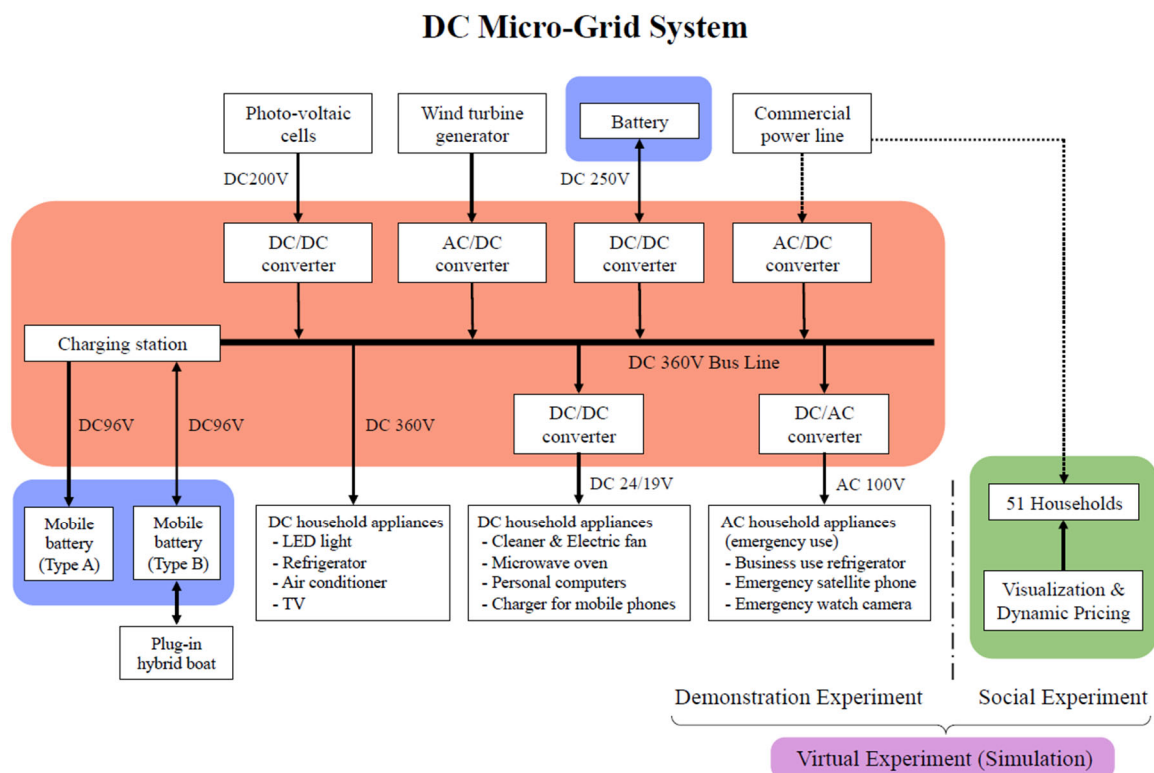


Figure 6. Block diagram of Nushima Island DC microgrid [79].

The performance of the Nushima Island microgrid was remarkable, achieving power conversion efficiencies exceeding 90% for the DC converters and an overall energy utilization efficiency of approximately 80%. Furthermore, the system demonstrated its reliability by providing stable power during emergencies, underscoring its potential as a resilient energy solution for isolated regions.

The project delivered substantial environmental benefits by reducing CO₂ emissions through the integration of renewable energy and efficient power management. Its success highlighted the scalability of similar systems, providing a valuable model for other islands and remote regions pursuing sustainable energy solutions. The Nushima Island DC microgrid demonstrated that DC-based systems can play a pivotal role in addressing energy challenges in remote communities while supporting broader environmental objectives.

4.6. Kirtland Air Force Base DC Microgrid

The Kirtland Air Force Base (KAFB) DC microgrid is located in Albuquerque, New Mexico, and serves as a testbed for advanced DC microgrid technologies [81]. It was

developed through a partnership between the U.S. Department of Energy (DOE) and the U.S. Department of Defense (DoD), this project was the first of its kind between the two agencies. The microgrid links together power generation and loads across Kirtland's DoD facilities, Sandia National Laboratories' Distributed Energy Technology Laboratory (DETL), and the Photovoltaic Systems Evaluation Laboratory (PSEL). It is a single-bus, ten-node, 250 kW DC microgrid that powers six housing units, a laundromat, and a community center, demonstrating the feasibility of decentralized energy systems.

The microgrid integrated renewable and conventional energy sources to meet the facility's power demands. It includes a 100 kW rooftop solar PV array as the primary energy source and natural gas generators as backup to ensure continuous operation during periods of low solar production. Energy storage is provided by 200 kW/200 kWh lithium-ion batteries housed in modular nanogrid units called "BlockBoxes". These batteries stabilize the system and balance loads efficiently. The system operates on a 750 V DC bus with a bipolar ± 375 V configuration, which enhances safety by reducing ground fault risks. Modular nanogrids connected through bidirectional converters manage energy distribution between the DC bus and local loads [81–83]. The radial architecture of the microgrid has been shown in Figure 7.

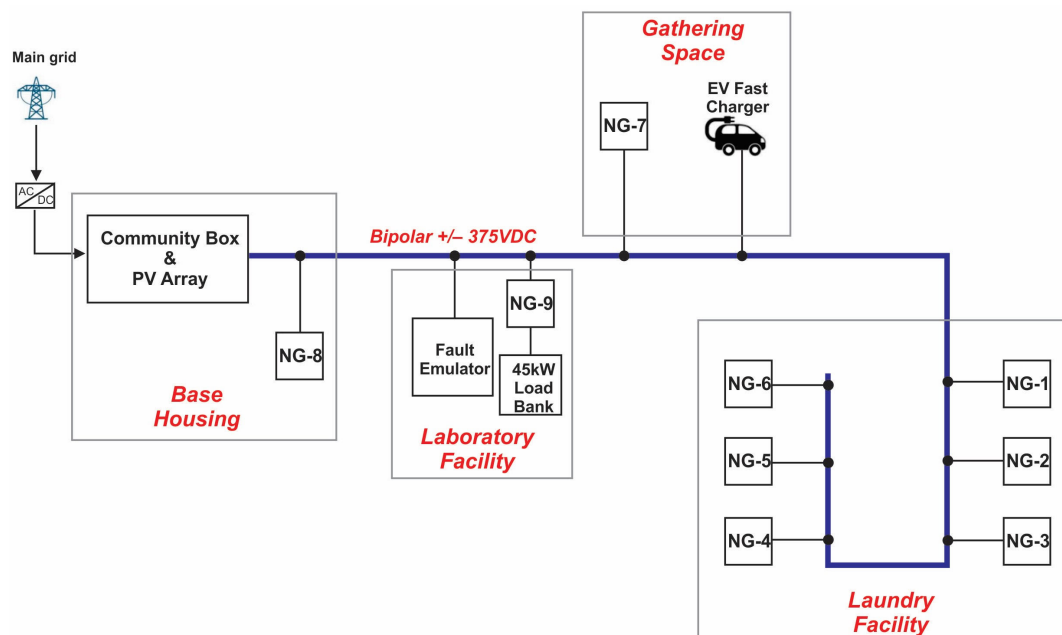


Figure 7. Radial architecture of KAFB DC microgrid.

Control and operation of the microgrid are managed by the Central Energy Park (CEP), which integrates solar PV, battery storage, natural gas generators, and the local utility grid. The CEP allows the system to operate in both grid-connected and islanded modes, ensuring power reliability during outages. Fault detection and protection are key features of the microgrid. Using high-impedance grounding and advanced monitoring systems, faults are detected and isolated within milliseconds, preventing damage and maintaining system stability.

The KAFB microgrid demonstrated strong performance in energy efficiency and resilience. The system successfully operated under simulated fault conditions which proves its reliability in extreme situations. These capabilities highlight the microgrid's potential as a robust solution for critical infrastructure.

The project offers significant scalability and adaptability. Its modular design and centralized control make it suitable for military and civilian applications. The success of

this proof-of-concept project supports the expansion of similar DC microgrids to enhance energy independence and reliability in both residential and industrial settings.

4.7. DC Microgrid at Pitt Ohio Trucking Terminal, Pennsylvania

The DC microgrid at the Pitt Ohio Trucking Terminal in Cheswick, Pennsylvania, was designed to showcase the cost-effectiveness and environmental advantages of DC power systems in commercial applications [84]. The 55,000-square-foot facility features 100 dock doors, 150 LED lights, natural light panels, compressed natural gas (CNG) tractors, and electric forklifts. As a LEED-certified facility, it underscores Pitt Ohio's dedication to sustainability and the integration of renewable energy solutions.

The microgrid is powered by a 50.4 kW PV system consisting of 180 panels, with vBoost 600 DC-DC converters stepping up the voltage to 380 V DC. Supplementary energy is provided by a 5 kW WindStax vertical axis wind turbine, which integrates into the system via a 48 V to 380 V boost converter. Energy storage is managed by a 75 kWh Aqueon battery system comprising five stacks. These batteries stabilize the microgrid and ensure continuous operation under variable weather conditions [84,85].

The microgrid used a 380 V DC system as its central power network, supplying energy directly to DC lights and other loads. It includes bidirectional inverters to convert 380 V DC to 208/480 V AC for non-DC loads. The energy management system coordinates power generation from solar, wind, and battery sources to meet the facility's energy requirements. During sunny periods, solar power is prioritized, while on cloudy days, wind and utility power provide supplementary energy. A transfer switch ensures uninterrupted power by switching to utility supply during system failures or low bus voltage conditions. Figure 8 shows the diagram of the microgrid.

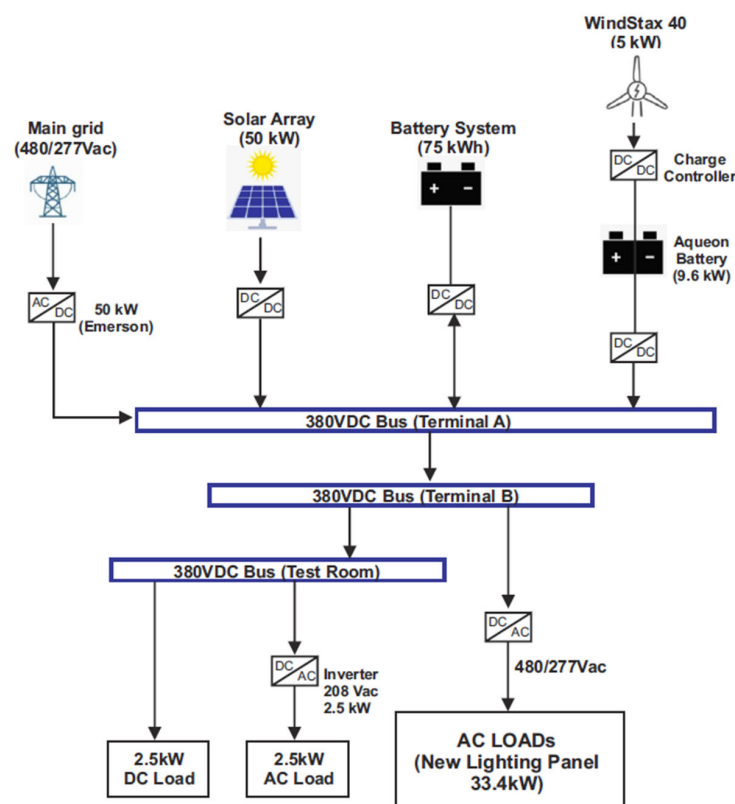


Figure 8. A diagram of the DC microgrid at Pitt Ohio Trucking Terminal.

Initial performance tests demonstrated the microgrid's capability to maintain steady-state operation, with voltage levels consistently ranging between 380 and 407 V DC. Renew-

able energy generation from solar and wind sources was optimized using local meteorological data, underscoring the feasibility of DC microgrids for commercial applications. The Pitt Ohio microgrid represents the first commercial installation in Pittsburgh to integrate 380 V DC technologies, providing a scalable model for similar facilities nationwide.

4.8. DC Microgrid at the Federal University of Pará (GEDAE-UFPA), Brazil

The Federal University of Pará (UFPA) DC microgrid was installed at the Grupo de Estudos e Desenvolvimento de Alternativas Energéticas (GEDAE) laboratory in Belém, Brazil [86]. This project was designed to evaluate the performance of a small-scale, low-voltage DC microgrid under real-world conditions. The system was specifically tailored to withstand the unique environmental challenges of the region, including hot and humid weather. Its main goal was to test the reliability, efficiency, and modularity of DC power systems while integrating commercially available equipment. The layout of the microgrid is shown in Figure 9.

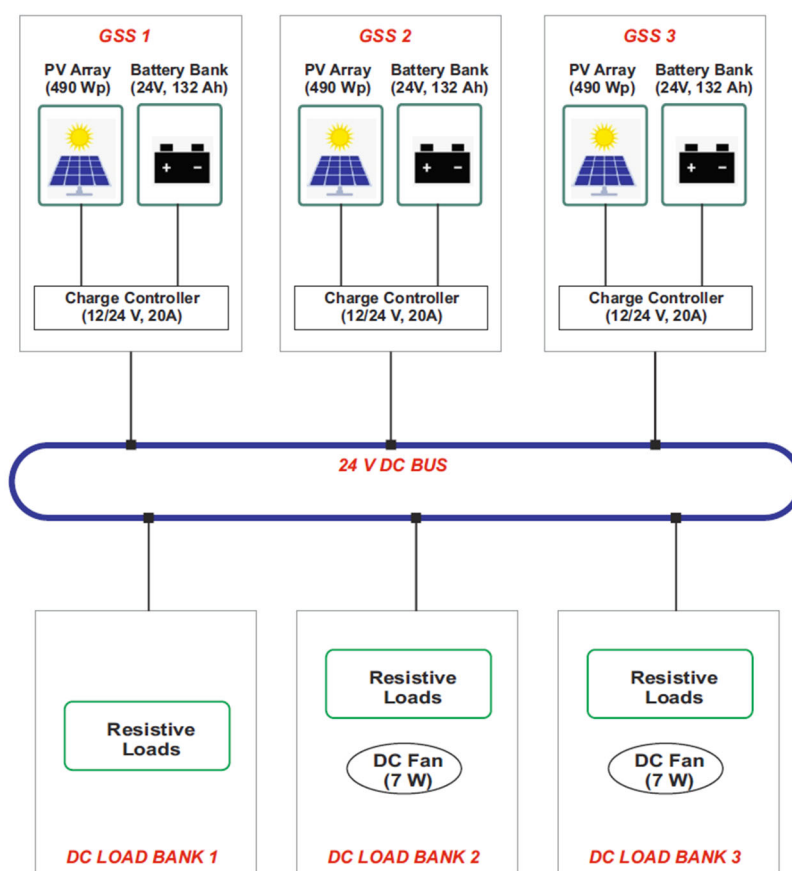


Figure 9. The layout of the DC microgrid at the Federal University of Pará (GEDAE-UFPA).

This microgrid is powered by three distributed generation nodes, each equipped with 490 Wp solar PV panels. Energy storage is provided by three battery banks, each rated at 132 Ah, which are connected to charge controllers that regulate their charging and discharging rates. The microgrid operates on a 24 V DC bus configured in a ring topology, which connects the generation nodes, battery banks, and load nodes. Loads include three variable DC load banks, which consist of resistive lamps rated at 40 W and DC fans rated at 7 W, enabling flexible testing scenarios.

The system's energy management is supported by commercial charge controllers that optimize PV performance using maximum power point tracking (MPPT) and regulate battery charging. Load profiles are pre-programmed to simulate real-world energy de-

mands, while the grid voltage is determined by the SOC of the battery banks. Although active bus voltage regulation is not implemented, the system maintains stable operation within a voltage range of 22 V to 26.45 V DC. During testing, the microgrid demonstrated consistent and reliable performance. Voltage variations affected load behavior, such as the brightness of incandescent lamps and the speed of DC fans; however, no operational faults were observed. The system also exhibited fault tolerance, allowing PV systems to operate independently of the battery banks and enabling reverse power flow between battery banks during periods of energy surplus.

A key feature of this microgrid was its modular design, which facilitates easy expansion through the addition of new generation or storage components. This project showed the potential of DC microgrids to deliver efficient and adaptable energy solutions, particularly in regions characterized by challenging environmental conditions and variable energy demands.

4.9. Coconut Island DC Microgrid, Hawaii, USA

The Coconut Island DC microgrid, located in Kaneohe Bay near Oahu, Hawaii, was developed to address the energy challenges of an isolated and storm-prone environment [87]. The project was led by the Hawaii Natural Energy Institute (HNEI) in partnership with the Okinawa Institute of Science and Technology (OIST) and Power Unit for Electric Systems (PUES) corporation, which contributed to establishing a swap battery charging station for project's electric vehicles. Additionally, University of Indonesia provided systems DC booster for DC mode to manage voltage. A unique feature of this microgrid was its hybrid functionality, capable of operating in both DC and AC modes to accommodate loads compatible with either power type. In DC mode, primary power was sourced from the PV system and the microgrid's battery. However, if a power shortage occurs in DC mode, the system seamlessly transitioned to its XW PRO 6.8 kW hybrid inverter, which connected the AC grid to the 48 V DC bus to ensure uninterrupted power supply.

The primary objective of the microgrid was to ensure a reliable energy supply for the research facilities it supports, serving as a testing ground for innovative renewable energy technologies and promoting sustainability in remote locations.

Technically, the system was powered by a 6.16 kW rooftop solar PV system consisting of two arrays with 11 panels each, rated at 280 W. Energy storage was provided by an 8 kW/8 kWh BESS with 96% roundtrip efficiency. The microgrid also included a swap battery charging station with 12 swappable batteries, each with a capacity of 1.4 kWh, supporting the project's EV. The system was powered from a 48 V DC bus that connects PV systems, ESSs, and hybrid appliances, including LED lighting and air conditioners capable of operating in both AC and DC modes. The schematic of the microgrid is shown in Figure 10.

Control and operation were managed by an industrial edge controller that optimizes energy flow and provides a user-friendly interface. Advanced safety measures were incorporated, including mechanical interlocks to prevent the simultaneous activation of multiple power sources. Fault handling mechanisms included voltage level adjustments and circuit isolation to maintain system stability and protect against power surges.

The microgrid demonstrated robust performance under varied operating conditions, achieving a 95% inverter efficiency and maintaining stable voltage levels in both AC and DC modes. This project served as a model for integrating renewable energy into remote and isolated locations. Its modular design allowed for future expansion, including the integration of additional energy sources or increased load capacity, further enhancing its scalability and applicability.

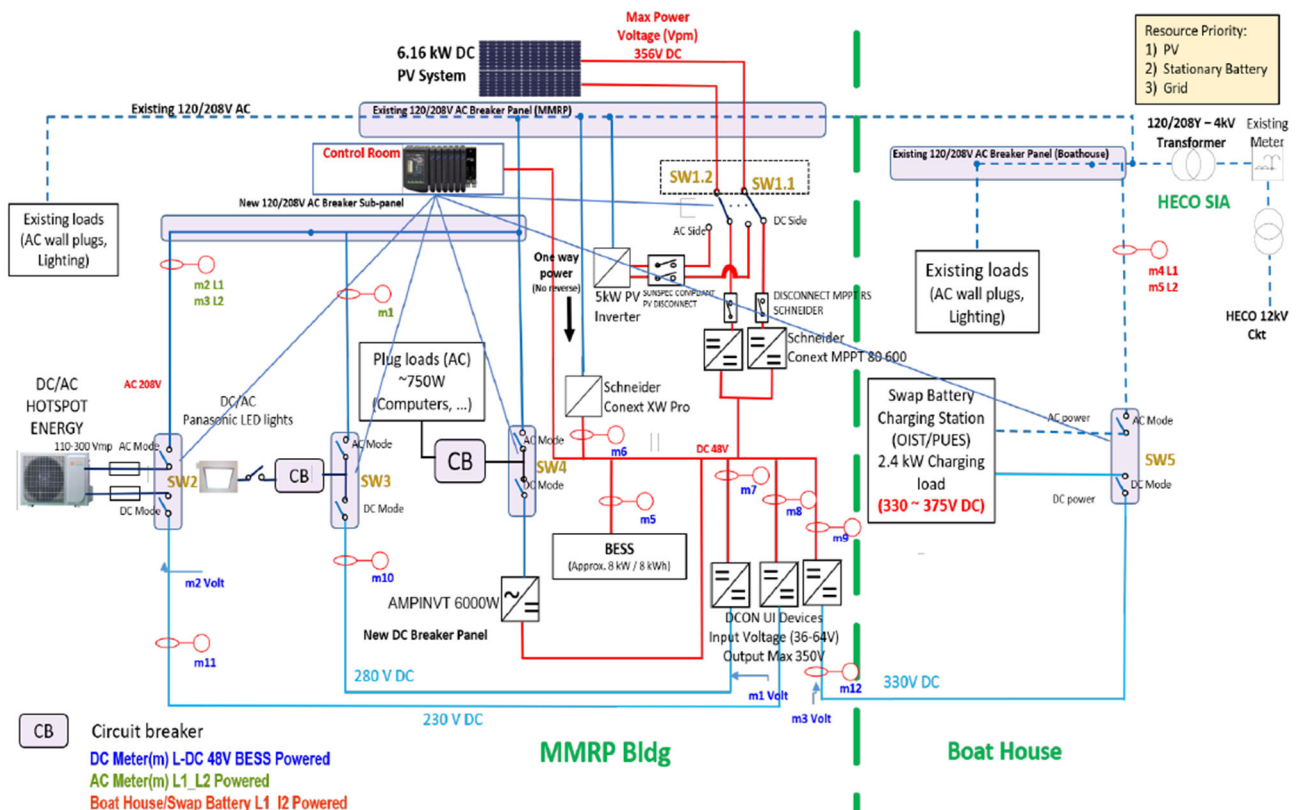


Figure 10. Schematic of Coconut Island DC microgrid [87].

4.10. 380VDC Power Supply System (500 kW Class) at TACC

A 380VDC power supply system was installed at the Texas Advanced Computing Center (TACC) at the University of Texas at Austin. The project was carried out through a partnership between the New Energy and Industrial Technology Development Organization (NEDO) and the state of Texas [88]. Running from August 2015 to March 2017, the initiative aimed to demonstrate the advantages of 380VDC power systems over conventional AC systems in terms of energy efficiency and reliability. The project also sought to validate the energy-saving potential of DC systems integrated with solar power generation, setting a target of a 15% reduction in energy consumption compared to similar AC systems.

The system was powered by a 200 kW rooftop solar photovoltaic (PV) array, configured to ensure compatibility with the 380 V DC bus. Energy storage is provided by lithium-ion battery compartment, which consists of 15 modules connected in series. The nominal voltage for each battery module is 22.2 V, giving the entire system a range of 270–378 V DC. The system's distribution infrastructure is built around a 380 V DC bus with N + 1 redundancy to ensure high reliability. It includes four 100 kW rectifier modules, which operate under adaptive power management to optimize efficiency based on load demand and solar power availability. Key loads include supercomputers, blade servers, LED lighting, and computer room air handlers (CRAHs). Figure 11 shows the configuration of this system.

An adaptive power management system was employed in maximizing energy efficiency by dynamically controlling the rectifiers. Under normal conditions, the system prioritizes solar power, followed by commercial grid power, and finally battery backup as needed. Voltage regulation and isolation mechanisms provide fault handling, ensuring operational stability during power surges or blackouts.

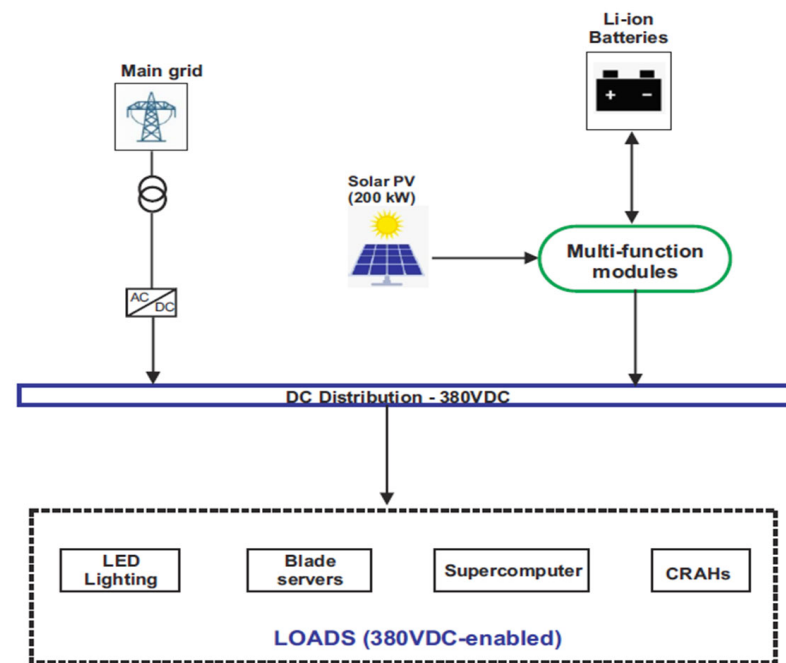


Figure 11. Configuration of 380VDC power supply system at TAC.

The performance of this 380VDC system exceeded expectations, achieving a 17% reduction in energy consumption compared to an equivalent AC system. This improvement corresponded to a 36% decrease in power losses and a reduction of 74.8 t-CO₂ in greenhouse gas emissions during the demonstration period. Additionally, the system significantly improved data center metrics, such as Power Usage Effectiveness (PUE) and Green Energy Coefficient (GEC), consistently outperforming the AC system in both areas.

The project demonstrated the sustainability and scalability of 380VDC power systems for commercial and academic applications. By significantly reducing carbon emissions and operational costs, it offers a compelling model for future implementations in data centers and other energy-intensive facilities.

4.11. 380-VDC Power Distribution System by NTT FACILITIES, Tokyo, Japan

NTT FACILITIES implemented a 380 V DC power distribution system at a 4 MW-scale cloud facility in Tokyo, Japan [89]. This project was part of a long-term initiative, launched in the early 2000s, aimed at advancing DC power systems for Information and Communication Technology (ICT) infrastructure. The system was designed to replace conventional AC and 48 V DC configurations with a more efficient and reliable architecture tailored for large-scale data centers.

The system is powered by a 6.6 kV AC supply from the utility grid, converted to 380 V DC through a modular rectifier system. The infrastructure is built around a 380 V DC bus with N + 1 redundancy, which includes an extra additional standby rectifier, ensuring uninterrupted operation even during component failures. The rectifier system is configured with a 5 + 1 modular design, where each module has a capacity of 100 kW, providing a total capacity of 500 kW. Backup power is provided by valve-regulated lead–acid (VRLA) batteries, designed to stabilize voltage and provide retention for up to five minutes during outages. Figure 12 shows the diagram of the power system. The system was also designed to support integration with renewable energy sources such as PV system and fuel cells.

The 380 V DC bus powers various data center equipment, including servers, storage units, and cooling systems, as well as DC-compatible appliances like LED lighting.

Adaptive power management optimizes the operation of the rectifiers, dynamically adjusting output to match load demand and maximize energy efficiency. Safety was ensured through high-resistance midpoint grounding, which limits ground fault currents, and voltage compensation mechanisms, which maintain stability during dips or surges.

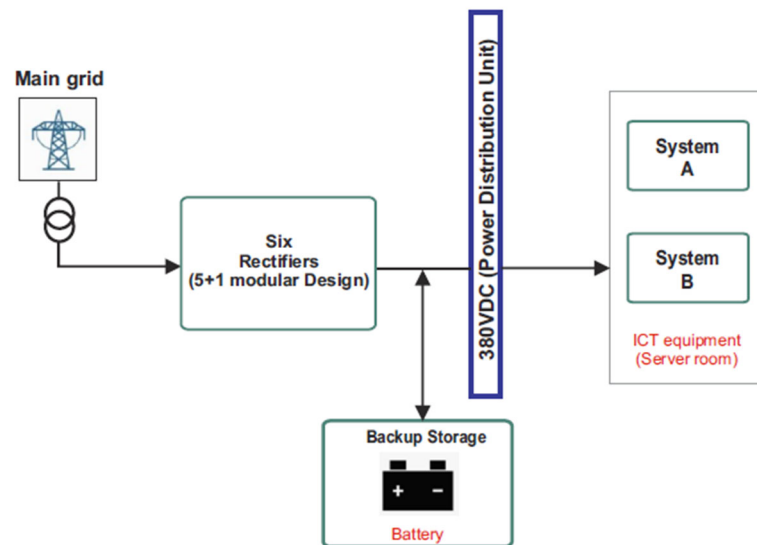


Figure 12. Diagram of 500 kW of 380-VDC power system at NTT FACILITIES.

The system demonstrated exceptional performance during its operation, achieving substantial energy savings by reducing power losses relative to AC systems. Its compact design delivered up to 31% space savings, offering a significant advantage for data centers with limited space. High reliability was consistently maintained, meeting the stringent standards necessary for data center operations. Additionally, the project contributed to international standardization efforts for 380 V DC systems, showcasing their scalability and applicability for large-scale ICT infrastructures.

By reducing energy consumption and carbon emissions, the project aligns with green ICT initiatives and provides a model for efficient and sustainable power distribution in data centers. The success of this system highlights the potential of 380 V DC technology to transform power management in critical infrastructure.

4.12. Fort Bragg DC Microgrid, NC

The DC microgrid at the Hercules Fitness Center on Fort Bragg Army Base, North Carolina, was developed as part of an initiative by Bosch in collaboration with the Department of Defense under the Environmental Security Technology Certification Program (ESTCP) [90]. This project was designed to improve energy efficiency, enhance resilience, and reduce costs while showcasing the advantages of DC power systems over traditional AC systems. Additionally, the microgrid aimed to serve as a scalable model for retrofitting existing buildings and supporting new construction.

The system features a PV system with a total capacity of 153 kW, installed in two phases. Phase one included a 31 kW DC system and a 14 kW solar PV array, mainly for an AC reference system, as depicted in Figure 13, which aided in comparing the performance of AC and DC microgrids. Phase 2 added 108 kW of solar power dedicated to charging the battery energy storage system (BESS). The microgrid utilized a 100 kWh BESS with bidirectional grid interconnection, enhancing resilience and optimizing energy use. A 380 V DC bus interconnects the solar PV array, battery storage, and building loads, enabling seamless integration with the utility grid [90–92].

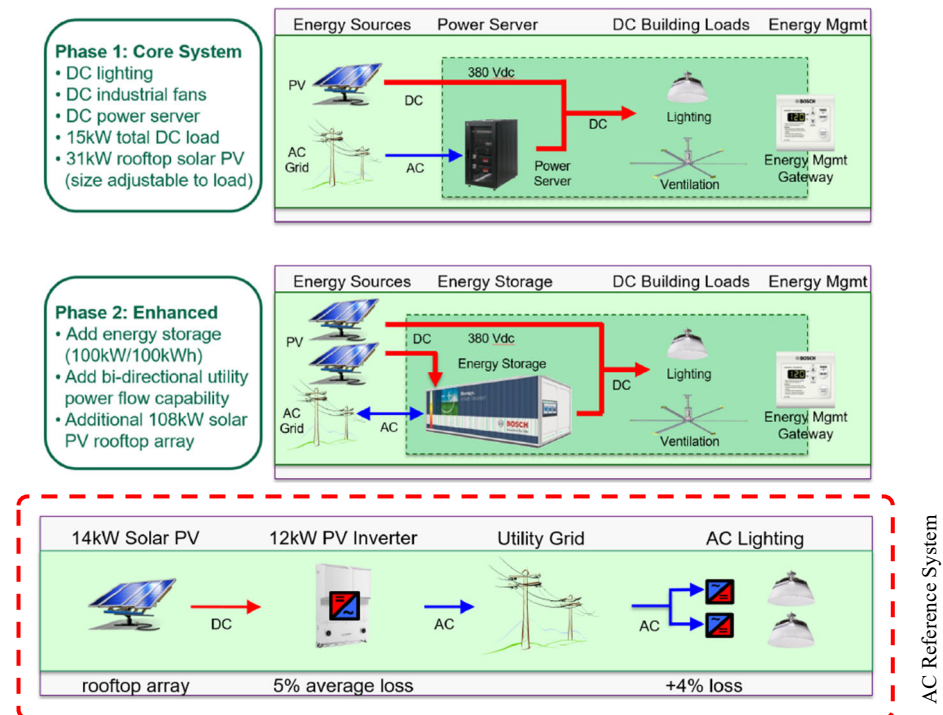


Figure 13. Block diagrams of Fort Bragg DC Microgrid [90].

The microgrid supplies power to critical loads in the fitness center, including 44 high-bay DC lights and 18-foot industrial ceiling fans. The energy management system prioritizes solar power for directly powering DC loads, with grid power or battery storage providing supplementary energy when required. The system incorporates dynamic MPPT to optimize solar PV performance and adaptive load balancing to ensure efficient energy utilization. During grid outages, the microgrid seamlessly transitions to islanded mode, maintaining power for critical loads. The microgrid block diagrams are presented in Figure 13.

Performance tests showed that the DC microgrid achieved 9% higher efficiency than AC systems, primarily due to reduced power conversion losses. The system also demonstrated robust resilience, ensuring continuous operation of critical loads during grid outages while extending backup capacity through the battery energy storage system. Furthermore, the microgrid seamlessly integrated with the existing building wiring, making it well-suited for phased retrofits and minimizing disruption during installation.

The Fort Bragg DC microgrid highlights the potential of DC systems to reduce carbon emissions and improve energy utilization. By highlighting the practical benefits of DC power, this project offered a scalable solution for enhancing energy independence and sustainability in both military and civilian applications.

4.13. Eindhoven DC Power Grid, Netherlands

The Eindhoven DC power grid was developed as part of the Direct Current Components +, focusing on powering lighting and other DC-compatible loads. The project investigated Grid (DCC+G) project and installed in an office building at the High-Tech Campus in Eindhoven, Netherlands [93]. Led by Philips Research, this initiative aimed to evaluate the feasibility and efficiency of 380 V DC power grids in commercial buildings show hybrid solar and grid-powered DC systems could reduce energy losses and enhance system integration compared to conventional 230 V AC systems.

The microgrid was powered by a combination of PV panels and grid. The solar system included nine modules, each rated at 225 W, providing a total capacity of 2.025 kWp. The

230 V AC mains grid was converted to 380 V DC using a 2 kW central rectifier unit. This configuration supplied power to 54 LED luminaires, each consuming 36.7 W DC, for a total load of 1982 W. The lighting system was divided into three groups, each connected via a dedicated 100 m cable. Power management was enhanced with a DC/DC converter featuring MPPT to optimize solar energy utilization. Additionally, a droop control function protected the system from overloading during high-voltage events. The schematic diagram of the system has been shown in Figure 14.

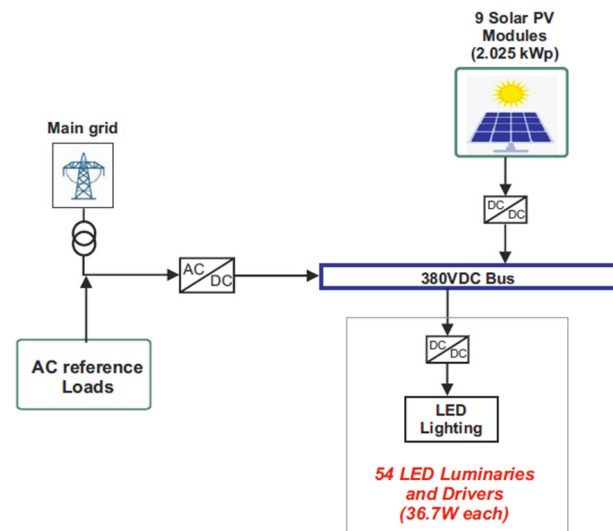


Figure 14. Schematic diagram of Eindhoven DC power grid.

The DC grid demonstrated notable energy efficiency improvements compared to traditional AC systems. It achieved an average efficiency gain of 2%, with potential savings of up to 5% under optimized conditions. Cable losses were notably reduced, as DC cables exhibited lower power losses than AC cables with the same configuration. Additionally, the LED lighting system powered by the DC grid consumed $0.87 \text{ W/m}^2/100 \text{ Lux}$, slightly lower than the $0.90 \text{ W/m}^2/100 \text{ Lux}$ recorded under AC supply. These results underscore the compatibility and efficiency of DC systems for modern lighting technologies.

The project demonstrated the potential of DC power systems to enhance energy efficiency and sustainability in commercial and office buildings. The modular design of the system enables scalability and future upgrades, providing a practical solution for integrating renewable energy sources and minimizing energy losses. By supporting the transition to more efficient building energy systems, the Eindhoven DC power grid contributes to broader efforts toward energy sustainability and the development of modern grid solutions.

4.14. DC Grid Prototype at Fraunhofer Institute, Germany

The Fraunhofer Institute in Erlangen, Germany, implemented a DC grid prototype as part of the European ENIAC R&D project “DC Components and Grid” (DCC+G) [94]. This system was designed to demonstrate the advantages of a 380 V DC power grid in an office building environment, focusing on energy efficiency, sustainability, and cost-effectiveness. The prototype integrates renewable energy sources, energy storage, and advanced power electronics to evaluate its potential compared to conventional AC systems.

The microgrid is powered by two primary energy sources. A PV system consists of two strings of 21 PV modules, each rated at 260 V, connected to the DC grid through maximum power point tracking (MPPT) converters. Additionally, a micro combined heat and power (μ CHP) unit, the EnerTwin, delivers 3 kW of electrical and 14.4 kW of thermal output using methane gas as fuel. The system also incorporates integrated battery storage,

which stabilizes voltage and provides backup power during grid outages. The distribution infrastructure operates on a central 380 V DC bus, employing droop control for voltage regulation and maintaining stable power flow across various subsystems. These subsystems include DC lighting, a low-power IT supply, a DC electric vehicle (EV) charger, and mixed AC/DC power monitoring units.

Power conversion is managed through two 15 kW rectifiers that convert AC grid power to 380 V DC. The system also incorporates multiple DC/DC converters to integrate solar PV and EV charging. This configuration minimizes energy conversion losses and reduces system complexity, contributing to the grid's overall efficiency. Figure 15 shows the diagram of the microgrid.

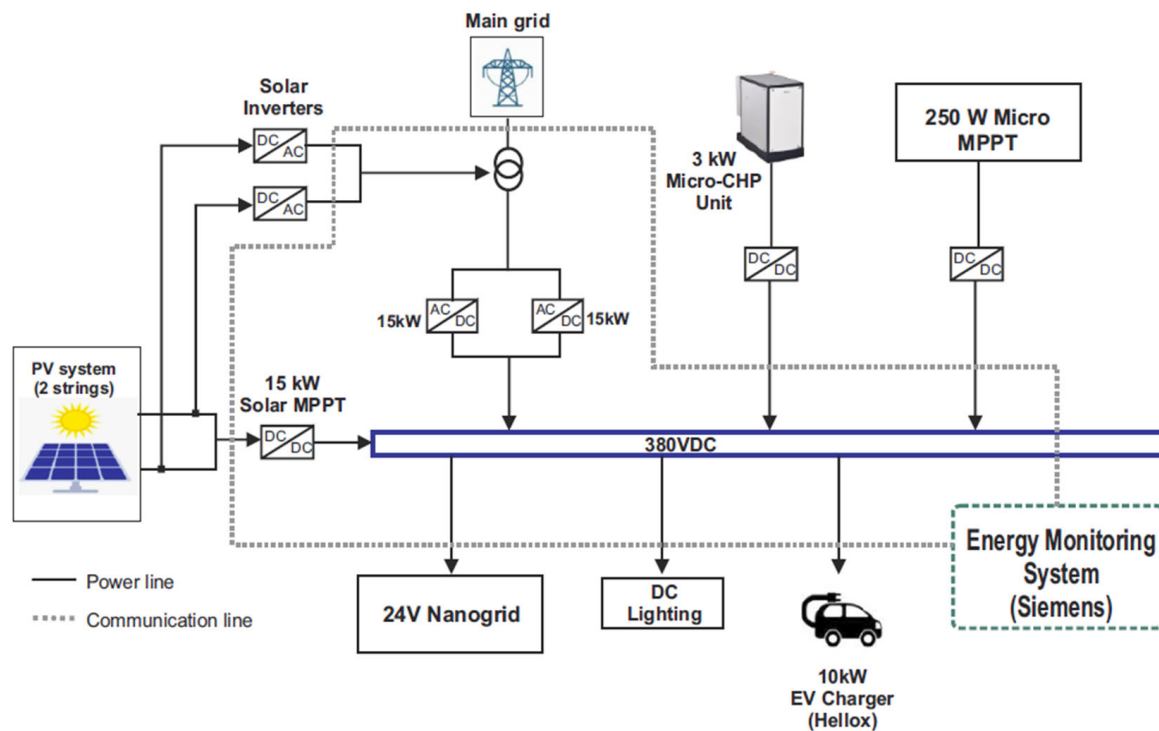


Figure 15. Schematic diagram of DC Grid Prototype at Fraunhofer Institute.

Performance tests showed that the DC system achieved a 2.7% efficiency improvement over AC grid system during typical operations, with efficiency gains reaching 5.5% on days with high local energy production. The DC-powered LED lighting system further demonstrated its advantages, reducing energy consumption to $0.87 \text{ W/m}^2/100 \text{ Lux}$ compared to $0.90 \text{ W/m}^2/100 \text{ Lux}$ for AC lighting. These results highlighted the potential of DC grids to enhance energy efficiency in modern buildings [92,94].

The project contributes to sustainability by supporting the integration of renewable energy sources and aligning with net-zero energy goals for commercial buildings. Its modular design underscores scalability for broader applications, including IT infrastructure and EV charging, while enabling future system upgrades. The Fraunhofer Institute's DC grid prototype highlights the potential of DC technology to improve energy efficiency and support environmentally friendly solutions in commercial and institutional settings.

4.15. CESI RICERCA DER Test Microgrid, Italy

The CESI RICERCA DER test microgrid, located in Italy, was developed as a low-voltage DC microgrid connected to a medium-voltage (23 kV) grid via an 800 kVA transformer [25]. The system integrates a range of distributed energy resources (DERs), advanced storage technologies, and controllable loads to evaluate its operational efficiency, scala-

bility, and energy reliability. Designed to operate seamlessly in both grid-connected and islanded modes, the microgrid offers a versatile platform for research and testing across various scenarios.

The microgrid is powered by multiple energy sources, including a 10 kW PV system, a 7 kVA diesel engine coupled with an asynchronous generator, and an 8 kVA simulated wind generator. Furthermore, the system incorporates five distinct PV fields utilizing various technologies, with a combined nominal capacity of 14 kW. This diverse mix of generation sources underscores the system's capability to seamlessly integrate renewable and conventional energy.

To support energy storage, the microgrid utilizes a mix of advanced systems, including a 100 kW lead–acid battery system with a 1 h runtime, Zebra batteries with a capacity of 64 kW and a 30 min runtime, a vanadium redox battery rated at 42 kW with a 2 h runtime, and a high-speed flywheel capable of providing 100 kW for 30 s. This hybrid setup ensures system stability and accommodates both short-term and long-term energy storage requirements, enabling the microgrid to manage varying load profiles and operational conditions effectively. The network configuration of the microgrid is illustrated in Figure 16.

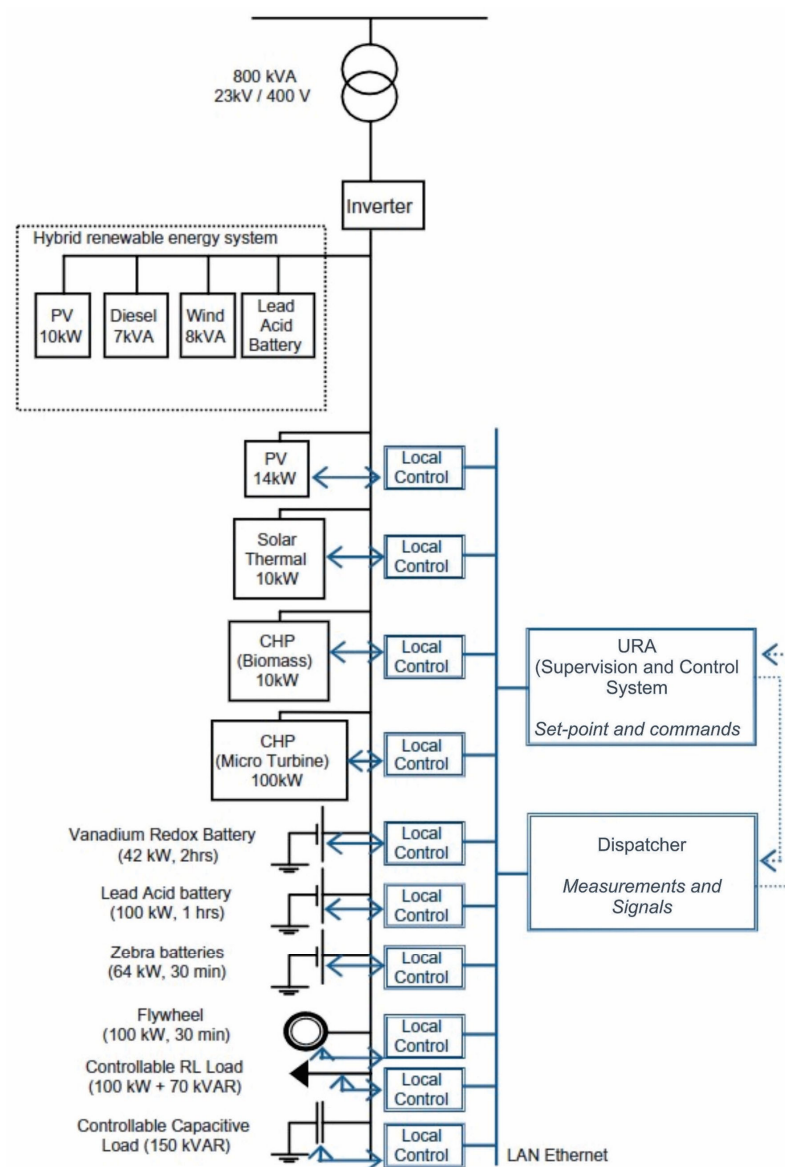


Figure 16. Network configuration of CESI RICERCA DER test microgrid [25].

The microgrid features a centralized Supervision and Control System (SCS), known as URA, to coordinate the operation of DERs, storage units, and controllable loads. The control architecture utilizes a hierarchical communication framework, integrating power-line carrier and 2.4 GHz wireless technology. The distribution infrastructure features controllable resistive-inductive (R/L) loads capable of providing up to 100 kW and 70 kVAR, as well as capacitive loads rated at 150 kVAR. This configuration enables precise demand-side management and optimized load scheduling [25,95,96].

Performance tests validated the microgrid's effectiveness in optimizing energy utilization and maintaining stable power delivery during both grid-connected and islanded operations. Reliable energy distribution was achieved through the implementation of advanced scheduling algorithms and real-time energy management strategies.

The CESI RICERCA low-voltage DC microgrid stands out for its innovative design, which integrates a hybrid combination of DERs and advanced storage solutions. Its modularity and scalability establish it as a versatile testbed for emerging technologies, showing advancements in microgrid design and energy management strategies. By addressing critical challenges in renewable energy integration and operational flexibility, the system offers valuable insights for both academic research and industrial applications.

5. Discussion

The analysis of the 15 case studies reveals several important trends in DC microgrid design and implementation. A common theme is the strong reliance on solar PV as the primary energy source, consistently paired with various battery storage solutions, most frequently lithium-ion, to enhance system reliability. Table 2 provides a summary of all the case studies, detailing key characteristics such as power rating, energy sources, storage capacity, grid connection mode, control strategy, voltage level, and primary applications.

Table 2. Summary of DC microgrid projects.

Case Study	Power Rating	Energy Sources	Storage and Capacity	Grid Connection Mode	Control Strategy	Voltage Level	Primary Application
Xiamen University, China	150 kWp (rooftop PV system)	Solar PV	200 Ah, 336 V lead-acid (~67 kWh estimated)	Grid-connected	Centralized (Cloud-based EMS)	380 V DC	Commercial building demonstration
Burlington DC Microgrid, Canada	~20 kW (approximate based on 2×8 kW PV + backup)	Solar PV, Natural Gas Generator	Vanadium redox battery system (20 kW/100 kWh)	Grid-connected	Decentralized	Bipolar ± 380 V DC	Industrial demonstration
Bosch DC Microgrid, California	286 kW (rooftop PV system)	Solar PV	180 kW lithium-ion battery	Grid-connected	Centralized (proprietary EMS)	380 V DC	Commercial facility (distribution center)
Obihiro Sanitation Center, Japan	PV systems rated at 20 kW + 30 kW from the main grid	Solar PV (primary); can draw from grid	25 kWh lithium-ion batteries	Islanded	Centralized	360–400 V DC	Office/building energy management
Nushima Island DC Microgrid, Japan	~9 kW (8 kW PV + 1 kW wind turbine)	Solar PV, Wind	46 kWh lithium-ion battery	Islanded	Decentralized	360 V DC	Island community power supply
Kirtland Air Force Base, USA	250 kW	Solar PV, Natural Gas Generators, Batteries	200 kW/200 kWh lithium-ion	Grid-connected	Centralized (via Central Energy Park)	750 V DC (bipolar ± 375 V)	Military testbed
Pitt Ohio Trucking Terminal, USA	50.4 kW (PV system) + 5 kW (Wind turbine)	Solar PV, Wind	75 kWh battery system (Aqueon)	Grid-connected	Distributed	380 V DC	Commercial (logistics/transportation facility)
Federal University of Pará (UFPA), Brazil	~1.47 kWp (3×490 Wp PV modules)	Solar PV	3 battery banks (each 132 Ah at 24 V; ≈ 9.5 kWh total)	Islanded	Centralized	24 V DC	Academic research laboratory

Table 2. Cont.

Case Study	Power Rating	Energy Sources	Storage and Capacity	Grid Connection Mode	Control Strategy	Voltage Level	Primary Application
Coconut Island, Hawaii, USA	6.16 kW	Solar PV	8 kW / 8 kWh battery energy storage system	Islanded	Centralized	48 V DC	Island community / remote facility
TACC, USA	500 kW-class system (200 kW PV array + main grid)	Solar PV; can draw from grid	Lithium-ion battery compartment ($\approx$ 200 kWh estimated)	Grid-connected	Distributed (adaptive PM system)	380 V DC	High-performance computing (data center)
NTT FACILITIES, Tokyo, Japan	500 kW (modular rectifier system)	AC supply (converted to DC), supports PV and fuel cells	VRLA batteries (exact capacity not specified)	Grid-connected	Adaptive / centralized	380 V DC	Data center / ICT infrastructure
Fort Bragg, USA	153 kW (total PV capacity from two phases)	Solar PV	100 kWh battery energy storage system	Grid-connected	Centralized	380 V DC	Military
Eindhoven DC Power Grid, Netherlands	$\sim$ 2 kWp (nine PV modules total)	Solar PV, supplemented by grid	(No dedicated storage reported)	Grid-connected	Distributed (droop control)	380 V DC	Urban commercial building (lighting focus)
Fraunhofer Institute, Germany	$\sim$ 30 kW (based on two 15 kW rectifiers)	Solar PV, μ CHP unit (methane-based)	Integrated battery storage (capacity approximated at $\sim$ 100 kWh)	Grid-connected	Decentralized	380 V DC	Commercial / institutional demonstration
CESI RICERCA DER Test Microgrid, Italy	$\sim$ 25 kW (10 kW PV + 7 kW diesel + 8 kW wind)	Solar PV, Diesel engine, wind generator	Hybrid storage: 100 kW lead–acid, Zebra batteries, vanadium redox, flywheel	Both grid-connected and islanded	Centralized	Low-voltage DC (as a low-voltage system)	Testing and validation / research platform

Considerably: centralized control is common in projects like Xiamen University and NTT FACILITIES, whereas distributed or decentralized approaches are favored in systems where flexibility and local autonomy are critical.

The comparative data demonstrate a significant diversity in system scale, voltage levels, and control strategies. Smaller systems, such as the UFPA microgrid or Coconut Island, typically operate at lower voltages (e.g., 24–48 V DC) and are designed for localized, often islanded, applications. In contrast, larger installations like Kirtland Air Force Base, Fort Bragg, and TACC operate at higher voltages (380–750 V DC) and are grid-connected to meet demanding industrial or military requirements. Moreover, control strategies vary

Another key insight from the case studies is the variation in energy storage and the challenges associated with standardization. While lithium-ion batteries are widely adopted for their efficiency and energy density, some projects continue to use lead–acid batteries in cost-sensitive scenarios. The choice of storage, along with the selected voltage level and control architecture, directly influences overall system performance and resilience. Despite the advantages observed, such as improved energy conversion efficiency and better integration of renewable sources, a universal standard for DC microgrid voltage, protection, and communication remains elusive, posing a barrier to broader adoption.

In summary, the case studies collectively illustrate that DC microgrids are emerging as viable and efficient alternatives to conventional AC systems. They offer flexible design options tailored to diverse applications, from academic research and commercial operations to military and remote community uses. However, to scale these technologies effectively, ongoing research must address standardization challenges, refine control strategies, and optimize storage solutions.

6. Challenges, Future Perspectives for DC Microgrids, and Conclusion

DC microgrids offer many advantages, but their widespread adoption is limited by technical, economic, and operational challenges. The notable challenges and future directions are discussed as follows.

6.1. Challenges

- **Standardization and Interoperability:** A lack of standardized components and protocols for DC systems complicates integration and scalability. Ensuring compatibility among devices from different manufacturers remains a significant hurdle.
- **Voltage Stability and Control:** DC microgrids often struggle with maintaining voltage stability under fluctuating loads and generation. Advanced control algorithms, though effective, require further optimization to balance performance and cost.
- **Protection and Fault Management:** Unlike AC systems, DC grids lack natural zero-crossing points, making fault detection and isolation more complex. This increases the cost and complexity of protective devices.
- **High Initial Costs:** The adoption of DC microgrids involves significant upfront investments in infrastructure, such as bidirectional converters, advanced storage systems, and energy management technologies.
- **Limited Awareness and Expertise:** Despite their benefits, DC microgrids face resistance due to the limited understanding of their operation and potential among stakeholders. Training and education are critical to addressing this gap.
- **Hybrid Integration Challenges:** Incorporating AC systems into hybrid DC/AC microgrids poses operational complexities, such as managing bidirectional power flow and ensuring seamless transitions between modes.

6.2. Future Perspectives

- **Establishing universal standards for DC microgrids** will streamline their implementation and promote global adoption. Governments, industry bodies, and researchers must collaborate to define guidelines and best practices for interoperability, communication protocols, and cybersecurity. While AC smart grids have well-established frameworks such as IEC 61850 and Smart Grid Architecture Model (SGAM), their direct application to DC microgrids remains limited due to fundamental architectural differences. However, adapting principles from SGAM could serve as a foundation for structuring communication layers and improving system coordination. Developing DC-specific extensions of existing smart grid models would bridge the gap between theoretical control strategies and real-world implementation. Standardized frameworks will enhance scalability, cybersecurity resilience, and seamless integration with larger energy systems, ensuring that DC microgrids evolve into more reliable and interoperable solutions.
- **Decentralized and Distributed Controls:** Shifting from centralized systems to distributed control approaches can improve scalability, resilience, and fault tolerance, particularly for large-scale and remote microgrids.
- **Integrated Renewable Systems:** The seamless integration of renewable energy sources, such as solar and wind, will drive the adoption of DC microgrids, particularly in off-grid and rural settings where access to conventional power is limited.
- **Cost Reduction through Modular Designs:** Modular and scalable DC microgrid architectures can reduce site-specific engineering costs, enhancing economic viability and making these systems accessible to a wider range of applications.
- **Enhanced Awareness and Training:** Outreach programs, educational initiatives, and industry workshops can address knowledge gaps and increase acceptance among stakeholders, fostering a more supportive ecosystem for DC microgrids.

DC microgrids hold immense potential for transforming energy systems, particularly in integrating renewable resources and supporting energy-efficient infrastructure. Overcoming existing challenges through innovation, policy support, and collaboration

will enable these systems to significantly contribute to achieving sustainable and resilient energy solutions.

In conclusion, this review examined the design, implementation, and performance of real-life DC microgrids. These systems show great potential to transform energy systems by integrating renewable energy sources, improving energy efficiency, and supporting decentralized power generation. The case studies discussed highlight the ability of DC microgrids to work effectively in different settings, including universities, industries, military bases, and isolated communities.

However, DC microgrids also face several challenges. These include high installation costs, technical difficulties in maintaining voltage stability and protection, and the absence of clear standards for their components and systems. Overcoming these challenges will require advancements in technology, better control methods, and global efforts to create standardized protocols. Providing training and raising awareness about the benefits of DC microgrids will also help encourage wider adoption.

As the world moves towards more renewable energy use and energy-efficient systems, DC microgrids are expected to play an important role in the future. With continued research, innovative solutions, and supportive policies, DC microgrids can provide clean, reliable, and accessible power to many communities. They have the potential to become a key part of building sustainable and resilient energy systems.

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