Title

Direct-DC Power in Buildings: Identifying the Best Applications Today for Tomorrow's Building Sector

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ABSTRACT

Driven by the increased use of direct current (DC) sources (photovoltaics, battery storage) and DC end-use devices (electronics, solid-state lighting, efficient motors), DC power distribution in buildings and DC microgrids have been proposed as a way to achieve greater efficiency, cost savings, and resiliency in a transitioning building sector.

Despite these important benefits, several market and technological barriers inhibit the development of DC distribution, and the market for DC in buildings is still largely in the demonstration phase. Therefore, to jumpstart this technology, a clear path forward must emerge at this early stage of deployment. The goal of this paper is to define specific end-use cases for which DC distribution in buildings is a value proposition today by defining clear efficiency and resiliency benefits while addressing barriers to implementation.

The paper begins with a technology and market assessment of DC distribution equipment, end uses, and technology standards. That is followed by results from an expert elicitation of DC power and building end-use professionals (e.g., electrical designers, building operators, engineers) and reports on-site visits and lessons learned from successful (and less successful) field deployments of DC distribution projects in North America. We present specific adoption pathways at the community and building level that can be implemented today, and evaluate them using qualitative and quantitative metrics, such as technology and market readiness, energy savings, and resiliency.

Introduction

Since the War of the Currents of the late 1800s, alternating current (AC) has dominated power distribution. In recent years, however, direct current (DC) has made a resurgence to challenge AC. Driven by the increased use of DC sources (photovoltaics, battery storage), DC end uses (electronics, electric vehicles, solid-state lighting) and advancements in power electronics technologies, DC power distribution in buildings has been proposed as a way to achieve greater efficiency, cost savings, and resiliency in a transitioning building sector. Numerous studies have estimated, through power loss simulations (Gerber et al. 2018; Denkenberger et al. 2012; Fregosi et al. 2015) or actual measurements (Boeke and Wendt 2015; Noritake et al. 2014) the potential energy savings of DC distribution in buildings with onsite DC generation, storage, and loads.

Other studies have evaluated the potential for cost savings from DC distribution (Vossos et al. 2018; Thomas, Azevedo, and Morgan 2012), which can be realized through simpler power electronics, fewer power conversions, and the combination of communications and power distribution. Also, buildings with DC distribution and electricity storage can provide resiliency benefits at a lower cost compared to equivalent systems with AC distribution (Che and Shahidehpour 2014). Other potential benefits of DC power distribution include lower maintenance requirements, longer-lived system components, and simpler load control (George 2006).

Despite these important benefits, the market for DC systems in buildings in the United States and abroad is still in the demonstration phase, with few actual buildings utilizing DC distribution. 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 (Gal et al. 2019; Vossos et al. 2019), there are several market and technological barriers that inhibit the development of DC distribution in buildings, such as the lack of a mature market for DC-ready equipment and converters, low awareness among practitioners, issues related to safety, grounding, and fault protection, and lack of consensus on core technology standards. The benefits of DC systems have been documented (and quantified in some cases), but they have often been analyzed individually (e.g., focusing on energy savings only), or at the building level (vs. for specific applications), without taking into account real-world opportunities and challenges to implementation.

The goal of this paper is to define specific end-use cases for which DC distribution in buildings is a viable solution today by defining clear efficiency and resiliency benefits while addressing barriers and minimizing problems to implementation. While similar work in scope has been performed in the past, with a focus on the residential sector (Pantano et al. 2016), this study provides the following novel contributions:

- It expands the study scope beyond the residential sector to commercial buildings and communities.
- It conducts a comprehensive market and technology assessment by evaluating DC standards and end-use devices, analyzing field deployments of DC power distribution in North America, and identifying DC products for electrical end uses in buildings.
- It utilizes the results of an expert elicitation of 20 DC power and building end-use professionals (electrical designers, building operators, engineers) to develop opportunities, lessons learned, challenges, and specific applications for DC distribution systems in buildings.
- It conducts a simulation-based energy savings analysis of DC vs. AC distribution for three end-use categories (lighting, electronics, motor-driven loads).
- It presents specific adoption pathways by evaluating each pathway's technological and market readiness, energy savings potential, and resiliency benefits.

Methodology

Technology review

Distribution Standards. AC distribution in buildings has little variation in most buildings, and AC voltages are generally standardized to specific categories. In contrast, DC can be deployed in a variety of ways, which differ in the topology of the wiring (e.g., radial, ring, ladder, and mesh bus architectures) and in whether the distribution system is managed. Managed DC technologies include communications for managing power distribution within the power cable (Christensen and Nordman 2014). Examples include USB and Power over Ethernet (PoE).

For this paper, we consider two categories of DC voltage levels; a 'low' voltage, (generally ≤ 60 Volts [V]) for powering loads less than 100 watts (W), which is consistent with National Electrical Code (NEC) 'Class 2' circuits and associated safety requirements, and a 'high' voltage (generally > 60 V and less than 1000 V) for powering loads greater than 100 W and for longer wire lengths. Low voltage levels include USB (5-20 V), 12 V, 24 V, and 48 V, the latter typically used in PoE[1] and telecommunications. For high voltage, 380 V has been used in North America in data centers and has been standardized by the Emerge Alliance (EMerge Alliance 2020), however, in Europe, China, and other countries, other distribution voltages have also been used and considered. Overall, DC building distribution voltages are still evolving. Voltage standards may result in defining a range (e.g., 350 - 400 V) and specifying common connectors and/or cabling requirements, which are required for interoperability across end uses and power system components. DC loads may operate at various voltage levels, which may differ from a typical DC distribution voltage currently used.

DC end-use devices. DC-input devices have been predominantly available in certain niche markets (e.g., recreational vehicles, off-grid systems, telecommunications) for decades. However, in grid-connected building applications, despite the gradual shift to more efficient DC-internal devices (electronics, solid-state lighting, brushless DC motors and/or variable frequency drives), most electrical end uses in buildings today have an AC power input and include a rectifier (or power supply) to convert AC to DC (Gerber, Liou, and Brown 2019; Garbesi, Vossos, and Shen 2011). We group DC end-use devices into the following categories: Lighting, electronics, motor-driven equipment, and other miscellaneous equipment, the latter encompassing end-use devices not included under the first three categories, such as resistive loads.

- Solid-state lighting operates on DC. Light-emitting diodes (LEDs) are current-controlled devices that use a driver to regulate luminosity. DC LED drivers are generally more efficient and less expensive than AC LED drivers because they use fewer power electronics and do not need to rectify the AC input.
- Electronic equipment is the fastest growing electric load in the building sector and operates on DC. Desktop computers, televisions, or other display equipment typically include an internal rectifier that converts 120 V AC to the device's main DC bus voltage. Increasingly, several -primarily portable- electronics are also DC-ready, i.e., they have a DC input and utilize a wall adaptor (or external power supply) to convert AC to DC. Cell phones, laptops, modems, and routers are examples of DC-ready electronics.
- Motor-driven equipment, such as fans, pumps, and refrigeration accounts for the largest electricity consumption in U.S. buildings. The most efficient equipment uses brushless DC motors and variable frequency drives, where applicable. These loads are DC-internal because they rectify the 60 Hz AC input to DC, and use a separate inverter to drive the motor at the desired AC frequency. Even more efficient DC-internal motors such as high-rotor pole switched reluctance motors and printed circuit board motors are coming on the market, which will provide additional savings.
- Other miscellaneous equipment includes items such as resistive heating elements. The latter are included in water heaters, cooking equipment (ovens, cooktops), toasters, hand

[1] PoE voltage ranges between 44 and 57 V DC, but 48 V DC is more common.

irons, blow dryers, etc. Resistive elements are indifferent to DC or AC, i.e., they can be connected to AC or DC distribution without any modifications or any energy benefit.

Deployment Case Studies

This section evaluates DC distribution case studies in residential and commercial buildings in North America (the United States and Canada). It focuses on identifying DC end-use loads and use cases, building types, and grid resiliency features at each site. The latter include onsite energy generation (typically solar photovoltaics), battery storage, and ultimately, the ability to operate in island mode.[2] The project team collected information on each deployment case study through site visits, phone interviews, and online research. Note that the following list of sites (Figure 1 and Table 1) is not intended to be a comprehensive list, but a snapshot of the market, to feed information for the development of the proposed adoption pathways. Figure 1 shows a map of 22 sites identified by the project team, including the DC end uses at each location.

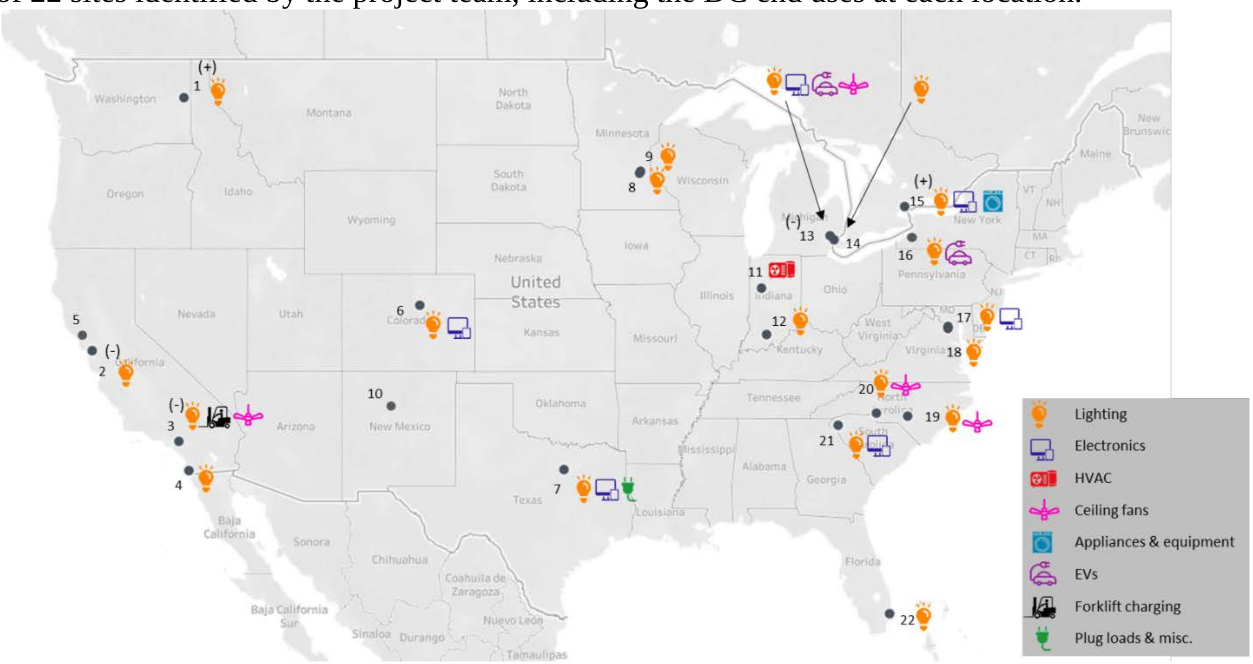

Figure 1. Map of DC distribution deployments in the United States and Canada. *Source*: Lawrence Berkeley National Laboratory (Map icons: thenounproject.com)
Note: Sites denoted with (-) are defunct/decommissioned; sites with (+) are in progress or the planning stage.

Table 1 provides additional information for each site shown in Figure 1. It includes the name and location of each site, a brief description of the DC distribution system, the distribution voltage or voltages) used to supply power to the end uses, the resiliency features of each site, and the source of information for each site.[3]

[2] While onsite solar photovoltaics and battery storage do not offer direct grid resiliency for buildings, they provide resiliency benefits by contributing to grid power demand reduction and potentially peak shaving. They are also prerequisites for buildings to operate in island mode, thus paving the way for them to do so in the future.
[3] Details on the field deployments, contacts, and information sources for each site are available upon request.

Table 1. Information on DC field deployments in the United States and Canada

#	Site & Location	Description	Distribution Voltage(s)	Resiliency Features*	Information Source**
1	Catalyst Building, Spokane WA	New zero energy (ZE)[4] building with direct-DC lighting	Unknown	☼ 🔋	URL
2	Whole Foods Market, Berkeley CA	Retrofit of supermarket with direct-DC lighting system	24 V	☼	URL
3	Honda Distr. Center, Chino CA	Retrofit of warehouse facility (DC load: 175 kW)	380 V	☼ 🔋	I, URL
4	Sust. resource Center, San Diego CA	Demonstration of small direct-DC lighting system (DC load: 800 W)	24 V	☼	URL
5	Silvercloud Winery, Glen Ellen CA	Microgrid connecting end uses, generation, and battery storage	380 V	☼ 🔋 ⏻	URL
6	Alliance Center, Denver CO	Proof of concept project in part of commercial office building	24 V, USB	☼	SV, I, URL
7	Sinclair Hotel, Ft. Worth TX	18-story hotel retrofit with PoE lighting (100%), electronics and appliances	PoE	N/A	SV, I, URL
8	Public School, Edina MN	Retrofit of classroom and office room to use PoE lighting (DC load: 600 W)	PoE	N/A	I
9	CEE building, Minneapolis MN	Partial cubicle area retrofit to PoE-supplied lighting (DC load: 480 W)	PoE	N/A	I
10	Kirtland Airforce Base Albuquerque NM	Residential community microgrid using DC bus to connect residences	380 V,750 V	☼ 🔋 ⏻	I, URL
11	Purdue Univ, West Lafayette IN	Retrofit of an entire house for DC distribution (demonstration)	380 V	☼ 🔋	I, URL
12	West Baden Springs Hotel, French Lick IN	Retrofit of >500 light fixtures to PoE (DC load: 4 kW)	PoE	N/A	URL
13	Smart Home, Detroit MI	Residential test bed for DC technologies and appliances	USB, 24 V, 380 V	☼ 🔋	I, URL
14	Bedrock Real Estate, Detroit MI	Retrofit of commercial office lighting system	24 V	N/A	URL
15	Sidewalk Toronto, Toronto CA	New all-electric residential neighborhood with low voltage DC	PoE	Unknown	I, URL
16	Burlington microgrid, Burlington CA	Manufacturing facility building (DC lighting load: 12 kW)	380 V	☼ 🔋 ⏻	I, URL
17	AGU building, Washington DC	6-story office building retrofit to ZE (all lighting & offices powered by DC)	24 V, USB, 48V	☼	SV, I, URL
18	Fort Belvoir, Alexandria VA	Partial demonstration fluorescent lighting system retrofit (DC load: 1 kW)	24 V	☼	URL
19	Fitness Center, Ft Bragg NC	Retrofit 44 lighting fixtures, 4 ceiling fans (DC load: 15 kW)	380 V	☼ 🔋 ⏻	I, URL
20	Livingston & Haven, Charlotte NC	25,000 ft^2 facility retrofit with high bay lights and ceiling fans (DC load: 15 kW)	380 V, 48 V	☼ 🔋 ⏻	SV, I, URL
21	Watt Center, Clemson SC	Partial retrofit to showcase PoE lighting and electronics (DC load: 5-10 kW)	PoE	N/A	SV, I, URL
22	PNC Bank, Ft. Lauderdale FL	ZE building with partial DC lighting system	24 V	☼	URL

*Resiliency features: ☼: Solar photovoltaics (PV); 🔋: Battery storage; ⏻: Ability to operate in island mode.
** Info source: SV: Site visit by the authors; I: Phone or face-to-face interview; URL: Online research.

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[4] Zero energy buildings utilize onsite renewable energy sources and energy efficiency measures to consume as much energy and they produce (via renewable sources) during a specified time (typically one calendar year). For more information, see https://www.energy.gov/eere/buildings/zero-energy-buildings.

Availability of DC End Uses

As discussed in the introduction, the lack of availability of DC appliances and DC system power converters is a key barrier for DC distribution systems. Table 2 summarizes the state of the DC appliance market in the United States for various device groups found in residential and commercial buildings. We utilize our findings from the field deployment assessment (Sites Avail.), as well as the results of our market survey of available products (Market Avail.) to identify market gaps, challenges, and opportunities.

Table 2. Availability of DC-ready devices

Device Groups	Device subgroups	DC Voltages	Sites Avail.	Market Avail.	Availability Comments
Electronics	TVs, cell phones, printers & scanners, audio, network and computing equipment	PoE, USB, 12V, 24V	⭑⭑	⭑⭑	- 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, 12V, 24V, 48V, 380V	⭑⭑⭑	⭑⭑	- More products available in commercial vs. res. sector - Most available field deployments use DC lighting. - PoE lighting requires efficient, distributed converters - 380V lighting is found in high bay applications
Refrigeration	Refrigerators, freezers, ice makers, vending machines	PoE, 12V, 24V, 380V	⭑	⭑	- Most available products used in the off-grid market - High voltage prototypes currently tested by major appliance manufacturers
Space heating & cooling	Heat pump/rooftop air conditioners, variable refrigerant flow units, portable & ceiling fans, radiant floor heating	12V, 24V, 380V	⭑	⭑	- 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	12V, 380V	Ø	⭑	- Some products available for mobile applications (12V microwaves) - Induction stoves & microwaves can be DC-powered
Water heating	Heat pump water heaters	380V	Ø	Ø	- Heat pump water heaters could be coupled with PV
Large Appliances & other motor loads	Clothes washers & driers, dishwashers, pumps, fans, compressors	380V	⭑	⭑	- High voltage residential appliances with dual (AC & DC) input have been tested by manufacturers. - Motor drives could be adapted to use a variety of DC input voltages. Retrofits may require UL certification
EV charging	DC fast charging equipment	380V	⭑	⭑	- Some companies are beginning to offer direct-DC charging equipment - Available sites have used custom DC chargers
Miscellaneous loads	Vacuum cleaner, humidifier, garage doors, hair dryer, iron, window shades, process loads	PoE, USB, 12V, 24V, 48V, 380V	⭑	⭑	- Low power loads (timers, motor controls, window shades) are available with PoE - Higher power loads can be powered with high voltage (380V) or battery-assisted lower voltage.

Notes:
⭑⭑⭑: Available; ⭑⭑: Available but with significant gaps; ⭑: Limited availability; Ø: Not available

As shown in Table 2, there is a direct correlation between DC devices available for sale in the market, and their corresponding availability in field deployments. In certain instances, field deployments have used (or plan to use) prototypes of DC appliances which are not available for sale, but rather custom-made by manufacturers or retrofitted to have a DC input by engineers.

Energy Savings by End-Use Category

In 2017, a subset of the authors of this paper conducted a simulation-based efficiency comparison between the AC and DC distribution system in modeled commercial buildings (Gerber et al. 2018). For this study, we conducted a similar analysis on the same analytical framework, but we focused on the savings of specific end use categories: Electronics, lighting, and motor-driven loads. Two commercial buildings (a medium office building and a mid-rise apartment building) were analyzed, using building dimensions and load profiles from the U.S. Department of Energy's EnergyPlus™ reference buildings (DOE 2017). All electrical end uses in the buildings were assumed to operate internally on DC. This means that for the buildings with AC distribution, all end uses require a load-packaged rectifier, i.e., an AC/DC power supply. The efficiency comparison for the two building types was conducted for three climate regions in the U.S. (Miami [hot], San Francisco [mild], and Duluth [cold] for ASHRAE climate zones 1A, 3C, and 7, respectively) for three use-cases: Without PV, with PV, and with PV plus battery storage.

Table 3 shows the efficiency savings from DC distribution for each end-use category and system configuration, averaged over all climate zones and building types. It should be noted that savings varied only slightly across climate regions primarily because the modeled PV system in each region was sized such that its generation matched the annual electricity use of each building. Also, the office building generally yielded higher savings compared to the mid-rise apartment due to the former's higher coincidence of load and PV generation. Regarding system configuration, as shown in Table 3, the most savings occur when most DC power generated locally is consumed by DC loads (even more so via a battery) and most power for DC loads comes from DC generation. Systems with PV and battery storage had the highest savings because of the fewer AC-DC and DC-AC conversions in the DC distribution system compared to the corresponding AC configuration. Overall, systems with battery storage utilize less grid power, therefore the DC distribution system uses less rectified AC power for distribution in the building.

Table 3. DC distribution efficiency improvement by end-use category and system configuration

End-Use Category	DC Distribution Efficiency Improvement (%)		
	No PV	PV	PV & Battery
Electronics	5.8%	8.3%	14.9%
LED Lighting	3.1%	5.1%	13.0%
Motor-Driven Loads	7.4%	10.3%	15.2%

Expert Elicitation

The project team conducted interviews with various industry stakeholders (e.g., electrical designers, contractors, trades, building owners/managers, DC equipment integrators and manufacturers), to collect information on their experience with DC distribution, and to solicit feedback on opportunities, challenges, and recommendations on DC distribution systems.[5] Overall, the project team conducted 20 in-depth interviews via phone or face-to-face meetings during site visits. Table 4 summarizes notable findings from this activity. Similar to the rest of

[5] It should be noted that interviews were also instrumental in identifying accurate and detailed field deployment information, which was presented earlier in the paper.

this paper, we correlate interviewees' feedback by end use category and rank issues and points raised by the number of occurrences (i.e., the number of interviewees making a similar point).

Table 4. Summary of expert elicitation feedback

	Interviewees' Feedback	interviewees #	Electronics	Lighting	Motor loads	Other end uses
Opportunities	Low voltage DC/PoE have reduced installation costs – no licensed electricians required	3	✓	✓		✓
	Low voltage DC/PoE is flexible and reconfigurable. (e.g., allows to move electrical outlets without worry of electrical shock)	2	✓	✓		✓
	PoE allows control of energy consumption on all switch ports	1	✓	✓		✓
Challenges	Misconception and lack of knowledge leads to lengthy/ expensive design and permit process	5	✓	✓	✓	✓
	DC metering and robust connector standards are currently unavailable	3	✓	✓	✓	✓
	Small companies providing DC technologies are risky (various have gone out of business)	3	✓	✓	✓	✓
	DC microgrid control systems are expensive and proprietary. No plug-and-play product available	2	✓	✓	✓	✓
	PoE switch cannot be fully turned off (security issues, standby losses)	1	✓	✓		✓
Recommendations	Involve big companies to avoid bankruptcy risk, and a small number of vendors for efficiency	4	✓	✓	✓	✓
	Permitting authorities must be involved early in projects	3	✓	✓	✓	✓
	DC system vendors should offer a package of DC end uses to consumers	3	✓	✓	✓	✓
	Dual-input devices would be compatible for both AC and DC distribution	2			✓	✓
	Spot inverters can be used for specialized devices without DC input	1				✓
Suggested applications & adoption pathways	Community microgrids of multiple buildings	3	✓	✓	✓	✓
	Lighting applications (commercial buildings)	3		✓		
	EV charging for commercial applications	2				✓
	Electronics and office equipment	2	✓			
	Big box buildings with warehouse and office space	1	✓	✓	✓	
	All-DC buildings, due to efficiency benefits	1	✓	✓	✓	✓

Adoption Pathways for DC Distribution in Buildings

This section utilizes findings discussed in previous sections and summarizes proposed applications of DC power in buildings, also called adoption pathways. Each proposed pathway addresses the motivation, potential benefits, challenges, and technical issues arising from its deployment. It is important to note that these adoption pathways are not mutually exclusive. We present applications for DC that are viable today and have high growth potential but limited, if any, current market penetration. For this reason, technologies and applications that are past the infancy stage and are currently generally considered viable (e.g., lighting for commercial buildings, data centers) for DC distribution, are not presented in this paper.

1. Residential Backup Power (electronics)

Description. 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), refrigerator, sump pump, security devices, medical devices, and a few lights. For California in particular, garage door openers sold are now required to have a backup battery, since many 2017 wildfire deaths were caused by the inability to escape during the grid outage (SB 969, 2018). 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 be installed by the customer. As such, they are an ideal solution for low- to middle-income residential applications.

Motivation. Residential DC backup circuits have several advantages over AC alternatives. In AC, there are two options for battery backup: using a separate battery in every critical load or using a dedicated UPS. One advantage of dedicated backup circuits with centralized storage is that distributed backup batteries will corrode and fail if not regularly maintained. DC distribution improves on the electrical efficiency and cost of integrating solar and storage. 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.

The Home Energy Router (*HERo*) is one example of a residential DC backup circuit, which is currently under development (Meier et al, 2019). The *HERo* 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 will use machine learning to tune its optimization parameters in real-time, and will monitor messages from grid operators. The *HERo* design team also notes that the *HERo* will be able to connect to other *HERo*s, if scaling is necessary.

Challenges and recommendations. Residential DC backup circuits will have to demonstrate a clear market incentive beyond efficiency. The target customers are low- to 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 load 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 the backup lifetime, reduce grid energy use, and potentially provide critical power during a grid outage.

2. **Community Microgrid (All end uses)**

Description. This pathway involves connecting multiple buildings to share the distributed energy resources (DERs) serving the buildings. The community could be a combination of commercial and/or residential loads with solar PV generation and battery storage. In the microgrid, all the energy is distributed through a DC bus which is connected to the incoming feeder of each building. DERs are connected directly to the DC bus without a need for inverters, and the buildings (end uses) within the microgrid can operate in island mode. The ideal implementation of this pathway would be in addition to the DC distribution system within community buildings, which would only be using AC inverters for loads that cannot be converted to DC. The microgrid may have an interconnection with the grid for import and export of energy through a central bidirectional converter. This pathway may be most appropriate for new construction, ZE buildings within communities.

Motivation. DC-DC converters are generally more efficient than DC-AC inverters (Gerber and Musavi 2019), therefore, eliminating the inverters for each DER connected to the microgrid improves overall distribution system efficiency. Another advantage of connecting multiple buildings with a DC-link is that the need for grid synchronization for DERs is eliminated. 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, as opposed to a more traditional AC microgrid.[6]

Challenges and recommendations. The biggest challenge from this scenario comes from the energy transaction component within the buildings in the microgrid. This challenge is magnified if the DERs and loads are owned and operated by different entities. One possible solution would be to have DERs centrally owned. Community microgrids would also require significant investment not only in the planning and installation phase and but also during operation/maintenance.

3. **BIPV Powering Local End Uses (electronics and miscellaneous loads)**

Description. 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 the building’s main distribution panel via a string inverter. However, module-level micro inverters will likely become more popular for AC BIPV systems because the building facades are much more susceptible to panel mismatch than roof-mounted panels. 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

[6] The project team has identified three installations that are based on this proposed pathway (sites #5, 10, and 16 shown in Table 1).

loads such as window blinds, window openers, electrochromic windows, occupancy and daylight sensors, and interior lighting.

Motivation. Recent studies have suggested BIPV should be integrated via parallel power optimizers connected by low-voltage DC distribution (Ravyts et al. 2019). As previously mentioned, module-level converters are ideal due to voltage mismatch. While power optimizers are better than 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 higher life span than AC micro inverters. 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, allowing such BIPV systems to be installed by construction workers without the need for a costly 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.

As 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). In addition, this also holds true for low-power devices in and near the building facade. Matching energy needs of in-facade devices to BIPV production (often with the use of electricity storage) can greatly reduce the capacity need for a connection to the AC system. The energy use of the in-facade devices will also be reduced by being directly DC-powered.

Challenges and recommendations. Since 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 a significantly impactful pathway. For the greatest impact, the BIPV circuit should connect to larger loads such as a lighting circuit, in-façade HVAC, or a DC power hub. The latter are available from various manufacturers.

4. Office Workstations (electronics, miscellaneous loads, and lighting)

Description. 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.[7] This pathway is most valuable when it allows for skipping AC power distribution to the workstations entirely. As workstation loads are high-value ones, 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 when grid-connected or not if power is short, and to keep total load under capacity limits.

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[7] In an existing ZE installation, building designers mentioned that the 100 W power limit was a key element for controlling occupant energy use by limiting the use of high-power devices such as resistance space heaters.

Motivation. This pathway avoids AC distribution to workstations entirely, therefore reducing costs while increasing efficiency and reliability. DC outlets and cables are also less bulky than their AC counterparts. Two distinct cases are individual workstations (as with conventional offices) and clusters of 2, 4, or more workstations that are contiguous and so could have a common infrastructure. While PCs and phones (mobile and desktop) can use Wi-Fi for communications, having Ethernet as an option is advantageous. Ethernet could be used as the power delivery mechanism to the workstation and so provide the needed communication pathways. Single Pair Ethernet would be preferable for this purpose. If more power is needed than a single Ethernet cable can provide, then multiple can be paralleled. This could be implemented via a hub that takes in Ethernet and puts out various forms of USB as well as Ethernet, for both data and power.

Challenges and recommendations. A key need for this pathway is the availability of DC-powered devices. Many are available today (PCs, monitors, phones, task lights), but a greater variety would help. In addition, a long-distance link technology is needed to get power to the workstation hub; this could be a 380V DC bus with a step-down converter to 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 open offices, bringing the power down from the ceiling or 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, therefore installation should be tied to a general retrofit and/or PV installation.

5. **Commercial EV Charging (EVs)**

Description. In this pathway, DC-input electric vehicle service equipment (EVSE) replaces traditional, AC-input Level 2 chargers, allowing for more flexible and more 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 power levels (6.6 kW) up to DC ultra-fast charger power levels (200+ kW) depending on the device ratings. The vehicle'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 from the customer's perspective (for economic reasons). DC EV charging can be grid-connected (in which grid power supplements power from PV and/or battery storage) or grid-independent (in which the entire system is self-contained to reduce utility demand charges). 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).

Motivation. 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 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 (vs. AC/DC) conversion (estimated to be higher for systems with battery storage) translates directly to reduced cost for companies selling charging services, making them more competitive. According to the project team's 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 EV charging equipment.

Challenges and recommendations. Apart from the lack of DC EVSE equipment in the market, voltage standards for both the supply 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 advantage versus AC-input equipment.

Discussion

DC power distribution in buildings with on-site generation, storage, and DC end uses has the potential for energy efficiency, reliability, and resiliency benefits. However, the lack of DC devices and power converters, technology standards, and low awareness among practitioners create significant barriers for the market adoption of this technology. The goal of this paper is to define specific end-use cases for which DC distribution in buildings is a value proposition today by defining clear efficiency and resiliency benefits, while identifying implementation barriers.

We conducted a technology and market assessment in which we reviewed DC standards and evaluated the applicability of DC distribution to end-use devices. This was followed by a comprehensive analysis of field deployments in North America and a review of available DC devices in the market. We also completed an expert elicitation of 20 DC power and building professionals to collect relevant information on their experience with DC distribution and to develop opportunities, recommendations, and proposed applications while identifying challenges. In addition, we conducted a simulation-based efficiency analysis of DC vs. AC distribution for three end-use categories (electronics, lighting, motor loads) for different building types and under different distribution system configurations (without PV, with PV, with PV and battery).

Based on our findings, we identified and elaborated specific adoption pathways for DC systems in buildings. Each pathway represents technology that can be implemented today, but with tomorrow's energy and building landscape in mind. Table 5 shows a qualitative summary of the proposed DC adoption pathways based on findings from the technology assessment, the market assessment of field deployments, and DC devices, and the energy efficiency analysis.

Table 5. Evaluation of the Proposed Adoption Pathways

#	Adoption Pathway	Technology Readiness	Market Readiness	Resiliency Benefits	Energy Savings Potential
1	Residential backup power	✯✯	✯	✯✯	✯✯
2	Community microgrid	✯✯	✯	✯✯✯	✯
3	BIPV powering local end uses	✯✯	✯	✯	✯✯
4	Office workstations	✯✯	✯✯	✯	✯✯
5	Commercial EV charging	✯	✯	✯✯	✯✯
Notes: ✯: Low; ✯✯: Medium; ✯✯✯: High;					

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