Overview of DC Distribution System in Low-Carbon Building–Part I: Configuration, Architectures and Applications

Zhiwei Wu, *Student Member*, *IEEE*, Fei Gao, *Member*, *IEEE*, Zongwen Zhang, Shuai Shao, *Member*, *IEEE*, Daniel J. Rogers, *Senior Member*, *IEEE*, Yuhong Zhu, Wei Li and Patrick W. Wheeler, *Fellow*, *IEEE*

***Abstract*—The building sector consumes approximately 32% of global energy and generates 34% of carbon dioxide emissions. Consequently, advancing energy conservation and emission reduction within this sector plays a critical role in mitigating the global climate crisis. Integrating photovoltaic (PV) generation, combined electrical and thermal energy storage systems, direct current (DC) distribution, and flexible load management technologies within buildings, synergistically optimized across the power source, energy conversion, and demand sides, creates pathways for decarbonizing the building sector. This review begins by elucidating the system's key configuration: building PV, energy storage systems (ESS), DC distribution systems and flexible loads, elaborating on their specific configurations and applications within the building environment. Subsequently, the paper reviews and analyzes low-voltage direct current (LVDC) voltage levels from the perspectives of existing standards and DC load demands. Focusing on DC distribution network topologies, this paper introduces unipolar and bipolar DC systems along with relevant studies, and reviews typical network configurations applicable to single buildings and building clusters. Following this, twelve global application case studies are presented and discussed, along with their key operational parameters. Finally, this paper discusses directions for technical standardization and future development trends.**

***Index Terms*—Building energy system, DC distribution system, DC microgrid, energy storage, flexible load, network topology, photovoltaic, practical applications, voltage levels.**

NOMENCLATURE

AC	Alternating current.
Ah	Ampere-hours.
ANSI	American National Standards Institute.
AI	Artificial intelligence.
BAPV	Building attached photovoltaics.
BIPV	Building integrated photovoltaics.
CCSA	Chinese Communication Standards Association.
DC	Direct current.
DER	Distributed energy resource.
DR	Demand response.
DSM	Demand side management.
ESS	Energy storage systems.
EV	Electric vehicle.
IEC	International Electrotechnical Commission.
IEEE	Institute of Electrical and Electronics Engineers.
ISO	International Organization for Standardization.
LVDC	Low-voltage direct current.
MTDC	Multi-terminal direct current.
PoE	Power over Ethernet.
PV	Photovoltaic.
SCR	Self-consumption rate.
SiC	Silicon carbide.
SoC	State-of-charge.
SSCB	Solid-state circuit breaker.
TCL	Thermostatically controlled load.
V2G	Vehicle-to-grid.
VC	Voltage class.

I. INTRODUCTION

THE global energy system faces two critical challenges: the growing scarcity of traditional fossil fuels and the environmental impact of energy production, including pollution and climate change. Consequently, decarbonization has become pivotal to achieving the objectives of the Paris Agreement. The United Nations Environment Programme's 2024 Emissions Gap Report specifies the required actions. To meet the agreement's goal of limiting the global average temperature increase to 1.5°C, global greenhouse gas emissions must be reduced by 42% by 2030 and 57% by 2035. [1].

The building sector's substantial contribution to global energy consumption and carbon emissions positions it as a critical area for decarbonization efforts. Consuming 32% of global energy and responsible for 34% of CO2 emissions [2], buildings are a key driver of the climate crisis, making research into their energy conservation and emission reduction urgently necessary. To address this challenge, both academia and industry have actively explored technological solutions, which have conventionally been categorized into supply-side and demand-side strategies aimed at enhancing energy efficiency and sustainability.

On the supply side, integrating PV systems is a key strategy for building decarbonization, offering a widely adopted clean energy alternative to fossil fuels [3], [4]. Buildings provide ample space for such distributed PV systems, and the technology has evolved from early rooftop applications BAPV to modern BIPV [5]. By merging power generation with architectural functions like facades, BIPV presents new decarbonization opportunities, particularly for high-density urban areas [6].

Reference [7] comprehensively assessed the PV installation and generation potential across 180,349 buildings in Hong Kong, revealing that building-applied PV could meet 12.7%~16.3% of the city's total electricity demand. This highlights the crucial role of BIPV systems in advancing the transition of Hong Kong's urban buildings towards a low-carbon future. Reference [8] investigated South Africa's PV resources and rooftop installation suitability, indicating that commercial building rooftops possess the potential for installing up to 12 GW of PV capacity, thereby assisting these buildings in achieving zero- or near-zero carbon targets. Given the inherent non-dispatchable nature of building PV generation, enhancing its on-site self-consumption rate within buildings constitutes a critical issue demanding urgent attention.

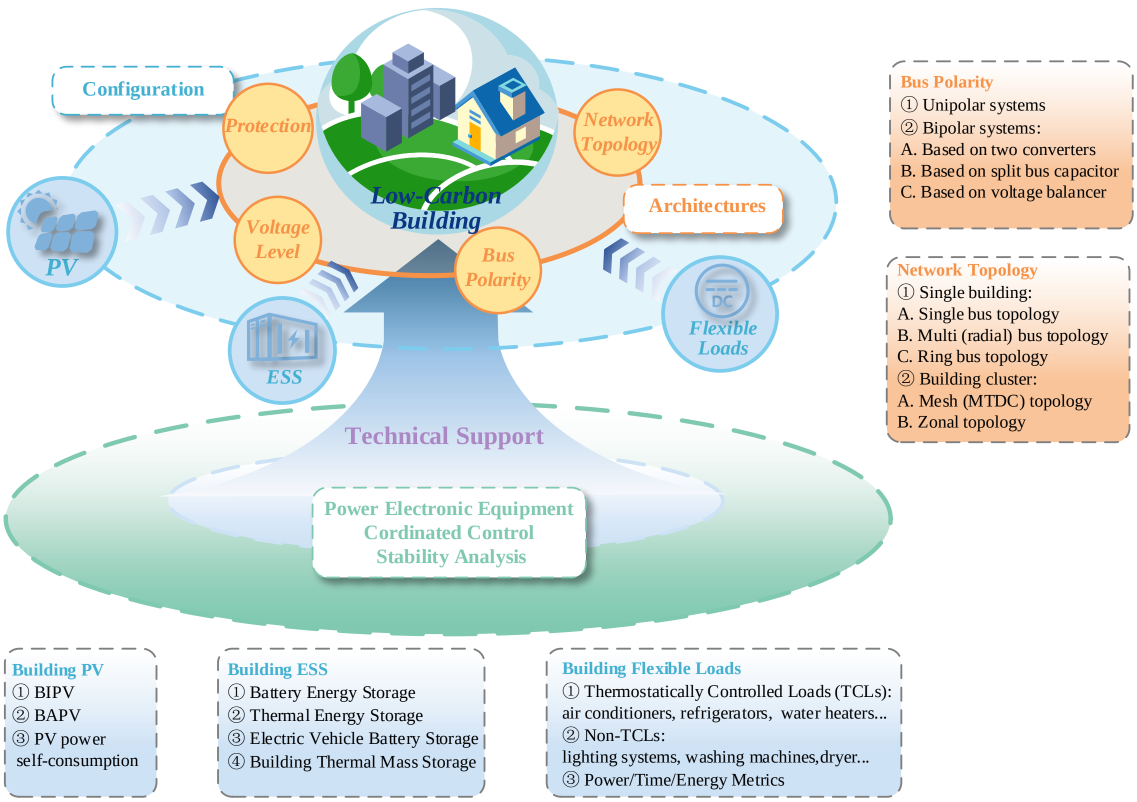

Fig. 1. Overview of DC distribution technology in low-carbon building.

On the DSM front, minimizing PV curtailment and maximizing the SCR represent key strategies for enhancing building energy efficiency, reducing emissions, and improving economic viability. One strategy to enhance PV self-consumption involves deploying ESS, enabling the effective temporal shifting of PV power and energy [9]. This approach not only mitigates the power fluctuations inherent in building PV generation but also contributes to grid stability and regulation. Research in [10] indicated that configuring a battery ESS with a capacity equivalent to 0.5~1 times the installed PV capacity can increase the PV self-consumption rate by 13%~24%. Another strategy for boosting PV self-consumption is applying load management techniques. This involves dynamically adjusting electricity usage patterns to shift dispatchable loads to periods of surplus PV generation, thereby enhancing on-site PV utilization. Studies in [11] demonstrated that while load shifting algorithms can effectively increase the self-consumption rate across various PV system configurations, their impact is relatively limited in AC systems employing conventional appliances. Reference [12] sampling 100 Dutch AC residential buildings, assessed the DSM potential of "wet appliances" (i.e., washing machines, dishwashers, and tumble dryers). The findings indicated that such DSM strategies could only increase the PV SCR by an amount equivalent to approximately 6% of the annual household electricity consumption. This suggests that relying solely on conventional DSM measures within traditional AC buildings faces limitations in significantly enhancing PV utilization. Consequently, achieving the efficient integration and coordinated management of diverse elements on both the supply and demand sides constitutes a key challenge in this domain.

Owing to their distinct advantages, including higher conversion efficiency, enhanced control flexibility, and greater ease of integrating PV and ESS, LVDC distribution systems have garnered significant attention in recent years [13], [14],

[15], [16]. By introducing LVDC distribution systems into buildings and establishing DC microgrids, the seamless integration and flexible control of PV generation, ESS, and flexible loads can be achieved. This offers a promising technological pathway towards achieving the low-carbon transition of buildings.

Although DC distribution systems face challenges such as the absence of natural zero-crossing point, lack of unified voltage standards, and higher costs of power electronic converters, they offer significant advantages over AC systems in low-carbon building applications [17], [18], [19], [20], [21]:

1) Higher energy conversion efficiency;
2) Absence of frequency synchronization and reactive power issues;
3) Simplified coordination and control of energy flow.

The application of DC microgrids has been extensively studied and implemented in various domains, including maritime vessels, rail transportation, and aerospace systems [22], [23], [24], [25]. References [23] and [24] provide a comprehensive two-part review of DC shipboard microgrids. Specifically, [23] focuses on the infrastructure, offering a detailed survey of power architectures and analyzing key functional blocks like energy storage systems and power converters. Complementing this, [24] addresses the operational aspects, reviewing the hierarchical control architectures, stability analysis methods for challenges like constant power loads and pulsed loads, and the associated protection schemes. Reference [25] investigated the application of microgrids incorporating renewable energy sources and ESS within the rail transportation sector, reviewing associated system architectures and control strategies. Reference [22] reviewed impedance modeling and stability analysis techniques within the context of more-electric aircraft DC microgrids. Reference [26] outlined the key characteristics, power electronic converters, control strategies, and stability issues associated with more-electric aircraft onboard microgrids. Reference [27] reviews the components, system architectures, and protection devices pertinent to all electric aircraft DC microgrids. Adopting such a DC distribution architecture offers potential for enhanced flexibility in power control and significant system mass savings.

DC microgrids require specifically adapted control strategies and hardware configurations to accommodate diverse application scenarios. This is because their power sources and loads have distinct characteristics; for instance, power sources can range from renewable energy to aircraft generators, while loads may include pulsed or constant power types. Buildings serve as superior platforms for the application of DC microgrids. The inherent advantages of DC microgrids can be fully leveraged in the building decarbonization process. Moreover, the unique characteristics of buildings offer additional application value for these microgrids. When applied in buildings, DC microgrid technology presents the following unique advantages [28], [29], [30], [31]:

1) Buildings provide ample installation space for PV systems.
2) Facilitation of the efficient integration of EVs, PV systems, BESS, and various DC loads (e.g., LED lighting, electronic devices);
3) Utilization of the building's inherent thermal mass for thermal energy storage, enhancing the control flexibility of thermal loads such as air conditioning;
4) Maximization of on-site PV energy consumption, with surplus power fed back to the AC grid, thereby enabling participation in grid ancillary services.

By integrating PV, ESS, and flexible loads within buildings, they can be transformed into multifunctional DC microgrids that combine generation, storage, consumption, and regulation capabilities. This approach enhances both the renewable energy utilization rate and overall energy efficiency of buildings at the supply-side and energy management levels. Consequently, it provides critical support for the building sector's low-carbon transition and contributes effective technological solutions to address climate change challenges. Fig.1 shows the Overview of DC distribution technology in low-carbon building.

The remainder of this paper is organized as follows: Section II outlines the key components of low-carbon building electrical systems and elaborates on their specific configurations within the building environment. A comparative analysis of system architectures for low-carbon buildings, discussing their voltage levels, network topologies, and applicability, is presented in Section III. Subsequently, Section IV presents practical engineering case studies of low-carbon buildings worldwide. The paper concludes with Section V, which also offers recommendations for future development directions.

II. ELECTRICAL CONFIGURATION

The schematic diagram of the system configuration is shown in Fig.2.

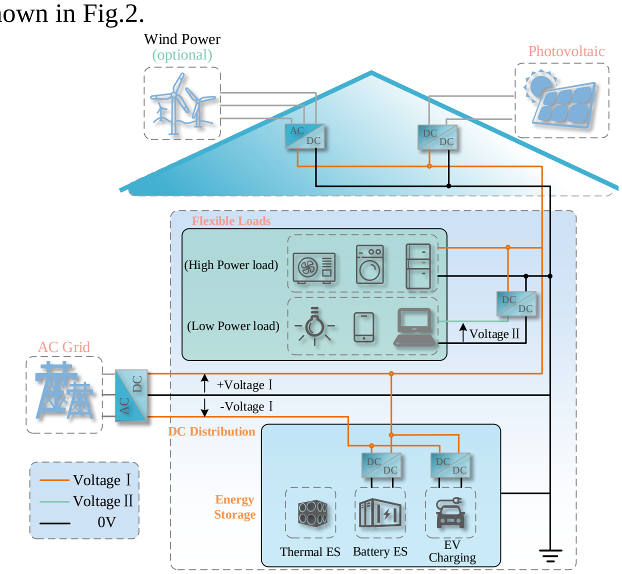

Fig. 2. Schematic diagram of the low-carbon building electrical system configuration.

The low-carbon buildings integrate PV generation, ESS, DC distribution, and flexible loads to establish a comprehensive building DC power system, thereby optimizing energy utilization efficiency. Such buildings possess dual functions of energy generation and flexible management, enabling them to dynamically respond to fluctuations in energy demand and variations in grid state. By implementing closed-loop energy management, low-carbon buildings achieve significant reductions in carbon emissions and represent a key technological pathway toward promoting sustainable development in the construction industry.

A. Building Photovoltaic

As a highly promising renewable energy technology, PV generation plays a crucial role in reducing CO_2 emissions and meeting building electricity demands. Although PV power generation exhibits inherent intermittency [21], building rooftops and facades offer ample space for the deployment of PV modules, presenting significant potential for achieving building energy self-sufficiency and lowering carbon emissions [32].

Currently, building PV systems are primarily categorized into two main types: BAPV and BIPV. BAPV involves retrofitting PV modules onto existing structures, an approach well-suited for such projects as the modules do not serve as integral building components. In contrast, BIPV integrates PV components with building elements [33], [34], forming composite units that possess the dual functions of power generation and serving as building envelope components.

Building PV systems, especially BIPV, provide large installation areas and are often simple to integrate. Beyond generating power, they also enhance a building's energy performance by creating a shading effect that reduces solar heat gain and lowers air conditioning loads. To maximize these benefits, current research in the field primarily focuses on optimizing system-level energy management and control strategies.

In the context of PV control, research primarily focuses on maximizing energy harvest and enhancing the level of on-site consumption for the generated PV power. The level of PV power self-consumption within low-carbon buildings is typically quantified using the PV Self-Consumption Ratio (PV_{SCR}) metric, as defined in (1):

$$PV_{SCR} = \frac{\sum P_{PV\_Load} + \sum P_{PV\_ESS}}{\sum P_{PV}} \tag{1}$$

where P_{PV_Load} denotes the PV power supplied to local loads, P_{PV_ESS} denotes the PV power directed to the ESS for charging, and P_{PV} represents the total power output of the PV system.

A higher PV_{SCR} value signifies a greater capability of the system for on-site consumption of the generated PV power. Therefore, enhancing this self-consumption ratio is a crucial supply-side measure for achieving building decarbonization.

Reference [35] addressed the shading effect imposed by upper structures on lower PV modules in multi-story building environments. By optimizing the tilt angle control strategy for BIPV shading elements, the study enhanced the overall PV power generation of the system. Reference [36] employed model predictive control for the optimal scheduling of PV systems equipped with battery storage, with the objective to simultaneously minimize battery degradation and maximize the PV_{SCR}. The contribution of this work is a control strategy that utilizes forecasts of generation and load to shift the battery charging profile to periods of peak PV generation. This approach ensures that battery capacity is available to absorb peak power, thereby reducing the battery's dwell time at high states of charge to minimize degradation.

The adaptive neuro-fuzzy inference system is an intelligent controller that integrates the learning capabilities of artificial neural networks with the linguistic reasoning of fuzzy inference systems to automatically learn key patterns from data. For instance, reference [37] proposed a control strategy based on an adaptive neuro-fuzzy inference system aimed at enhancing the utilization efficiency of building PV energy. Reference [38] proposed an optimized exponential droop control strategy for building PV systems. The control parameters of this strategy are dynamically adjusted based on the building's power generation and load profiles, aiming to mitigate voltage fluctuations at the point of common coupling and maximize PV energy self-consumption.

B. Building Energy Storage

The inherent intermittency of renewable energy sources poses significant challenges to the stable operation of building electrical systems, particularly concerning the maintenance of DC voltage stability and the avoidance of PV curtailment. ESS address these challenges by enabling energy time-shifting to balance supply and demand fluctuations. This effectively transforms intermittent renewable sources into dispatchable resources, thereby enhancing system flexibility and reliability [39], [40].

Building energy storage technologies have evolved into various forms tailored to different building characteristics [41], and application requirements. Prevalent types include: battery energy storage, thermal energy storage, storage utilizing EVs batteries, and building thermal mass storage. The principles and characteristics of these technologies are summarized in Table I. Fig. 3 illustrates four types of ESS employed in low-carbon buildings and their fundamental operating principles. Buildings can be equipped with a single storage technology or a hybrid combination of multiple types, depending on specific needs. Such synergistic applications can further enhance system flexibility and contribute to achieving carbon emission reduction targets.

Optimal capacity configuration and operational control strategies for building ESS are hot topics of current research. Optimal sizing of the ESS capacity is a critical aspect of system design. Reference [42] employed time series analysis, feedforward neural networks, and mixed-integer linear programming to optimize ESS capacity, aiming to bolster operational flexibility in islanded and grid-connected modes. Reference [43] introduced an ESS planning methodology based on Markov models, which incorporates time-of-use tariffs and aims to maximize the annual arbitrage benefit as the primary optimization objective. Reference [44] presented a techno-economic optimization approach leveraging genetic algorithms for ESS capacity sizing in nearly zero-energy buildings. This method integrates considerations of critical factors including meteorological data, PV self-consumption ratio, and battery lifespan. Reference [45] utilized particle swarm optimization to determine the optimal operational schedule for hybrid ESS in buildings, encompassing both thermal ESS and battery ESS. The contribution of this work is a co-optimization strategy for peak load shaving that significantly reduces the required battery ESS capacity by utilizing waste heat from the building's air conditioning system to charge the thermal ESS.

TABLE I
ENERGY STORAGE IN LOW-CARBON BUILDINGS

Type	Principle	Equipment	Advantage	Disadvantage
Battery Energy Storage System [45], [46], [47]	Stores and releases electrical energy through reversible electrochemical reactions.	Lithium-ion batteries, lead-acid batteries, flow batteries	• Fast response capability • Relatively high energy density • High application flexibility / Versatility • High efficiency • High technology maturity	• High initial investment cost • Potential safety risks Sensitivity of performance and lifespan to operating temperature
Thermal Energy Storage System [30], [45]	Stores or releases thermal energy by utilizing the temperature change (sensible heat) or phase transition (latent heat) of a storage medium.	Water storage tanks, phase change material storage units	• Cost-effective for specific applications • Generally high safety • Relatively simple maintenance	• Relatively low energy density; • Susceptible to static heat/cooling losses • Often requires significant installation space
Electric Vehicle Battery Storage[48], [49], [50], [51]	Enables bidirectional power flow (charging/discharging) between the EV battery and the building/grid	EVs batteries, bidirectional chargers (supporting V2G functionality)	• Enhanced utilization of EV battery assets; • Provides mobile and distributed storage resources; • Potential for grid service provision	• Frequent charge/discharge cycles may accelerate battery degradation • Availability is uncertain • Reliant on compatible bidirectional charging infrastructure
Building Thermal Mass Storage [52], [53]	Utilizes the thermal capacity of the building's structural components to passively absorb, store, and slowly release thermal energy	Building structural components (e.g., concrete slabs, walls, masonry structures)	• Very low / negligible marginal cost (leverages existing building structure); • Passive operation, typically requires no active control system	• Slow thermal response • Difficult to control precisely • Effectiveness is highly dependent on building design and local climate conditions

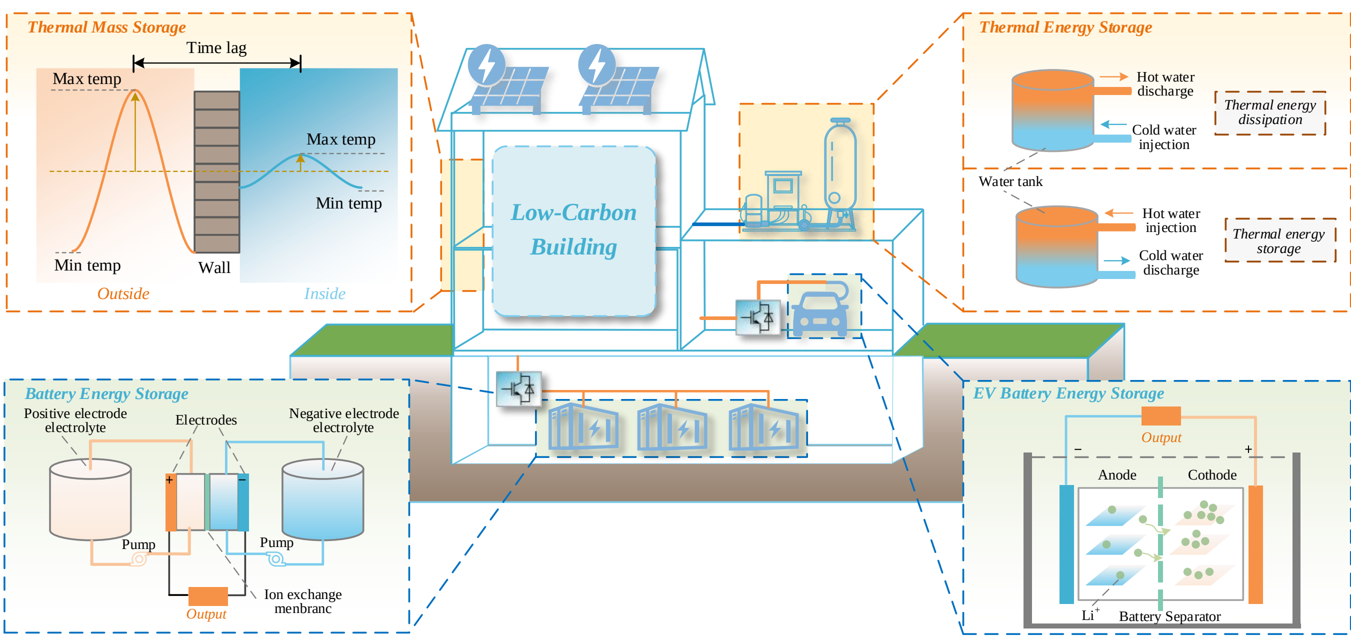

Fig. 3. Schematic diagram of energy storage system for low-carbon buildings.

Dual-timescale energy management is a strategy that splits the building's dispatch problem into two levels based on component response times. The longer, hourly timescale manages slow assets like fuel cells and thermal storage for the main energy balance, while the shorter, minute timescale uses fast resources like batteries and demand response to counteract real-time uncertainties. Reference [54] introduced a dual-timescale energy management strategy founded on a two-stage robust optimization model to coordinate thermal and electrical energy management in buildings. The strategy focuses on robustly addressing uncertainties associated with RES generation and load demands while guaranteeing occupant thermal comfort.

As a critical component of low-carbon buildings, ESS not only facilitate peak load shaving but also effectively mitigate the grid impacts associated with the integration of distributed renewable energy sources.

C. Building DC Distribution System

1) DC Distribution System advantages

In the transition towards low-carbon buildings, LVDC distribution technology, compared to conventional AC systems, establishes a more suitable infrastructural platform for enhancing energy efficiency. Key advantages of employing LVDC distribution systems in low-carbon buildings include:：

a) Inherent compatibility and flexible Integration: LVDC systems exhibit inherent compatibility with PV modules, ESS, DC appliances, and other DC sources and loads. This compatibility reduces the number of energy conversion stages, thereby achieving higher overall efficiency within the building energy system [55]. Devices can be directly connected to the DC bus via power electronic converters and managed through distributed control strategies for coordinated optimal control. This simplifies system interfaces and enhances both integration flexibility and operational adaptability [56].

b) Enhanced energy efficiency and reliability: Compared to AC systems, LVDC systems benefit from the absence of reactive power and synchronization requirements. They facilitate the integration of generation, distribution, and consumption at the building scale, optimizing local energy utilization and conversion. Moreover, for modern appliances like variable speed compressor refrigerators, a direct DC supply eliminates the need for an inverter, which significantly reduces conversion losses and improves overall energy transfer efficiency [57]. Furthermore, dynamic coordination with distributed generation and storage effectively enhances the power supply reliability of the building energy system [58].

c) Facilitation of EV integration and smart interaction: Amidst the rapid development of EVs, LVDC systems provide an ideal platform for efficient and flexible energy interaction between buildings and EVs [59]. LVDC serves as a natural charging interface for EVs, significantly reducing the number of power conversion stages and associated losses. Moreover, through advanced load management and energy scheduling strategies, building LVDC systems can support V2G or building-to-grid applications, offering ancillary services to the external AC grid [60], [61].

2) DC Distribution System Protection

In building DC distribution systems, components such as PV, ESS, and loads are interconnected through flexible and controllable power electronic converters. This creates a power electronics dominated system that offers significant operational flexibility but also introduces complex protection challenges [62], [63].

a) Challenges in DC Distribution Systems

First, DC systems lack a natural current zero crossing point, and their low impedance results in a very high rate of rise of fault current (di/dt). The fault current level is also highly variable due to the intermittency of distributed generators, as well as dynamic load demands [64]. Consequently, DC protection systems must be far more sensitive than their AC counterparts, requiring fault interruption within milliseconds to prevent damage to sensitive and costly power electronic equipment [65].

Second, the control strategies of power electronic converters, which typically limit fault currents to low multiples of the rated current or initiate a rapid shutdown, can make faults difficult to detect [66]. Furthermore, the bidirectional power flow resulting from the building's interaction with the grid can cause misoperation or non-operation of non-directional protection schemes [67].

To address these two key challenges, current research in DC protection focuses on two primary areas: fault detection methods and fault isolation equipment. The protection framework for the DC distribution system is shown in Fig. 4.

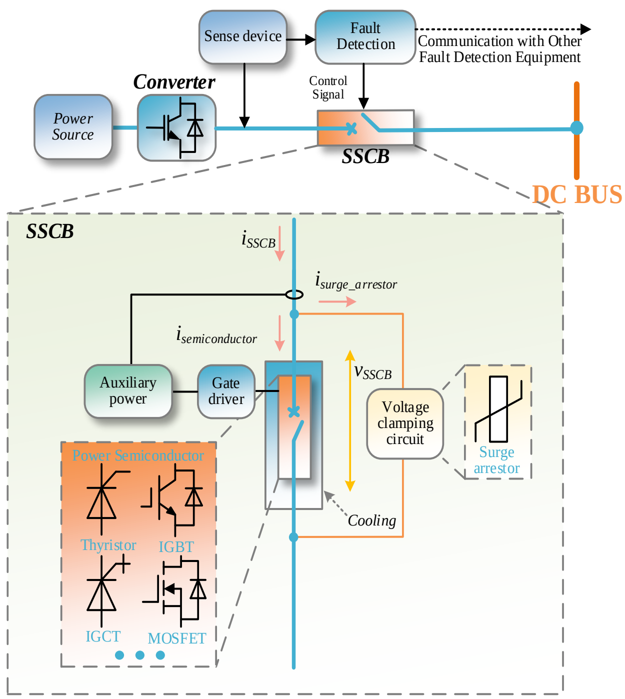

Fig. 4. Protection framework for the DC distribution system.

b) Fault Detection:

The technological frontier in fault detection has advanced from traditional methods relying on current magnitude to more sophisticated and sensitive techniques. These can be broadly categorized into signal processing-based and artificial intelligence-based schemes.

Signal Processing-Based Methods: These methods leverage the dynamic characteristics of fault signals. For example, reference [68] proposes a novel short-circuit protection method that monitors the turn on d*v*/d*t* of SiC MOSFETs, enabling an extremely fast fault response and enhanced noise immunity. Similarly, reference [69] presents a high-speed fault identification algorithm that utilizes the current derivative (d*i*/d*t*) signals from both line terminals to effectively detect and classify faults.

Artificial Intelligence-Based Methods: AI techniques are also widely applied to improve detection accuracy and robustness. Reference [70] proposes an enhanced differential protection scheme that uses a decision tree algorithm to process differential current and its first derivative for fault detection, followed by a K nearest neighbor algorithm for classification. To address the limitations of fixed thresholds, reference [71] introduces a two stage algorithm combining discrete wavelet transform for feature extraction with an artificial neural network for adaptive thresholding. Similarly, reference [72] presents a data-driven framework that uses highly comparative time series analysis to automatically extract a wide range of interpretable features, which are then synthesized by a softmax regression classifier to achieve high accuracy with a lower computational burden compared to deep-learning approaches.

c) Fault Isolation Equipment:

At the fault isolation level, the SSCB has emerged as a critical device for LVDC systems [73]. SSCBs leverage the fast switching characteristics of power electronics to interrupt current within microseconds. An SSCB is primarily composed of power semiconductor switches for current interruption and a voltage clamping circuit to absorb stored energy and suppress destructive overvoltages during turn-off [74], [75]. When a fault is detected, the power semiconductor device turns off in microseconds, interrupting the current without any mechanical parts or arcing. The voltage clamping circuit then activates to absorb residual energy from the system's inductance, protecting the switch from overvoltage damage. The absence of arc ablation and mechanical wear grants SSCBs higher reliability and a longer operational lifespan [75].

Research on SSCBs primarily focuses on enhancing their breaking performance and improving cost-effectiveness.

Enhancing Breaking Performance: The switching performance of power semiconductors is a key determinant of the breaker's interruption speed. To this end, wide-bandgap devices like SiC are increasingly used to enhance SSCB performance. For instance, reference [76] demonstrates an SSCB for LVDC systems using SiC MOSFETs for fast operation. Furthermore, reference [77] introduces a SiC JFET based cascade module topology to achieve superior voltage balancing. A self-powered bidirectional SSCB based on SiC JFETs has also been proposed in [78], which eliminates the need for external auxiliary power.

Improving Cost-Effectiveness: A major focus of SSCB research is cost reduction, as costs are often driven by expensive, fully controlled semiconductor switches. One approach is to use more economical components; for example, reference [79] proposes a cost-effective breaker using semi-controlled switches (e.g., thyristors) with coupled inductors. Another approach is to reduce the component count through innovative topologies. Reference [80] presents a single-branch SSCB that uses an air-core coupled coil to commutate the main thyristor, significantly reducing component count. For multi-port systems, reference [81] introduces a multi-port thyristor-based SSCB where all ports share a single auxiliary branch, lowering costs in complex DC microgrids.

In summary, the LVDC system protection combines advanced fault detection algorithms with fast acting SSCBs. This synergistic approach forms the core strategy for addressing the unique challenges of DC faults, ensuring the safe and reliable operation of LVDC distribution systems in buildings.

The application scope of LVDC distribution technology holds significant promise. At the building level, for instance, reference [82] has validated an inverter-less DC home microgrid by combining "source-load voltage matching" with a wireless sensor network to enhance energy transfer efficiency and reduce costs. LVDC distribution systems also have the potential to scale from individual buildings to community-level and city-level integrated energy management systems, which enables broader-scale energy optimization and reductions in energy consumption and emissions [83]. The specific architecture of building LVDC distribution systems will be discussed in detail in Section III.

D. Building Flexible Loads

1) Flexible Loads Classification

Building flexible loads, enabled by advanced energy management technologies and intelligent control methods, transform conventional rigid electrical loads into dynamically adjustable forms, allowing them to respond flexibly to grid signals or user requirements [84], [85]. This flexibility enables building loads to effectively coordinate with DER and ESS. Consequently, they can actively participate in grid DR programs, adapt to DER variability, contribute to higher DER on-site utilization rates, reduced building carbon emissions, and the preservation of user energy requirements and comfort levels [86].

Loads within buildings are primarily categorized into TCLs and non-TCLs. TCLs, exemplified by air conditioners, refrigerators, and water heaters, constitute key flexible resources with significant DR potential. Particularly in commercial buildings, air conditioning load can account for over 50% of the peak demand [87]. The substantial thermal mass of building structures (i.e., the capacity of materials to absorb, store, and slowly release heat) [88] provides air conditioning systems with considerable operational flexibility. This allows their energy consumption to be dynamically adjusted based on external weather conditions, building thermal characteristics, and user comfort settings—while maintaining occupant thermal comfort [89], [90], [91]. Coordinating TCLs operation with intermittent renewable energy generation can effectively reduce reliance on fossil fuels. Furthermore, non-TCLs, such as lighting systems, typically account for 10%-15% of total building energy consumption [92]. Leveraging sensors and advanced control systems, lighting loads can be optimized based on external daylight availability and indoor occupancy status [93], [94].

Lighting systems offer rapid response capabilities, providing fast DR services by instantly reducing load levels [95]. For certain household appliances in residential buildings (e.g., washing machines, dryers, dishwashers), their operation times can be flexibly shifted to off-peak periods with lower electricity prices or higher renewable energy availability, further optimizing energy consumption patterns [96].

2) Flexible Loads Evaluation Metrics

Fig. 5 shows the power modulation profile of a flexible load during a DR event. Following the DR event, the load power typically returns to its baseline level. However, due to the deferred satisfaction of some energy requirements, a short-term surge in energy demand may occur immediately after the response period. This phenomenon is known as the “rebound effect” [97]. To quantify the flexibility potential and response characteristics of building loads, existing research has proposed evaluation metrics across multiple dimensions. These typically include power modulation capability, response duration, adjustable energy capacity, and economic benefits [86].

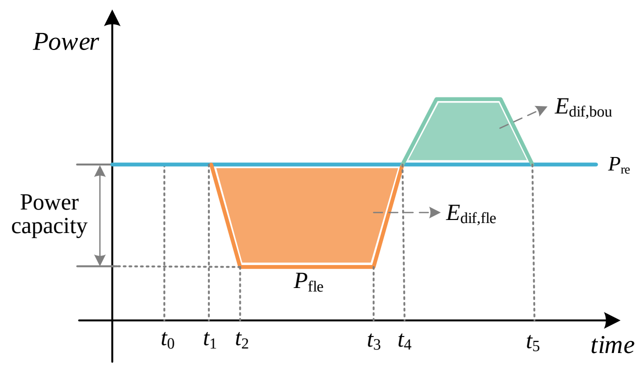

Fig. 5. Illustration of a flexible load power profile during demand response.

a) Power Metrics

Power metrics quantify the magnitude of power adjustment during the flexible regulation process. Common metrics include the instantaneous power adjustment ΔP [98] and the average power adjustment ΔP_{ave} [99], defined by (2) and (3), respectively:

$$\Delta P(t) = P_{\text{fle}}(t) - P_{\text{re}}(t) \quad t \in [t_0, t_4] \tag{2}$$

$$\Delta P_{\text{ave}} = \left(\int_{t_0}^{t_4} |P_{\text{fle}}(t) - P_{\text{re}}(t)|\, dt \right) / (t_4 - t_0) \tag{3}$$

References [100] and [12] defined two normalized metrics to evaluate the DR intensity of flexible loads: Int_a, representing the intensity normalized by building floor area, and Int_h, representing the intensity normalized by the number of occupants. Their calculation methods are provided in (4) and (5), respectively.

$$\text{Int}_a = \frac{\Delta P_{\text{ave}}}{A_{\text{building}}} \tag{4}$$

$$\text{Int}_h = \frac{\Delta P_{\text{ave}}}{N_{\text{household}}} \tag{5}$$

Furthermore, the ramp-down rate, denoted as Ram_{down}, is defined as the ratio of the maximum power adjustment achieved by the flexible load to the time taken to reach this maximum adjustment level, as presented in (6).

$$\text{Ram}_{\text{down}} = \frac{P_{\text{fle\_max}}}{t_2 - t_1} \tag{6}$$

the variables used in the power metric formulas (2)~(6) are defined as follows: P_{fle} represents the actual power consumption of the flexible load during the regulation period; $P_{\text{fle\_max}}$ represents the maximum achievable power adjustment capacity of the flexible load; P_{re} represents the baseline power consumption of the flexible load (i.e., power without regulation); t_0 and t_4 represent the start and end times of the DR event, respectively; A_{building} represents the total floor area of the building; $N_{\text{household}}$ represents the number of households or occupants in the building; t_1 and t_2 represent the start time of the flexible power regulation and the time at which the maximum power adjustment is reached, respectively.

b) Time Metrics

Time metrics are employed to evaluate the demand flexibility of building loads. Key time indicators include: the response start time (T_{st}), the ramp-up time (T_{ra}), the duration of the flexibility provision ($T_{\text{dur,fle}}$), and the duration of the subsequent recovery or rebound phase ($T_{\text{dur,bou}}$). These parameters can be calculated using (7), respectively.

$$\begin{aligned} T_{\text{st}} &= t_1 - t_0 \\ T_{\text{ra}} &= t_2 - t_1 \\ T_{\text{dur,fle}} &= t_3 - t_2 \\ T_{\text{dur,bou}} &= t_5 - t_4 \end{aligned} \tag{7}$$

where t_3 represents the time when the DR regulation period is commanded to end; t_5 represents the time when the rebound effect concludes.

c) Energy Metrics

Energy metrics are primarily used to quantify the change in energy consumption or the adjustable energy capacity of flexible loads during DR periods. $E_{\text{dif,fle}}$ represents the energy consumption reduction achieved by the flexible load during the flexibility provision period, calculated via (8); Additionally, the peak load reduction intensity (Int_e) and the peak load reduction rate (μ) are key metrics for evaluating peak shaving performance, calculated using (9) and (10), respectively [101]. The change in energy consumption during the payback effect period, $E_{\text{dif,bou}}$ can be calculated using (11) [102]; The net energy consumption change over the entire DR event, $E_{\text{dif,tot}}$ is given by (12).

$$E_{\text{dif,fle}} = \int_{t_0}^{t_4} |P_{\text{fle}}(t) - P_{\text{re}}(t)|\, dt \tag{8}$$

$$\text{Int}_e = \frac{\int_{t_0}^{t_4} |P_{\text{fle}}(t) - P_{\text{re}}(t)|\, dt}{A_{\text{buiding}}} \tag{9}$$

$$\mu = \int_{t_0}^{t_4} |P_{\text{fle}}(t) - P_{\text{re}}(t)|\, dt \Big/ \int_{t_0}^{t_4} P_{\text{re}}(t) dt \tag{10}$$

$$E_{\text{dif,bou}} = \int_{t_4}^{t_5} |P_{\text{fle}}(t) - P_{\text{re}}(t)|\, \text{d}t \tag{11}$$

$$E_{\text{dif,tot}} = \int_{t_0}^{t_4} |P_{\text{fle}}(t) - P_{\text{re}}(t)|\, \text{d}t + \int_{t_4}^{t_5} |P_{\text{fle}}(t) - P_{\text{re}}(t)|\, \text{d}t \tag{12}$$

d) Benefit Metrics

Benefit metrics aim to evaluate the overall advantages derived from flexible load regulation across multiple dimensions, such as economic and environmental aspects. Different stakeholders (e.g., building owners, grid operators, policymakers) may prioritize distinct benefits: owners often focus on economic returns, while the latter groups might emphasize CO_2 emission reductions and enhanced grid operational stability.

Common benefit metrics include: the total operational cost savings ($C_{\mathrm{op,tot}}$), calculated using (13); the operational cost reduction rate (φ), calculated using (14) [103]; and the CO_2 emission reduction (E_{m}), calculated using (15) [104].

$$C_{\mathrm{op,tot}} = \int_{t_0}^{t_4} \left\{ \left[P_{\mathrm{fle}}(t) - P_{\mathrm{re}}(t) \right] \times k(t) \right\} dt + \int_{t_4}^{t_5} \left\{ \left[P_{\mathrm{fle}}(t) - P_{\mathrm{re}}(t) \right] \times k(t) \right\} dt \quad (13)$$

$$\varphi = \frac{\int_{t_0}^{t_4} \left\{ \left[P_{\mathrm{fle}}(t) - P_{\mathrm{re}}(t) \right] \times k(t) \right\} \mathrm{d}t + \int_{t_4}^{t_5} \left\{ \left[P_{\mathrm{fle}}(t) - P_{\mathrm{re}}(t) \right] \times k(t) \right\} \mathrm{d}t}{\int_{t_0}^{t_4} \left[P_{\mathrm{re}}(t) \times k(t) \right] \mathrm{d}t + \int_{t_4}^{t_5} \left[P_{\mathrm{re}}(t) \times k(t) \right] \mathrm{d}t} \quad (14)$$

$$Em = \int_{t_0}^{t_4} \left\{ \left[P_{\mathrm{fle}}(t) - P_{\mathrm{re}}(t) \right] \times \lambda \right\} \mathrm{d}t + \int_{t_4}^{t_5} \left\{ \left[P_{\mathrm{fle}}(t) - P_{\mathrm{re}}(t) \right] \times \lambda \right\} \mathrm{d}t \quad (15)$$

where k(t) represents the real-time electricity price at time t; λ represents the equivalent CO_2 emission factor for electricity purchased from the public grid.

The evaluation metrics reviewed above, based on the dimensions of power, time, energy, and benefit, can inform the assessment of building flexibility performance; however, a unified standard is currently lacking. As low-carbon building DC distribution systems become more widespread, the evaluation of flexibility performance is anticipated to receive increasing attention and necessitate further development.

III. DC Distribution System Architectures

A. Voltage Level of Building DC Distribution

Low-carbon buildings increasingly utilize LVDC distribution systems, owing to their significant potential in reducing costs, enhancing the integration efficiency of DERs and ESS, improving system reliability, and promoting energy savings [105]. Typically, LVDC is defined as DC voltage below 1500 V, and various international organizations and countries have established corresponding voltage level standards [13], [58], [106].

1) Current Status and Development of Voltage Levels

a) IEC International Standards

The IEC 60038 standard [107] specifies 27 LVDC voltage levels within the 2.4V to 1500V range, as detailed in Table II. Notably, this includes the widely applicable 48V standard, employed in fields such as telecommunications and battery energy storage. Bipolar ±750V systems, along with derived ±375V line configurations, are currently finding application in building power systems.

TABLE II
IEC 60038 DC Voltage Level

Preferred	Supplementary
1500	600
750	250
440	125
220	80
110	40
96	30
72	15
60	9
48	7.5
36	5
24	4.5
12	4
6	3
	2.4

unit:Volt(V)

b) China Standards

The Chinese national standard GB/T 35727-2017 [108] stipulates LVDC power distribution voltage levels within the 110 V to 1500 V range, as detailed in Table III. It gives preference to three primary voltage levels and their derived bipolar system configurations, while also listing seven alternative levels. The selection of these voltage levels considers international standards from organizations like IEC, IEEE and ITU, alongside specific domestic applications within China (e.g., metro traction, household appliances, data centers, and EVs charging).

TABLE III
China GB/T 35727 DC Voltage Level

Preferred	Supplementary
1500(±750)	
	1000
750(±375)	
	600
	440
	400
	336
	240
220(±110)	
	110

unit:Volt(V)

c) German Standards

Germany utilizes a voltage band approach (VC1-VC4) to define LVDC power distribution voltage levels, as shown in Table IV. This methodology grants distribution system operators the flexibility to select operating voltages within a specified range (U_2-U_3) [105]. This approach aims to ensure equipment compatibility for operation at the chosen voltage level. A noteworthy aspect is the inclusion of a specific 440 V level within the VC system. This level is strategically established to facilitate the large-scale deployment of cost-effective, 650 V-rated silicon power electronic devices within switched-mode power supplies.

TABLE IV
Germany DC Voltage Level

Voltage class	Use case	U_2	U_3
1	Distribution to/in residential and commercial buildings	320	440
2a	Distribution to/in industrial applications	440	800
2b	Distribution to/in DC charging parks	440	1000
3a	Industry applications with active in feed converters	620	750

3b	Industry applications with uncontrolled rectifiers as connection to the AC grid	485	750
4	Long distance and high-power distribution	1280	1500

unit:Volt(V)

Consequently, the current landscape of LVDC distribution systems is characterized by the coexistence of multiple voltage levels and a lack of unified standards, which impedes the widespread adoption of these systems development.

2) DC Load Voltage applications

Fig. 6 visually summarizes an investigation conducted by the IEC regarding LVDC load voltage. This comprehensive report surveyed global DC load voltage level, the applications ranging from light loads to building mains. Crucially, the report's analysis of these diverse voltage requirements highlights that the variety of standards poses a barrier to the wider adoption of LVDC, underscoring the need for standardization [109].

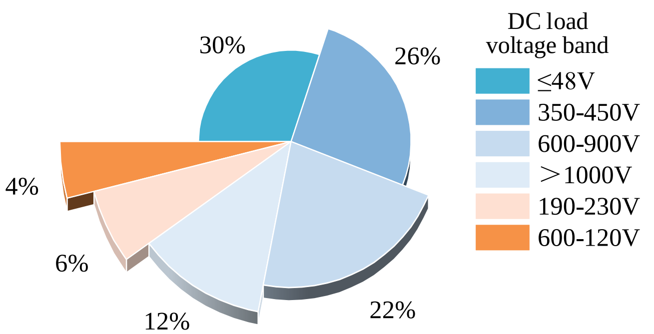

Fig. 6. Statistical distribution of LVDC load voltage requirements based on an IEC survey.

The survey reveals that DC loads rated at ≤48V account for 30% of the total, while those in the 350~450V and 600~900V ranges constitute 26% and 22%, respectively. Collectively, these three voltage categories cover 78% of DC loads, indicating their broad applicability and suggesting that a limited number of unified voltage standards could meet the requirements of most devices in low-carbon buildings.

In practice, the selection of voltage level typically depends on the power demand. Higher power ratings generally necessitate correspondingly higher voltage levels to minimize line losses and enhance power delivery capability. For instance, the 600–900V range is suitable for large loads in building (e.g., elevators, EVs charging stations); the 350~450V range primarily serves household appliances; while the safe 48 V level is widely employed for low-power devices and end-user equipment [13], [58].

Within the safety extra-low voltage range, PoE technology facilitates the simultaneous transmission of data and electrical power over a single Ethernet cable [110], [111], offering a solution for achieving both synergistic control and energy efficiency in building distribution system. The native DC architecture of PoE enables seamless integration with emerging DC power distribution systems, thereby enhancing overall system efficacy. Specifically, this technology can eliminate the inefficient AC-DC conversion stage within end-devices, such as LED luminaires, while its inherent data link provides capabilities for granular device monitoring and management [112], [113]. The primary advantages of deploying PoE include[114], [115]: 1) lowers the installation costs; 2) enables smart controls; 3) facilitates integration; and 4) enhances user experience. The latest IEEE 802.3bt standard [116] leverages all four twisted pairs within the Ethernet cable to increase the maximum power delivery to 90W (Type 4). This represents a substantial increase from the 15.4W specified by the earlier IEEE 802.3af standard [117], greatly expanding the application scope of PoE. However, this advancement in power level introduces new challenges, particularly concerning thermal management in high-density cable bundles. Furthermore, balancing high data-rate transmission with high current-carrying capacity imposes stringent requirements on cable selection and overall system design [114]. In summary, PoE is evolving from a network convenience into a foundational low-voltage DC power distribution technology, poised to become a critical infrastructure component for future low-carbon buildings.

B. Topologies of Building DC Distribution

1) Bus Polarity

a) Unipolar Systems

The unipolar bus architecture is noted for its structural simplicity and relatively straightforward control. Compared to bipolar configurations, it generally requires lower-cost AC/DC converters [20]. A typical topology is illustrated in Fig. 7.

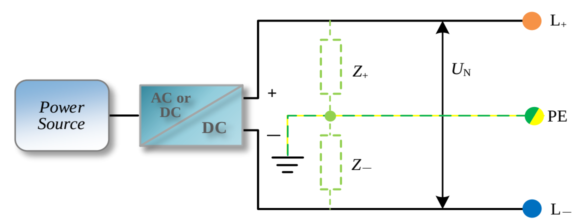

Fig. 7. Schematic diagram of unipolar topology in DC distribution system.

Since a unipolar bus offers only a single voltage level, accommodating diverse load voltage requirements typically necessitates constructing a system comprising multiple unipolar buses, each operating at a distinct voltage level.

b) Bipolar Systems

Bipolar DC systems employ a three-wire configuration (positive, negative, neutral), offering two distinct voltage levels: pole-to-neutral and pole-to-pole. Such systems can be configured using two converters, bus split capacitors, or voltage balancers. A typical topology for these systems is illustrated in Fig. 8. Compared to monopolar systems, bipolar systems offer significant advantages in terms of efficiency, reliability, and safety [16], [118]. The bipolar configuration enables both the implementation of a lower DC bus voltage or a higher DC bus voltage, depending on which set of two wires is used for connection, thereby reducing the voltage conversion range requirements of the connected loads and generators and making the operation of power converters more efficient [119]. Moreover, it improves the reliability of the power supply since the distribution of the loads is implemented by the connection to different power lines. In this way, if a failure occurs in one set of the supply lines, the other set of supply lines remains unaffected, ensuring continued power supply to unaffected loads [120]. Due to the presence of the neutral line, the ground voltage in bipolar systems is typically only half of the total system voltage, which reduces the risk of electric shock and lowers the requirements for insulation materials. Additionally, by monitoring the current in the neutral line, short-circuit faults can be detected more quickly, further enhancing system safety.

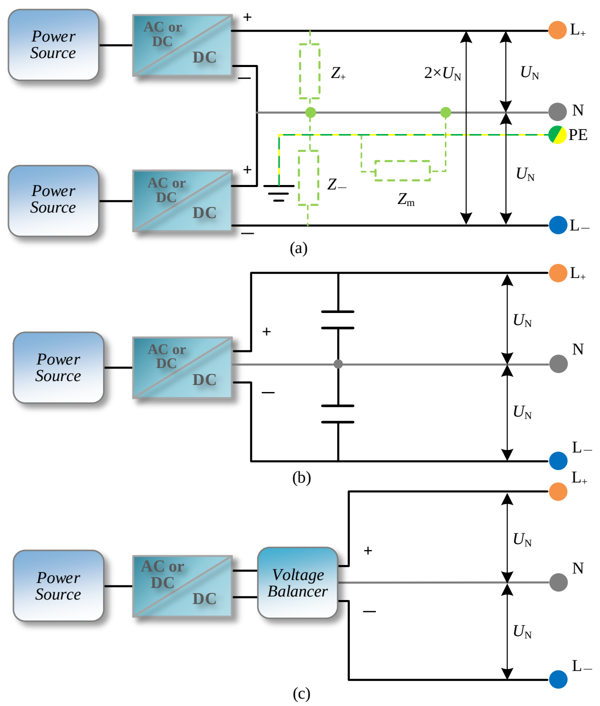

Fig. 8. Schematic diagram of bipolar topology in DC distribution system. (a) Based on two converters. (b) Based on split bus capacitor. (c) Based on voltage balancer

The primary challenge facing bipolar DC buses is the power imbalance between the positive and negative poles [16], [121], [122]. The integration of CPLs in low-carbon buildings can exacerbate line voltage drop, particularly under low-voltage conditions, further degrading system voltage stability and balance [123]. This may lead to increased neutral current, higher line losses, and voltage deviations between the positive and negative poles, consequently reducing system efficiency and equipment reliability. In extreme cases, this imbalance can even cause equipment damage and compromise overall system stability. Common approaches to mitigate or suppress voltage imbalance in bipolar systems primarily include the use of voltage balancers and the implementation of advanced control strategies.

Voltage balancers mitigate load imbalance by enabling bidirectional power transfer between the positive and negative poles [118]. Architecturally, they can be classified as either centralized or distributed. To address the voltage imbalance issue: Reference [124] proposed an impedance-adjustable three-port DC-DC converter. This work provides a control scheme that allows the converter to dynamically vary its input impedance to compensate for voltage imbalances in bipolar DC grids. By independently controlling the current drawn from the positive and negative poles, the converter can reduce the overloading effect on the weaker line, providing a load-side solution to voltage balancing issues. Reference [125] introduced a structurally simplified bipolar DC-DC balancer capable of automatic voltage balancing under phase-shift and pulse-width modulation control, while also achieving zero-voltage switching over a wide voltage range; Reference [126] targeting long-distance LVDC systems, presented a four-port converter integrating voltage balancing and equipment grid-connection functions, offering a potential alternative to distributed balancers.

Regarding control strategies: Reference [127] proposed a strategy combining voltage balancing and hierarchical energy management, utilizing balancing and voltage restoration controls within the secondary control layer to compensate for voltage deviations. Reference [28] investigated a method based on automatic commutation switches that suppresses power imbalance by adjusting the power supply polarity of DC loads. Furthermore, reference [128] presented an optimization method for unbalanced voltages based on a current injection Newton-Raphson power flow algorithm. Its key contribution is the use of a voltage sensitivity matrix, derived from the power flow's Jacobian matrix, to formulate a multi-objective quadratic programming problem that simultaneously reduces generation costs and mitigates voltage unbalance.

Research on bipolar DC systems primarily focuses on applying advanced control strategies and optimizing voltage balancer topologies. The objective is to achieve system power balance and reduce neutral current, thereby fully leveraging the advantages of these systems in low-carbon building DC distribution networks.

2) Bus Topology

Building DC power distribution system topologies can be categorized based on application scale into single-building and building-cluster types. A comparison of the topologies and their respective application scenarios is presented in Table V.

a) Single Building Topologies

1. Single-Bus Topology

The single bus topology, shown in Fig. 9(a), is valued for its structural simplicity and ease of control [62]. Its straightforward design minimizes energy conversion stages, making it effective for directly supplying DC loads like electric vehicles [129]. However, it is prone to single-point failures and sensitive to load variations, limiting its use to applications with lower reliability needs. Efficiency is constrained by voltage drops over long transmission distances, which can increase losses [129].

2. Multi-Bus/Radial topology

Depicted in Fig. 9(b), the multi-bus or radial topology enhances system reliability, flexibility, and efficiency by using multiple buses. Its redundant design and ability to isolate faulty buses make it ideal for applications requiring moderate power supply reliability. By maintaining voltage stability and reducing conversion stages, this topology achieves higher efficiency compared to the single-bus design, with fewer losses from fault propagation [129].

3. Ring-Bus Topology

As illustrated in Fig. 9(c), the ring bus topology addresses the limitations of the single bus by offering multiple power paths for sources and loads [23], [130]. This setup ensures high reliability and rapid fault isolation, making it suitable for applications needing continuous power supply. The redundant paths also enhance voltage stability, reducing energy conversion losses and improving overall efficiency [129].

b) Building Cluster Topologies

Building-cluster systems typically employ more complex and redundant topologies to ensure efficient and flexible power supply among multiple building units, types include:

1. Mesh Topology

The mesh topology, also known as the Multi-Terminal DC (MTDC) topology, is shown in Fig. 9(d). Its interconnected structure provides high redundancy and reliability [131], though it demands precise control of DC power flow and robust DC circuit breakers [132]. While this topology supports reliable power delivery, its efficiency is moderately impacted by the complexity of control systems and potential losses from additional switch elements [129].

2. Zonal Topology

The zonal topology is illustrated in Fig. 9(e). The zonal topology is designed for zonal autonomy, with each zone equipped with independent power sources, converters, loads, and energy storage units [133]. DC circuit breakers facilitate fault isolation and operational mode switching, boosting reliability and flexibility. By localizing power management, this topology minimizes global conversion losses, making it highly efficient for large-scale systems [129].

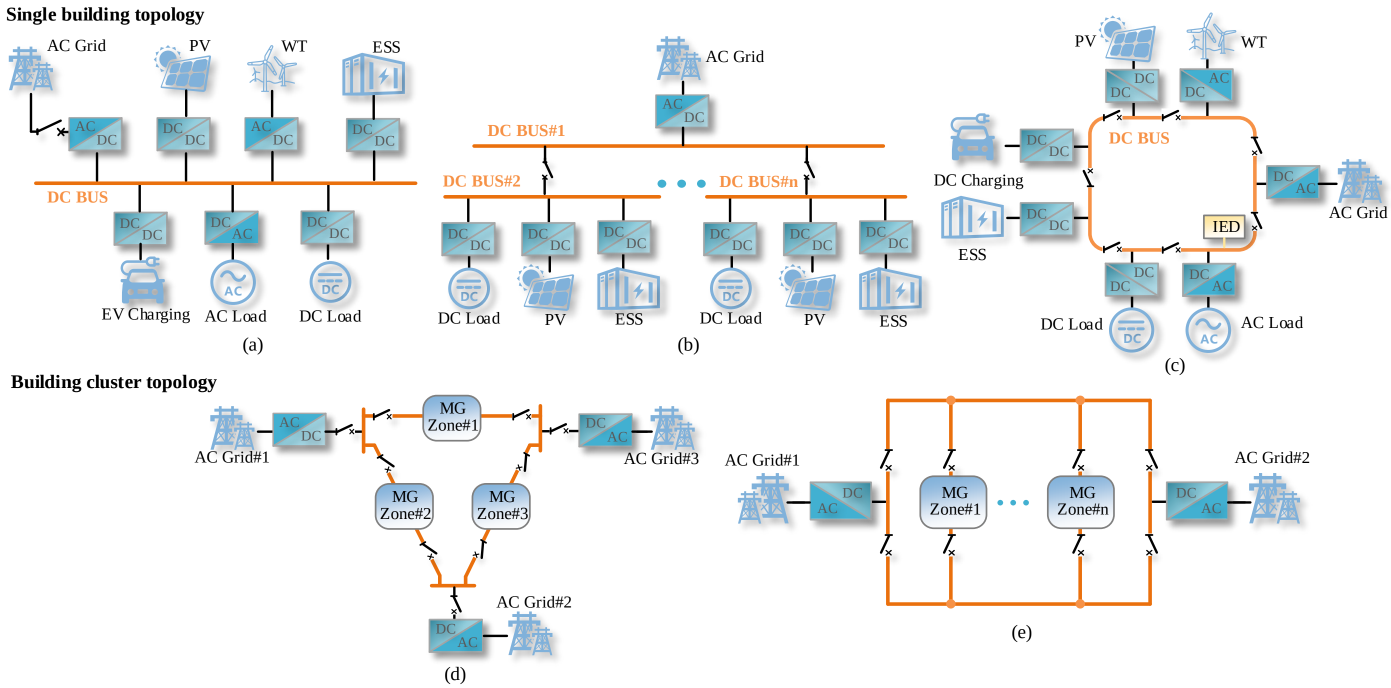

Fig. 9. Building DC distribution systems topology. (a) Single-bus topology. (b) Multi-bus/Radial topology. (c) Ring-bus topology. (d) Mesh/MTDC topology. (e) Zonal topology.

TABLE V

COMPARISON OF BUILDING DC DISTRIBUTION SYSTEM TOPOLOGIES

Building Type	**Topology Type**	**Control & Protection Complexity**	**Power Supply Reliability**	**Efficiency**	**Recommended Application Scenarios**
Single Building	Single-Bus Topology	Low	Low	Medium	Residential Buildings
	Multi-Bus Topology	Medium	Medium	High	Public Buildings
	Ring-Bus Topology	High	High	High	Industrial Buildings
Building Cluster	Mesh Topology	High	High	Medium	Public Building Cluster, Industrial Building Cluster
	Zonal Topology	High	High	High	Public Building Cluster, Industrial Building Cluster

C. Directions for Technical Standardization

The widespread adoption of DC distribution systems in low-carbon buildings requires robust technical standardization to ensure interoperability, safety, efficiency, and scalability. While significant progress has been made in recent years, gaps in standards remain. This section discusses key directions for standardization.

Standardization efforts for DC microgrids in buildings focus on several critical areas, including system architecture, voltage levels, power quality, grounding, protection, and integration with emerging technologies. Current standards are scattered across organizations such as the IEC, IEEE, ISO, ANSI, CCSA, etc [134].

1) Existing Standards

Existing standards provide foundational guidelines for DC distribution system, which mainly includes the following aspects:

Architecture and Voltage Levels: Standards define DC microgrid structures and voltage classifications. IEC 60038-2021 outlines standard voltages for DC systems [107], while GB/T 35727-2017 provides guidelines for medium and low-voltage DC distribution in China [108].

Sources, Storage, and Loads: Guidelines cover integration of PV, [135] batteries [136], and DC loads such as plug-in devices [137], motors [138], and EV charging [139].

Grounding Arrangements: IEC define TN, TT, and IT grounding systems adapted for DC, focusing on safety and fault isolation [140].

Protection Techniques: IEC standards address electric shock hazards [141], overcurrent [142], and transient overvoltage [143].

DC Metering and Power Quality: Reference [144] define power quality indices such as harmonic content ratio, total harmonic distortion rate, voltage fluctuation coefficient, flicker percentage, voltage unbalance coefficient, voltage deviation percentage, and voltage sag depth. These differentiate DC from AC by addressing zero-frequency characteristics.

2) Future Standards Needed

The literature underscores significant gaps in current standards, including their fragmented nature and lack of building-specific focus, which impede the widespread adoption of DC microgrids [130]. Addressing these deficiencies requires enhanced international collaboration among standardization bodies to develop cohesive, application-tailored guidelines.

Harmonized Voltage Levels: Future IEC updates should establish globally recognized voltage standards, such as 380 V for unipolar systems and ±750 V for bipolar configurations, to streamline the development of DC-compatible equipment, reduce manufacturing complexities, and facilitate plug-and-play integration across building clusters.

Comprehensive Power Quality Framework: Reference [144] identify inconsistencies in power quality definitions, proposing a structured index system with correlations such as harmonics-fluctuations, voltage deviations-steady unbalances, and voltage sags-transient unbalances. Standards in these aspects should be integrated into future IEC and IEEE standards to establish a unified framework for monitoring and mitigating DC specific disturbances.

Advanced Grounding and Protection: The absence of natural zero crossing in DC systems poses challenges for fault interruption, a gap highlighted by current standards [130]. Future standards should develop building-specific protection schemes, including advanced DC circuit breakers and grounding configurations tailored for arc faults, battery safety, and overvoltage protection.

IV. Engineering Application Case Studies

Globally, numerous low-carbon building DC distribution systems integrating PV and ESS have been implemented across various building types, including office buildings, university campuses, industrial parks, and residential complexes. These deployments have validated the feasibility of low-voltage DC distribution systems in building applications. Existing low-carbon DC building projects have demonstrated advantages in several key areas, including clean energy utilization, enhanced energy efficiency, reduced carbon emissions, and grid interaction capabilities. This highlights the potential of DC distribution technology for achieving high efficiency and sustainability in building applications.

Notably, low-carbon building DC distribution systems have provided essential electricity access in off-grid rural areas of Africa [145], thereby improving the living conditions of residents in these developing regions.

A. Project of Fraunhofer IISB

In 2017, the Fraunhofer Institute for Integrated Systems and Device Technology (Fraunhofer IISB) in Erlangen, Germany, successfully implemented a unipolar, single bus architecture building DC distribution system with a nominal voltage of ±380V [146]. Fig. 10 shows the schematic diagram of the system's architecture.

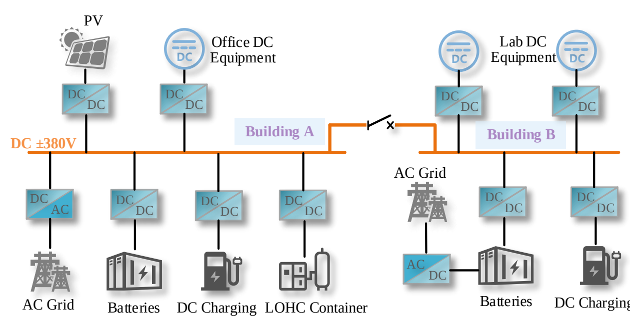

Fig. 10. Schematic overview of the Building DC distribution system at Fraunhofer IISB.

This demonstration project integrated PV generation units, ESS, and bidirectional AC-DC converters. It serves an area exceeding 1000 square meters of building space, providing power support for offices, laboratories, and EVs charging facilities. The PV array has a peak output power of 43 kW. The lithium-ion battery ESS has a total capacity of 60 kWh, with a peak discharge power of 100 kW and a maximum output voltage of 600 V.

The DC distribution systems architecture based on high-efficiency power electronic converters, optimizes energy transfer and conversion. Specifically, the PV and ESS converters achieve efficiencies exceeding 99%. A 96kW bidirectional AC-DC converter enables energy feedback to the AC grid or storage via liquid organic hydrogen carrier technology.

Experimental operating data indicate that, compared to traditional AC systems, the DC distribution system achieves an overall efficiency improvement of approximately 3%, with this advantage reaching up to 10% during periods of peak local generation [147].

B. Project of Etratech Inc. Headquarters

In 2017, Etratech Inc., located in Ontario, Canada, implemented a bipolar, ring bus architecture building DC distribution demonstration project with a nominal voltage of ±380V. A schematic diagram of the project's architecture is presented in Fig. 11.

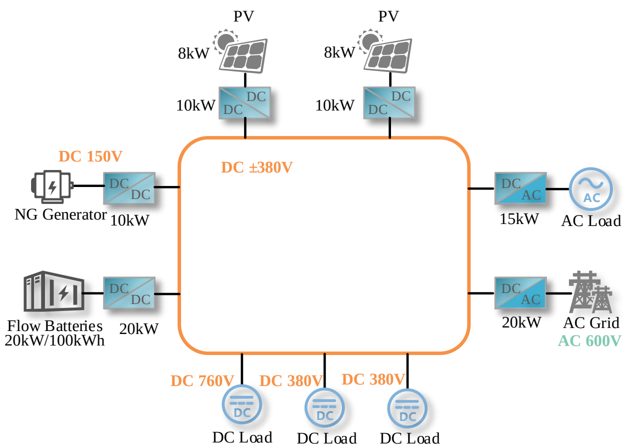

Fig. 11. Schematic overview of the building DC distribution system at Etratech Inc. headquarters.

This demonstration project integrated a 20 kW/100 kWh vanadium redox flow battery ESS unit, two 8 kW PV arrays, a 10 kW natural gas generator, and a 380V DC LED lighting network.

The PV system comprises 64 modules, each with a 255 W rating, divided into two groups and connected to the ±380 V DC bus architecture via electrically isolated DC/DC converters. The flow battery is connected to the system via a ±380 V bipolar DC bus. Its associated bidirectional DC/DC converter features a charge/discharge mode switching time of less than 20ms and is equipped with a bus voltage balancing device to maintain voltage symmetry between the positive and negative poles. The project replaced traditional 400 W metal halide lamps with 380 V DC powered LED high bay fixtures. Experimental data show that when the LED operate at 80% of their rated power, the overall energy saving efficiency reaches 54%, and the lighting uniformity improves by 33%.

The hierarchical control strategy decomposes the complex control of a microgrid into three distinct levels, each with a different objective and response time. The primary control is the fastest, using local measurements and droop methods to ensure stable power sharing among generation units, though this introduces voltage and frequency deviations. The secondary control acts on a slower timescale, using communication to send a common correction signal that restores these deviations and brings the system's voltage and frequency back to their nominal values. Finally, the tertiary control is the highest and slowest level, responsible for managing the power flow between the microgrid and the main electrical grid, often for economic optimization or to handle emergency conditions [148]. The system employs a three-level hierarchical control strategy. The primary control is voltage regulation. The secondary control is SoC optimization. The tertiary control focuses on economic dispatch, while also making flexibly adjustments to the converters and lighting system [149].

C. Project of Kanazawa Institute of Technology

In 2018, the Hakusanroku Campus of Kanazawa Institute of Technology, located in Hakusan City, Japan, implemented a 360V unipolar, single-bus building DC distribution system. This system serves faculty and staff dormitory buildings and a greenhouse strawberry cultivation facility, aiming to achieve on-site consumption of locally generated renewable energy. Fig. 12 presents a schematic diagram of the project.

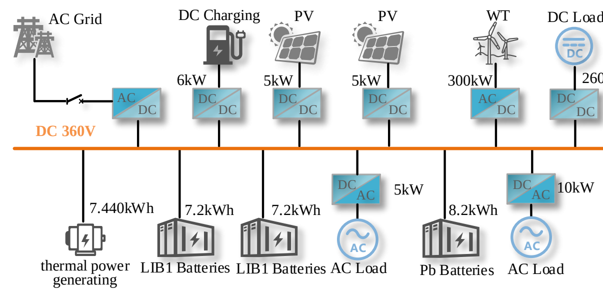

Fig. 12. Schematic overview of the building DC distribution system at Kanazawa Institute of Technology.

The system configuration includes 64 PV modules, each rated at 255 W (totaling 16.3 kW), a 20 kW/100 kWh all-vanadium redox flow battery ESS, a 15 kW lead-acid battery bank, and a 10 kW Stirling engine powered by wood pellets. The load side includes 48 × 380 V DC LED high-bay fixtures (each with a maximum power of 230 W), an 18,000 BTU DC air conditioning unit, and five 7 kW DC charging stations.

The project employs a distributed voltage control strategy. By continuously monitoring DC bus voltage deviations, the ESS's charging and discharging power is proportionally adjusted, with the goal of maximizing islanded operation time. Operational monitoring data indicate that the system can sustain islanded operation for 23.1 hours, a 25% improvement compared to traditional droop control. The DC lighting system achieves 54% energy savings, and the annual carbon emissions reduction is 12.3 metric tons of CO_2 equivalent [150].

D. Project of Shenzhen IBR Future Complex.

In 2019, the Shenzhen IBR Future Complex Project, located in Shenzhen, China, implemented a building DC distribution system with a nominal voltage of ±375 V/48 V and a bipolar, multi-bus architecture. This six-story office complex (with a building area of 5,000 m²) is the first demonstration building in China to integrate photovoltaic, energy storage, direct current, and flexible load technologies into a single, comprehensive system. Fig. 13 shows a schematic diagram of the project.

The project's energy system comprises: a dual-array rooftop PV system (with a total installed capacity of 150 kW and covering an area of 1,200 m²); 110 kWh of lead-carbon battery ESS (50 kWh centralized main storage and 60 kWh distributed storage across different levels); and a 60 kW DC charging terminal cluster. The total DC load demand is 388 kW, consisting of: a 215 kW variable-frequency air conditioning system, an 85 kW smart lighting network, 68 kW of power outlets for digital devices, and 20 kW for EV charging facilities.

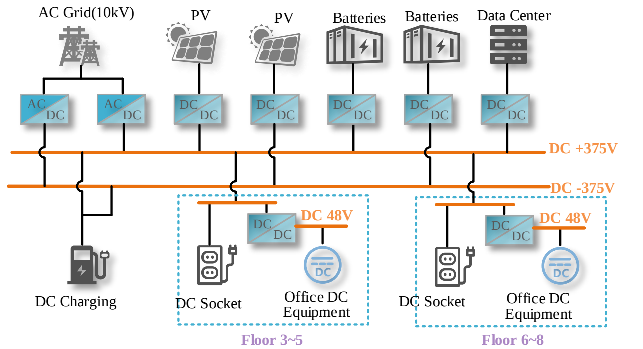

Fig. 13. Schematic overview of the Building DC distribution system at Shenzhen IBR future complex project.

The project utilizes an active control algorithm based on DC bus signaling, enabling dynamic switching between four operating modes to optimize energy exchange with the grid in real-time. The building's annual energy consumption intensity is 49.1 kWh/(m²·a), representing a 46.6% reduction compared to the 2019 benchmark for office buildings in Shenzhen of 91.8 kWh/(m²·a), resulting in an annual carbon dioxide emissions reduction of 1,675 metric tons [151], [152].

E. Project of Ambohimanga Village

In 2021, a rural building DC distribution system project in Ambohimanga, Madagascar, integrated multiple microgrid units, effectively mitigating the lack of electricity access in rural areas of sub-Saharan Africa. This project implemented a unipolar ring architecture DC distribution system with a nominal voltage of 60V DC. A schematic diagram of the system is shown in Fig. 14.

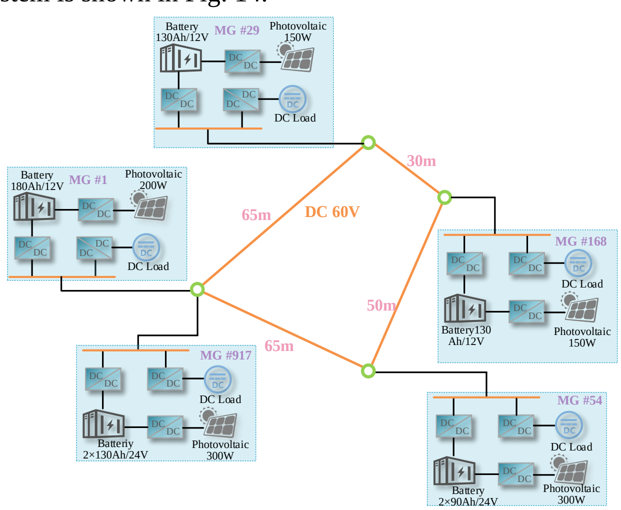

Fig. 14. Schematic overview of the Building DC distribution system at Ambohimanga Village.

Each microgrid unit within the project is equipped with several hundred watts of PV panels and a lead-acid battery ESS with a capacity of several hundred ampere-hours (Ah). For instance, microgrid unit No.1 features a 200W PV array and a 180 Ah/12 V storage system, while microgrid unit # 917 includes a 300 W PV array and a 2×130 Ah/24 V storage system. These individual microgrid units are interconnected to a 60 V DC bus via bidirectional buck-boost converters. The DC bus powers irrigation pumps and agricultural harvesting equipment. Due to the absence of established standards for DC voltage levels, the designers selected 60 V, considering both safety and voltage drop across the cables. Given the practical constraints of the rural area, with no access to an AC grid, a ring architecture was implemented to enhance the reliability of the power supply [153].

Rural areas in sub-Saharan Africa often lack reliable telecommunications infrastructure. Therefore, a communication-less, decentralized control strategy was chosen to avoid reducing project reliability and increasing technical costs. This strategy dynamically adjusts power exchange based on battery SoC and DC bus voltage deviations.

The project provides essential energy for lighting, daily life activities, and agricultural production in a region of rural Africa that previously lacked energy access.

F. Project of Zhuangshang Village

In 2022, the Zhuangshang Village building DC distribution system project, located in Ruicheng County, Shanxi Province, achieved full-capacity grid connection. This project is a unipolar, single-bus architecture DC distribution system with a nominal voltage of 750V/220V DC. A schematic diagram of the project is shown in Fig. 15.

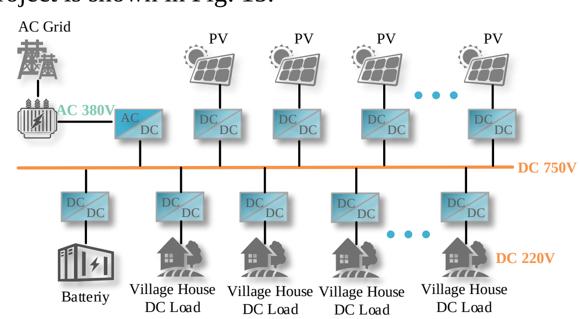

Fig. 15. Schematic overview of the building DC distribution system at Zhuangshang Village.

The project installed 5,000 PV modules, each rated at 400 W, across the rooftops of 71 households, resulting in a total installed capacity of 2 MW and an ESS capacity of 717 kWh.

The project utilizes a high-efficiency DC distribution system to achieve effective utilization and flexible dispatch of clean energy, with a measured overall efficiency of 91.7% and an average total line loss of only 4%. It generates an average of 2.4 million kWh of electricity annually, saving 966 metric tons of standard coal, reducing CO_2 emissions by 2,392.8 metric tons, and completely eliminating pollution sources such as straw burning and coal dust, thereby improving the village environment and achieving zero carbon emissions. This project promotes rural energy transition and sustainable development, serving as a model for low-carbon energy applications globally.

G. Project of Line Maintenance Building of the Zhuhai Hengqin Power Supply Company

In 2023, the Line Maintenance Building project for the Zhuhai Hengqin Power Supply Company of China Southern Power Grid, located in Zhuhai, China, was completed. With a total construction area of 14,047.17 m², the building serves multiple functions, including administrative offices, multi-purpose conference rooms, staff dining facilities, and equipment maintenance spaces. This project is a unipolar, multi-bus architecture DC distribution system with a nominal voltage of 750 V/400 V/48 V DC. Both the 750 V DC and 400 V DC buses in this project incorporate two independent power inputs, ensuring a high degree of reliability for the site. Fig. 16 shows a schematic diagram of the project.

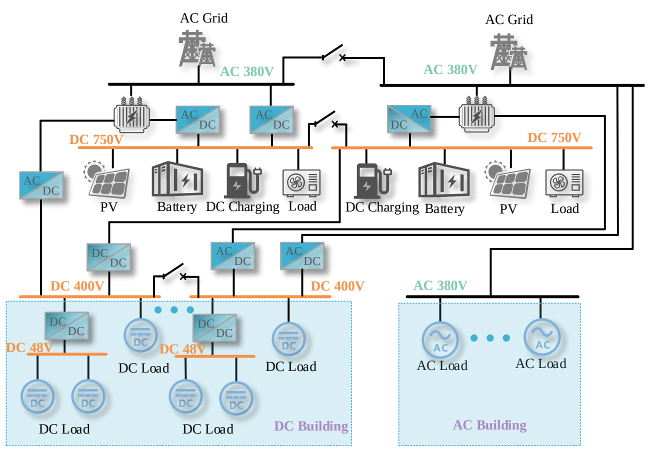

Fig. 16. Schematic overview of the building DC distribution system at the line maintenance building of the Zhuhai Hengqin power supply company.

The project’s energy system includes rooftop PV arrays and a BIPV system on the charging station canopy, with an annual generation of 212,142 kWh, which can be 100% consumed on-site. The project also incorporates a lithium iron phosphate battery ESS with a total capacity of 600 kWh, used to mitigate PV fluctuations and enhance PV energy utilization. The power interaction terminal includes 20 bidirectional DC charging units (two 120 kW fast-charging stations and 1840 kW standard charging stations), supporting both scheduled charging and V2G energy transfer [154].

Regarding the control strategy, the project employs an energy management strategy based on time-of-use electricity pricing. Project operational data indicate that PV generation replaces 20.86% of traditional energy consumption, the building's operational energy intensity is 31.7% lower than that of a benchmark building, and a load flexibility adjustment capability of 62.29% is achieved.

This project represents an endeavor to integrate buildings with the power grid, exploring the low-carbon potential of buildings, enhancing grid load regulation capabilities, promoting supply-demand balance in the power system, and providing a valuable reference for achieving simultaneous decarbonization of buildings and the power sector.

Table VI summarizes 12 global low-carbon building engineering applications, providing key configuration parameters, while Fig. 17 illustrates their geographical distribution.

TABLE VI
GLOBAL APPLICATIONS OF LOW-CARBON DC BUILDINGS

Project Name	Location	Building Type	Year	DC Voltage Level	Configuration	Schematic
Fraunhofer IISB [146]	Erlangen, Germany	Office	2016	DC±380/ 48 V	PV: 43 kW ESS: 60 kW	Bipolar, Multi-Bus Topology
The ABN AMRO Pavilion [155]	Amsterdam, Netherlands	Office	2017	DC350 V	PV: 17.655 kW	Unipolar, Single-Bus Topology
Etratech Inc. Headquarters [149]	Burlington, Canada	Commercial Building	2017	DC±380	PV: 16 kW ESS: 100 kWh	Bipolar, Ring-Bus Topology
Tongli Regional Low-Voltage DC Project [105], [156]	Suzhou, China	Building Complex	2018	DC±750/ ±375/220/48 V	PV: 6.21 MW ESS: 2 MWh	Bipolar, Multi-Bus Topology
Kanazawa Institute of Technology (Hakusanroku Campus) [150]	Hakusan, Japan	University Campus	2018	DC360 V	PV: 6.7 kW ESS: 22.8 kW Wind Turbine: 300 W, Charging Station: 6 kW	Unipolar, Single-Bus Topology
Pulse Building of Delft University of Technology [157]	Delft, Netherlands	University Campus	2018	DC350 V	PV: 150 kW	Unipolar, Single-Bus Topology
Honda Torrance Campus [158]	Torrance, USA	Industrial Park	2018	DC380 V	PV: 2 MW ESS: 1400 kW	Unipolar, Single-Bus

Shenzhen IBR Future Complex Project [151], [152]	Shenzhen, China	Office	2019	DC750/ ±375/48 V	PV: 150 kW ESS: 110 kWh Charging Station:60kW	Bipolar, Multi-Bus Topology
Campus of Sultan Qaboos University [159]	Muscat, Oman	University Campus	2020	DC48 V	PV: 5 kW ESS: 15 kW Fuel Cell: 5 kW Diesel Generator: 6 kW	Unipolar, Single-Bus Topology
Ambohimanga Village [153]	Ambohimanga, Madagascar	Rural Residential	2021	DC60 V	PV: 1.1 kW ESS: 15.84 kWh	Unipolar, Ring-Bus Topology
Zhuangshang Village [160]	Yuncheng, China	Rural Residential	2022	DC750/ 220 V	PV: 2 MW ESS: 717 kWh	Unipolar Single-Bus Topology
Line Maintenance Building, Zhuhai Hengqin Power Supply Company [154]	Zhuhai, China	Office	2023	DC750/ 400/48 V	PV: 255 kW ESS: 600 kWh DC Charging: 120 kW×2, 40 kW×18	Unipolar, Multi-Bus Topology

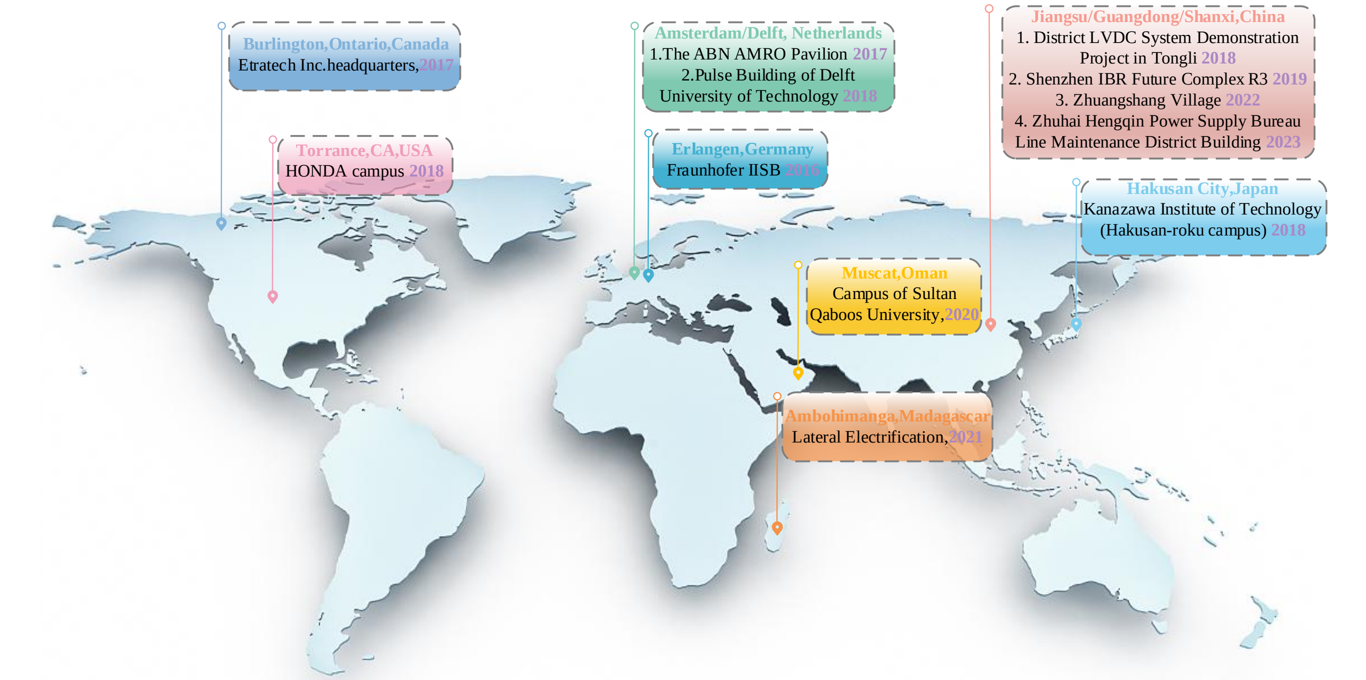

Fig. 17. Map illustrating the global distribution of the twelve low-carbon DC building application projects analyzed in this paper.

V. Conclusion and Future Challenges

A. Conclusion

This paper reviews the configuration, architectures, and applications of low-carbon building DC distribution systems that integrate PV, combined electrical and thermal energy storage, DC distribution, and flexible load. By enabling synergistic optimization across the supply-side, energy conversion, and demand-side, these systems offer a viable pathway toward decarbonizing the building sector. The key aspects reviewed in this paper are summarized as follows:

1) Review of Key Configurations: The essential components of low-carbon building DC distribution systems are elucidated, encompassing BIPV/BAPV, ESS, DC distribution networks, and flexible loads. Practical applications of BIPV/BAPV are surveyed, emphasizing the increased PV self-consumption rate as a primary objective for low-carbon buildings. An expanded classification framework for building ESS is propose. This framework moves beyond conventional storage to innovatively incorporate building thermal mass and EV batteries by leveraging inherent building characteristics. Recent advancements in ESS capacity sizing and operational control strategies are summarized. Furthermore, the main classifications of flexible loads within buildings are reviewed, along with key evaluation metrics defined across four dimensions: power, time, energy, and cost-effectiveness.
2) Examination of System Architectures: The architectures of low-carbon building DC distribution systems are examined. Firstly, current LVDC voltage levels are reviewed based on existing international and national standards, correlated with survey data on DC load

voltage requirements. The analysis highlights that the proliferation and coexistence of numerous voltage standards pose a significant barrier to the wider adoption of LVDC distribution; insights into future voltage standardization trends are also discussed. Secondly, concerning network topologies, the configurations and characteristics of unipolar and bipolar systems are reviewed, along with research progress on power imbalance suppression techniques specific to bipolar systems. Finally, five typical topological structures suitable for both single buildings and building clusters are synthesized, accompanied by a comparative analysis and discussion of their respective application contexts.

3) Analysis of Practical Applications: Twelve practical application case studies and demonstration projects of low-carbon building DC distribution systems implemented globally are reviewed and summarized. These cases span diverse scenarios, from rural residences to university campuses, and include details on their key technical parameters and operational performance. The findings indicate that building DC distribution systems demonstrate significant potential for enhancing building energy efficiency and reducing carbon emissions. Furthermore, they offer a viable solution for improving electricity access and quality of life in energy-poor regions.

B. Future Challenges

1) The coexistence of multiple LVDC voltage levels exacerbates standardization challenges for DC distribution networks and associated equipment, constraining the development and proliferation of DC appliances. This, in turn, impedes the widespread global adoption of low-carbon buildings. Consequently, standardization research for building LVDC voltage levels is urgently needed. Such standardization may comprehensively evaluate key factors including safety, load compatibility, and power matching.
2) Currently, unified standards for evaluating building flexibility and the performance of energy saving and emission reduction are in lack. Consequently, the establishment of consistent testing methodologies and quantitative metrics is crucial to accurately assess the energy conservation potential, emission reduction performance, and demand response capabilities of low-carbon buildings. This will provide effective guidance for engineering design and technological dissemination.
3) Further research into advanced building energy management systems is imperative to effectively coordinate the thermal mass of building materials, the energy storage potential of EVs, and the dispatchability of flexible loads. Furthermore, system design may integrate considerations of grid policies and temporal energy consumption characteristics in building, aiming to optimize energy utilization efficiency and maximize the energy saving and emission reduction benefits of buildings.

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Zhiwei Wu (Student Member, IEEE) was born in Fuzhou, Jiangxi, China. He received the B.Eng. degree in electrical engineering from the Faculty of Electric Power Engineering, Kunming University of Science and Technology, Kunming, China, in 2021, and the M.S. degree in electrical engineering from the School of Electrical and Electronic Engineering, North China Electric Power University, Beijing, China, in 2024. He is currently pursuing the Ph.D. degree in electrical engineering with the School of Electrical Engineering, Shanghai Jiao Tong University, Shanghai, China.

His research interests include modeling, coordinated control and stability analysis of DC distribution systems.

Fei Gao (Member, IEEE) received the Ph.D. degree in electrical engineering from the Power Electronics, Machines, and Control (PEMC) Research Group, University of Nottingham, Nottingham, U.K., in 2016.

From 2010 to 2012, he worked with Jiangsu Electric Power Research Institute, Nanjing, State Grid Corporation of China. From 2016 to 2019, he was a Postdoctoral Researcher with the Department of Engineering Science, University of Oxford, Oxford, U.K. Since 2019, he has been with Shanghai Jiao Tong University, Shanghai, China, as an Associate Professor. His current research interests include modeling, control, power management, and stability of microgrids and more electric transportation systems.

Dr. Gao was the recipient of the European Union Clean Sky Best Ph.D. Award in 2017 and IET Control & Automation Runner-Up Ph.D. Award in 2018.

Zongwen Zhang received the B.S. degree in electrical engineering from Chongqing University, Chongqing, China, in 2024. He is currently working toward the M.S. degree in electrical engineering with Shanghai Jiao Tong University, Shanghai, China.

His research interests include modeling, control, stability analysis, and energy management of dc distribution systems.

Shuai Shao (Member, IEEE) received the B.S. degree in electrical engineering from Zhejiang University, Hangzhou, China, in 2010, and the Ph.D. degree in electrical and electronic engineering from the University of Nottingham, Nottingham, U.K., in 2015.

In 2015, he was a Lecturer with the College of Electrical Engineering, Zhejiang University, where he was promoted to Associate Professor in January 2020. He authored or co-authored more than 80 peer-reviewed journal and conference papers. His research interests include solid-state transformers, bidirectional dc–dc converters, and fault detection in power converters.

Dr. Shao was a Guest Associate Editor for the IEEE JOURNAL OF EMERGING AND SELECTED TOPICS IN POWER ELECTRONICS and CES *Transactions on Electrical Machines and Systems.*

Daniel J. Rogers (Senior Member, IEEE) received the M.Eng. and Ph.D. degrees in electrical and electronic engineering from Imperial College London, London, U.K., in 2007 and 2011, respectively.

He is currently an Associate Professor with the Department of Engineering Science, University of Oxford, Oxford, U.K. He conducts research in collaboration with industry and has been an investigator on U.K. EPSRC research projects in the areas of power electronics, grid-scale energy storage, and microgrids. His research interests include power electronics ranging from active control of transistor switching to circuit and control system design, through to novel applications enabled by wide-bandgap devices.

Yuhong Zhu received the bachelor's degree in Polymer Materials and Engineering from Central South University, Changsha, China, in 2020. She is currently pursuing a Master of Engineering Management (MEM) with Zhejiang University, Hangzhou, China.

She is currently with Hangzhou Biaojian Technology Co., Ltd., Hangzhou, China, focusing on material testing technologies and the development of standardization systems.

Wei Li received his bachelor's degree in public utility management from Zhejiang University of Technology in 2008.

He is currently with the Economic Research Institute of State Grid Wenzhou Electric Power Supply Company. His research focuses on efficient coordination and stable operation of power grids under high-penetration renewable energy integration, optimization technologies for integrated energy systems in multi-energy complementary scenarios, and trusted data authentication and traceability solutions for accurate carbon emission measurement and accounting.

Patrick W. Wheeler (Fellow, IEEE) received the B.Eng. (Hons.) degree in electrical engineering and the Ph.D. degree in electrical engineering from the University of Bristol, Bristol, U.K., in 1990 and 1994, respectively. His Ph.D. dissertation was titled “Matrix Converters.”

In 1993, he moved to the University of Nottingham and was a Research Assistant with the Department of Electrical and Electronic Engineering. In 1996, he became a Lecturer with the Power Electronics, Machines and Control Group, University of Nottingham, Nottingham, U.K. Since January 2008, he has been a Full Professor in the same research group. He is currently the Director for Global Engagement in the Faculty of Engineering and the Head of the Power Electronics, Machines and Control Research Group. He was the Head of the Department of Electrical and Electronic Engineering, University of Nottingham, from 2015 to 2018. He has authored or coauthored more than 1000 academic publications in leading international conferences and journals.

Dr. Wheeler is a member of the IEEE PELs AdCom and was IEEE Power Electronics Society Vice-President for Technical Operations from 2020 to 2024.