Photovoltaics and Energy Storage Integrated Flexible Direct Current Distribution Systems of Buildings: Definition, Technology Review, and Application

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***Abstract*—For a future carbon-neutral society, it is a great challenge to coordinate between the demand and supply sides of a power grid with high penetration of renewable energy sources. In this paper, a general power distribution system of buildings, namely, PEDF (photovoltaics, energy storage, direct current, flexibility), is proposed to provide an effective solution from the demand side. A PEDF system integrates distributed photovoltaics, energy storages (including traditional and virtual energy storage), and a direct current distribution system into a building to provide flexible services for the external power grid. System topology and control strategies at the grid, building, and device levels are introduced and analyzed. We select representative work about key technologies of the PEDF system in recent years, analyze research focuses, and summarize their major challenges & future opportunities. Then, we introduce three real application cases of the PEDF system. On-site measurement results demonstrate its feasibility and advantages. With the rapid growth of renewable power production and electric vehicles, the PEDF system is a potential and promising approach for large-scale integration of renewable energy in a carbon-neutral future.**

***Index Terms*—Demand response, direct current, energy flexibility, energy storage, low-carbon building, photovoltaics.**

I. INTRODUCTION

WITH the increasingly severe impact of global climate change, reducing greenhouse gas emissions has become a key for sustainable human development [1]. Many countries and regions have set ambitious plans to achieve carbon neutrality in 10 to 40 years [2]. Literature indicates a consensus that near-complete decarbonization of electricity generation and electrification of other sectors (e.g., building, transport, and industry) play an integral role in achieving carbon neutrality [3]. For a decarbonized power grid in the future, it remains challenging to ensure reliable performance, as conventional fossil fuels will be largely replaced by renewable energy sources (RESs) [4].

To build a renewable-dominated power grid, two questions arise: (1) where to install enough renewable generators, such as solar panels and wind turbines, and (2) how to coordinate between power demand and power supply, owing to the intermittent nature of RESs.

First, solar and wind resources are not as energy-intensive as conventional fossil fuels, and thus require large areas for installation. Unlike thermal power plants, centralized solar or wind power plants are usually located far away from urban areas (i.e., the main end-use). In this respect, long-distance power transmission lines and large-scale grid-level energy storage systems are necessary, resulting in high infrastructure investment and low utilization rates [5]. Instead, distributed generators, especially distributed photovoltaics (PV), have attracted increasing research interest and commercial investments [6]. With the technologies of building-attached photovoltaics (BAPV) or building-integrated photovoltaics (BIPV) [7], various kinds of buildings [8], [9] can provide large surface areas for PV installation. Many studies revealed a potentially high share of total power generation by distributed PV in many countries or regions, e.g., 38.6% in the USA [10], 24.4% in the EU [11], 29% in Canada [12], and 32% in Israel [13]. Furthermore, an economic analysis of distributed PV in 344 cities of China's mainland demonstrated PV electricity prices can be lower than grid-supplied prices without subsidies, which indicates a high possibility of distributed PV replacing coal-fired power plants [14]. Therefore, researchers and policymakers have concluded that PV is ready to become one of the main energy sources in a future power grid [6].

Second, unlike a fossil-fuel-based power system, a future power grid with high solar and wind penetration will require more system flexibility resources to cope with intermittent supply [15]. Energy storage technologies are the key to realizing flexibility of a decarbonized power grid [16]. Compared with grid-level energy storage, distributed energy storage combined with electrical terminals (such as distributed batteries) has outstanding advantages in increasing the utilization rate of renewable energy, reducing the capacity of power transmission

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& distribution systems, and improving grid security [17]. However, the current cost of distributed energy storage (especially batteries) still seems too high to support large-scale installation [18]. With the increasing number and battery capacity of electric vehicles (EVs) worldwide [19], EVs are gradually regarded as a reliable and economical source of distributed energy storage by vehicle-to-grid (V2G) or vehicle-to-building (V2B) technologies [20]. This potential will have an increasingly strong coupling relationship with buildings, because EVs are parked in or near buildings over 90% of the time, and their charging process is deeply integrated with the local power distribution systems [21].

The effective solutions to the two questions above for grid decarbonization are distributed renewable energy generation and distributed energy storage, respectively, which both have a close connection with buildings. This type of building is a smart nanogrid [22], a prosumer (i.e., a consumer who produces electricity) [23], and later defined as an energy-flexible building [24], which has the ability to manage its demand and generation according to climates, user needs, requirements of the external power grid, etc. As the largest end-use electricity sector, the building sector will have great flexibility in the future, thereby being decisive for reliable performance of the future power grid [25], [26]. Various existing technologies can enhance energy flexibility of buildings, such as BAPV/BIPV [7], distributed batteries [18], V2B/V2H [20], and demand-side management [27] (e.g., smart appliances and thermal storage in buildings). However, there is still a lack of a general system framework integrating related technologies in buildings. The main challenge is control strategies with high adaptability and scalability for energy management.

This paper proposes a power distribution system of buildings called a PEDF system, representing the three key components (i.e., photovoltaics, energy storage, and direct-current (DC) power distribution system) and the aim (i.e., energy flexibility). Section II introduces the concept, principles, system topology, and control strategies of the system. Section III reviews the related key technologies and discusses the challenges & future opportunities. Section IV introduces three typical application cases: an office building, a building + EVs, and a residential building. To our knowledge, this is the first study to systematically propose a general power distribution system at the building level that can follow the instructions of power use from grid operators, which may shed light on the challenge of a renewable-dominated and carbon-neural future.

II. Definition

A. Concept

A typical PEDF power distribution system of buildings is shown in Fig. 1. "**P**" in this abbreviation mainly refers to

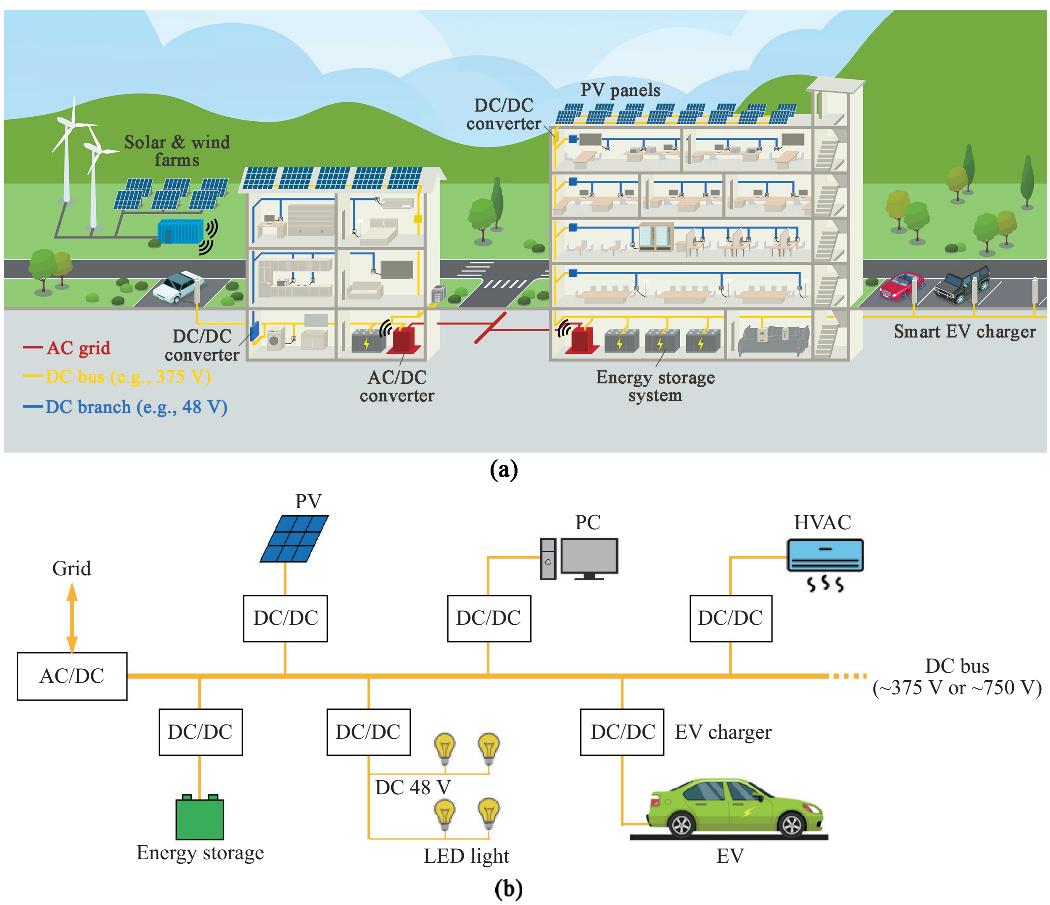

Fig. 1. PEDF system, a novel power distribution system of buildings. (a) A street view, including a residential building, an office building, parked EVs, and solar & wind farms. (b) The microgrid of a building, in which the AC/DC converter sets the DC bus voltage based on a reference power and all the DC-DC converters response according to the variable DC bus voltage.

distributed PV, such as solar panels, flexible solar films [28], and solar glass [29]. They can be fixed on roof/facades, around the building, or even as building components. Other distributed generations, such as distributed wind turbines, can be included as an energy source in the system. "**E**" in the abbreviation refers to energy storage devices or systems, such as distributed or centralized batteries, chillers or heat pumps equipped with thermal storage systems (e.g., water tank, ground, and systems using phase change materials), and EVs connected to smart chargers which are arranged at the parking lot in or around a building. "**D**" in the abbreviation refers to a low-voltage DC power distribution system at the building level. Owing to the increasing DC nature of energy sources, loads, and storages in buildings, these components can be simply connected to a DC bus through power electronic converters with distributed control strategies. "**F**" in this abbreviation refers to energy flexibility. The PEDF system aims to transform a building from a conventional rigid load to an energy-flexible node in the power grid. It simultaneously acts as an energy producer, storage, regulator, and load with demand response. Consequently, power supply from the external grid can be actively and largely adjusted to follow fluctuating power generation instead of being equal to power consumption.

B. Principles

A power grid evaluates its supply-demand situation and sends a reference power (P^*) or a related parameter to the PEDF system. Thus, feed-in power to the DC bus of this system is $P^* + P_{\mathrm{PV}}$, in which P^* is controlled by the AC/DC converter, and the PV generates P_{PV}. To achieve power balance, a variable DC bus voltage (U_{DC}) within a certain range (e.g., 80%–107% of the rated voltage [30]) is a control signal to coordinate all devices in the system. Typical operation states of the PEDF system are explained as follows.

1) *Stable state:* The system operates smoothly when the total load (including all the electrical appliances, EV chargers, and energy storage systems) can be met by $P^* + P_{\mathrm{PV}}$, and U_{DC} is within limits (i.e., $U_{\mathrm{DC,min}} < U_{\mathrm{DC}} < U_{\mathrm{DC,max}}$).

2) *Heavy load state*: U_{DC} drops when the total load is higher than $P^* + P_{\mathrm{PV}}$. Each appliance responds to this voltage drop and reduces its load accordingly based on its control strategy. EV chargers and energy storage systems reduce charging power or even switch to a discharge mode. Thus, the total load decreases to approach $P^* + P_{\mathrm{PV}}$. If $P^* + P_{\mathrm{PV}}$ is too low to approach (i.e., U_{DC} reaches $U_{\mathrm{DC,min}}$), the AC/DC converter increases feed-in power to stabilize U_{DC} to $U_{\mathrm{DC,min}}$.

3) *Light load state*: U_{DC} increases when the total load is lower than $P^* + P_{\mathrm{PV}}$. Each appliance responds to this voltage rise and increases its load accordingly based on its control strategy. EV chargers and energy storage systems increase charging power. Thus, the total load increases to approach $P^* + P_{\mathrm{PV}}$. If $P^* + P_{\mathrm{PV}}$ is too high to approach (i.e., U_{DC} reaches $U_{\mathrm{DC,max}}$), the PV and the AC/DC converter decreases feed-in power to stabilize U_{DC} to $U_{\mathrm{DC,max}}$.

Based on the principles above, the main characteristics of the PEDF system are as follows.

1) The PEDF system is not a simple aggregation of PV systems, energy storage systems, and DC appliances. It is an organization of smart devices and appliances to realize energy flexibility. The DC-bus-voltage-based distributed control strategy of each component plays a crucial role.

2) The PEDF system changes the strategy of power transmission and distribution from "top-down" (i.e., electricity is mainly generated by centralized power plants and then distributed to terminal users) to "bottom-up" (i.e., the distributed PV and wind generation is first self-consumed by terminal users and then transmitted to the power grid if there is surplus).

3) The PEDF system is regarded as an energy-flexible node that a power grid can dispatch. It can provide peak-shaving and valley-filling services now and will contribute to making full use of renewable power when there is high penetration.

C. System Topology and Control Strategies

To realize these concepts and principles, the topology and control strategies of the PEDF system at the grid, building, and device levels are illustrated in Fig. 2 and analyzed as follows:

1) Grid level

As shown in Fig. 2(a), the PEDF system acts as a dispatchable node in the power grid. Specifically, the external power grid participates in determining P^*, and the PEDF system can self-regulate to follow this instruction. There are at least three ways to determine P^* in different situations of the power grid:

1) *Time-of-use (TOU) electricity price*: If the TOU electricity price is adopted in the local power grid, the PEDF system can optimize its power demand curve in advance (e.g., setting P^* at each time interval of the next day) to minimize electricity cost. Meanwhile, the PEDF system can provide peak-shaving and valley-filling services.

2) *Incorporation into the existing power dispatch system*: The PEDF system can also be incorporated into an existing power dispatch system as a virtual power plant [31]. Taking a typical 10,000 m^2 office building with 100 EVs parking nearby as an example, the PEDF system connecting all of them can provide megawatt-level regulation services for the local power grid. In this way, the power dispatch system can directly send a P^* signal to the PEDF system for real-time control.

3) *Interaction with PV stations or wind farms*: With a connection between a centralized PV station or wind farm with the PEDF system, P^* can be determined in advance according to predicted generation. If the actual power consumption of a building with the PEDF system perfectly follows P^*, this building can be regarded as a net-zero carbon building in operation.

2) Building Level

Figure 2(b) illustrates two typical topologies of a PEDF system at the building level. First, a small-scale building (e.g., a family house and a small office building) can configure a single PEDF system with a reasonable maximum feed-in capacity. This type of building adopts a typical DC bus topology, as shown in Fig. 2(b) (left), which is recommended in low-voltage DC microgrids for energy effectiveness [32]. Besides, a large-scale building or a community (e.g., an industrial park), requires large power capacity. It is inappropriate to design a single PEDF system in this situation, because of the high cost of high-power electronics and difficulty in coordinating multiple battery packs. Instead, as shown in Fig. 2(b) (right), it can

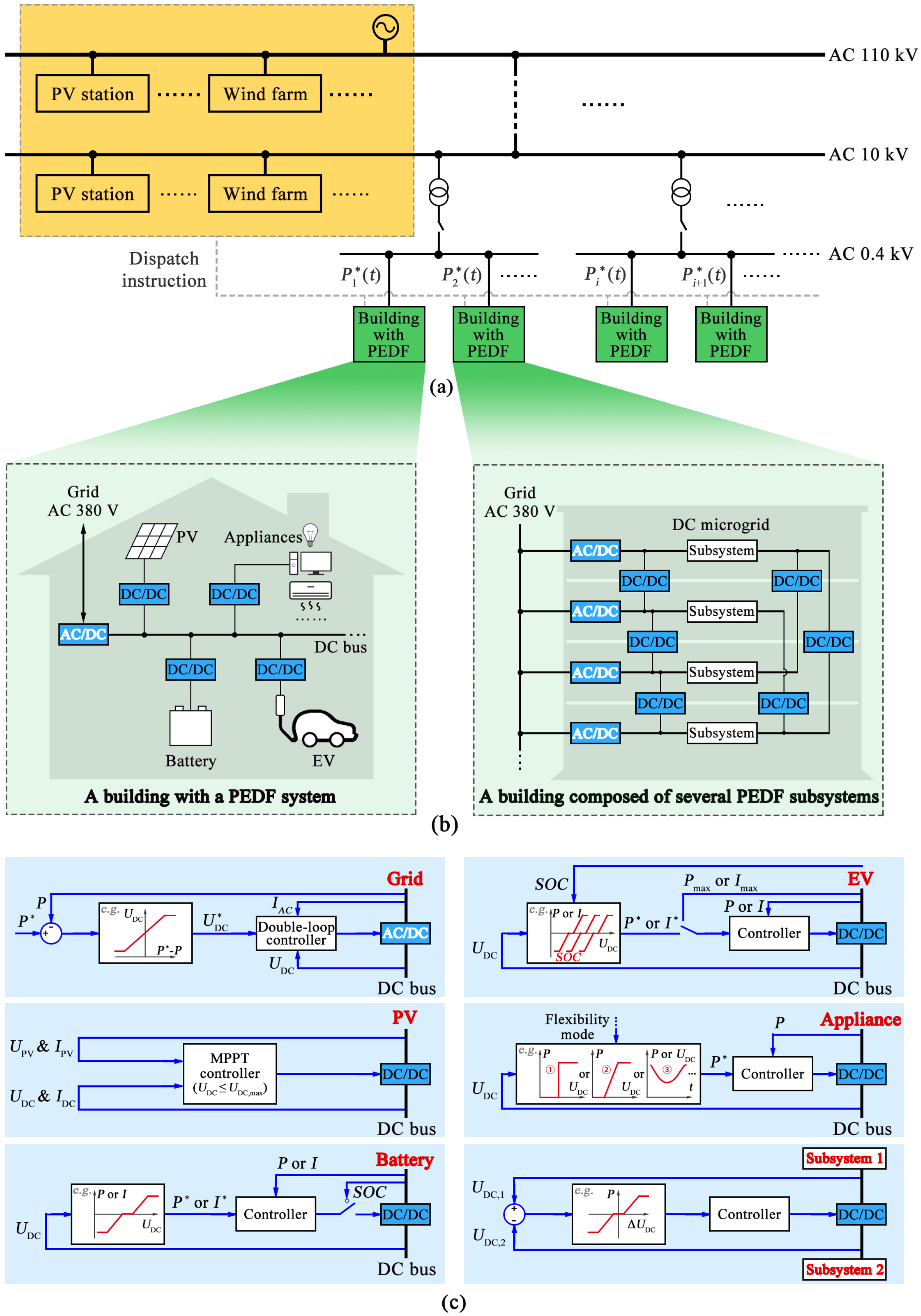

Fig. 2. Topology and control strategy of the PEDF system at multiple levels, including (a) grid level, (b) building level, and (c) device level.

be designed as a DC microgrid with several PEDF subsystems, in which each subsystem has a DC bus topology, i.e., Fig. 2(b) (left). These subsystems are connected to the power grid by AD/DC converters and interconnected by DC/DC converters. This mesh topology can realize energy interconnection in a large system, contributing to power supply reliability when adopting a large number of powers electronic devices and intermittent RESs.

As for energy management, the PEDF system takes a variable DC bus voltage as a control signal to coordinate all devices in the system, unlike current DC buildings commonly setting a fixed system voltage. In this way, each device locally monitors DC bus voltage and its operating parameters for its own control and does not need to communicate with each other for centralized energy management. In other words, the control module of each device performs its own energy management. This distributed control strategy can largely simplify energy management and ensures system scalability.

3) Device Level

The main devices in the PEDF system are smart power electronic converters with programmable controllers, including an AC/DC converter connected to the external power grid, a DC/DC converter connected to PV, a DC/DC converter connected to batteries, smart EV chargers, electric appliances, and a DC/DC converter connecting two subsystems. Their control strategies, shown in Fig. 2(c), are explained as follows.

1) *AC/DC converter connected to the power grid:* Based on P^* explained in "*1) Grid level*", the AC/DC converter first measures power intake from the grid (P), and then calculates a reference DC bus voltage (U_{DC}^*) based on a built-in function ($U_{\mathrm{DC}}^* = f(P^* - P)$). This function can be designed as a series of predefined voltage levels, a continuous function, a machine-learning-based model trained by historical data, etc., with the following characteristics: (1) U_{DC}^* has a positive correlation with ($P^* - P$); (2) U_{DC}^* has a lower limit ($U_{\mathrm{DC,min}}$), indicating the minimum power demand of the PEDF system; (3) U_{DC}^* has a upper limit ($U_{\mathrm{DC,max}}$), indicating the maximum power consumption ability of the PEDF system.

With the above calculated U_{DC}^*, the AC/DC converter controls U_{DC} to U_{DC}^* using the conventional double-loop control strategy [33], including a current loop to enforce power factor correction (PFC) and a voltage loop to achieve output voltage regulation. If input power from the external grid becomes zero, such as power grid failure, the DC bus voltage control (i.e., to set U_{DC}^*) transfers to PV, batteries, and EVs, successively, to ensure normal operation.

If U_{DC} reaches the $U_{\mathrm{DC,min}}$ or $U_{\mathrm{DC,max}}$, but P still cannot reach P^*, this failure to follow instructions will lead to a higher electricity price or even a punitive damage according to the contract with the local power grid operator.

2) *DC/DC converter connected to PV:* The maximum power point tracking (MPPT) control technique [34] is applied to the DC/DC converter connected to PV to maximize power harvest. In addition, if the U_{DC} reaches $U_{\mathrm{DC,max}}$, the DC/DC converter changes strategy. It controls U_{DC} to $U_{\mathrm{DC,max}}$, which means curtailment of surplus PV generation. Subsequently, if U_{DC} drops, the DC/DC converter adopts the MPPT control again.

3) *DC/DC converter connected to batteries:* Hierarchical control [35] is applied to the DC/DC converter connected to batteries for charge/discharge control, i.e., to set a reference charge/discharge power or current (P^* or I^*) based on U_{DC}. As shown in Fig. 2(c), the main function of the hierarchical control, i.e., P or $I = f(U_{\mathrm{DC}})$, consists of three zones, including a dead zone in the middle to avoid frequent battery charge/discharge micro-cycles owing to voltage drop of the DC bus, a droop control zone on the two sides of the dead zone to stabilize DC bus voltage, and a constant zone on the two sides of the droop control zone to limit charge/discharge power or current. State-of-charge (SOC) of the batteries is introduced into the control strategy to avoid overcharge/over-discharge. Parameters of the control strategy can be optimized by a machine learning-based model, based on historical data of DC bus voltage variation.

4) *Smart EV charger:* Unlike a conventional EV charger adopting a constant charge power or current, a smart EV charger can regulate charge/discharge power or current according to the power supply-demand situation of the PEDF system. The smart EV charger first acquires instructions from the EV battery management system (including the EV's SOC and the maximum allowable values of charge/discharge power or current, i.e., $P_{\max}$ or $I_{\max}$) and measures U_{DC}. Then, the smart EV charger adopts an SOC-based battery control strategy to set a reference charge/discharge power or current (P^* or I^*). As shown in Fig. 2(c), the main function of the control strategy, i.e., P or $I = f(U_{\mathrm{DC}}, SOC)$, has three similar zones to those of the batteries. Specifically, charging power rises with increase in U_{DC}. As U_{DC} increases, an EV with a low SOC prioritizes charging; as U_{DC} decreases, an EV with a high SOC first reduces its charge power and even transfers to a discharge mode. In addition, the above-calculated P^* or I^* is limited by $P_{\max}$ or $I_{\max}$ to ensure EV battery safety.

5) *Electric appliances:* Most electric appliances in the PEDF system are supposed to be controllable, excluding some for a special power guarantee, like computer servers and medical equipment. Controllable appliances are classified according to the flexibility services they can provide, i.e., interruptible load (e.g., non-essential lights), curtailable load (e.g., variable-frequency air-conditioners, fans, and pumps), time-shiftable load (e.g., heater/chiller with a heat storage system and portable electronic devices), etc. [36] These controllable appliances realize energy flexibility by their corresponding control strategies. From the view of product design, these electric appliances should offer a button or other interactive interface for users to choose their preferred flexibility mode (i.e., control strategy).

6) *DC/DC converter connecting two subsystems:* As illustrated in Fig. 2(b) (right), a bidirectional DC/DC converter connects the two PEDF subsystems. The difference in DC bus voltage between the two connected PEDF subsystems (ΔU_{DC}) is the key parameter of the control strategy, as shown in Fig. 2(c). When ΔU_{DC} is within a dead zone, the DC/DC converter is turned off to avoid frequent bidirectional energy flow, which means the two PEDF subsystems are disconnected. When ΔU_{DC} exceeds the dead zone, a certain amount of

energy, which positively correlates with ΔU_{DC}, flows from the subsystem with a higher U_{DC} to the lower one. This control strategy for energy interconnection among various PEDF subsystems contributes to full utilization of solar power and reliability of the power supply.

III. Technology Review

Based on the definition, this section reviews the four related key technologies of the PEDF system (i.e., "*Photovoltaics*", "*Energy storage*", "*Direct current*", and "*Flexibility*").

We first conduct a bibliometric analysis on the publications indexed in the Web of Science database. Fig. 3 illustrates the search results, which are based on the search query in Table I. Publications about the four key technologies were limited before 2010 but have experienced sharp increases since then. This indicates the four key technologies in the building sector have attracted increasing attention in the background of decarbonization. The largest share of publications is "Energy storage", followed by "Photovoltaics", "Flexibility", and "Direct current". However, in the recent ten years, "Flexibility" has the largest average annual increase rate (41.3%), followed by "Direct current" (25.7%), "Energy storage" (25.6%), and "Photovoltaics" (25.5%). This indicates the great potential of building energy flexibility is still under exploration.

Based on the above bibliometric analysis, we select the most representative work about the four key technologies of the PEDF system in recent years, analyze research focuses, and summarize their major challenges & future opportunities. Fig. 4 gives an overview of the technology review, which is explained in detail as follows.

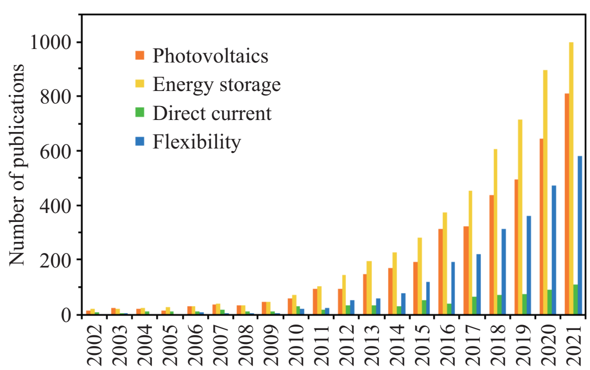

Fig. 3. Research trend of the key technologies of the PEDF system in recent 20 years. Data source: Science Citation Index Expanded, Web of Science Core collection. The detailed search query is listed in Table I.

TABLE I
SEARCH QUERY OF THE KEY TECHNOLOGIES IN THE PEDF SYSTEM

No.	Searching query
0	Topic = ("buildings" OR "a building" OR "office building" OR "office*" OR "residential building" OR "residence*" OR "home" OR "houses" OR "commercial building" OR "industrial building") AND ("energy" OR "power" OR "electric*")
1	Topic = ("solar power" OR "photovoltaic*")
2	Topic = ("energy storage" OR "battery" OR "batteries")
3	Topic = ("direct current" OR "DC")
4	Topic = ("energy flexible*" OR "demand response" OR "demand response" OR "load shift*" OR "load shed*" OR "resilient*")

Note: No. 0 limits the publications to the field of building energy. No. 0 AND No. 1 derive the publications about "Photovoltaics"; No. 0 AND No. 2 derive the publications about "Energy storage"; No. 0 AND No. 3 derive the publications about "Direct current"; No. 0 AND No. 4 derive the publications about "Flexibility". We adopt the above search query in Science Citation Index Expanded of Web of Science.

A. Photovoltaics

Research into distributed PV applied in buildings (i.e., BAPV/BIPV) can be generally classified into three categories: *Macro level*, *Building level*, and *Module level*.

1) Macro level: Potential evaluation and resource detection

Studies at the macro level mainly focus on distributed PV potential evaluation and existing resources detection at community/city/national level.

Studies about PV potential evaluation emerge prior to large-scale installation, for the purposes of urban planning and policy making. The hierarchical methodology is commonly used to estimate overall potential, including physical potential (i.e., solar radiation), geographic potential (i.e., available surface area), and technical potential (i.e., generation efficiency), in which the geographic potential is the most challenging to assess [37]. Thanks to rapid progress in geographic information system (GIS) and machine learning techniques, the geographic potential currently can be accurately quantified with big data [38], e.g., lighting detection and ranging (LiDAR) data, aerial images, satellite images, city digital surface models (DSM), or their combinations (generally $\leq$2 m per pixel to match the size of buildings) [39], [40]. From the view of urban design, researchers further emphasize influence factors in practice for prediction fidelity, such as the balance between energy production and aesthetic design [41], urban shading and solar reflection [42]. Most of these studies focused on building rooftops [38], which have the largest potential to receive solar radiation, whereas building façades have also attracted researchers' attention in recent years [43]. Based on the above techniques, literature indicates that distributed PV can potentially cover 20%–40% of annual power demand in most countries or regions [10]–[13].

With increasing installed capacity of distributed PV worldwide, detection of existing PV resources is equally important, but more challenging, due to the requirements of a higher spatial resolution (generally $\leq$0.3 m per pixel to match the size of PV panels) and more data from buildings. The detection process applies deep learning algorithms at each step, including labeling aerial images with PV [44], [45], estimating their sizes [46], [47], estimating their 3D orientations using time-series data of power generation [48], [49]. For the latest progress, Mayer *et al*. [50] developed a 3D-PV-Locator (i.e., a deep neural network model based on aerial images and 3D building data) to accurately detect rooftop-mounted PV systems and provide their azimuth and tilt angles.

2) Building level: System design for optimal utilization

Studies at the building level mainly focus on how to use distributed PV generation. A majority of current PV installations are grid-connected, whereas many studies indicate that self-consumption mode is more grid-friendly and economical for end users [51], which is exactly the aim of the PEDF system proposed in this paper.

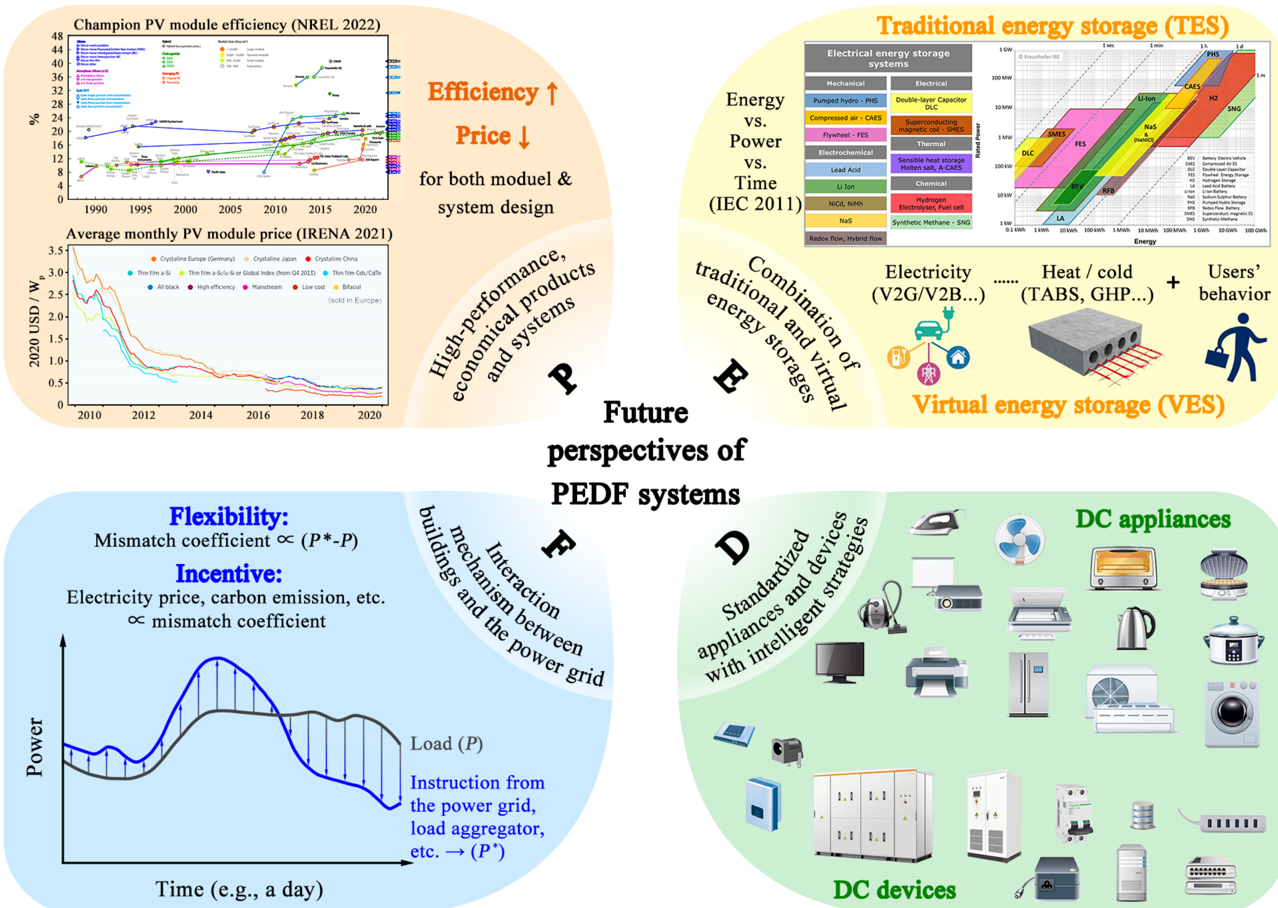

Fig. 4. Research focuses, major challenges, and future opportunities of the PEDF systems. *Photovoltaics*: High-performance, economical products and systems. *Energy storage*: Combination of traditional and virtual energy storages. *Direct current*: Standardized appliances and devices with intelligent strategies. *Flexibility*: Interaction mechanism between buildings and the power grid.

Based on this principle, the matching property between the distributed PV generation and building load is supposed to be carefully considered an optimal system design. Office buildings [52] and residential apartments [53] in cities are usually high-rise buildings with high energy intensity or limited effective area for PV installation. This results in a low percentage of the annual building load supplied by PV (generally <30%). Thus, nearly-complete self-consumption of the distributed PV generation could be set as the aim of these systems, which can be realized by energy storage systems [51], demand-side management [54], combination of roofs and other façades for PV installation [55], etc.

Furthermore, there are also many buildings with low energy intensity or large effective area for PV installation, such as low-rise houses in rural areas [40], airport terminals [56], [57], gymnasiums [58], and industrial buildings [59]. The above literature indicates that these buildings' PV generations can far surpass their annual loads. This kind of building alone or in aggregation could be designed as a virtual power plant to provide schedulable power supply to the grid, e.g., a solar-rich county in China [60].

In summary, more future studies on system configuration and control strategies are necessary to propose typical utilization modes for distributed PV resources at the building level, which will support guidelines for PEDF system design. Potentially, a distributed PV system at the building level is recommended to be designed towards either a nearly-complete consumer or a schedulable producer to avoid over-frequent energy interaction with the grid.

3) *Module level: performance improvement*

For PV modules, with rapid technological progress and industrialization in recent years, energy efficiencies of most commercial products currently range from 20% to 30% [61], and their prices have fallen sharply to 0.2–0.4 USD/W_p [62]. A recent market survey [7] indicates that crystalline silicon-based solar cell technologies currently offer the greatest advantages for BIPV applications, because a utility-scale PV mass-market induces rapid technological innovations (e.g., long service life, high efficiency, and aesthetic design) and price pressure. Towards a decarbonized future, more high-performance and economical PV products are needed for application in buildings, which are supposed to fulfill the requirements of both power generation and architectural design. Recent technological advances have provided more potential approaches, such as new materials to achieve higher efficiency and lower price (e.g., CIGS solar cells [28] and perovskite solar cells [63]), dynamic PV modules to achieve higher energy gain [64], thermal management of PV modules (e.g., integration of phase change materials [65] and radiative sky cooling [66]).

B. Energy Storage

Research into distributed energy storage in or around buildings mainly focuses on *traditional energy storage (TES)* and *virtual energy storage (VES)*, which are summarized as *generalized energy storage (GES)* [67], [68] in literature.

1) Traditional energy storage (TES)

Effective, safe, and cost-competitive TES technologies, especially electricity storage, are essential for the PEDF system to integrate RESs. Each TES technology has its unique advantages and challenges; thus, anyone alone cannot meet all the requirements [17]. International Electrotechnical Commission (IEC) systematically compared the main TES technologies from three dimensions, i.e., energy capacity, rated power, and time scale [69]. After about a decade of technology development, Schmidt *et al*. [70] analyzed the levelized cost of storage for 9 TES technologies from 2015 to 2050. Towards a decarbonized future, they found that lithium-ion batteries (LIBs) are likely to be the most competitive choice, especially for short duration within a day; hydrogen storage will be cost-efficient for long duration applications, such as seasonal energy storage. Moreover, Albertus *et al*. [71] pointed out that short-duration energy storage plays a major role when annual wind & solar generations on a regional grid are 20% to 50%, whereas long-duration energy storage is likely needed to further raise wind & solar share to over 70%.

For short-duration energy storage, much research has focused on various aspects of electrochemical energy storage (especially for LIBs), such as new battery materials and battery management systems [72]. LIBs have advantages in a flexible installation location, easy installation, fast and steady response time, and relatively high cycle efficiency [73]. Therefore, LIBs are widely-accepted as the most potentially distributed energy storage to stabilize future grids [74]. These characteristics make LIBs an attractive technology for distributed energy storage in a PEDF system; however, the performance and cost are still the major bottlenecks in large-scale applications.

For long-duration energy storage, these technologies generally have large energy capacities, and thus are less considered as distributed energy storage in or around buildings. In recent years, there have been some studies using distributed hydrogen energy storage to coordinate PV generation and building loads in a year [75]. However, as indicated by [71], its cost-efficiency and current necessity still seem unclear.

2) Virtual energy storage (VES)

VES, i.e., schedulable loads and distributed energy storage with end users, is an economic alternative to TES for providing grid services currently and in the future [76]–[78]. Based on normal end-use demands, VES generally consists of electrical and thermal energy storages.

For electrical energy storage, recent reports on global LIBs market [79], [80] indicate EVs (34%–54%) have surpassed consumer electronics (33%–40%) as the dominant application, whereas stationary energy storage only account for 6%–17%. Thus, EVs and consumer electronics with smart charging & discharging systems are two promising VESs at the user side.

Many studies indicated there is a strong coupling relationship between EVs and buildings [81]. Private vehicles (over 80% of vehicles [19]) are parked in or around buildings for more than 90% of their lifetime [82]. EVs' charging process is deeply integrated with building energy systems [83], which makes the charging load inseparable from the building energy consumption. Many studies utilized this coupling nature and designed systems & strategies to promote energy interaction between buildings and EVs, i.e., as VES [84]. Barone *et al*. [83] proposed a building-to-vehicle-to-building ($V2B^2$) system to transfer electricity among multiple buildings by an EV battery. Fretzen *et al*. [85] compared three charging scheduling strategies to promote a temporal match between rooftop PV generation and EV charging at a city scale. Zhou *et al*. [86] proposed an energy paradigm framework with V2B to realize a transition from the negative towards the positive district energy sharing networks. Borge-Diez *et al*. [87] proposed to combine V2H and V2B to improve energy efficiency and reduce peak demand in buildings.

As for massive consumer electronics and other appliances, current internet-of-thing (IoT) techniques (such as Wi-Fi, 5G, and power line communication) can help to exploit their potential as VES, i.e., controlling charge/discharge processes [88]. For example, Khadilkar *et al*. [89] proposed a personal comfort system with an LED light and a desk fan powered by a laptop battery. However, their low energy intensities and highly-random use patterns are the main factors limiting large-scale application.

For thermal energy storage, heating, ventilation, and air-conditioning (HVAC) systems, which generally account for 30%–80% of a building's energy use, are undoubtedly the most potential VES at the user side [25], [36]. This part of load can be shifted using a building thermal mass, thermal storage systems, and various phase change materials (PCM, like ice, paraffins, and eutectic salts) [90]. Studies in this field mainly focused on using HVAC systems together with the building thermal mass as VES to provide peak-shaving service, coordinate with renewable generations, and reduce operating cost.

First, for HVAC systems alone, Song *et al*. [91] modelled an inverter air-conditioner as a thermal battery (TB), which can work with a power dispatch model for demand response. Many studies indicate that centralized HVAC systems in large-scale buildings, like airport terminals, have larger energy storage potential, including terminal devices with PCM [92], water storage systems [93], ice storage systems [94], etc. Geothermal heat pump systems with smart control strategies are also a potential approach for demand response, since they can utilize the thermal mass of the ground [95], [96]. For more complex combined cooling, heating and power systems with thermal storage, Wang *et al*. [97] proposed a multi-agent system-based optimal control method to minimize operation cost, as well as reduce the mismatch between the energy supply and demand.

Second, for a combination of HVAC systems and building thermal mass, Hughes *et al*. [98] proposed a first-order linear dynamical model to simply but accurately capture the building thermal dynamics for grid regulation. Jin *et al*. [99] utilized the heat storage capability of buildings and developed a dynamic economic dispatch model of a hybrid energy microgrid to minimize daily operation cost. Zhang *et al*. [100] compared the influence of different thermostat control strategies on using the thermal mass of a single-family dwelling in the heating condition. The building thermal mass can be deeply integrated with HVAC terminals (i.e., thermally active building system, TABS [101]) to further exploit its energy storage potential [102]. Chen *et al*. [103] coupled passive building thermal mass and the active energy storage system to experimentally achieve 0.5 h to 2 h demand response.

In summary, in addition to TES, VES can provide a practical solution to the current urgent need for energy storage. In this way, users' behavior and acceptance significantly influence the performance of VES. Therefore, more future research into optimal control strategies for each kind of VES is still needed to balance between the available capacity of VES and users' satisfaction. Moreover, the composition of various VES resources in typical building scenarios (including office building, residential building, commercial building, etc.) need to be investigated for both design and operation purposes, and coordination strategies among them are equally important.

C. Direct Current

In 2006, Pang *et al*. [104] indicated that DC distribution systems in buildings had advantages in system simplicity and energy efficiency with the increase of distributed renewable generations and DC loads. PV systems and electricity storage systems have a DC nature. Besides, rapid development of power electronic technology improves performance of a DC microgrid and promotes the trend of DC appliances [105]. Thus, an increasing number of projects have applied a DC microgrid in buildings, e.g., office buildings [106]–[108], commercial buildings [109], [110], college buildings [111], [112], residential buildings [113], and data centers [114]. Many studies demonstrated the advantages of a DC microgrid in buildings over a conventional AC microgrid, including improving energy efficiency, reducing climate change impact, improving power quality & reliability, simple but robust control strategies, supporting off-grid systems in remote/isolated areas, safety for end use, etc. [32], [108]–[110], which are analyzed as follows.

First, a DC microgrid can improve energy efficiency, because it reduces power conversion stages from the source to the end [115]. Reported energy saving rates generally vary from 2% to 19% in buildings (related to system topology, converter performance, voltage level, etc.), e.g., 10%–19% by calculation [104], 3% by experiment [106], 6%–8% by a project-based simulation [109], 12%–18% by simulation [110], 2%–5% by a test bed [116], and 15% by simulation [117]. Therefore, DC microgrids in buildings are demonstrated to have a lower life-cycle environmental impact (indicated by the CO_2 equivalent) than conventional AC microgrids [108].

Second, a DC microgrid with only the voltage tightly controlled can provide better power quality than AC, which has the problem of harmonics [118]. Moreover, a DC microgrid can improve power security of buildings, because it can be disconnected from the grid in case of fault [108]. However, the introduction of various power electronic converters also brings some issues, such as voltage oscillations, voltage ripple, and voltage sag & swell. They are generally defined in the current standards (like IEC 61000 and IEEE 1159) and considered in technical studies [118]. However, as indicated by [107], the simulation and experiments of their accumulated impacts on a full-scale building are still lacking.

Third, a DC microgrid has many simple but robust control strategies, which are not available in an AC microgrid. For example, the droop control is based on DC voltage information transferred in the power line. It can be applied to simply parallelize multiple sources and support load sharing in a DC building with high reliability [119]. These DC-based distributed control strategies are the key components in the hierarchical control framework of a grid-friendly building to manage multiple control objectives at various time scales, which ensures system adaptability and scalability [120].

Fourth, for safety issues, Glasgo *et al.* [121] reviewed the literature and found there is no scientific consensus on whether AC or DC is more harmful physiologically if contacted. However, compared with early-determined AC voltage levels for end use ranging from 110 V to 230 V, the safety issue related to DC voltage level is highly concerning, currently. Existing cases and standards of DC buildings worldwide gradually show a convergence to two voltage levels at the end use (i.e., 380 V for high power loads and 48 V for the rest [32]), which are also recommended by the recent-issued standard in China on direct current power distribution of civil buildings (T/CABEE 030–2022) [30]. Thus, current standardization of voltage levels has made DC a safe choice for end use.

Despite the above advantages, DC application in buildings is a less hot topic compared with the other three technologies of the PEDF system (see Fig. 3), indicating that the necessity of DC is still questioned. An AC & DC hybrid microgrid seems more practical currently, because AC appliances and power distribution system are much mature [111], [112]. Specifically, for technological issues, there are still limited availability and incompatibility of DC components [122]. Safety and protection issues of DC microgrids are still the concern when it comes to large-scale application [105], [123]. Besides, non-technical obstacles include industry professionals unfamiliar with DC [121], the building owner's or the operating team's acceptance for new technology and uncertainty [122], etc.

Possible future perspectives are summarized as follows. Standardization and industrialization of key components in the DC microgrid of buildings (especially for DC appliances and DC devices) can further improve reliability and techno-economic feasibility of the PEDF system. Greater coverage of common appliances is still in urgent need to fulfill various requirements and reduce cost. Furthermore, the intelligent control strategy of each type of DC appliance should be carefully designed to realize flexible power regulation based on the principles of the PEDF system, as described in Section II.B. In addition to DC appliances, DC devices of the microgrid are also a bottleneck of the PEDF system, such as DC/DC converters, AC/DC converters, DC plug, DC socket, and DC switch. Lifetime and protection methods of these power electronic devices is a matter of concern when voltage of the DC bus varies within a certain range.

D. Flexibility

Energy flexibility is the main purpose of the PEDF system, which is achieved by integrating the above three technologies. It has enjoyed the most rapid development among the four in recent years, shown in Fig. 3. The concept of energy-flexible buildings (or grid-responsive/grid-interactive buildings) arose from the requirements of the power grid for demand response, including load shedding, load shifting, modulation, etc. [124], [125]. International Energy Agency (IEA) Energy in Buildings and Communities (EBC) Annex 67 project (2014–2020) [24] systematically studied and proposed its definition: The energy flexibility of a building is the ability to manage its demand and generation according to local climate conditions, user needs, and energy network requirements. The follow-up project IEA EBC Annex 82 (2020-2025) [126] scales from a single building to building clusters for low-carbon energy systems at the community/city level. Besides, many countries or organizations also have launched projects in this field, such as [127], [128].

Existing literature indicates that the great energy-flexible potential of buildings has attracted the attention of researchers from both the fields of buildings and power systems. In China, macro analysis [129] indicates about 60% of the annual power generation of China's carbon-neutral power system in 2050 (about 8 trillion kWh) will come from wind and solar energy. If the energy-flexible potential of buildings is fully exploited by the PEDF, they can not only self-consume 3.1 trillion kWh of the distributed solar generation, but also effectively utilize 2.6 trillion kWh of the renewable generation from centralized solar and wind plants. In the USA, future buildings with high energy efficiency and flexibility are expected to meet 75% of their demand from on-site generation on average [130], helping to avoid up to 800 TWh of annual electricity use and 208 GW of daily net peak load in 2050 [26].

Technical studies into energy-flexible buildings in recent years have been conducted from different perspectives. Early studies [125] mainly focused on specific measures to improve energy demand flexibility in buildings, including renewable energy generation, HVAC systems, energy storage systems, building thermal mass, appliances, etc. With the concept of energy-flexible buildings, Li *et al*. [131] emphasized an overall view to treat the flexibility as a whole, instead of a series of independent technologies, in which research into control strategies, occupant behavior, and rewarding schemes are important but lacking. In addition to traditional peak-shaving services with a timescale of hours, Wang *et al*. [132] reviewed the studies using HVAC systems in non-residential buildings to provide ancillary services to smart grids, i.e., fast response with a timescale of seconds or minutes. Although energy-flexible buildings have regulation abilities at various timescales, Tang *et al*. [36] indicated there is no clear match between these abilities and current grid service programs, which results from lacking quantification methods of buildings' energy flexibility and business models with incentives. Similarly, Li *et al*. [133] found there is no common consensus on the quantification method for residential buildings' energy flexibility. However, different quantification methods may favor different system solutions (such as control strategies [100]), leading to much confusion among building designers and engineers. From the view of grid operators, due to the difficulties in communicating with each end user and quantifying its flexibility, learning-assisted methods [134] and distributed multi-agent systems [135] are widely applied for building-to-grid (B2G) interaction in smart grids, which leads to complexity and uncertainty of the system. Besides, most existing studies on energy-flexible buildings (85%) are based on simulation rather than tests in real buildings [133]. Chinde *et al*. [136] argued that a building electrical system simulation with higher time resolution and higher-quality calibration data is necessary for investigating the contributions of energy-flexible buildings to the power grid.

The above analysis indicates there are many existing technologies to realize energy-flexible buildings; however, the bottleneck to fully exploit their potential in real application is an interaction mechanism between buildings and power systems. Specifically, (1) at the end user level, how to design an incentive mechanism to balance between the profit by flexible energy use and the users' overall satisfaction; (2) at the building operator level, how to quantify its own energy flexibility (i.e., the ability for grid dispatch); (3) at the grid operator level, how to interact with a massive number of buildings.

Thereby, we summarize some future perspectives on the practical methods and effective incentives to fully exploit the energy flexibility of buildings as follows.

First, a hierarchical framework [137] is a possible method for daily interaction between buildings and power systems, in which a load aggregator acts as a coordinator between building clusters and a grid operator. The grid operator sends regulation instructions to the load aggregator based on a contract of power dispatching. The load aggregator splits the instructions and dispatches sub-instructions to the subordinate buildings. The split is based on each building's energy flexibility declared previously, which can be quantified by a mismatch coefficient related to the difference between its actual load curve and a standard load curve [138]. The load aggregator can contain various types of buildings [139] and EVs nearby [140] to utilize their load complementary characteristics. Each subordinate building can adjust its power intake under the constraints of service quality [141]. If a building cannot follow its instruction, a coordinating mechanism among the buildings under a load aggregator can ensure overall regulation performance [142].

Second, a highly-distributed energy-flexible system (e.g., with swarm intelligence [143] and reinforcement learning for distributed control [144]) may be a potential solution in the future, if all the participants in the power system have enough intelligence and can communicate with each other unimpededly, e.g., by wireless communication or power line communication. Then, an elaborately designed indicator and its transactions are the key to system simplification and stabilization. TOU pricing in the current electricity market is a mature method; however, there is a risk of highly fluctuating electricity prices in special events, leading to a power supply crisis [145]. In the background of decarbonization, the real-time carbon emission factor [146], carbon emission flow information [147], or marginal emission factors [148] are potential alternatives, which can further be designed to relate to low-carbon certification or other economic incentives.

Third, incentive-based methods, like direct load control of high-power equipment, could be an effective way for fast demand response in some accidental events [149], [150].

IV. Application

Based on the four key technologies, this section introduces three typical application cases of the PEDF system, including, an office building, an office room with EVs, and a residential building, as shown in Fig. 5.

A. Office Building

Figure 5(a) illustrates a six-floor office building block with a floor area of 5,000 m^2 located in Shenzhen, China. It is the first building for real use that realizes the concept of PEDF systems.

The building block has two PV arrays on the roof (approximately 1,200 m^2), providing a total power of 150 kW_p. The energy storage system of the building block uses lead-carbon (PbC) batteries with a total capacity of 110 kWh, of which 50 kWh are centralized, and the rest are distributed on each floor. The DC microgrid of the building block adopts a bipolar topology with three wires for power supply [107], including a positive wire (+375 V), a negative wire (−375 V), and a neutral wire. Thus, it provides three voltage levels to meet the demands of various electrical terminals, including a high DC voltage of 750 V (connecting the positive and negative wires), a medium DC voltage of 375 V (connecting the positive/negative wire and the neutral wire), and a low DC voltage of 48 V (bucked from 375 V).

Based on these components and the aforementioned control strategies, the PEDF system of the building block can realize various operation modes (illustrated on Nov. 27th, 2020), including PV supply, grid supply, PV+grid supply, battery charge, and battery discharge. By switching among these modes along with variation of DC bus voltage, power intake from the grid can follow a prescribed value preset by the power dispatch system (illustrated on May 13th, 2021). Therefore, this building block can be regarded as an energy-flexible node from the perspective of the power grid.

Although the PEDF system has been successfully applied in this real building, some experience can help to improve its performance in future projects. Despite the advantage of providing two voltage levels (i.e., 375 V and 750 V), the bipolar DC microgrid has increased system complexity, cost, and difficulties in maintenance. Accompanying problems include: (1) voltage balance of the two DC poles under an unbalanced load condition; (2) more power electronic devices and related cables requiring a high withstand voltage (i.e., 750 V); (3) a higher possibility of system failure and related workload of maintenance.

B. Office Room + EVs

Figure 5(b) illustrates an office room with a floor area of 20 m^2 located in Beijing, China. It is a typical office case with EVs as VES to realize the concept of the PEDF without any TES.

There are two series of rooftop PV panels in this case, i.e., one with the tilt angle of 2° (48 m^2, 10 kW_p) and the other with the tilt angle of 37° (48 m^2, 10 kW_p). Three smart EV chargers (6.6 kW/charger) can adjust the charging power with variation of input DC voltage and EV's SOC. The DC microgrid of the office room adopts a unipolar topology for the power supply. The main voltage level of the DC bus is designed to be 375 V, and other voltage levels (such as 48 V) are converted from the DC bus by various power electronic devices.

Based on these components and aforementioned control strategies, we performed an experiment on Mar. 21st, 2022, to present an example of the workday operation with the office load (including lighting, HVAC, computers, etc.) and the charging load of two employees' EVs. PV generation and office load changed independently in this day. The two EVs arrived at about 8:00 and left at about 19:00, during which time the charging power of each charger could vary within 0–6.6 kW. In this way, the two EVs with smart chargers acted as VES based on the variable DC bus voltage set by the AC/DC converter. Consequently, power intake of this PEDF system from the gird can be controlled as a constant without any TES, and meanwhile the charging demands of EVs can be fully met (i.e., EV leaving with SOC of about 90%). If there is a clear requirement for demand management in the future, the power intake can be accordingly regulated.

The above experiment demonstrates the feasibility of taking EVs with smart chargers (even controllable charging only without discharging) as VES in the PEDF system. In this way, the building can achieve energy flexibility safely and economically. Currently, there is a surging demand for installing PV panels and EV chargers in existing buildings worldwide. This PEDF system, i.e., a building-connected solar charging system, is a practical approach to meet this demand, because there is no need to increase the capacity of the transformer connecting the grid, and the peak load for EV charging can be shaved by the building.

C. Residential Building

Figure 5(c) illustrates a residential building with a floor area of 40 m^2 located in Zhuhai, China. It is a full-scale experimental platform representing a replicable small family residence with a PEDF system.

Installation area of the roof PV panels is 30 m^2 (5 kW_p). The energy storage system uses lithium-titanate (LTO) batteries with a total capacity of 6.6 kWh. The DC microgrid of the residence adopts a unipolar topology for power supply. The main voltage level of the DC bus is designed to be 400 V, and other voltage levels (such as 48 V) are converted from the DC bus by various power electronic devices.

Based on these components and the aforementioned control strategies, the PEDF system of the residence can realize various operation modes (illustrated on Sept. 28th–29th, 2021), including PV+grid supply, PV+battery supply, PV+battery+grid supply, battery charge, etc. By switching among these modes, solar power is fully consumed in the

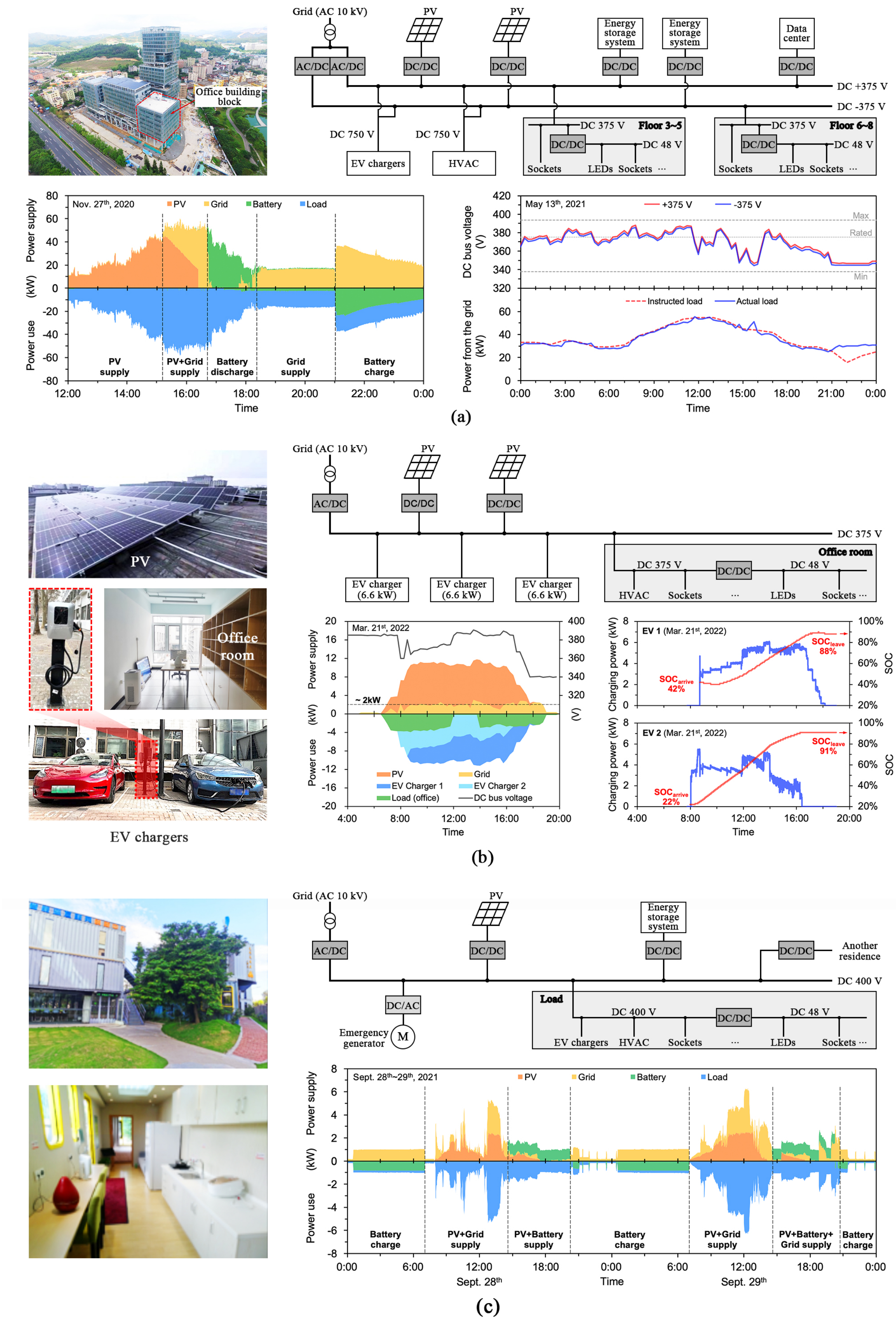

Fig. 5. Application cases of the PEDF system. (a) An office building block located in Shenzhen, China. (b) An office room with three smart EV chargers located in Beijing, China. (c) A residential building located in Zhuhai, China.

daytime; meanwhile, the battery is charged in the nighttime (approximately 21:00–7:00). It is discharged when PV generation decreases, but the load still exists (approximately 15:00–21:00). Therefore, this residence has the ability of peak-shaving for the power grid. In addition, these residences with the PEDF systems connect with each other by the DC/DC converters (introduced in "*Section II.C.3.f*") to form a large community. In this way, resources of these PEDF systems (e.g., PV panels and batteries) can be maximally used, and this community can provide a greater power regulation ability than that of a single residence.

This type of residence can provide novel patterns of energy supply and demand in urban and rural areas. Most PV generators cannot meet the demand for family use in urban areas, because of the limited exterior surface area of residential buildings (mainly apartments) for PV installation. In this situation, a residence is a flexible load for the grid, which can follow the instructions of power use. Furthermore, there is a larger area around a residence for PV installation for rural areas, such as roofs of farmhouses and livestock houses, uncultivated lands, and fishponds (i.e., floating PV). Meanwhile, the power consumption of residential buildings is lower than in urban areas. Thus, a residence with a larger amount of PV generation can supply surplus power to the power grid according to the instructions from the power dispatch system.

V. Conclusion

For a carbon-neutral society, a future power grid with high penetration of renewable energy will require a flexible demand side to cope with the intermittent supply side. This paper proposes a general power distribution system of buildings, namely, PEDF system, to provide an effective solution from the demand side. The PEDF system integrates distributed photovoltaics, energy storages (including TES and VES), and a DC distribution system into a building and realizes energy flexibility using distributed control strategies based on variable DC bus voltage. We select the representative work about the key technologies of the PEDF system in recent years, analyze their research focuses, and summarize their major challenges & future opportunities. It is indicated that if the energy-flexible potential of buildings is fully exploited by the PEDF, they can not only self-consume the distributed solar generation, but also effectively utilize much of the renewable generation from centralized solar and wind plants. Nevertheless, the bottleneck in real application is the interaction mechanism between buildings and power systems, which still needs theoretical studies and engineering practices. Then, we introduce three real application cases of the PEDF system, including, an office building, an office room with EVs, and a residential building. Field test results demonstrate they can follow the instructions of power use from grid operators. Therefore, a PEDF system contributes to integration of renewable energy for grid decarbonization. In conclusion, the PEDF system is not just a low-voltage power distribution system in buildings. More importantly, it is likely to bring a revolution to the power grid, i.e., to change the strategy of power transmission & distribution from "top-down" to "bottom-up". Further development of the PEDF system requires close interdisciplinary collaboration, including architecture, building technology, electrical and electronic engineering, computer science, and mechanical engineering.

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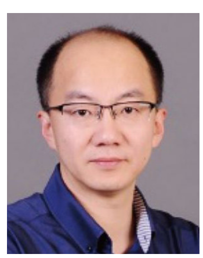

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