DC Lighting and Building Microgrids

Pacific Northwest
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OPPORTUNITIES AND RECOMMENDATIONS

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Direct current (DC) electricity has the potential to improve the resiliency, reliability, and energy efficiency of building systems. DC facilitates the ability to more easily and directly connect renewable resources such as solar photovoltaics (PV) and energy storage batteries to DC building loads such as light-emitting diode (LED) lighting, computers and electronics, electric vehicle chargers, and variable-speed heating, ventilation, and air conditioning (HVAC) equipment. The improved efficiency of the combined technologies can result in an estimated 10–18% in energy savings.[1] When configured as a microgrid, PV systems and batteries can power DC building loads in the event of a grid outage, improving the resiliency of homes and businesses. Despite the myriad benefits and opportunities provided by DC, its adoption in the market has been slowed by both the lack of available equipment and standards and the challenge of overcoming the status quo of building electrification.

APPROACH

Supported by the U.S. Department of Energy (DOE), Pacific Northwest National Laboratory (PNNL) conducted research to characterize the current state of DC lighting and building microgrid market and technologies. This research included extensive literature reviews, interviews of 28 subject matter experts and manufacturers, and a formal Request for Information (RFI) to DC lighting and microgrid controller manufacturers. The RFI aimed to characterize availability and trends in the technical aspects of DC lighting and microgrid products and systems, as well as qualitative analyses of the opportunities and challenges facing the industry. The RFI was released on April 23, 2020, and garnered 46 responses over 9 weeks. PNNL's research identified a growing market of available technologies along with significant potential benefits including energy savings, resiliency, reliability, and reduced costs. This paper explores the findings of this research and offers recommendations for all stakeholders concerning moving forward with these beneficial technologies.

DC BUILDING MICROGRIDS CAN ENHANCE RESILIENCE

Building microgrids are localized grids that can disconnect from the traditional power grid and continue to operate while power is down, usually by drawing from on-site PV and energy storage systems such as batteries. Storms, wildfires, and unexpected power outages can result in costly downtime, but microgrids can provide homes and businesses with electricity during these events, improving resiliency.

Microgrids can be either alternating current (AC) or DC or a hybrid. AC electricity is an electric current that periodically reverses direction, while DC flows in one direction. Rotating steam turbine driven generators used in fossil fuel power plants produce AC electricity, while solar PV panels produce DC electricity. Similarly, some rotating building loads such as large fans and HVAC compressors may require AC electricity to operate,[2] while other building loads including computers, electronics, and LED lighting require DC to operate.

In a traditional AC building microgrid (Figure 1a), the utility grid supplies AC electricity that is distributed to building equipment and outlets. On-site PV panels and energy storage batteries generate and store energy as DC but then must convert this power into AC to connect to the building's electrical system. AC electricity flows through the building only to be converted back to DC to power the DC-based building loads. Typically, the first conversion (from DC to AC) occurs at the battery or PV inverter, while the second conversion (from AC to DC) occurs in a power supply typically located at the end-use

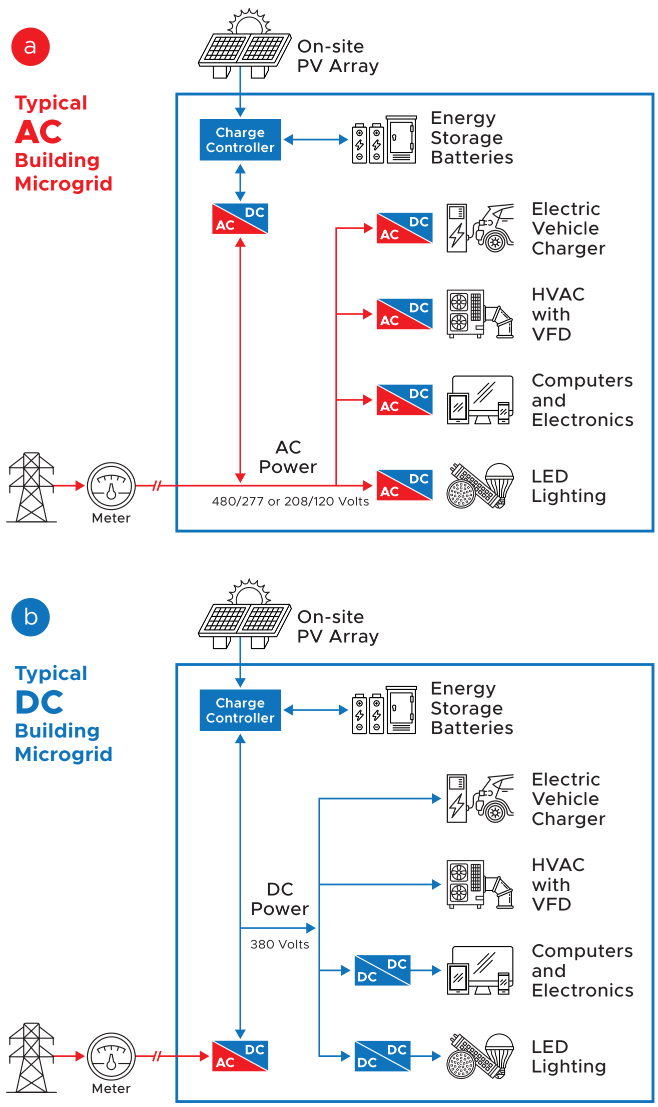

Figure 1: Simplified depiction of (a) a typical AC building microgrid and (b) a typical DC building microgrid.

1 Gerber, Daniel & Vossos, Vagelis & Feng, Wei & Marnay, Chris & Nordman, Bruce & Brown, Richard. (2017). A simulation-based efficiency comparison of AC and DC power distribution networks in commercial buildings. Applied Energy. 10.1016/j.apenergy.2017.05.179.

2 Although some rotating motors require AC to operate, if a variable frequency drive (VFD) is used to vary the speed of the motor, then the VFD must first convert the AC to DC in order to vary the frequency and motor speed.

equipment (e.g., an LED driver within a light fixture or at a power supply used for a computer or electronics). Each time there is a conversion, an efficiency loss (typically 5–10%) occurs, and every converter represents a potential failure point for the connected devices and systems.

Conversely, in a DC building microgrid (Figure 1b), AC electricity from the utility grid is immediately converted to DC at the building level. DC is then distributed through the building, directly connecting the DC-based PV and storage battery systems to the DC building loads. Typically, 380 V DC is used to power large building loads such as HVAC systems and electric vehicle chargers. The 380 V DC is often down-converted to a lower DC voltage to power smaller building loads such as LED lighting and electronics. To enhance resiliency, PV panels and energy storage batteries are sized and configured such that they can power all or some of the DC loads in the building, including during a grid outage. Equipment and associated energy losses to convert DC to AC and AC to DC are significantly reduced or eliminated from the system, providing an estimated 10–18% in efficiency savings[3] at the building level compared to the typical AC building microgrid. These significant savings can reduce the required size and/or capacity and associated capital cost of PV panels and energy storage batteries.

STATE OF THE DC LIGHTING AND BUILDING MICROGRID CONTROLLER MARKETS

Implementing a DC building microgrid requires building loads that accept DC and a controller to couple it to PV and energy storage batteries. LED lighting technology is a potentially easy and available DC-based building load that can be used to connect to a DC building microgrid. PNNL's research assessed the current availability

and characteristics of both DC lighting and DC microgrid controller technologies. Although the vast majority of LED lighting products available in the market today accept AC at their input and are therefore compatible with traditional AC building infrastructure, a growing number of products can also or alternatively accept DC at their input. PNNL's research found that there are now 22 different manufacturers offering LED lighting fixtures with DC input as a standard option. The manufacturers represent large industry conglomerates as well as small start-ups and offer a wide range of fixture options. Of these 22 manufacturers, 17 offer a specific type of DC lighting technology using Power over Ethernet (PoE), which has been growing in popularity. PoE lighting typically utilizes a category 5/6/7 ethernet cable to distribute both power and data to lighting fixtures over a single cable while offering integration benefits with other systems due to the use of the TCP/IP protocol. Other non-PoE types of DC lighting systems exist that most typically utilize 24 or 48 V DC to distribute power to lighting devices to comply with the EMerge Alliance "Occupied Space Standard."[4] The EMerge Alliance is an industry consortium whose mission is to promote DC and hybrid AC/DC power systems to provide greater resiliency, safety, operational surety, and sustainability.

The microgrid equipment that directly connects the DC power from on-site PV and/or energy storage batteries to DC building loads such as LED lighting is referred to as a DC building microgrid controller. These controllers can be

3 Gerber, Daniel & Vossos, Vagelis & Feng, Wei & Marnay, Chris & Nordman, Bruce & Brown, Richard. (2017). A simulation-based efficiency comparison of AC and DC power distribution networks in commercial buildings. Applied Energy. 10.1016/j.apenergy.2017.05.179

4 https://www.emergealliance.org/standards/occupied-space-2/

> **Standardization of the voltages provided by DC microgrid controllers and accepted by DC LED lighting products is necessary to create an interoperable ecosystem of products from multiple manufacturers.**

off-the-shelf solutions sometimes referred to as "power servers" or can be custom-engineered and assembled from different components controlled by software. PNNL's research identified seven DC building microgrid controller solutions that are currently available. Most of these are currently available from smaller companies, with large industry conglomerates focusing their current offerings on AC rather than DC building microgrid solutions.

AT WHAT VOLTAGE?

Voltage is an important compatibility issue for DC lighting and the DC building microgrid controllers that power them. DC building microgrid controllers are designed to produce a specific DC voltage to power DC building loads. Usually (by manufacturer offering), the voltage produced is 380 V DC; however, there is some variability across the available systems. In some cases, the 380 V DC is converted to a lower DC voltage such as 24 V or 48 V to power lighting or other loads. On the receiving end, LED lighting loads are designed to accept a particular voltage from the power source. Similar to microgrid controllers, there is variability across manufacturers in what is

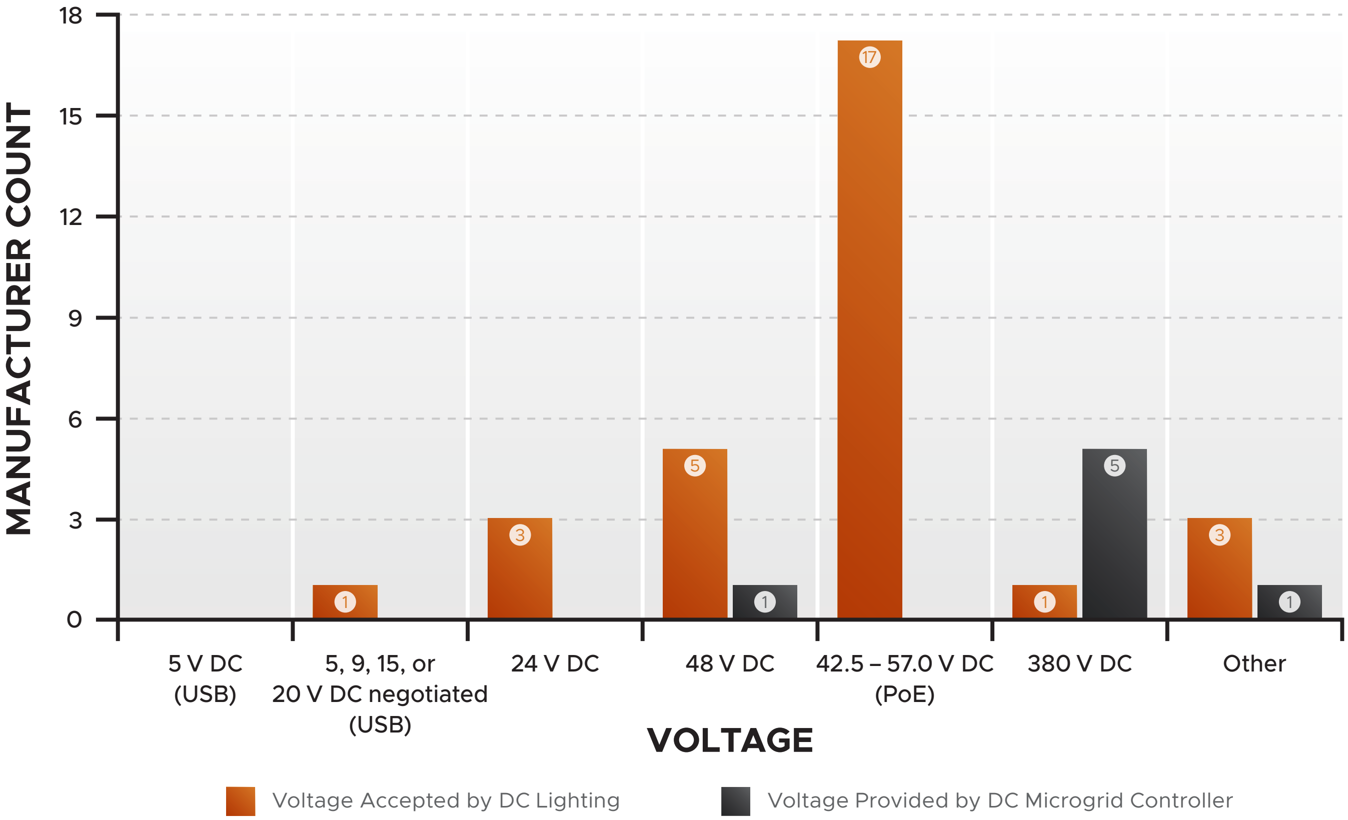

Figure 2: Comparison of the number of DC lighting manufacturers with products that accept each voltage category and the number of microgrid controller manufacturers with products that provide each voltage category.

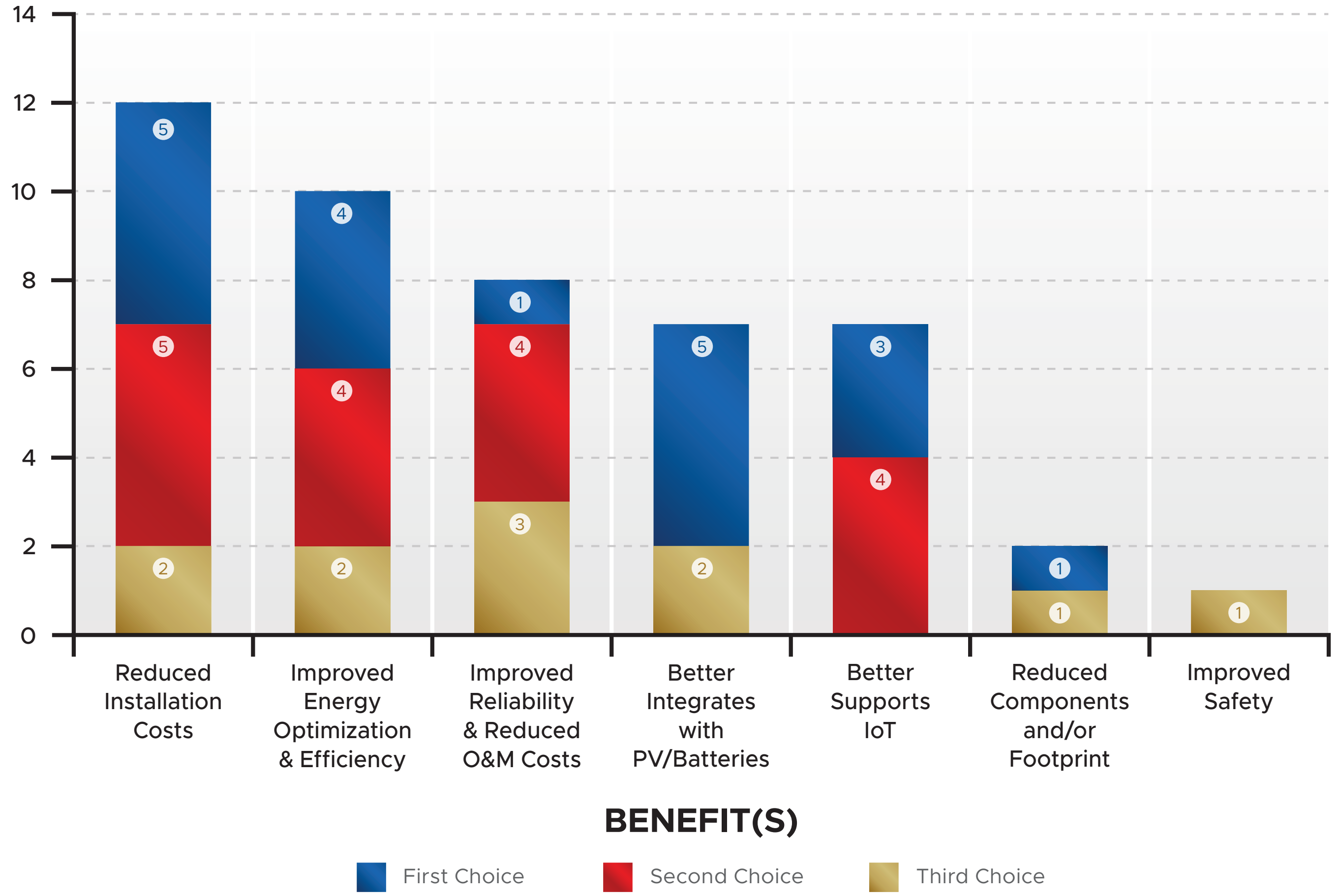

Figure 3: Top three value proposition choices for DC lighting and building microgrids from RFI and interview respondents.

offered. Typically, DC LED lighting is designed to accept either PoE voltages defined by the IEEE 802.3 Standard (42.5–59 V) or by the EMerge Alliance (24 V or 48 V). See Figure 2.

Standardization of the voltages provided by DC microgrid controllers and accepted by DC LED lighting products is necessary to create an interoperable ecosystem of products from multiple manufacturers and to ultimately support large-scale adoption. As shown in Figure 2, a significant number of manufacturers now offer lighting that accepts the PoE voltage range as a standard option. However, PoE systems rely on a centralized PoE switch to distribute DC power to the light fixtures, and PoE switches that natively accept the common 380 V DC supplied by building microgrid systems are not yet available. Instead, all currently available PoE switches accept AC power at their input to be compatible with existing building infrastructure and then convert this to DC that is distributed to PoE fixtures. This is a critical issue that, if resolved, would enable building owners to install a DC building microgrid solution and take advantage of the wide variety of manufacturers and luminaires that offer PoE lighting without requiring AC-to-DC conversions. Lighting is not the only possible DC load; therefore, the DC microgrid voltage will have to be aligned with the voltage(s) accepted by other building loads.

BENEFITS BEYOND ENERGY

Although an efficiency savings of 10–18% for a DC lighting and building microgrid is significant, it is the non-energy benefits that can be most compelling. PNNL's RFI and interviews asked respondents what the top three value

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propositions are for DC lighting and DC building microgrids. Figure 3 indicates the combined results of the RFI and interviews. The top-cited benefit was reduced installation costs, a benefit that is achieved through low-voltage DC wiring. By establishing plug-and-play power and data connections, eliminating the need for a conduit, and enabling installation or reconfiguration by non-electricians,[5] significant installation and reconfiguration cost savings are possible with low-voltage DC. More work is needed to objectively quantify this benefit.

Also high on the list of ranked value propositions was improved reliability and reduced operation and maintenance costs. Reliability of equipment and systems can be improved by reducing or eliminating the DC-to-AC and AC-to-DC conversion circuits or equipment. For example, the typical life of a PV panel is 30 years, whereas the typical lifetime of the inverter that converts the PV DC output to AC is only 15 years.[6] In fact, inverters receive the largest amount of service calls for operation and maintenance of PV systems.[7] A similar situation exists for lighting and many other end-use loads that currently include AC-to-DC conversion circuitry. LED lighting is often touted as having lifetimes of 60,000 or even 100,000 hours. This value is a representation of the light output of the LEDs and not the life of the overall LED fixture. The LED driver is a weak point and will typically fail well before the LEDs. In a recent DOE study that implemented accelerated stress testing on LED drivers, 64% of the drivers failed within the 6,000 hour accelerated testing period, with all failures attributed to the Stage 1 driver circuitry that performs the AC-to-DC conversion.[8] Reducing or eliminating conversion circuitry from building loads can improve the reliability of equipment and reduce associated maintenance costs.

PROGRESS FORWARD, BUT BARRIERS REMAIN

Moving from AC-powered buildings to DC-powered buildings requires changes to equipment, devices, wiring methods, installation practices, codes, and standards.[9] Significant progress has been made in all areas, with several noteworthy projects having already adopted the combined technologies. The recently completed headquarters of the American Geophysical Union in Washington, D.C., is a prominent example of how PV directly coupled to DC lighting can help achieve a Zero Energy Building.[10] At Fort Bragg, NC, the U.S. Army installed a DC microgrid that included DC lighting in 2016; the resiliency

5 Electrical licensing requirements for low-voltage wiring vary by state, county, or city. Some may require licensed electricians to install low-voltage wiring for lighting, while others may require a lower level low-voltage license or no license at all. See https://www.nsca.org/need-a-low-voltage-license/.

6 Fu, Ran, David Feldman, and Robert Margolis. 2018. U.S. Solar Photovoltaic System Cost Benchmark: Q1 2018. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-72399. https://www.nrel.gov/docs/fy19osti/72399.pdf.

7 Thiagarajan, Ramanathan, Adarsh Nagarajan, Peter Hacke, and Ingrid Repins. 2019. Effects of Reactive Power on Photovoltaic Inverter Reliability and Lifetime. 46th IEEE Photovoltaic Specialists Conference. Chicago, IL.

8 Davis, Lynn, Kelly Rountree. 2019. Accelerated Stress Testing Results on Single-Channel and Multichannel Drivers: Final Report. US Department of Energy 2018. https://www.energy.gov/sites/prod/files/2019/08/f65/ssl_rti_single-multi-channel_driver_final_0.pdf.

DC microgrids provide is an important benefit for critical facilities such as military bases.[11] In 2018, Honda installed a DC microgrid with DC lighting at its parts distribution center in Chino, CA, because of the system's efficiency and resiliency benefits.[12] Even with these projects, more work is needed to demonstrate the viability of the technologies for large-scale adoption.

As part of its research, PNNL asked a subset (seven manufacturers, one researcher, and one government policy expert) of those interviewed as part of this study to identify the barriers facing adoption of DC lighting and DC microgrids. The most commonly stated barriers were the immovability of the industry status quo, lack of agreement on a standard voltage, lack of available equipment that accepts DC input, and a lack of awareness among building owners and designers about DC technologies and benefits. Changing building equipment and practices that have been the status quo for 120 years from AC to DC will not happen quickly. Although progress has been made to define common voltages, such as those specified by the EMerge Alliance, and a growing number of lighting manufacturers are aligning their offerings around PoE standards, full standardization remains elusive due to lingering gaps between DC microgrid controllers and the DC loads they power. The slow growth of DC has also created a chicken-and-egg scenario around the availability of DC building equipment. Many equipment manufacturers are unwilling to divert resources to developing DC equipment without a significant market to support it, and that market will not develop without more equipment choices and competition. Finally, customers, who often do not have enough information concerning the cost and benefits, are unwilling to adopt an unfamiliar system even though it could offer significant advantages. There is also a lack of objective data to quantify benefits, especially

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9 Manufacturers of equipment and devices must develop versions that natively accept DC electricity rather than AC. DC electricity, especially low-voltage DC, has different safety and installation considerations and practices relative to traditional line-voltage AC. Accordingly, the National Electric Code in recent versions has significantly expanded guidelines for low-voltage DC lighting and wiring methods. Further standards to support the greater use of DC in buildings are under continual development.

10 https://building.agu.org/

11 https://www.serdp-estcp.org/News-and-Events/Blog/Direct-Current-Building-Scale-Microgrid-Platform

12 https://cltc.ucdavis.edu/dc-building-scale-microgrid-platform and https://powerpulse.net/bosch-and-johnson-controls-partner-on-dc-microgrid/

non-energy benefits that are cited as key to the value proposition. Increasing the visibility of DC lighting and DC building microgrids, improving the availability of DC-powered equipment, providing more objective and quantified data on technology benefits, and promoting these to consumers should help increase adoption.

RECOMMENDATIONS FOR MOVING FORWARD

Realizing the significant benefits of DC will require concerted efforts to address the remaining barriers. Building owners, designers and specifiers, utilities, manufacturers, and researchers all have roles to play to bring this technology to the mainstream,

- **Building owners, developers, designers, and specifiers** should consider a DC lighting and DC building microgrid solution for projects where PV and/or energy storage batteries are being installed, especially where energy resiliency is important. Costly downtime due to unexpected power outages can be mitigated by a building microgrid. In addition, the added efficiency savings of DC can help achieve a Zero Energy Building, gaining Leadership in Energy and Environmental Design (LEED) certification points for both DC power systems[13] and LEED Zero.[14]

- **Utilities and energy-efficiency programs** should consider programs and/or pilot projects to encourage the installation of DC lighting and DC building microgrids for both efficiency and grid benefits. A potential electricity savings of 10–18% is significant, and when properly configured, microgrid systems with energy storage can mitigate the challenge to the grid of intermittent power generation from PV and other renewable generation sources.

- **Lighting manufacturers** should support standardization activities for DC voltage and wiring and offer options for DC input to lighting fixtures or drivers, including 380 V, 24 V, 48 V, and PoE. PoE system manufacturers should offer a PoE switch with 380 V DC input to connect directly to DC building microgrids.

- **Microgrid controller manufacturers** should support standardization activities for DC voltage and offer at a minimum an option for 380 V DC output so that building load equipment manufacturers have a single voltage to design their equipment to accept.

- **HVAC manufacturers** should develop options for energy-efficient HVAC equipment that include 380 V DC input, especially for equipment with variable-speed drives or brushless DC motors that can be easily modified to accept DC. The lack of available HVAC equipment that accepts 380 V DC was a frequently cited barrier to fully DC building microgrids.

- **Electric vehicle charger manufacturers** should develop options that accept DC input without AC-to-DC conversions. As is the case with HVAC, the lack of available electric vehicle chargers that accept DC input was a frequently cited barrier to fully DC building microgrids.

- **Researchers** should conduct studies to objectively validate DC benefits. Beyond energy savings, DC lighting holds significant potential for reducing installation cost and material use and for improving reliability, but by how much and under what conditions is still unknown. Many claims are made by vendors about the technology but lack objective validation. Along with energy savings, the top-cited benefits should be objectively evaluated to help building owners and designers overcome the uncertainty gap to make more informed decisions.

  This research should be prioritized for the technologies and applications with the most compelling DC value propositions, whereby DC has greater potential for adoption. A recent report from Lawrence Berkeley National Laboratory and the National Renewable Energy Laboratory identified these as "adoption pathways"[15] that are niche applications of DC with compelling values. These pathways can be a stepping-stone to address the status quo and realize full-scale adoption.

  Finally, researchers should inform and support the development and update of industry standards necessary to support the adoption of DC, such as the voltage standardization gaps identified in this paper.

13 https://www.usgbc.org/articles/new-leed-pilot-credit-encourages-energy-savings-dc-power-systems

14 https://www.usgbc.org/programs/leed-zero

15 Vagelis Vossos, Melanie Gaillet-Tournier, Daniel Gerber, Bruce Nordman, Richard Brown, Willy Bernal, Omkar Ghatpande, Avijit Saha, Michael Deru, Stephen Frank. "Direct-DC Power in Buildings: Identifying the Best Applications Today for Tomorrow's Building Sector", In American Council for an Energy Efficient Economy (ACEEE) Study on Energy Efficiency in Buildings. 2020.

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