Adoption Pathways for DC Power Distribution in Buildings

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Contributor: Gabe Arnold

Driven by the proliferation of DC energy sources and DC end-use devices (e.g., photovoltaics, battery storage, solid-state lighting, and consumer electronics), DC power distribution in buildings has recently emerged as a path to improved efficiency, resilience, and cost savings in the transitioning building sector. Despite these important benefits, there are several technological and market barriers impeding the development of DC distribution, which have kept this technology at the demonstration phase.

Keywords: feasibility of DC power distribution ; efficient buildings ; direct-DC ; microgrids ; renewable energy ; DC distribution ; Direct Current ; sustainability

1. Introduction

Since the war of the currents of the late 1800s, alternating current (AC) has dominated power distribution in the building sector. During the 21st century, however, direct current (DC) has made a resurgence to challenge AC, especially in behind-the-meter applications. DC power distribution in buildings has recently emerged as a path to improved efficiency, resilience, and cost savings in a transitioning building sector, thanks to three factors: (1) the increased market penetration and cost reductions of DC sources, such as photovoltaics (PV) [1] and battery storage [2]; (2) the availability of DC end uses, such as electronics, electric vehicles (EVs), and solid-state lighting [3]; and (3) recent advancements in power electronics technologies.

DC distribution in buildings with onsite DC sources powering DC end uses can lead to energy savings of up to 18 percent compared to AC distribution, according to power simulation studies [4][5][6] and field measurements [7][8]. Other studies have evaluated the potential cost savings from DC distribution, which can be realized through simpler power electronics, fewer power conversions, and the combination of communications and power distribution [9][10]. Furthermore, in buildings with DC distribution, onsite PV and electricity storage can provide resiliency benefits at a lower cost compared to equivalent AC systems [11][12]. Additional potential benefits of DC power distribution include fewer maintenance requirements, longer-lived system components, and simpler load control [13].

Despite these important benefits, the market for DC distribution in grid-connected buildings in the United States and globally is still in the demonstration phase, with few actual buildings utilizing DC directly from an onsite DC source to power building end uses (direct-DC). Although DC is used widely with Ethernet and Universal Serial Bus (USB), it is rarely linked to DC generation and storage. As previous studies have highlighted [14][15], several technological and market barriers impede the development of DC in buildings. First, the current electricity transmission system is based on AC, and each grid-connected building is supplied with AC power, requiring a conversion to DC for powering DC loads, when local DC generation (e.g., PV, storage) is not available. Other important barriers include the lack of a mature market for DC-ready equipment and converters; low technical and market awareness among practitioners; technological issues related to safety, grounding, and fault protection; and a lack of consensus on core technology standards. As mentioned above, the benefits of DC systems have been documented and quantified in some cases (e.g., efficiency). However, such benefits have mostly been evaluated individually or at the building level, and less often for specific applications, without considering real-world opportunities and challenges to implementation.

Related Work

Several studies have assessed the feasibility and potential benefits of DC in buildings for specific applications or end uses, typically through evaluation of experimental setups, modeling work, or a combination thereof. Such studies generally focus on specific system configurations (e.g., explicit voltage levels) and a single or limited set of metrics, with efficiency being the most prominent.

In data centers, DC distribution has been implemented successfully for more than a decade, and the associated efficiency benefits (approximately 5–7 percent energy savings [16]), reliability benefits [17], and improvements in power quality [18] have been studied extensively [19]. Several papers have also evaluated DC lighting for commercial buildings in particular, where solar generation is generally synchronous with lighting usage. Thomas et al. [20] conducted an economic analysis of DC systems in a commercial building and found a 5% reduction in levelized annual costs for direct-DC LED lighting systems compared to similar AC systems, while Frank et al. [21] estimated 6–8 percent energy savings for a direct-DC high bay lighting system without battery storage over an equivalent AC system. With regard to DC-powered air conditioning systems, Aguilar et al. [22] evaluated a hybrid (grid and solar-powered) heat pump and estimated a 74 percent reduction of carbon emissions at a 16 percent lower annualized system cost in comparison to a baseline, grid-powered air conditioning unit. Further, in a study on the use of DC microgrids for DC fast charging of EVs [23], the authors found that such configurations facilitate vehicle-to-grid operations and integration with distributed energy resources (DERs). Finally, ref. [24] presented a framework for analyzing the effect of line voltage in residential DC distribution systems and highlights the importance of wire gauge, line voltage, and end-use loads for maximizing efficiency benefits in such systems.

Other studies have assessed how DC distribution can be applied in the building sector using a more qualitative approach, namely, by seeking expert feedback and recommendations. In 2014, a workshop with 50 attendees from various disciplines, was held in Sacramento, California, to identify opportunities, barriers, and future research directions to enable DC distribution in the built environment [25]. In 2016, a research study for the California Energy Commission solicited stakeholder input on DC power systems through a workshop of approximately 30 participants, electronic surveys with 39 respondents, and 10 detailed interviews with DC system researchers, designers, policymakers, and manufacturers [15]. Glasgo et al. [26] conducted telephonic interviews of 17 DC distribution experts and stakeholders to gain a better understanding of the greatest non-technical barriers to the deployment of DC systems. In another study, the United States National Electrical Manufacturers Association surveyed 39 participants (consisting primarily of equipment manufacturers) on the benefits, barriers, and recommendations for DC in buildings. Finally, Aloise-Young et al. [27] interviewed personnel in four commercial buildings in Colorado that had various levels of success with DC distribution, drawing conclusions from their experience and identifying a roadmap for successful implementation of DC distribution in buildings. **Table 1** summarizes the main conclusions and recommendations of these studies.

Table 1. Summary of expert feedback on DC distribution systems.

Study	Expert Feedback Method	Main Conclusions and Recommendations
[25]	• Workshop **(50 attendees)**	• Develop demonstration projects benchmarking best-in-class DC vs. AC devices • Incorporate methodology that accounts for total cost of ownership • A regulatory roadmap is needed to accelerate DC systems’ implementation
[15]	• Workshop **(39 attendees)** • Interviews **(10 participants)** • Electronic surveys **(39 respondents)**	• Conduct research and data on cost • Deploy demonstration projects to validate performance, cost, and raise awareness • Develop protection standards and reach an agreement on DC voltage standards • Conduct research on power quality issues in DC vs. AC systems • Lack of DC devices is a major barrier
[26]	• Interviews **(17 participants)**	• Greatest barriers are lack of awareness among professionals and lack of DC devices and power system components • Training programs for engineers and electricians could increase awareness • Targeted use cases in which DC is clearly advantageous over AC could help jumpstart the technology

Study	Expert Feedback Method	Main Conclusions and Recommendations
[28]	• Survey **(39 participants)**	• Lack of DC products, standards, and pilot projects are major barriers • More communication and outreach are required • Outreach, policies, and standards are needed to encourage DC
[27]	• Interviews **(8 participants)**	• The main technological barriers are the lack and incompatibility of DC system components • Successful installations require an owner willing to “champion” the project • Due to the risks associated with emerging technologies, project financing, bidding, and contracting are key aspects of successful projects

2. Adoption Pathways

2.1. Office Workstations

Contemporary office electrical loads are dominated by electronics: computers, monitors, desk phones, and charging for mobile devices. Other common loads are lighting, portable fans, and, in some buildings, space heaters. All of these are amenable to DC powering; with short distances, USB is a viable choice, able to provide up to 100 W. In an existing ZE installation, building designers mentioned that the 100 W power limit was a key element for controlling occupant energy use, because it limited the use of high-power devices such as resistance space heaters. This pathway is most valuable when it skips AC power distribution to workstations entirely. Workstation loads have high value to users; therefore, ensuring that their power delivery is reliable—backed by a battery—can be important. That same battery can also be used to time-shift PV power. Managed DC can prioritize loads if power is short and can keep the total load under capacity limits.

This pathway avoids AC distribution to workstations entirely, thus having the potential for cost reductions while increasing efficiency and reliability. DC outlets and cables are also less bulky than their AC counterparts. Two distinct cases are individual workstations (as in conventional offices) and clusters of two, four, or more workstations that are contiguous and so could have a common infrastructure. While mobile and desktop computers and phones can use Wi-Fi for communications, having Ethernet as an option can be advantageous. Ethernet could be used as the power delivery mechanism to a workstation, providing the needed communication pathways. Single Pair Ethernet, which uses two cables that deliver up to 50 W each, could be preferable for this purpose, primarily due to its small size and low cost [29]. If more power is needed than a single Ethernet cable can provide, then multiple cables can be placed in parallel. This could be implemented via a hub that takes in Ethernet and outputs various forms of USB as well as Ethernet, for both data and power.

A key prerequisite for this pathway is the availability of DC-powered devices. Many DC-powered devices are available today (PCs, monitors, phones, task lights), but having a greater variety would be helpful. As shown in **Table 1**, all electronic devices are DC-internal but there is limited availability of DC-ready products. This will require better standardization and consolidation of the various low-voltage connectors to one or two types that can accommodate most workstation voltage and power levels. In addition, a long-distance link technology is needed to supply power to workstation hubs; this could be a 380 V DC bus with a step-down converter that could power low-power loads locally. Basic mechanisms for prioritization and power allocation are also needed; these can build on capabilities already present in USB and Ethernet. For systems with multiple parallel step-down converters, an efficiency optimization algorithm that regulates current between the converters could be used to optimize the system efficiency [30]. See **Figure 1** for a conceptual schematic of this proposed configuration. For open office spaces, bringing power down from the ceiling or up from the underfloor to a collection of adjacent workstations can be convenient. While cost savings can occur in any building, energy savings will generally rely on being coupled to PV (with or without battery storage); therefore, installation should be tied to either a general retrofit, PV installation, or in combination.

Table 3. Availability of DC-ready devices.

Device Groups	Device Subgroups	"Standard" DC Voltages	Sites Avail.	Market Avail.	Availability Comments
Electronics	**TVs, cell phones, printers, and scanners; audio, network, and computing equipment**	**PoE, USB, 12 V, 24 V**	★★	★★	- Electronics are DC-internal but there is limited availability of DC-ready products - Input voltages vary. USB/USB-C input becoming more common. PoE input is also available.
Lighting	**General, landscape, high bay, and task lighting**	**PoE, 12 V, 24 V, 48 V, 380 V**	★★★	★★	- More products available in commercial vs. residential sector - Most available field deployments use DC lighting - PoE lighting is the most available voltage - 380 V lighting is found in high bay applications.
Refrigeration	**Refrigerators, freezers, ice makers, vending machines**	**PoE, 12 V, 24 V, 380 V**	★	★	- Most available products used in the off-grid market - High-voltage prototypes currently tested by major appliance manufacturers.
Space heating and cooling	**Heat pump/rooftop air conditioners, variable refrigerant flow units, portable and ceiling fans, radiant floor heating**	**12 V, 24 V, 380 V**	★	★	- Small capacity (≤18,000 BTU) units available for off-grid applications - Retrofitted ceiling fans for high bay applications are available in field deployments - Major manufacturers have tested DC HVAC systems.
Cooking	**Induction cooking, microwave ovens**	**12 V, 380 V**	Ø	★	- Some products available for mobile applications (12 V microwaves) - Induction stoves and microwaves can be DC-powered.
Water heating	**Heat pump water heaters**	**380 V**	Ø	Ø	- Heat pump water heaters could be coupled with PV.

Device Groups	Device Subgroups	“Standard” DC Voltages	Sites Avail.	Market Avail.	Availability Comments
Large appliances and other motor loads	**Clothes washers and driers, dishwashers, pumps, fans, compressors**	**380 V**	★	★	- High-voltage residential appliances with dual (AC and DC) input have been tested by manufacturers - Motor drives could be adapted to use a variety of DC input voltages. Retrofits may require Underwriters Laboratories (UL) certification.
EV charging	**DC fast charging equipment**	**380 V**	★	★	- Some companies are beginning to offer direct-DC charging equipment - Available sites have used custom DC chargers.
Miscellaneous loads	**Vacuum cleaners, humidifiers, garage doors, hairdryers, irons, window shades, process loads**	**PoE, USB, 12 V, 24 V, 48 V, 380 V**	★	★	- Low power loads (timers, motor controls, window shades) are available with PoE - Higher power loads can be powered with high-voltage (380 V) or battery-assisted lower voltage.

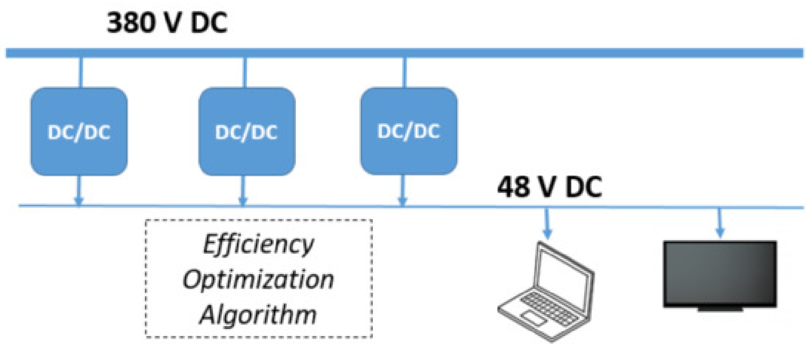

Figure 1. Example of DC-powered PoE lighting system.

2.2. PoE Lighting

PoE lighting uses category 5/6/7 Ethernet cables to both provide DC power and enable network communication with lighting fixtures, sensors, and devices. The availability of PoE EUDs has grown quickly during the past decade. For lighting specifically, a recent study identified more than 17 lighting manufacturers who offered the technology in a wide range of lighting fixtures [31]. Beyond lighting, PoE is expected to grow as other devices and building loads adopt it for power and data exchange. PoE utilizes the TCP/IP protocol, making it well suited for smart buildings that require integration and data exchange between building systems and devices.

This pathway would target an established DC technology and apply it to lighting. PoE lighting availability and adoption are growing quickly. Its potential benefits extend beyond energy efficiency, also including lower deployment costs, simplified installation, flexibility, integration with other systems, and improved reliability. The network management software allows power draw monitoring at each port and managing the power that can be drawn. PoE systems have the inherent capability to measure their energy usage, which can be leveraged for energy optimization and management. An additional benefit is that PoE is already standardized and established for phones and security systems, and therefore a supply chain and qualified workforce to install PoE systems already exists. Reconfigurability may become another driving factor, as single touch-safe cables and devices can be installed in spaces where no AC outlets may be accessible. Non-electricians, such as IT personnel or staff, can reconfigure PoE lighting fixtures or other devices as needed to adapt to the changing needs of the space. **Figure 2** shows an example direct-DC PoE lighting system.

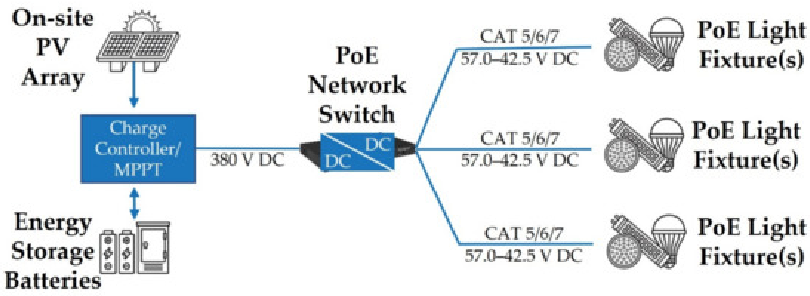

Figure 2. DC-powered PoE lighting system.

Current POE lighting systems may not be as energy-efficient as traditional AC lighting systems in some applications, due to power losses in CAT 5/6/7 cabling and standby power losses in PoE switches [32]. Standards, distributed architectures, and larger gauge cables are available to reduce cable losses; however, more work is needed to deploy these practices in the market. PoE switches need improvements to reduce losses, especially in no-load and dimmed conditions for lighting. An additional challenge is that there are no PoE switches available that accept DC power at the input, so an inverter is required to connect PoE lighting to PV panels and energy storage batteries. Should PoE switches be able to accept DC, lighting could be powered directly from PV and battery storage, which would offer additional energy savings, grid, and reliability benefits. PoE is limited to 100 m of cabling from the network switch to each end-use device. Longer runs are possible through PoE power injectors, which effectively remove the need to have an additional network switch at longer distances, with the caveat that they can cause energy losses. PoE systems allow for IP-addressable devices with high visibility, controllability, and permit integration with other building systems (e.g., alarm systems) present on the network. PoE systems also require the use of hardware and software, especially related to the IT network. Software and firmware updates must maintain compatibility among all the system components to operate properly; this is critical during installation and maintenance.

2.3. EV Charging

In this pathway, DC-input electric vehicle service equipment (EVSE) replaces traditional, AC-input level 2 or AC-input DC fast chargers, allowing for more flexible and efficient EV charging. DC-input chargers still follow existing DC fast charger interconnection standards (e.g., CHAdeMO, CCS), but the EVSE input is fed by a DC bus rather than a 3-phase AC system. EVSE power levels can be flexible, ranging from typical AC level 2 (6.6 kW) to DC ultra-fast charger power levels (200+ kW), depending on the device ratings. The EV's onboard rectifier (AC/DC converter) power rating is no longer a constraint.

DC EV charging is most appropriate for EVSE coupled with PV systems via a DC link. This reduces complexity, eliminates the need for inverters and grid synchronization, and increases efficiency. This is especially true when battery storage is also used—for instance, to mitigate peak demand events from DC fast charging, which can be beneficial from the utility's perspective (for reliability reasons) or the customer's perspective (for economic reasons). DC EV charging can be grid-connected (in which grid power supplements power from either PV, battery storage, or both) or grid-independent (in which the entire system is self-contained to reduce utility demand charges). As discussed in earlier studies [15][33], EV charging is most beneficial in applications where EV charging and local PV generation are coincident. Such applications may include commercial parking spaces with onsite PV canopies (e.g., company parking garages, electric school bus depots), and residential solar community systems. For such applications, fleet management software may be appropriate for regulating vehicle and battery charging and usage based on current and expected PV generation.

DC-coupled EVSEs can also offer resiliency features by charging critical vehicles from PV or battery storage without requiring an AC microgrid (and its associated complexity). The power electronics, including communications and control components, of DC-input EVSEs would require minor modifications, resulting in simpler hardware and control schemes. Even though DC-input EVSEs are still at the demonstration phase, at scale, DC-coupled chargers would have fewer components and cost less than their AC counterparts. The estimated 2–3% efficiency gain from DC/DC (versus AC/DC) conversion (which is estimated to be higher for systems with battery storage) translates directly to reduced cost for companies selling charging services, making them more competitive. See **Figure 3** for a conceptual schematic of the above configurations. According to the researchers technology and market assessment, there is a limited number of companies offering DC-input chargers, while two existing sites have installed or plan to install DC-input EVSE.

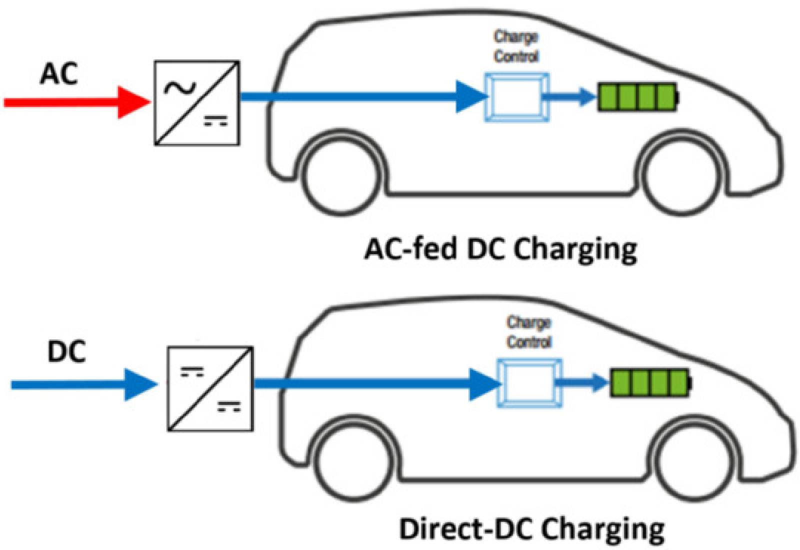

Figure 3. AC-fed versus direct-DC EV charging.

Apart from the lack of DC EVSE equipment on the market, voltage standards for both the supply side and the EV side would need to be developed and negotiated. Vehicle-to-EVSE communication standards would need to accommodate a wide range of available DC power levels. For supply standards, it would be important to align any developed standards between the DC building industry and DC fast charger manufacturers. Further, to showcase the potential benefits of DC EV charging, existing and planned projects should demonstrate their efficiency and cost advantages compared to AC-input equipment.

2.4. Residential Backup Power

Residential DC backup power refers to a lightweight electronic solution that provides resiliency to the various user-selected critical loads in a home. Critical loads often include communication devices (e.g., a Wi-Fi router), refrigerators, security devices, medical devices, and select lights. For California in particular, garage door openers being sold are now required to have a backup battery, because many 2017 wildfire deaths were caused by the inability to escape during the grid outage [34]. These lightweight DC backup units contain ample storage and often include a solar input port. They operate at touch-safe voltages, rarely require permitting, and can often be installed by the customer.

Residential DC backup circuits have several advantages over AC alternatives. With AC distribution, there are two options for battery backup: using a separate battery in every critical load or using a dedicated uninterrupted power supply (UPS). However, backup batteries are less likely to be maintained regularly, and therefore more likely to fail. This is one advantage of using dedicated backup circuits with centralized storage that is distributed. The backup circuits' centralized AC/DC gateway converter has power electronics that enforce a one-way connection to the grid and can feature regulated port-based point-to-point power delivery. Point-to-point power distribution is only possible with DC and greatly eases the technical challenges of load management and shedding.

One example of a residential DC backup circuit is the Home Energy Router (HERo), which is currently under development [35]. The HERo (**Figure 4**) features ports for solar, storage, and DC loads via USB-A, USB-C, and PoE. The unit can eventually be designed to take dual AC or DC input. Its price-based controller can use machine learning to tune its optimization parameters in real-time and can monitor messages from grid operators.

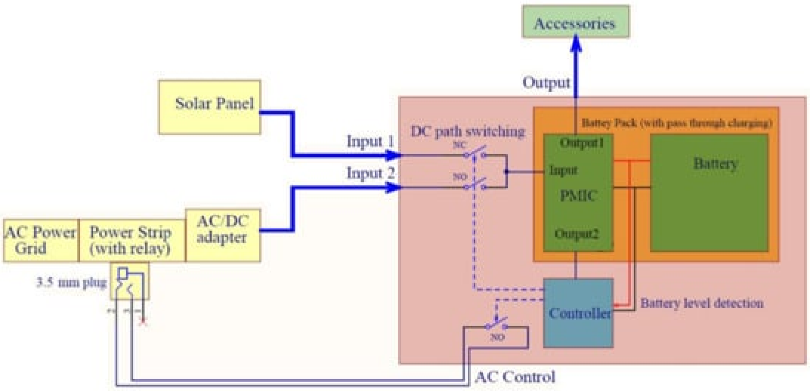

Figure 4. Statewide electrical Block diagram for the HERo. (Source: Belkin).

Residential DC backup circuits will have to demonstrate a clear market incentive beyond efficiency. The target customers are likely middle-income households, whose occupants will often want to install the backup units themselves. As such, the units must be as inexpensive, safe, and as easy to use as possible. These DC backup units will have to drive the DC end-use market because, in the current market, dual AC or DC loads likely will not exist without such a driver. In addition, users will have to assign load shedding prioritization manually, because power communications protocols do not currently identify devices and priority. One key marketing advantage over AC distributed backup batteries is the ability to connect a user-mounted solar panel, which will improve backup lifetime, reduce grid energy use, and potentially provide critical power during a grid outage.

2.5. Community Microgrid

Although the typical practice today is a behind-the-meter microgrid solution for single buildings with solar PV and storage, the community model has several potential advantages. This pathway involves a community microgrid that can operate in island mode, which connects multiple buildings and allows them to share the community's DER assets. The community includes a combination of commercial, residential, or both loads, with solar PV generation and battery storage. DC community microgrids feature a DC bus that connects to each building's electricity feeder. DERs can connect directly to the DC bus, and the buildings (end uses) within the microgrid can operate in island mode. While the DC microgrid would ideally serve DC loads within buildings, in the near future, an inverter is likely required for this pathway to come to fruition. The microgrid may have an interconnection with the grid for the import and export of energy through a central bidirectional gateway inverter. This pathway may be most appropriate for newly constructed ZE building communities.

While community microgrids can be AC, a DC topology offers many distinct advantages. First, DC-DC converters are inherently more efficient than DC-AC inverters [36]; therefore, eliminating the inverters for each DER connected to the microgrid improves overall distribution system efficiency. In addition, the manufacturing bill of materials is lower in a DC system, suggesting that the upfront cost of a DC system will be lower at economies of scale. The DC link eliminates the need for the DERs to synchronize in phase with each other or with the grid, greatly simplifying the control topology and allowing for highly distributed systems. Further, the microgrid's gateway inverter can perform grid services such as reactive power compensation. In the DC community microgrid configuration, DERs can be connected with the use of DC-DC converters to match the bus voltage, resulting in overall higher system reliability due to the fewer required power electronics, and better power quality, compared to a more traditional AC microgrid [37]. The project team has identified three installations based on this proposed pathway, and more are under planning or development.

Several other advantages make DC ideal for the scalability of a community microgrid. First, the microgrid could be designed such that the distribution feeder does not need to be upgraded. In a DC system, the power through the feeder is limited entirely by the size of the gateway inverter. Second, many community microgrids do not have the space for community storage assets, making highly distributed storage solutions ideal. However, highly distributed (~10 kW or less) storage solutions are not available for AC microgrids, because there are currently no battery inverters that can grid-form together in parallel on the same bus. The prolific use of power electronics in DC microgrids easily allows for DC solutions with highly distributed storage. Finally, community microgrids would ideally control power-sharing between homes with co-optimization. The use of power electronics at every node makes DC the ideal topology for a highly controlled microgrid.

Perhaps the most prominent challenge to grid-connected DC community microgrids is uncertainty from regulatory bodies and electrical utilities, particularly for non-utility-backed microgrids that may jeopardize the utility earnings and investment in existing electrical distribution [38]. DC community microgrids can be an excellent front-of-the-meter opportunity for utilities that accept the new technology. Front-of-the-meter solutions would also require extensive training for utility linemen to ensure operation. In contrast, behind-the-meter solutions would require operation and maintenance from the

DC microgrid provider. Another challenge is in repurposing or augmenting the original AC infrastructure to support a DC microgrid. To support a DC microgrid, the existing wires will likely need to be reinforced to handle a higher current, because the DC voltage is often lower than that of the original AC system. However, the main infrastructure challenge is the potential need for both AC and DC power distribution lines. This challenge arises in community retrofits where there are customers who do not want to participate. In this case, the infrastructure must support both AC and DC wires, leading to one of two expensive options. The first is to replace the poles with ones that are tall enough to accommodate the required clearance between the AC and DC wires. The other option is to underground the DC cables, which is more expensive but more elegant. In general, DC community microgrids are best suited for newly constructed neighborhoods. In particular, neighborhoods with ample yard space for individual or shared assets are ideal. Nonetheless, with the increasing demand for resiliency and EV charging, DC community microgrids may still be the most attractive solution for retrofits, despite the potentially higher upfront cost. **Figure 5** shows a diagram of a group of buildings in an existing neighborhood block, some of which (shaded blue) are participating in the microgrid, while others have opted out. For more information and a case study on neighborhood microgrids)

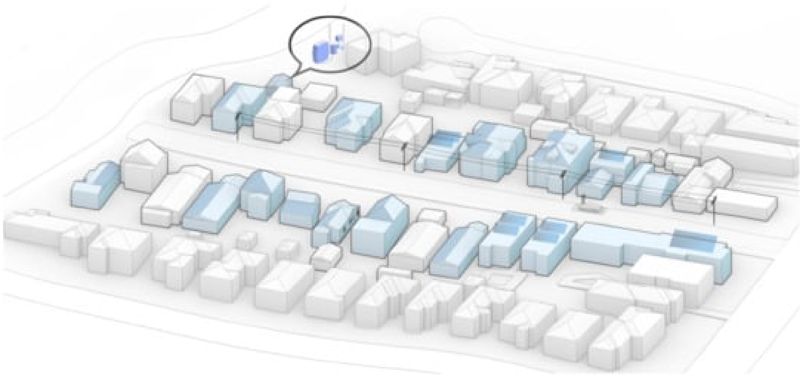

Figure 5. Community microgrid in an existing neighborhood setting (retrofit) (source: California Institute for Energy and Environment, UC Berkeley EcoBlock).

2.6. Building-Integrated PV Powering Local End Uses

Building-integrated PV (BIPV) refers to the integration of PV cells into a building's facade, which often includes windows, awnings, and outward-facing concrete. It differs from building-applied PV (BAPV) in that the PV is integrated during construction, rather than applied afterward. BIPV is often connected to a building's main distribution panel via a string inverter. However, module-level microinverters will likely become more popular for AC BIPV systems because building facades are much more susceptible to panel mismatch than roof-mounted panels [39]. For DC systems, power optimizers also solve this problem and may be the pathway for connecting loads directly to BIPV systems. These systems can easily include close-proximity loads, such as window blinds, window openers, electrochromic windows, occupancy and daylight sensors, and interior lighting. **Figure 6** shows a conceptual schematic for a direct-DC BIPV system.

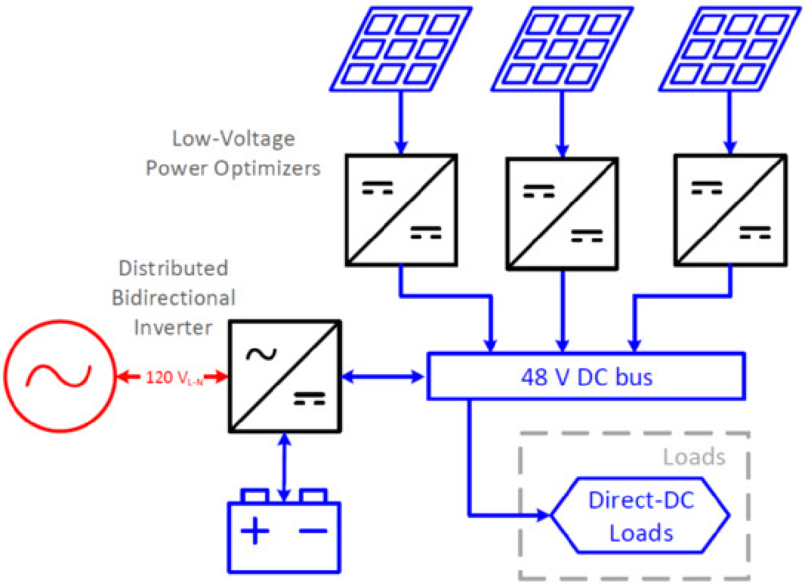

Figure 6. Direct-DC BIPV system powering local end uses.

Recent studies have suggested BIPV should be integrated via parallel power optimizers connected by low-voltage DC distribution [40]. Module-level converters are ideal due to voltage mismatch. While power optimizers can be superior to microinverters in cost and efficiency, the key metric of comparison is life span, because it is very difficult to replace modules and converters. DC power optimizers require fewer electrolytic capacitors, resulting in a slightly longer life span than AC microinverters. However, it is important to use parallel power optimizers because a single failure in a series power optimizer string disables the entire string. Parallel power optimizers are conducive to low-voltage DC (<60 V), allowing such BIPV systems to be installed by construction workers without the need for a licensed electrician. Low-voltage DC systems are also immune to AC disturbances and have additional options for grounding and isolation, which further helps to increase the BIPV system's life span [40]. Because a BIPV installation may involve many separate elements, being able to connect them via low-power DC, rather than with AC circuits, should have a significant advantage in cost, cable size, and installation complications (e.g., building shell penetrations). This also holds for low-power devices in and near the building facade. Matching the energy needs of in-facade devices to BIPV production, often with the use of electricity storage, can greatly reduce the capacity needed for a connection to the AC system. The energy use of in-facade devices will also be reduced by being directly DC-powered.

Because parallel power optimizers are ideal for BIPV systems, it can make sense to add certain loads to the BIPV circuit. The system's gateway inverter must be low-cost but bidirectional so that these loads can be powered in absence of sunlight. Although the easiest pathway is to add close-proximity loads to the BIPV circuit, loads such as window shades, openers, and electrochromic windows are not significantly impactful pathways. For the greatest impact, the BIPV circuit should connect to larger loads, such as a lighting circuit, in-façade HVAC, or DC power hub. The latter are available from various manufacturers. Another recommendation is to integrate communications on the DC circuit for connected end uses, such as sensors, cameras, and actuators, which may be beneficial not just from a resilience perspective, but also from a security perspective.

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