# DOCKETED

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# BSTD-16-02 Product Performance, Monitored versus Reported

BSTD-16-02 Product Performance, Monitored versus Reported

Based on staff replies to my comment, staff is unfamiliar with Dr. Deming's work as it applies to reducing uncertainty of product performance.

Does the Energy Commission make use of a quality management program that is on par with Dr. Deming's? Please identify the program and any certifications the Energy Commission has for quality management.

If uncertainty of installed performance is to be resolved, perhaps a approach that allows staff to identify if the variation is coming from the test procedure or the test subject is required.

Perhaps I have overlooked where real-time humidity is reported.

In https://efiling.energy.ca.gov/GetDocument.aspx?tn=230511

The staff's reply is:

"Staff notes that the CVRH project monitored real-time humidity and temperature."

Is humidity reported? I am having trouble finding where staff placed such a report for the record in 19-BSTD-02 proceeding, pursuant to Title 20 1208.

Please place into the record in 19-BSTD-02 proceeding, the raw data the staff is considering for this prescriptive standard staff wishes the Energy Commission to adopt.

Please also consider the Energy Commission's publication of CEC-500-2019-038.pdf

https://ww2.energy.ca.gov/2019publications/CEC-500-2019-038/CEC-500-2019-038.pdf

CEC-500-2019-038.pdf says the following:

"HVAC accounts for the largest use of electricity in homes and commercial buildings in the United States. Modern air conditioners and heat pumps include variable speed compressors and fan motors with variable frequency drives (VFDs), which require power to go through a DC phase before converting to the desired AC frequency. The most efficient air conditioners use VFDs and DC permanent magnet motors. Variable-speed operation of compressors and fans allows the output of HVAC equipment to be closely matched to the needs of the building occupants, thus improving energy efficiency."

Which report should the public believe for improving energy efficiency?

Which report uses the best science?

Steve Uhler
sau@wwmpd.com

*Additional submitted attachment is included below.*

Energy Research and Development Division

FINAL PROJECT REPORT

# Direct Current as an Integrating and Enabling Platform for Zero-Net Energy Buildings

Scoping Study

**California Energy Commission**

Gavin Newsom, Governor

**April 2019 | CEC-500-2019-038**

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The authors would like to thank the industry partners and technical advisory committee members who assisted the project, especially Brian Patterson, Paul Savage, Peter May-Ostendorp, Katherine Dayem, Byron Benton, Andrew Yip, Sharmila Ravula, John Sauselle, Doug Avery, Pete Horton, Jim Saber, Gabriel Taylor. The authors also would like to thank the workshop participants, survey respondents, and phone interviewees who provided very useful information with which to assess the state of the market for DC power in buildings.

# PREFACE

The California Energy Commission's Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solution, foster regional innovation and bring ideas from the lab to the marketplace. The California Energy Commission and the state's three largest investor-owned utilities – Pacific Gas and Electric Company, San Diego Gas and Electric Company and Southern California Edison Company – were selected to administer the EPIC funds and advance novel technologies, tools and strategies that provide benefits to their electric ratepayers.

The Energy Commission is committed to ensuring public participation in its research and development programs which promote greater reliability, lower costs and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

*Direct Current as an Integrating and Enabling Platform for Zero-Net Energy Buildings* is the final report for the Direct Current as an Integrating and Enabling Platform project, contract number EPC-14-015, conducted by Lawrence Berkeley National Laboratory. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

# ABSTRACT

There is increased interest in using direct current power distribution within zero-net energy buildings to connect very efficient end-use equipment, such as solid-state lighting and variable speed motors, with on-site solar generation and energy storage. While the potential benefits of direct current technology – such as reduced energy conversion losses and improved power quality – are attractive, there is a lack of information and experience with implementing direct-current systems in buildings. This report addresses this information gap, presenting the results of a scoping study of direct current in very efficient, or zero-net energy, buildings.

The study assessed the current state of technology and markets for direct current power to identify barriers and opportunities for adoption of this technology in the building sector. The assessment found a general consensus in the literature that direct current can save energy, while the key barriers to adoption are higher cost, a lack of direct-current compatible products, and relative inexperience among building designers, engineers, and contractors.

The study team then used the information compiled through the market and technology assessment to develop a set of guidelines and templates for "early adopter" building owners and designers to use in implementing direct current in buildings today. The design templates reflect that direct current options are available for nearly all building end uses, particularly lighting and electronics. The whole-building guidelines developed in this study reflect best-practice power architectures for direct current distribution in buildings, based on energy modeling and life-cycle cost analysis. The energy modeling showed potential energy savings of zero to 15 percent of baseline electrical energy use, with higher savings for buildings with photovoltaics and large battery storage, and when on-site solar production is coincident with power demand.

This study shows good potential for direct current in commercial buildings, with a need for more demonstrations and standardization to ease barriers and speed adoption.

Keywords: energy efficiency, distributed energy resources, power distribution, direct current, zero-net energy, power electronics

Please use the following citation for this report:

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# EXECUTIVE SUMMARY

California has an ambitious set of policy goals to mitigate global climate change and reduce the environmental impacts of the energy sector. These policies include: Assembly Bill 32 (Núñez, Chapter 488, Statutes of 2006), which mandates reduction of greenhouse gas emissions to 1990 levels by 2020; Senate Bill 350 (de León, Chapter 547, Statutes of 2015), which requires a minimum of 50 percent renewable energy in California's power mix by 2030; the California Public Utility Commission's Long-Term Energy Efficiency Strategic Plan (2008), which requires all new residences to be zero net energy (ZNE) by 2020 and new commercial buildings by 2030; Governor Edmund G. Brown, Jr.'s Executive Order B-16-2012, which sets a goal of 1.5 million electric vehicles by 2025; and Assembly Bill 2514 (Skinner, Chapter 469, Statutes of 2010), which sets a goal for 200 megawatts of customer-sited storage.

These goals for the energy sector will require a large increase in building efficiency, including integration with renewable power. Direct current (DC) distribution can make the best use of electricity from on-site solar arrays and energy storage systems by reducing the need to convert DC to alternating current (AC), and avoiding the energy losses inherent in those conversions. The use of DC in buildings also helps facilitate controlling and monitoring of power loads and disconnecting from the grid in the case of power system failure, and can lead to simpler and more reliable electric circuits in buildings.

Since the end of the 19th century, when Thomas Edison and Nicola Tesla fought the war of the currents, electricity generation, distribution, and end-use technologies have changed significantly. Early DC power systems were based on small-scale, localized power plants because DC could not be transmitted over long distances without significant power losses. In contrast, AC systems used transformers to efficiently distribute power at higher voltage for long-distance transmission, which enabled centralized power plants and was thus more cost-effective than small-scale power plants at the time.

Today, although high-voltage DC transmission is technically feasible, a complete restructuring of the electric power grid to replace AC with DC would be impractical. Several recent trends, however, have renewed interest in the use of DC for certain applications. The number of electric end uses that operate on DC is on the rise with the proliferation of solid-state lighting and consumer electronics. Nearly all office equipment – monitors, computers, copiers, and servers – are natively DC. The most efficient appliances also operate internally on DC, with brushless DC permanent magnet motors driving fans, pumps, and compressors, with variable frequency drives where variable output is needed. The rapid penetration and cost reduction of solar photovoltaic systems, the increasing demand for battery storage systems (often combined with solar), and growing electric vehicle sales are creating an array of building-sited equipment that produces, stores, and consumes electricity in DC.

DC distribution can provide benefits from maximizing the use of electricity generated by an on-site solar system by eliminating energy used to convert power from DC at the solar array to AC within the building electricity system and back to DC to power DC equipment in the building. In buildings with battery storage, energy savings can be even higher since batteries operate as a DC load and source.

Despite these potential benefits, there are considerable barriers to transitioning from traditional AC-powered electric systems to DC distribution systems in buildings. More research, information, guidelines, and training are needed to understand the savings potential and costs for implementing DC and AC-DC hybrid power systems.

## Project Purpose

The purpose of this project was to compile information that will guide technology research and help overcome barriers to DC power systems in buildings. The main goals were to:

- Research and evaluate the feasibility, market barriers, savings potential, and cost-effectiveness for DC distribution systems in zero net energy residences and commercial buildings.
- Address DC system reliability, safety, policy, codes, education, and customer needs and perceptions.
- Evaluate integration of DC systems in buildings with renewable generation, electric end uses, electric vehicle charging, and battery storage.

## Project Methodology

This project consisted of three main tasks:

1. Technology and Market Assessment of DC Distribution Systems in Buildings.
2. Design Templates for Residential and Commercial DC and AC-DC Hybrid End-Uses.
3. Design Guidelines for Residential and Commercial DC and AC-DC Hybrid Zero Net Energy Buildings.

In the first task, the project team summarized market and academic literature on the energy savings, costs, design, availability, benefits and barriers of DC and AC-DC hybrid distribution systems and equipment in buildings. This was done through an extensive literature review on existing research and case studies using approximately 250 references. The team also collected new information through a stakeholder workshop with approximately 30 attendees and through electronic surveys with 39 respondents, followed by 10 in-depth interviews with DC system researchers, designers, policy makers, and manufacturers.

Based on the information collected in the first task along with continuing team research and stakeholder feedback (including from the project's Technical Advisory Committee), the project team reviewed the potential application of DC distribution for residential and commercial end-use systems. The main products of this effort were evaluation and design templates for consumers, building engineers, and architects interested in implementing DC distribution systems in buildings, with a particular focus on zero net energy buildings. These templates summarize the current state of the market, provide information on product availability, benefits, barriers, and costs, and offer recommendations on implementing DC distribution for the following end uses and systems:

- Lighting
- Heating, ventilation and air conditioning systems
- Electronics and appliances
- Electric vehicle charging
- Energy storage systems
- Renewable energy integration

While the second task focused on implementation of DC for typical end-use systems, the goal of the third task was to evaluate whole-building DC system viability, performance, and costs for residential and commercial, new construction and retrofit use cases, and under various implementation scenarios for buildings with solar systems, solar systems plus electric vehicles, and solar systems plus electric vehicles and energy storage. The project team analyzed these scenarios based on drawings, specifications, metered energy data and cost data from two existing zero net energy buildings, one residential and one commercial. The team distilled the findings of the analysis into a best practices DC building design guidelines document for early adopters of DC systems in buildings that offers recommendations on DC distribution system configuration, benefits, and barriers from the perspective of implementation cost and energy savings.

## Project Results

### Technology and Market Assessment

The following discussion reflects findings from the literature review and feedback from the project's Technical Advisory Committee, stakeholder workshop, electronic surveys, and follow-up telephone interviews.

*Energy Savings*

The review of existing research revealed a significant variance in energy savings from DC distribution, depending on the building type, distribution system topology, and study type. Modeling studies estimate energy savings ranging between 2 and 14 percent, whereas experimental studies measure savings between 2 and 8 percent. Several factors can significantly affect energy savings:

- Coincidence of DC loads and DC generation: When power demand coincides with times of solar generation, DC can be fed directly from an on-site solar array to DC appliances in the building. Therefore, commercial buildings with daytime operation (such as office buildings) have higher energy savings potential compared to residential buildings.
- System configuration and converter efficiencies: The building's power system configuration (for example, number of power conversions, DC voltage levels, and the types of loads supplied with DC) affects energy savings. Also, when comparing similar buildings with either AC or DC distribution, the relative operating efficiencies of the power converters in the two systems will strongly influence savings.

- Battery storage: The presence of battery storage can greatly increase energy savings through the elimination of power conversions from DC to AC and back to DC, which occur in a typical AC system with solar and battery storage.

*Non-Energy Benefits*

Based on input from the workshop and surveys, it appears that DC systems do allow for easier integration of renewable energy, power, communications, and controls. Existing research in DC data centers has demonstrated that the elimination of certain power system components in DC systems can significantly increase system reliability. Furthermore, the ability of DC systems to seamlessly act as microgrids (that is, to be islanded from the grid) can improve resiliency, especially during disasters with extended grid outages. DC microgrids are effectively de-coupled from the AC grid even when not completely islanded from the grid, which makes the end-use equipment on the DC microgrid less susceptible to frequency and voltage disturbances on the grid. Although such benefits are widely discussed in the literature and among DC power advocates, they have not been thoroughly investigated, substantiated, or quantified.

*Costs*

Research indicates first cost is one of the main barriers for implementing DC systems in buildings, especially for retrofits of legacy AC systems. DC systems in buildings have a potential for lower first cost compared to AC systems, primarily due to the use of fewer components and the simplicity of the electrical circuitry. Reaching this potential requires the appropriate economies of scale. Certain end-use applications where DC power is starting to see adoption, such as DC data centers and lighting, may be better suited for commercialization.

*Market Adoption*

The review of market activity found a growing number of DC case studies and demonstration projects underway in the United States and worldwide. Early commercial adoption of DC systems is primarily in data centers and commercial lighting systems. Several international and domestic organizations (such as EMerge Alliance, Alliance to Save Energy, Passive House Institute, and CLASP) are advocating for DC, spurring research and raising awareness. Despite these developments, DC power systems in buildings are still in their nascent stage. There are significant technological and market barriers that inhibit market adoption of DC distribution in buildings, including the lack of market-ready DC appliances and power distribution system components, electrical protection schemes and guidelines, and the limited awareness of DC systems and their potential benefits among potential specifiers and purchasers.

*Standards*

The team’s review indicated that several standards exist that already address DC distribution. Most standards dealing with electricity, and especially those focusing on safety, already cover the subject of DC. However, they do so in an indirect way that it makes them difficult to interpret, expensive for permitting, and unlikely to be used specifically for DC. The EMerge Alliance, which has developed 24-volt and 380-volt DC distribution standards, is spearheading efforts to develop explicit DC and AC-DC hybrid standards. Information technology standards

(Power over Ethernet and universal series bus) are also being implemented for distribution of DC to low power loads, such as electronics and lighting.

### Design Templates for End-Use Systems

The design templates review the current state of the market and provide design guidance for the major building end uses. The templates cover alternative DC designs and practices for each end-use system, discuss DC product availability, benefits, costs and challenges of DC distribution, and offer recommendations for implementing DC in current building projects.

#### *Lighting*

Solid state lighting and fluorescent lighting with electronic ballasts can be compatible with DC power. Solid state lighting, which uses a DC-DC driver, has the potential to be more efficient and more reliable when directly DC powered, by avoiding an additional power conversion stage in AC-DC drivers. In the commercial sector, lighting demand and solar generation are closely matched, creating an opportunity for energy savings with direct-DC distribution from solar to lighting end uses. Another benefit of DC lighting is the ability to reconfigure and to have easier control by transmitting power and communications over the same cabling infrastructure. The lighting industry is changing rapidly and DC lighting products are currently commercially available, with several companies offering DC lighting solutions (DC solid-state bulbs, Power over Ethernet, 24-volt DC and 380-volt DC lighting systems) for residential and commercial applications. Although these products cost more than AC lighting, they are expected to become less costly in the near future.

#### *Heating, Ventilation, and Air Conditioning Systems*

Heating, ventilation, and air conditioning (HVAC) accounts for the largest use of electricity in residential and commercial buildings. The most efficient systems include DC motors and variable frequency drives, which are DC-compatible. In the commercial sector, air conditioning loads are largely synchronized with solar generation, thus creating an opportunity for electricity savings from DC HVAC systems directly coupled with DC sources. As the market moves to more efficient, DC-compatible HVAC systems, the development of DC-ready products (that is, those with a DC power input) will be key for the implementation of DC HVAC systems in buildings.

#### *Electronics and Appliances*

Consumer electronics and information technology equipment operate internally on DC power, and often accept DC directly from an external AC/DC power supply (for example, laptops and cell phones). These power supplies are typically inefficient – 75 percent to 90 percent peak efficiency – so supplying DC directly to electronic loads could lead to significant electricity savings. Appliances like refrigerators, washers, pumps, water heaters, and so on typically operate on AC power, but can be DC-compatible with the use of permanent magnet DC motors, which are more efficient than their AC counterparts. Electronics can be powered with DC power via Power over Ethernet, universal series bus type-C, or at other low voltages (12-, 24-, or 48-volt DC). For appliances, the market for DC appliances is focused on off-grid and recreational applications such as recreational vehicles and boats, but there is a lack of available products for grid-connected systems. High power appliances could be powered via a hardwired 380-volt DC connection while low power plug loads could be supplied at lower voltages.

*Electric Vehicle Charging*

Electric vehicle charging is an inherently large DC load that generally coincides with solar generation in commercial buildings, thus creating an opportunity for electricity savings by directly supplying DC power for vehicle charging. In residential settings, however, vehicle charging and solar generation are not typically synchronized since most residential charging occurs at night. Level 1 and Level 2 charging, typically used in residential and commercial buildings, provide AC power directly to the vehicle and thus do not benefit from direct-DC distribution. DC fast charging, on the other hand, is used in public and commercial settings and supplies high power (greater than 20 kilowatt) DC to the vehicle. Because of its high-power requirements, direct-DC fast charging may exceed the capacity of local DC sources (solar or battery storage) and therefore require limiting the charge rate to match the local power system capabilities. Direct-DC charging at lower charging speeds is technically feasible and is being commercially developed. DC-DC vehicle chargers are currently not available, although they are technically feasible.

*Battery Storage Systems*

Battery storage systems, increasingly common and cost-effective in buildings, store and distribute DC power. Benefits of buildings with battery storage include grid resiliency, ability to store excess renewable energy for use at a later time, and time-of-use arbitrage by load shifting. Battery storage can increase the electricity savings of a DC distribution system coupled with solar by approximately 5 percent to 10 percent, depending on battery capacity. DC-coupled battery storage systems are typically more efficient than AC-coupled systems, and are more compatible with DC distribution. Also, buildings with existing DC-coupled battery storage systems are easier to retrofit to DC distribution, and therefore may incur fewer capital costs compared to existing AC-coupled battery storage systems.

*Renewable Energy Integration*

On-site solar or other renewable DC generation, directly coupled through a DC distribution system to battery storage and DC loads, can help reduce energy use and carbon emissions. Although products for directly distributing DC power to loads are not generally commercially available, several companies are developing turnkey solutions that allow this direct coupling of DC sources and loads. Centralized multiport converters (with both DC and AC inputs and outputs) that direct power flow from the solar array to loads and battery storage are key for grid-connected DC distribution systems. To increase reliability and minimize system costs, these systems should be designed with a small and standardized set of DC-DC conversions.

## Design Guidelines

The design guidelines examine the building design process from the whole-building perspective, for integrating solar systems, electric vehicles, and battery storage in residential and commercial buildings with DC and AC-DC hybrid distribution. The recommendations are based on analysis of energy and economic performance of DC versus AC distribution in new construction buildings.

*Energy Modeling*

To estimate the energy savings potential of each DC system compared to its AC counterpart, for each building configuration (solar; solar plus electric vehicles; and solar plus electric vehicles and battery storage) the project team used the baseline AC building design, solar generation and end-use load data and a corresponding DC distribution system configuration for the same generation and end-use loads. The modeling was performed using Modelica, a power simulation software program, which accounted for power distribution losses for each distribution system.

Energy savings range from about 0 to 15 percent depending on building type and system configuration. DC distribution is most efficient for systems with solar and incrementally larger battery storage, and when electricity use generally matches solar generation (that is, in the commercial building).

*Economic Analysis*

The economic analysis considered several categories of cost differences between the AC and DC systems: capital costs, operating costs based on the results of the energy modeling, and installation and maintenance costs. The results of the economic analysis reflect current market prices for equipment.

The economic analysis shows that DC systems are not cost effective for residential buildings with today's cost premiums, but depending on their electricity savings and load profile, DC systems may yield a desirable return on investment for commercial buildings. These results are driven primarily by capital cost differences between the AC and DC systems, and the higher number of power system components for the DC system, which is actually AC-DC hybrid. Another important factor is the current cost premium of DC components; for example, DC distribution panels are assumed to be 30 percent more expensive than AC panels. An all-DC system would include fewer components, incur less design, project management, and maintenance costs, and perform better financially and more efficiently. However, the lack of DC-ready appliances makes this scenario infeasible at present.

## Technology Transfer

The findings from this project serve as a scoping study to assess the feasibility and savings potential for DC and hybrid DC-AC systems in buildings. As such, the research team targeted outreach to other researchers, product manufacturers, standards organizations, and policymakers. The results of the research were documented in a technical report summarizing the technical and market status of DC power in buildings, as well as a guidebook documenting the current best practices in implementing DC power for individual building end-uses and whole-building integrated design. In addition, the findings were documented in three peer-reviewed papers at academic conferences. The research team also engaged stakeholders in the DC power field through a public workshop, a design review, and Technical Advisory Committee meetings. Findings from the study were discussed with the Energy Commission's codes and standards staff in the Title 20 and 24 offices of the Energy Efficiency Division, and were also submitted in comments on the 2018-2020 Electric Program Investment Charge Investment Plan.

## Benefits to California

Based on the energy modeling discussed earlier, projections for PV penetration, electricity demand, prices, and growth rates, the project team estimated benefits to California ratepayers for a 10-year period (2021 – 2030). The results of this are presented in Table ES-1.

**Table ES-1: Benefits to California Ratepayers from Direct Current Distribution**

| Parameter | Residential | Commercial |
|---|---|---|
| Cumulative energy savings 2021–2030 (GWh) | 2,245 | 5,680 |
| Cumulative operating cost savings 2021–2030 ($million) | 418 | 925 |
| Cumulative $CO_2$ emissions* reduction 2021–2030 (million metric tons) | 0.6 | 1.6 |
| Energy savings fraction of total electricity sales 2021–2030 | 0.2% | 0.5% |

***Assuming 0.28 kilogram/kWh $CO_2$ emissions factor**

Source: Lawrence Berkeley National Laboratory

## Conclusions and Recommendations

California's energy policy envisions a future energy landscape that can best be realized through a highly integrated and interoperable grid with very energy efficient end uses combined with on-site energy generation, electric vehicles, and energy storage. DC power distribution can serve as an integrating platform for the various electrical components within buildings that are needed to realize this vision.

Successful market development of DC systems in buildings requires the availability of reliable, cost-competitive end-use appliances and equipment that can directly use and enable DC power, as well as mature standards that address DC power distribution voltages, connectors, and protection schemes. Further, DC power distribution in buildings appears to have multifaceted benefits that cross traditional boundaries. While this would seem to be an advantage, not having a single benefit that is a clear winner appears to be another impediment. Policymakers and advocacy groups typically focus on a specific attribute (for example, energy savings) when deciding to promote and incentivize a specific technology. However, the strategic value of DC power requires a systems approach that encompasses the easier integration of on-site renewable generation with digital building controls, battery storage, and electric vehicle charging, to energy savings from reduced power losses, to the potential for increased resiliency and reliability.

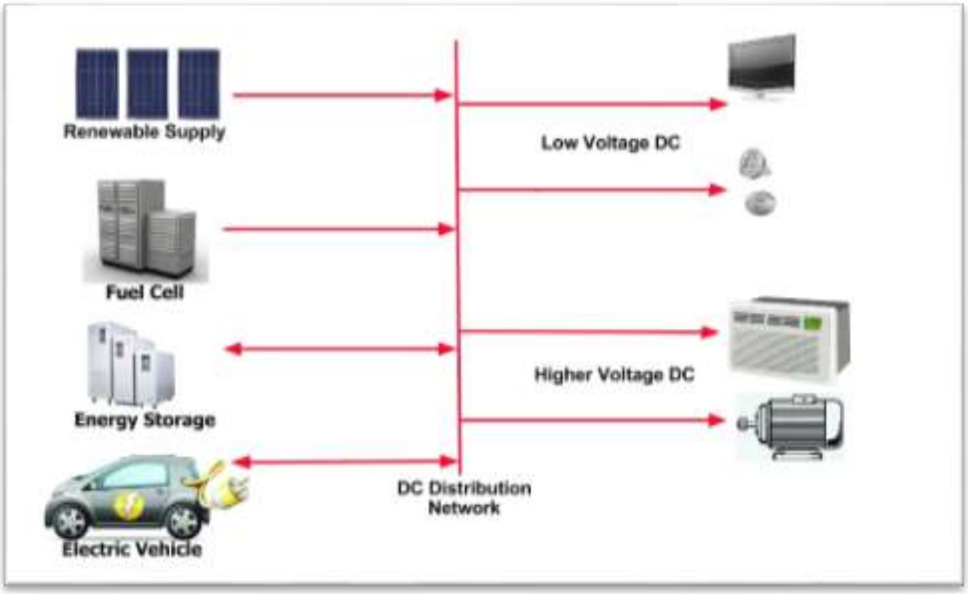
For this reason, additional field demonstrations of DC power distribution in zero net energy buildings are needed to carefully evaluate and quantify the whole spectrum of potential DC benefits. Demonstration projects also would help to address any integration and safety issues, allow manufacturers to field-test their DC-ready products, and raise stakeholder awareness. With the proliferation of distributed DC generation, battery storage, electric vehicles, and efficient DC appliances, the future of end-use loads in the building sector is expected to be DC. However, at this point, DC adoption should focus on specific end-use applications for DC in which the benefits are well understood and the barriers to adoption (information and risk) are lower. Finally, to support a more rapid market transition to DC power systems, a sustained web-based resource hub for DC systems with DC product databases, specs, design guidelines, and case studies, would be beneficial, and would also help reduce the "soft costs" associated with decision-making and collecting the necessary information and strategies for developing DC distribution systems in buildings.

# CHAPTER 1: Introduction

California's energy policy envisions a future energy landscape that can best be realized through a highly integrated and interoperable grid with very energy efficient end uses combined with on-site energy generation and storage. Direct current (DC) power distribution architectures have been proposed as a way to integrate the various electrical components within buildings that are needed to realize this vision, more efficiently and at a lower cost than traditional alternating current (AC) power systems. This report's purpose is to summarize the current state of knowledge about the feasibility, cost effectiveness, market barriers, customer needs, and savings potential for DC or hybrid DC-AC systems to power zero net energy (ZNE) residences and commercial buildings, subdivisions, and communities. Particular focus is on residential and light-commercial building applications.

The all-AC power systems in use today were developed during a time when nearly all power generation and end-use devices were natively designed for AC power. Increasingly, however, power systems need to integrate resources and loads that are natively DC: photovoltaics (PV) generation, storage (batteries), fuel cells, and efficient end-use devices (electronics, light-emitting diode lighting, DC motors with variable-speed drives, and so on). DC power distribution offers an ideal integrating platform for these modern power components, offering energy savings and improved reliability with potential for lower first cost. Furthermore, the efficiency, reliability, and ease of control of DC power distribution could be a low-cost element to achieving ZNE buildings, helping California meet its ZNE and global climate change goals.

**Figure 1: Direct Integration of Direct Current Generation and End-Use Loads**



Source: Lawrence Berkeley National Laboratory

Various aspects of DC electrical systems – including DC microgrids, data centers, residential appliances, batteries, fuel cells, lighting, electronics, communications, and renewable sources – have been studied or promoted by industry. These studies and other industry efforts generally conclude that DC power offers energy savings, potential for lower capital cost, and power quality and reliability improvements. These results are similar to those found with high-voltage DC transmission systems used in the United States, Europe, and Asia. However, there is very little performance information on DC systems in residential or commercial buildings in the United States.

This report is organized as follows:

- Chapter 2 reviews existing academic and market literature about the design, availability, and performance of DC distribution systems and equipment in buildings. It then summarizes new information collected during the course of this study through a stakeholder workshop and a survey and in-depth interviews conducted with power system researchers, designers, and manufacturers.
- Chapter 3 reviews the current state of the market and provides guidance on DC and AC-DC hybrid systems in residential and commercial settings for the major building end uses. It describes the AC baseline and alternative DC designs and practices for each end-use system, discusses DC product availability, benefits, costs and challenges of DC distribution, and offers recommendations for implementing DC in the near future.
- Chapter 4 presents whole-building design guidelines for integrating power generation and DC components into a commercial or residential building, in the most practical and cost-efficient way possible. This chapter covers recommended system configurations and reviews efficiency gains, technical design considerations, grid integration considerations and economic impacts of DC and DC-AC hybrid systems. These design guidelines walk through the design process of three basic system configurations – all-AC, all-DC, and DC-AC hybrid – for integrating solar photovoltaic systems, electric vehicles and battery storage.
- Chapter 5 presents the benefits to California ratepayers. This analysis utilizes the energy use analysis performed in chapter 4 as well as projections of solar penetration, electricity demand, pricing, and growth rates in California to generate the potential energy, operating cost, and carbon dioxide ($CO_2$) emissions savings from DC distribution systems.
- Chapter 6 describes efforts the research team conducted to communicate the findings from this study to other researchers, the buildings and power system industry, and policymakers.
- Chapter 7 concludes with a summary of the findings and suggested next steps based on all the information compiled and collected.

# CHAPTER 2:
# Technology and Market Assessment

## Literature Review

The research team reviewed existing literature on DC power distribution in both entirely and hybrid AC-DC buildings. The literature review, consisting of approximately 250 references, focused on information related to DC demonstration projects and building case studies, energy savings, costs, non-energy benefits, current market status, and market and technical barriers. Overall, the team found that a large number of studies concentrated on estimating potential energy savings from DC, while less research has been performed on the cost-effectiveness of DC end uses and systems, or on the quantification of the less tangible, non-energy benefits of DC distribution. This chapter summarizes the project team's main literature review findings related to these topics of interest. See Appendix A for a list of the references collected in this study.

### Energy Savings

Several studies have investigated the potential electrical energy savings from DC distribution in buildings, the results of which are based either on modeling efforts or on a combination of analytical models and measurements in actual demonstration buildings where energy use of the DC system is compared side-by-side to an equivalent building with AC distribution.

As shown in Table 1, energy savings from DC distribution in buildings may vary, depending on the loads served by DC and their load profile, and the building distribution configuration. It also appears that modeling studies produce a wider range of energy savings compared to experimental studies: calculated energy savings based on modeling range from 2 percent to 14 percent, whereas in experimental studies the savings range from 2 percent to 8 percent.

The following factors and system parameters can significantly affect energy savings:

- Battery storage: The presence of battery storage can greatly increase energy savings through the elimination of power conversions from DC to AC and back to DC, which occur in today's typical AC systems with solar and battery storage.
- Coincidence of solar output and load: When power demand occurs while solar energy is generated, DC can be fed directly from the solar array to DC-ready appliances in the building. At the same time, a direct-DC system with high coincidence of solar and load uses less rectified AC power from the electric grid, which effectively reduces the DC system's energy losses.
- Power system component efficiencies: The operational efficiencies of rectifiers (AC/DC), inverters (DC/AC), and DC converters (DC/DC) – and specifically, the relative operational efficiencies of power system components in the DC system (mostly the efficiencies of DC/DC converters and central rectifiers) compared to those in the AC system (that is, efficiencies of inverters and power supply/rectifier efficiencies at the appliance level) –

can determine energy savings. In the foreseeable future, potential increased demand and research and development for DC systems will lead to higher efficiencies for DC system converters. On the other hand, technology advancements and regulatory standards for internal and external appliance power supplies are also expected to improve efficiencies for such components. Regardless, direct-DC systems require less power conversions than AC systems (even more so in systems with battery storage), and are therefore expected to keep their theoretical efficiency advantage.

**Table 1: Direct Current System Electric Energy Savings Estimates for Residential and Commercial Buildings**

| Study Type | Scenario* | Electricity Savings |
|---|---|---|
| Modeling | Generic building with battery Storage | 2%–3% [1] |
| | All-DC building (res. and com.)<br>No battery storage | 5% residential<br>8% commercial [2] |
| | All-DC residential building | 5% w/o battery<br>14% w/ battery [3] |
| | All-DC residential building | 5.0% conventional building<br>7.5% smart bldg. (match PV-load) [4] |
| Experimental | LED** DC system (no battery storage) | 2% measured<br>5% potential [5] |
| | LED DC system (no battery storage) | 6%–8% (modeled) [6] |
| | All-DC office building; Battery storage and EV | 4.2% [7] |
| | All-DC building<br>Electric Vehicle, No battery storage | 2.7%–5.5% daily energy savings [8] |

***All scenarios include a local DC source, (typically solar photovoltaics). ** LED = Light emitting diode**

**Note: Reported energy savings are compared for a building with DC distribution relative to a building with AC distribution and equivalent end uses.**

Source: Lawrence Berkeley National Laboratory

- DC Voltage and system configuration: DC line voltage (typically 380V for high power loads, and 24V or 48V DC for low power loads) can impact wire losses.
- Power system configuration: Finally, the power system configuration and topologies (i.e., the type and number of components in the system, and how these components are electrically connected to each other) can determine the number of power conversions within the building and therefore energy savings.

Table 2 summarizes the power system component peak efficiencies used in energy savings calculations from recent literature, as well as from product surveys (see appendix B for more details on the converter efficiency surveys). Converter efficiencies are dependent both on voltage conversion levels, as well as converter power ratings.

**Table 2: Power System Component Peak Efficiencies**

| Component | Peak Efficiencies* (%) | |
|---|---|---|
| | Literature Review | Product Surveys (Average Values) |
| AC-DC Central Rectifier | 93.0 [3]; 96.5 [1]; 96.9 [8]; 97.0 [2], [4]; 98.0 [4] | 97.5% (25kW) |
| DC-AC Inverter | 95.0 [3]; 96.9 [6]; 97.6 [1] | 96.9% |
| DC-DC Conv. (380V to 24/48V) | 95.0 [3], [8]; 96.0 [1] | 90.6% (0-1 kW)<br>97.5% (1-5 kW) |
| MPPT** and Charge Controller | 97.4 [5]; 97.6 [1], [8]; 98.0 [3] | 98.3% |
| Appliance AC-DC Conv. (high wattage) | 90.0 [3]; 94.2 [8]; 96.5 [1] | 93.7% |
| Appliance AC-DC Conv. (low wattage) | 87.0 [3]; 87.9 [7]; 91.7 [8]; 95.0 [1] | 87.6% |
| LED Driver | 93.3 [7]; 94.9 [8]; 97–98 [6] | 92% |
| EV Charger | 96.0 [7]; 97.2 [8] | N/A |

*** Numbers in brackets refer to the list of references at the end of the report. Most studies use peak or nominal efficiencies when calculating potential DC system energy savings. For operational efficiencies, see Appendix B, which includes efficiency curves for various converters.**

****MPPT = maximum power point tracker**

Source: Lawrence Berkeley National Laboratory

## Non-Energy Benefits

Several studies claim that DC systems in buildings have important benefits, such as power quality, reliability and controllability, resilience during grid outages, interoperability, and others, compared to AC systems [2], [9]–[12].[1] Sannino et al [13] state that DC systems offer the potential for better reliability, as they are usually capable of being decoupled from the grid. In addition, AlLee and Tschudi [14] claim that, by eliminating power distribution units and the inverter on the output of the uninterruptible power supply system, data centers using a 380 volt (V) DC distribution system are 200 percent to 1,000 percent more reliable (when estimating uptime) than equivalent AC systems when a direct connection to the battery bus is available, and cite telecommunications systems (operating at 48V DC) as an example. However, regarding power quality, although DC distribution systems in buildings are often touted for fewer harmonics and lower voltage distortion compared to equivalent systems with AC distribution, Whaite et al. [15] note that DC distribution systems may also experience harmonics due to the presence of power converters connecting the DC bus to an AC grid, or even by scaling up or down DC voltage with the use of bidirectional DC/DC converters. Overall, although non-energy benefits of DC systems in buildings are widely discussed in the literature and among DC power advocates, they have not been thoroughly investigated, substantiated, or quantified.

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[1] Numbers in brackets refer to the list of references provided at the end of the report.

## Case Studies and Demonstration Projects

There are numerous emerging case studies and demonstrations for DC systems in buildings. A few notable examples are described below, and shown geographically in Figure 2.

**Figure 2: Worldwide Direct Current Case Studies**

Source: Lawrence Berkeley National Laboratory

1. Bosch, in collaboration with the California Lighting Technology Center, has developed a demonstration project in Chino, California, funded by the Energy Commission's Electric Program Investment Charge (EPIC) program. The project's goal is to demonstrate the benefits of DC distribution in commercial buildings by implementing a solar powered, direct-DC, 380V distribution system powering lighting, ceiling fans, and forklift chargers. [16]
2. The Alliance for Sustainable Colorado is retrofitting a portion of a 40,000 square foot commercial building from AC to DC distribution. The building will be fed by solar power and other renewable DC sources, will include battery storage, and will be able to act as a DC microgrid. This project's goal is to create a scalable demonstration that will showcase the benefits of DC distribution in commercial buildings. [17]
3. NextHome in Detroit, Michigan, is a demonstration DC test bed developed by NextEnergy, featuring solar-generated direct-DC power for lighting, ceiling fans, a DC computing center, floor heating, home appliances, battery storage, and bidirectional vehicle charging. The Next Home features a solar array providing direct-DC via a main DC bus operating at 380V to a 13.2 kilowatt-hour battery, stepped down to 24V DC at the load level. [18]
4. Aquion Energy, an energy storage company, and Ideal Power, a power converter manufacturer, partnered to install a microgrid showcasing their technologies at Stone

Edge Farm, an organic winery in Sonoma, CA. The system includes a 32 kilowatt (kW) PV array, a 350 kilowatt-hour (kWh) capacity of battery storage provided by Aquion, and a 30kW multi-port converter from Ideal Power. This system does not power DC end-uses, but uses a DC-coupled configuration between the PV array, the multi-port converter, and the batteries. Note that Aquion has since filed for Chapter 11 Bankruptcy. [19]

5. Bosch has implemented a DC microgrid demonstration project, funded by the U.S. Department of Defense, in Fort Bragg, North Carolina, which includes a 15 kW PV array powering 44 DC induction lights, 4 DC ceiling fans, and a 100 kW lithium-ion battery storage system. A side-by-side equivalent AC system reportedly uses 8 percent more electricity compared to the DC microgrid. A highlight of the Bosch DC power system configuration is that maximum power point tracking (MPPT) is not applied directly after the PV array, but rather at the AC/DC gateway converter, allowing for higher system efficiency. [6]

6. The Hawaii Natural Energy Institute is developing a hybrid 500kW DC/AC microgrid at the Moku o Lo'e (Coconut island) in Hawaii. [20] The project includes DC power sources (PV, fuel cells, wind) and battery storage, and distributes DC and AC power to various DC and AC end-use loads. Its Partners include Nextek Power Systems, the Okinawa Institute of Science and Technology, and the Naval Research Lab.

7. Philips is developing a Power over Ethernet (PoE)-powered lighting system at Clemson University, which will include more than 45,000 light points. The system is expected to lead to a 70 percent energy savings over traditional lighting systems in similar buildings and will feature luminaire-integrated controls, which will be accessible and controllable remotely via a web interface. [21]

8. ARDA Power has designed a DC microgrid that will be built in Burlington (Ontario), Canada. The project will showcase a microgrid for a manufacturing and office building, and includes DC (16 kW PV) and AC (10 kW diesel/gas generator, microturbine), battery storage, a 30 kW bidirectional inverter, AC and DC loads. [22]

9. Philips has implemented a grid-connected, PV-powered DC test bed installation for an office LED lighting system at the Eindhoven (Netherlands) High Tech Campus, and compared its energy performance against an equivalent AC system. The site has demonstrated 2 percent electricity savings and 5 percent potential savings for the DC system. [5]

10. Fraunhofer has built a DC office building test bed, which includes a grid-connected, 380V direct-DC system, battery storage, DC lighting, EV charger, and a 24V DC nanogrid for electronic loads. The DC system demonstrated electricity savings ranging from approximately 2.7 percent to 5.5 percent over an equivalent AC system. [8]

11. The Beijing University of Civil Engineering and Architecture is conducting research to demonstrate the energy and non-energy benefits of DC distribution in buildings.

Researchers at BUCEA have estimated 11 percent savings from shifting to an all-DC system from the current AC system. [23]

12. Xiamen University in China implemented a DC microgrid. The direct-DC system consists of a 150 kW PV array, 30 kW air conditioning system, 40 kW EV charging station, and 20 kW LED lighting. Researchers concluded that efficient DC microgrid applications should include a bidirectional inverter and battery storage, and that a hybrid DC-AC building distribution system would be more suitable for today's commercial buildings. [24]
13. NTT Facilities is developing a demonstration DC microgrid for an office building in Hokkaido, Japan. The DC system includes a PV array, Li-ion battery storage, LED lighting, a refrigerator, electronics, and an EV. NTT researchers report that the DC system yields 4.2 percent electricity savings compared to the same system powered by AC. [7]
14. The Island City in Fukuoka, Japan, has made available a demonstration AC/DC residential project. The Smart House uses AC distribution to power electric loads through an inverter that is interfacing with the AC grid and a 380V DC system consisting of a PV array, wind turbine, and battery storage. [25]

The majority of these demonstration projects are focused either on showcasing building DC distribution systems as a proof of concept, or on estimating electricity savings. As discussed in the next sections, few of these studies address cost issues, or attempt to quantify non-energy benefits often associated with DC distribution, such as higher power quality, reliability, and resiliency.

## Cost

A relatively small but growing number of studies have addressed the cost-effectiveness of DC distribution on retrofit or new construction in residential or commercial buildings. Most studies compare the relative cost difference of the power system components required by AC and DC systems. For example, Willems and Aerts [4] made this comparison and found that the overall hardware cost for the AC system is slightly higher than the one for the DC system, mainly due to the presence of AC/DC power converters at the appliance level and a PV array inverter (instead of a cheaper MPPT) for the AC system. However, the authors also noted that a central bidirectional rectifier for the DC system was not accounted for in the cost calculation.

Another study by Foster Porter et al. [26] found that in a mature DC market, DC distribution for electronic end uses is beneficial not only from an operating cost perspective, but also from the perspective of capital upfront cost. However, lighting, motor, and resistive end uses were not cost-effective for conventional, code-compliant buildings. For ZNE buildings, due to the presence of the PV system and the inverter for the AC system, all end uses other than resistive loads were cost-effective. Overall, this study found that electronics, followed by heating, ventilation and air conditioning (HVAC) were the most cost-effective applications for DC power in buildings. Furthermore, according to Planas et al. [27], metering costs, converters, and distribution costs are lower for DC systems, although due to generally lower voltage distribution and technology maturity in AC systems, system protection costs are higher for DC systems.

King and Brodrick [28] report that electricians typically charge by the number of receptacles in the residential sector and state that due to National Electrical Code (NEC) requirements for the relative distance between receptacles, the number of receptacles in a DC house would be similar to the one for an AC house, while electrician retrofit costs (of converting an existing AC building to DC) would be higher than new construction costs. Regarding retrofit costs, Glasgo et al. [29] estimated that the cost of an AC-to-DC residential retrofit is approximately $6,000 to $10,000, and concluded that the high capital costs of such a conversion would not be recovered by the energy cost savings of DC distribution. For low-voltage distribution (<50V), costs can possibly be reduced because the DC distribution system can use less expensive cabling and installation labor than a traditional AC system.

DC lighting products and systems, such as the Armstrong 24V DC commercial ceiling grid [30], have been in the market for about a decade, and may already be cost-competitive in some applications. Specifically, PoE lighting systems with occupancy, daylighting, temperature, and other controls currently developed and marketed by Philips, Cisco, NuLEDS, and Eaton, among others, claim significant cost savings compared to traditional AC systems. According to Philips, PoE lighting can lead to a 25 percent reduction in installation cost due to 87.5 percent less mains wiring compared to conventional wiring systems for lighting [31]. Similarly, Eaton claims that their PoE DC lighting systems can lead to a 40 percent reduction in materials and installations costs [32].

## Barriers

There are many fundamental and systemic barriers hindering the market transformation to DC and hybrid electric systems:

- Safety and fault protection: Per Monadi et al. [33], fault detection and fault resistance detection methods applicable to AC systems are not always applicable to DC systems. Therefore, they recommend further research on protection schemes, grounding methods, and DC circuit breakers (of medium to high voltage).
- The lack of mature standards and guidelines, which are also an impediment for the application of protection schemes in DC systems [20].
- Lack of DC-ready appliances [26], [9], [11] and power distribution system components.
- Market and awareness barriers stemming from the entrenched AC distribution system. Customers, installers and contractors, standards and code bodies, as well as policymakers are less familiar with DC systems, and therefore unlikely to embrace them. Anecdotally, a recent effort to develop a DC demonstration project in Fort Collins, Colorado [34], was halted when the contractor for the project could not get bonded, because of the DC nature of the distribution system. Instead, the project proceeded with AC distribution in the building.

### Standards

Many new standards for DC power have been developed in recent years and more are in process with the goal of creating international standards for DC power systems and applications. An early leader in these efforts has been the EMerge Alliance, whose main goal is to help create DC standards directly, or by catalyzing standards creation through other organizations like IEC, IEEE, the National Fire Protection Association (NFPA), and others. Most standards dealing with electricity, and especially those focusing on safety, already cover the subject of DC. Unfortunately, they do so in such an indirect way that it makes them difficult to interpret, expensive for permitting, and unlikely to be used for DC, thus hindering the adoption of DC power. For this reason, explicit and rapid development of DC and AC-DC hybrid electrical standards and codes are vital for widespread market adoption. Another key factor for DC standards is the increasing use of information technology standards – namely PoE and universal series bus (USB) – for distribution of low-voltage DC power in buildings to power DC products such as electronics and lighting.

According to a recent report by the IEC [35], the majority of the standardization efforts for DC relate to the addition of provisions for DC in the existing AC standards. However, the same report notes that there are specific differences between AC and DC that should be addressed specifically for DC. These include:

- Standardized DC voltages, including voltage variation, particularly for application with battery storage.
- Standardized DC plugs and sockets. Such products must address arcing and load disconnection while in active mode.
- Further investigation of human health effects from DC power.
- Other differences such as protection against voltage and current surges overvoltage and overcurrent protection, fault detection, grounding principles, arcing, and corrosion.

The EMerge Alliance has a codes and standards reference list for the numerous DC and hybrid standards and plans to update it regularly. See the list in Appendix E and updates at http://www.emergealliance.org.

## Stakeholder Input

### Summary of Stakeholder Workshop

The project team held a stakeholder workshop on March 15, 2016, at the Los Angeles Electrical Training Institute (operated by the International Brotherhood of Electrical Workers). Approximately 30 stakeholders from a variety of institutions, including manufacturers, policy makers, non-profits, and research organizations, attended the workshop. The workshop solicited input and advice on the technology, policy, and market development needs for adoption of DC and AC-DC hybrid systems in residential and commercial buildings. It focused on ZNE buildings with PV, battery storage, and EV charging.

Key findings, recommendations, and questions from the workshop are listed below. For more details on the workshop proceedings, see appendix C

- Standards and open protocols should be developed to jumpstart production of DC products by industry. As demand for DC products grows, economies of scale will reduce costs to consumers.
- Stakeholders need to agree on DC voltages so that products can be designed around international DC standards. Common voltage levels are 24V, 48V, 125V, and 380V.
- Demonstrations are critically needed to showcase DC performance at both end-use applications and the ZNE systems applications. Also, real metering data are needed to resolve differing views about savings potential of DC or hybrid DC/AC versus all-AC buildings.
- Battery storage and EVs, due to their inherently DC nature, have significant advantages for integrating with ZNE buildings with PVs and interconnecting with smart grid systems.
- More research is needed to understand and resolve power quality issues in both AC and DC systems.
- The industry should exploit "Trojan horses" (for example, plug loads, residential electronics, emergency lighting) to get DC into use and expand familiarity and comfort of end users. For the foreseeable future, large AC loads may need to remain on the grid.
- PoE lighting and other applications are emerging with several companies (NuLEDS, Volt Server, Lumencache, and others) offering solutions that take advantage of the digital power and embedded data capabilities.
- Issues related to ZNE buildings include the need to agree on a common definition of ZNE , the energy use requirements for ZNE over the building's lifetime, the sizing of battery storage (that is, initial requirement versus likely requirement over the life of the building), and the allocation of shared renewables in community-scale projects.
- A key challenge for retrofits is the need to develop transformational schemes for retrofits, which must involve the entire supply chain for building retrofits, from equipment manufacturers and distributors, to designers and architects, to building contractors and trades. Industry should take advantage of less intrusive technologies and solutions, such as using existing wiring for DC distribution.
- DC/ZNE buildings have multiple stakeholders. Utilities, government agencies, and regulators can raise consumer awareness and demand through incentives like rebates. Also, designers, builders, installers, and operators will require training and education in order to accept and implement DC distribution in buildings.

To provide insight about the important issue of codes and standards for DC power, Brian Patterson of the EMerge Alliance provided a summary at the workshop of the current state of codes and standards. He first pointed out that DC and hybrid AC/DC standards and systems are common for a number of applications such as telecom facilities, off-grid systems, and mobile transportation, including large ships (both commercial and military). Mr. Patterson pointed out that codes already allow DC systems in an indirect way, through the basic electrical design criteria, but compliance for DC systems requires extra calculation and effort, so it is important that DC standards are adopted explicitly into the code books. For typical building systems, specific DC standards are now listed in the Institute for Electrical and Electronics Engineers (IEEE), the International Electrotechnical Commission (IEC), and the NEC. These standards have been developed in the last 10 years, with the EMerge Alliance leading the way in North America.

## Stakeholder Survey Results

As one part of this research effort, the study team tapped the knowledge and experience of DC power experts, thought leaders, and stakeholders to identify the state of DC adoption, including DC equipment suppliers, customers, designers, builders, industry, government, environmental organizations, regulatory bodies, policy makers, and utilities. This information gathering helped to assess the state of the art and identify industry and customer needs and barriers.

The team developed a comprehensive stakeholder list, and e-mailed these individuals, asking them if they would like to volunteer to respond to an online questionnaire (11 questions).[2] Thirty-nine of the survey recipients returned responses, four of which were incomplete. A summary of the online survey results is presented below.

To profile and understand the spectrum of survey respondents, the first question asked about activities related to DC power distribution and about end uses in buildings in which the respondent or their organization was involved. Activities included research, product development, manufacturing, field deployment/installation, sales, codes and standards/policies, other, and not applicable. Many of the respondents were involved in multiple aspects of DC power, as reflected by the fact that 39 respondents claimed participation in over 92 activities. On average, respondents were involved in more than two activities, and as many as six, although 16 respondents indicated that they were involved in just a single activity (Figure 3).

Figure 4 breaks down the percentage for each type of activity, as identified by the survey respondents. Nearly 33 percent of the respondents participate in research activities, and 17 percent are active in codes and standards/policies. Approximately 15 percent of respondents participate in field deployment/installation and product development. Sales, manufacturing, and “other” each tallied under 20 percent of the responses.

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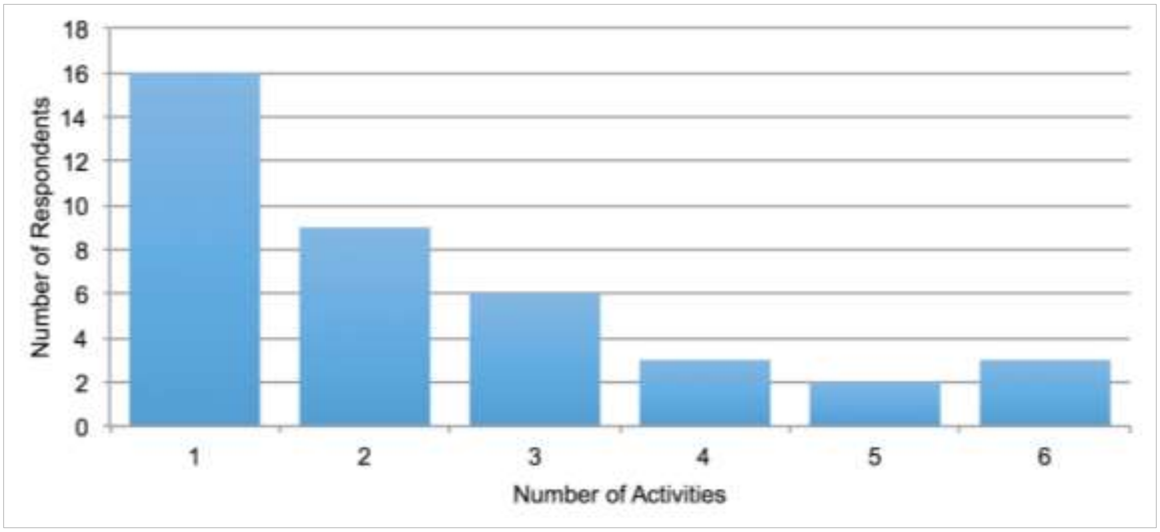
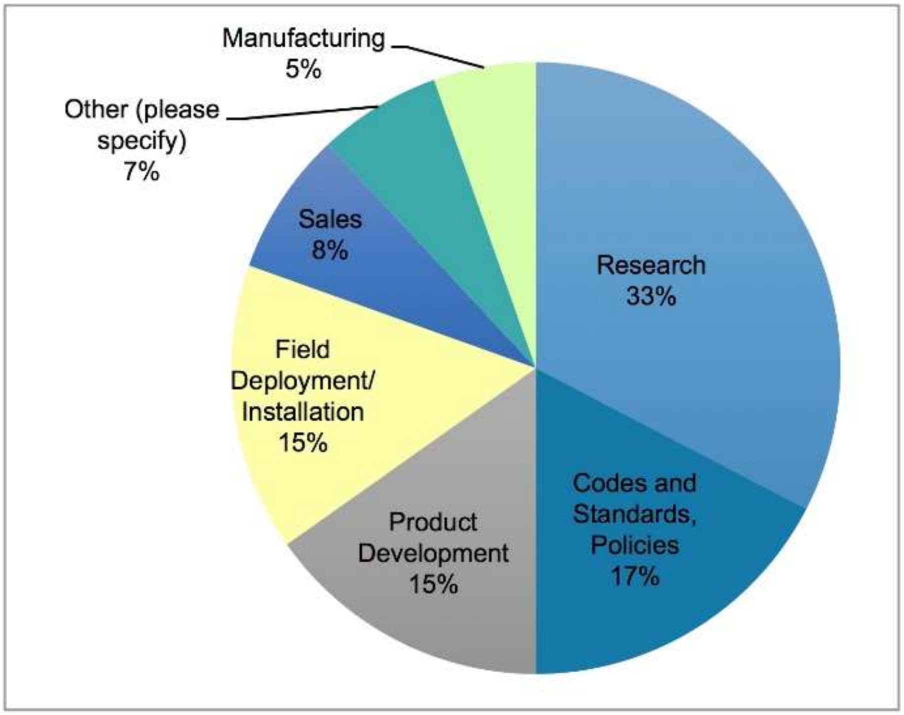
[2] The survey questionnaire is available in Appendix D.

**Figure 3: Question 1, Number of Respondent Activities**



Source: Lawrence Berkeley National Laboratory

**Figure 4: Question 1, Types of Respondent Activities**

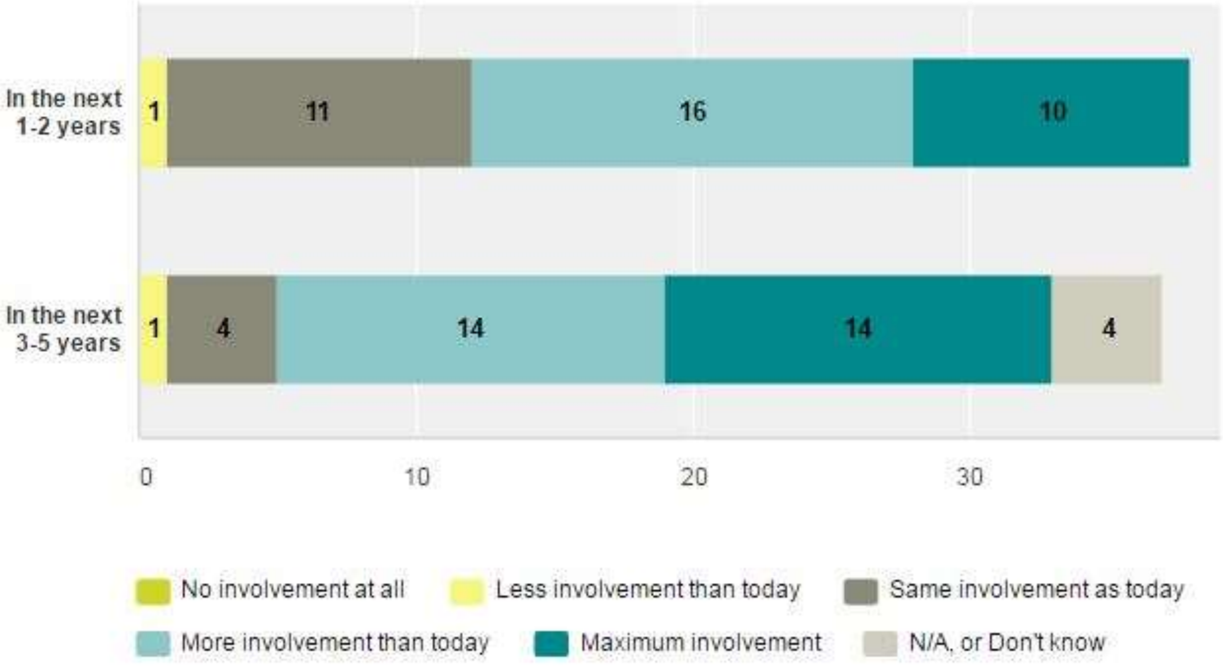


Source: Lawrence Berkeley National Laboratory

Questions 2 and 3 of the survey addressed respondents' anticipated involvement in DC power activities, as well as their perception of how DC markets will evolve in the foreseeable future (over the next one to two years and three to five years).

- Question 2 Responses: Respondents anticipate that their participation will increase in the next one to two years, and further accelerate in the next three to five years (Figure 5).

**Figure 5: Question 2, Respondents' Anticipated Involvement in Direct Current Power in the Foreseeable Future**



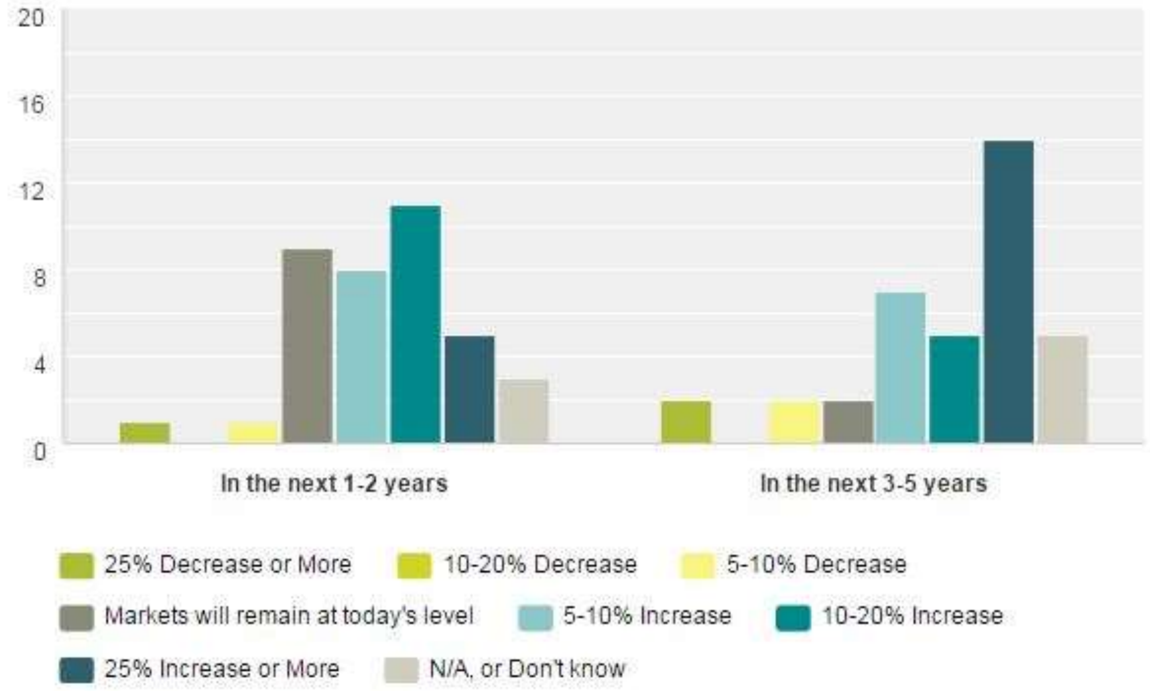
Source: Lawrence Berkeley National Laboratory

- Question 3 Responses: In the next one to two years, 30 percent of respondents anticipate a 10 percent to 20 percent increase in markets. In the next three to five years, approximately 40 percent of the respondents expect a 25 percent or more increase in markets (**Error! Reference source not found.**).

Question 4 focused on applications for DC power in the building sector, and questions 5 and 6 asked about respondents' rating of DC power by end-use application in residential and commercial buildings, respectively.

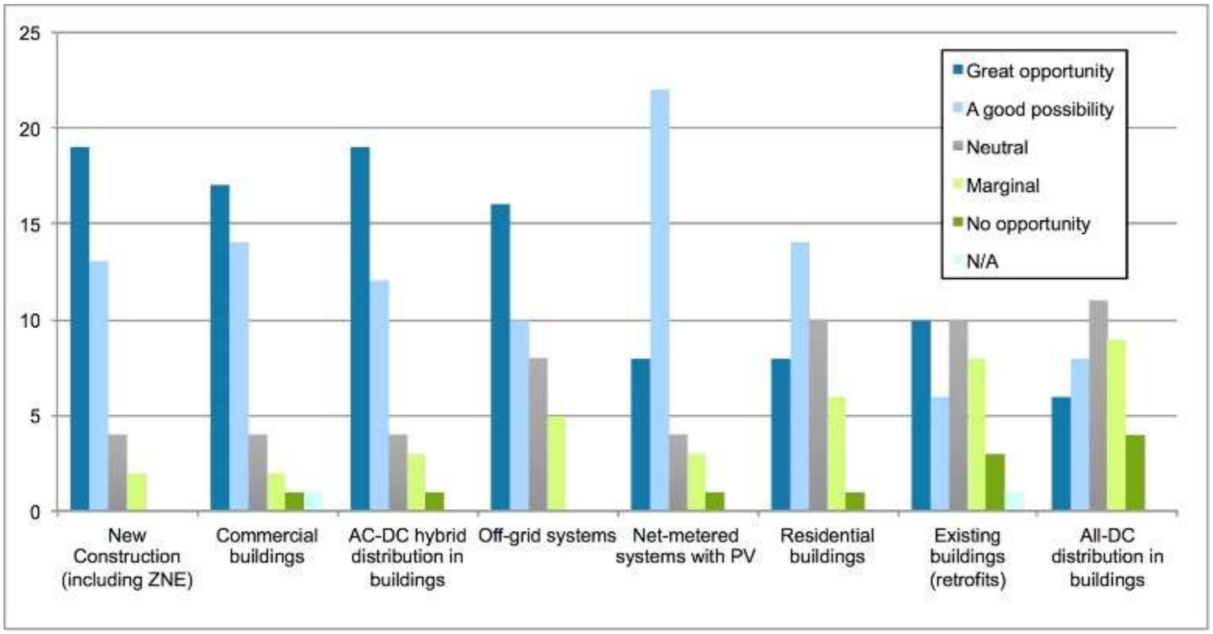
- Question 4 Responses: Respondents believe that new construction (including ZNE), commercial buildings, AC-DC hybrid buildings, and off-grid systems hold the most promise, while retrofits and all-DC buildings face challenges such as cost, availability of components, and others (Figure 7).
- Question 5 Responses: Respondents selected EV charging, backup and emergency systems, and lighting as affording the greatest DC opportunity in the next three to five years in residential buildings; electronics was a close fourth. Notably, clothes and dish washing and drying, and water heating were last (Figure 8).
- Question 6 Responses: Respondents most frequently selected lighting, EV charging, backup and emergency systems, and electronics as the most promising end-use applications for commercial buildings. Space cooling/heating, refrigeration, and small appliances were in the middle, and water heating and clothes and dish washing and drying were last (Figure 9).

## Figure 6: Question 3, Respondents' Anticipated Market Development of Direct Current Power in the Foreseeable Future



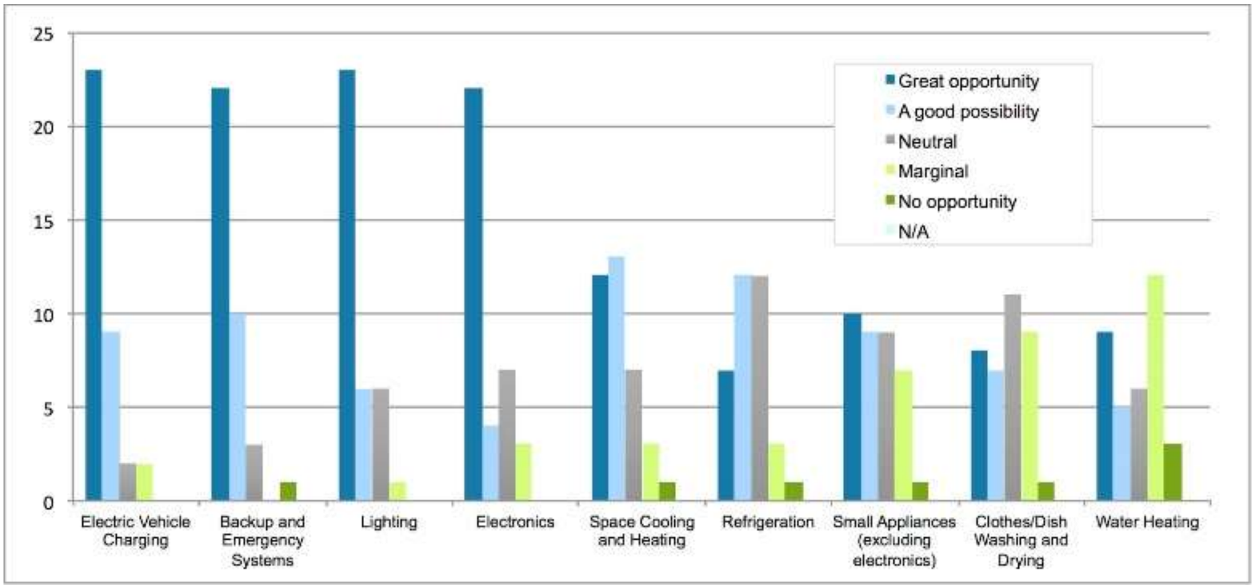
Source: Lawrence Berkeley National Laboratory

## Figure 7: Question 4, Respondents' Rating for Applications of Direct Current Power in Buildings for the Next 3–5 Years



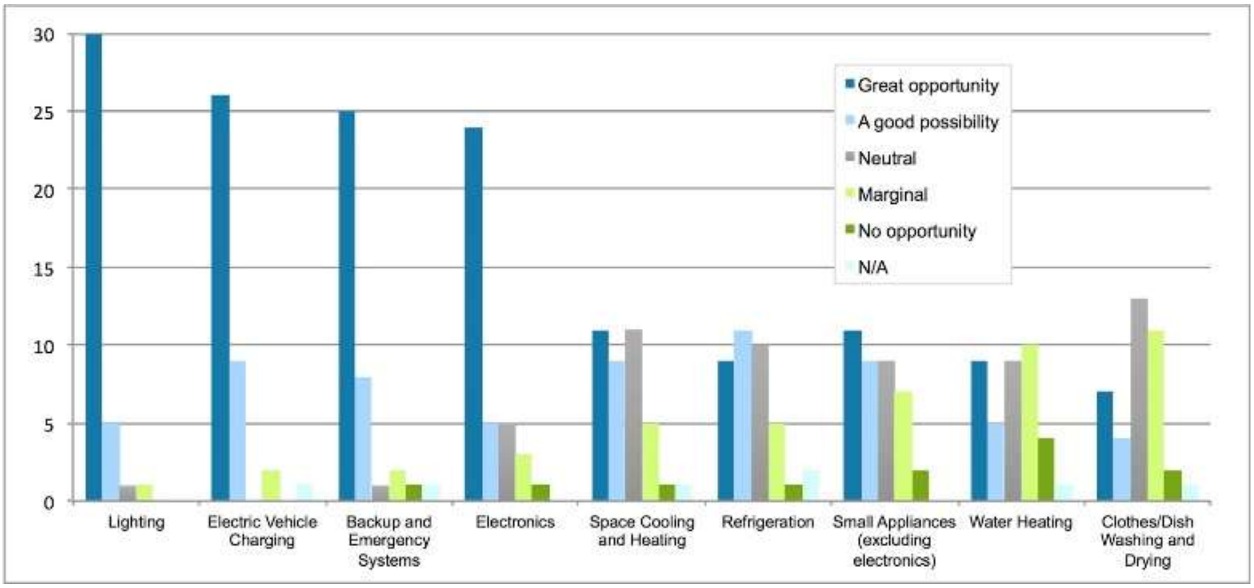
Source: Lawrence Berkeley National Laboratory

**Figure 8: Question 5, Respondents' Rating for End Uses of Direct Current Power in Residential Buildings for the Next 3–5 Years**



Source: Lawrence Berkeley National Laboratory

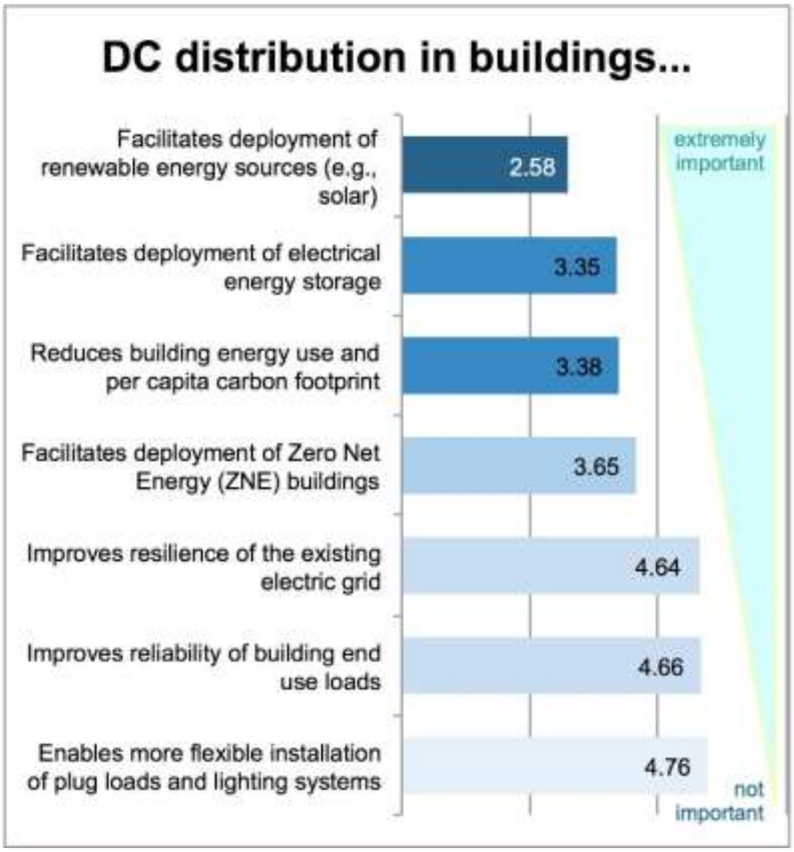
**Figure 9: Question 6, Respondents' Rating for End Uses of Direct Current Power in Commercial Buildings for the Next 3–5 Years**



Source: Lawrence Berkeley National Laboratory

- Question 7 Responses: Question 7 asked respondents to order the importance of roles that DC distribution can play to accelerate change in buildings. Respondents rated deployment of renewable energy sources, energy storage, and reduction of energy usage and per capita carbon footprint as the most critical reasons to develop DC distribution in buildings. Improving reliability and flexible installation of plug loads and lighting were ranked as the least pressing roles for DC distribution in buildings (Figure 10).

**Figure 10: Question 7, Respondents' Rating of Benefits Associated with Direct Current Distribution in Buildings**



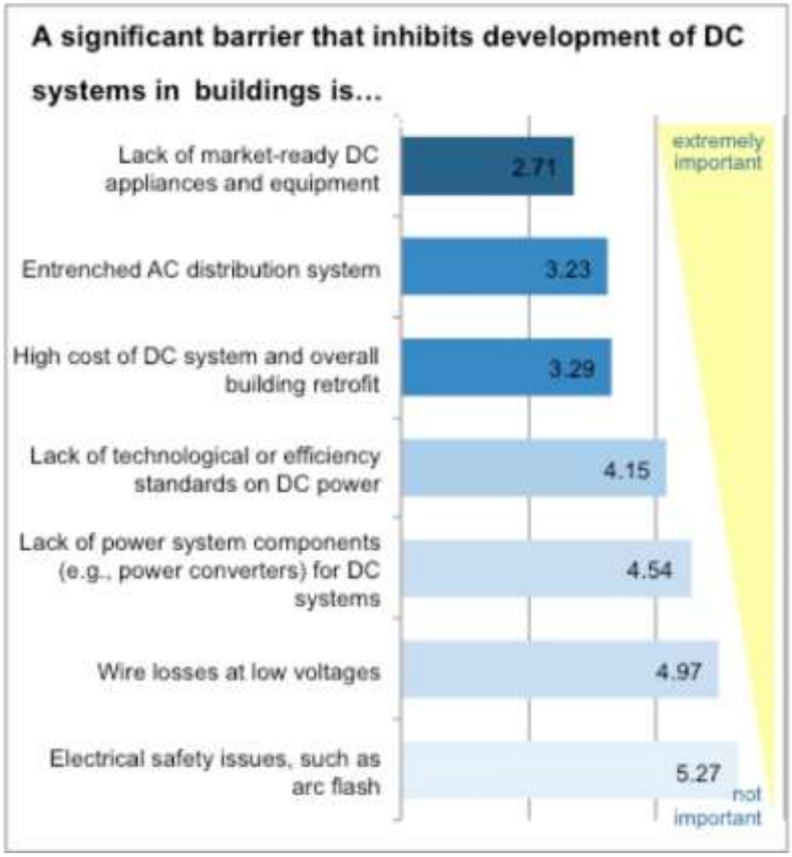
Source: Lawrence Berkeley National Laboratory

- Question 8 Responses: Question 8 asked respondents to order the relative importance of barriers inhibiting development of DC systems in buildings. Respondents rated lack of market-ready DC appliances and equipment, an entrenched AC distribution system, the high cost of a DC system and overall retrofit, and lack of technology and efficiency standards as the most challenging obstacles impeding development of DC systems in buildings. Lack of power system components, wire losses at low voltages, and electrical safety issues were ranked as less pressing barriers for DC distribution in buildings (Figure 11).

Questions 9, 10, and 11 requested open-ended responses from survey respondents.

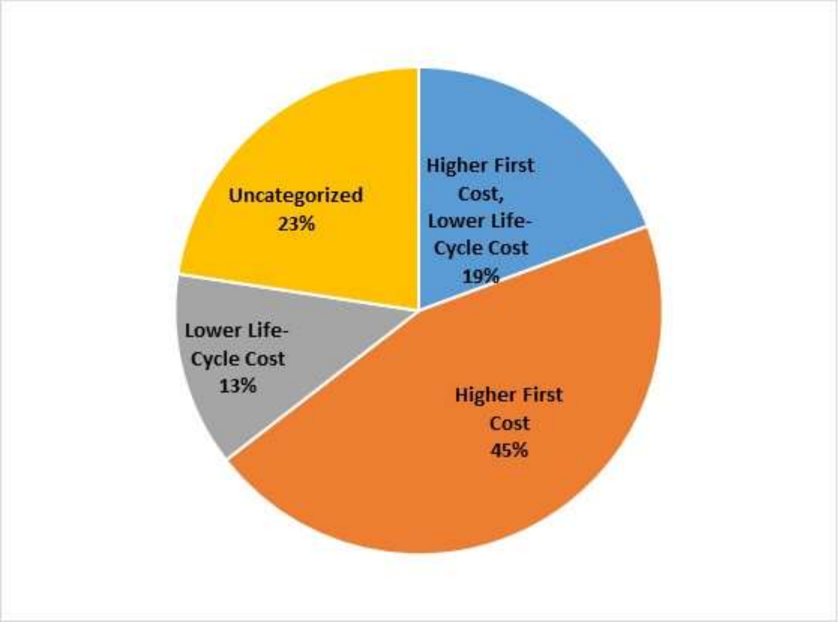
- Question 9 Responses: Regarding the relative cost of DC systems compared to AC systems, of the 31 respondents, 14 stated that DC first costs would be higher than AC; 9 thought that DC systems would have higher operating costs but lower operating or life-cycle costs, and 4 responded that DC systems would have lower life-cycle costs compared to AC systems. Respondents anticipated costs ranging from savings of 30 percent to increasing costs at 500 percent (Figure 12).

**Figure 11: Question 8, Respondents' Rating of Barriers Associated with Direct Current Distribution in Buildings**



Source: Lawrence Berkeley National Laboratory

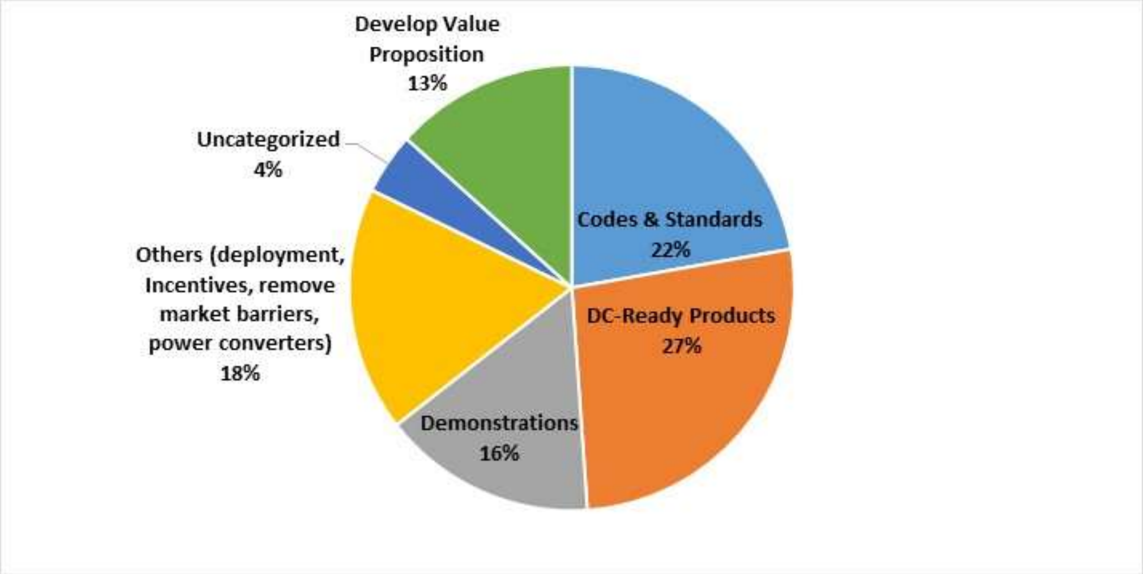
**Figure 12: Question 9, Respondents' Rating of Direct versus Alternating Current System Cost**



Source: Lawrence Berkeley National Laboratory

- Question 10 Responses: Regarding the next critical steps to accelerate adoption of DC power in buildings received 31 responses. The top categories were the development of DC–ready products and codes and standards, followed by the need for additional demonstration projects. Other recommended steps were the development of a compelling market proposition for DC, the removal of market barriers, development and improvement of power converters for DC systems, and the availability of incentives (Figure 13).

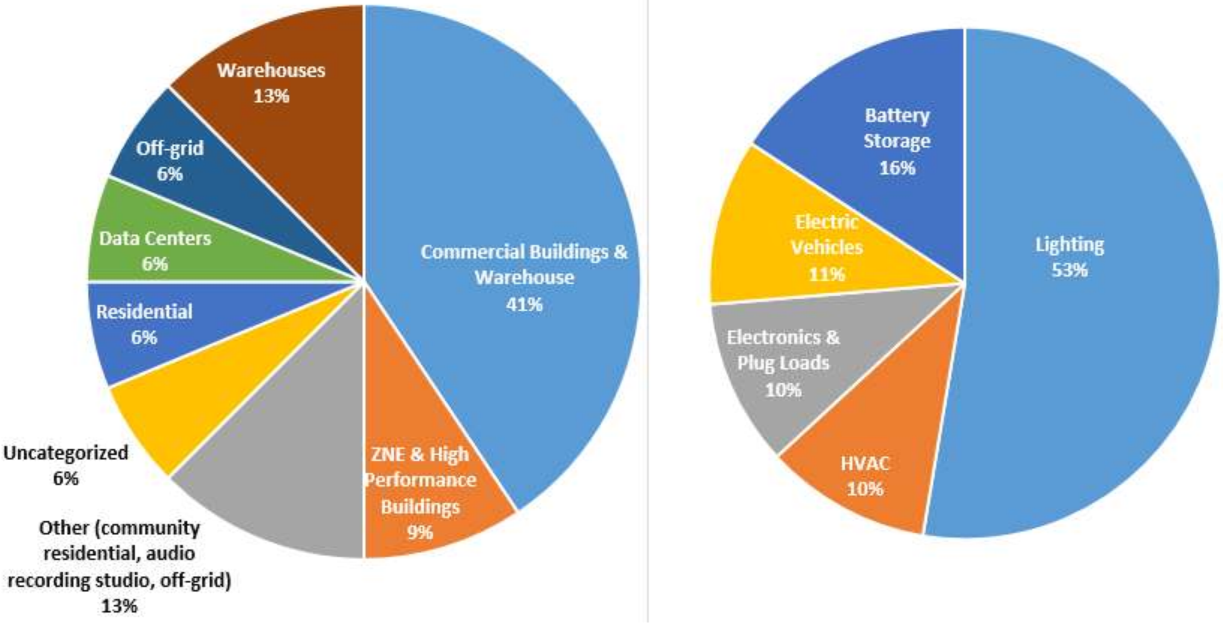
**Figure 13: Question 10, Respondents' Categorization of the Critical Next Steps to Accelerate Adoption of Direct Current Power in Buildings**



Source: Lawrence Berkeley National Laboratory

- Question 11 Responses: Regarding the ideal case study for deployment of DC power in buildings, the top case studies chosen by respondents for deployment of DC power were commercial buildings and warehouses (including big box retail, medium to large office buildings, buildings with large rooftop area for PV integration, office buildings), followed by ZNE buildings (commercial and residential), residential buildings, data centers, and off-grid applications. With regard to the ideal end-use loads, lighting was the dominating end use, followed by battery storage, HVAC, EVs, and electronics and plug loads. Note that PV integration was an overarching theme throughout responses (Figure 14).

**Figure 14: Question 11, Respondents' Ranking the Ideal Case Studies for Direct Current in Buildings Categorized by Building Type (left) and End-Use Application (right)**



Source: Lawrence Berkeley National Laboratory

## Telephone Interviews

At the end of the survey questionnaire, participants were given the option to participate in an in-depth telephone interview.[3] The study team selected 10 respondents from those who elected to participate in a telephone interview, representing a range of backgrounds.

Several respondents mentioned cost as one of the main areas where further data and research are needed. They also identified it as one of the main factors that will determine DC adoption in the foreseeable future. For example, an architect working on a DC retrofit project, highlighted the need for cost information since building owners and institutions make their decisions primarily based on first cost. According to John Wang of ABB, in principle, the cost of DC converters should be less than their AC counterparts, but this is not always the case in practice because existing component topologies and configurations may require redesign, while the lack of demand for DC products does not create the necessary economies of scale to reduce manufacturing costs. In addition, Steve Pantano of CLASP noted that one of the potential benefits of DC systems are fewer components (namely, AC/DC power supplies within appliances), which could lead to reduced manufacturing, shipping, and consumer costs. Peter May Ostendorp of Xergy Consulting noted that, to determine feasibility of DC systems in the future, the actual costs at maturity for DC (including both operational and first costs) should be estimated.

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[3] The interview oral consent script and list of interview questions are available in Appendix D.

Further, quite a few interviewees pointed out that demonstration projects are key to better validate cost and performance of DC systems, identify and address integration and design issues, and raise awareness among stakeholders. Interviewees also stated that the lack of sufficient offerings of DC-ready products and power system components are a significant barrier for DC systems. Dr. Sandra Vanderstoep, who is the director for the Alliance for Sustainable Colorado DC project, referred to the unavailability of DC HVAC systems as a significant barrier to the AC to DC building retrofit the Alliance is implementing. Further, Jim Saber of NextEnergy emphasized the need to increase the market share of DC-ready appliances, but also mentioned that converting appliances to accept both AC and DC "would not be very hard." For this reason, Steve Pantano highlighted the Adapt initiative led by CLASP, which aims to advance DC-ready appliances by raising manufacturers' and consumers' awareness and engagement in DC power. On the other hand, John Wang stated that manufacturers are unlikely to develop DC products as long as DC standardization schemes, and protection standards in particular, have not been developed.

Despite these barriers, many participants were optimistic about DC in buildings. Several noted the increasing number of established (Cisco, Philips, Eaton) and start-up (Voltserver, Lumencache, NuLeds) companies developing DC lighting solutions (primarily through PoE) as a sign of a DC resurgence in lighting systems and controls. Pete Horton with Legrand's electrical wiring systems division, elaborated that controls manufacturers are currently analyzing how DC systems can help them add value to their customers and are developing potential products. With regard to end-use applications for DC, respondents mentioned DC lighting applications, IoT systems, and DC data centers. Also, on data centers, and other energy-intensive end uses (e.g., refrigerated warehouses), Stephen Frank with the National Renewable Energy Laboratory noted that DC can have a cascading effect on the energy used by HVAC systems.

# CHAPTER 3: Evaluation and Design Templates for Homes and Businesses

This chapter reviews the current state of the market and provides guidance on direct current DC and AC-DC hybrid systems in residential and commercial settings for the following uses and systems:

- Lighting
- HVAC systems
- Electronics and appliances
- EV charging
- Energy storage systems
- Renewable energy integration

This guidance is intended to be useful for consumers, building engineers, and architects interested in installing DC distribution systems in buildings, with a particular focus on ZNE buildings. The chapter describes the AC baseline and alternative DC designs and practices for each end-use system, discusses DC product availability, benefits, costs and challenges of DC distribution, and offers recommendations for the foreseeable future.

## Lighting

### Description

#### Residential Lighting

Lighting for home applications varies and is either hard-wired into a building's electrical system or plugged into an outlet (portable light fixtures). Hard-wired lighting includes recessed cans, ceiling-mounted, wall-mounted, exterior, and others. Plug-in light fixtures are predominantly table and floor lamps, which can represent a substantial share of the light fixtures in a residence. Home lighting typically uses 120V single-phase AC to multiple light fixtures in each room. Fixtures tend to be Edison (E26) socket-based, requiring lamps to contain their own internal LED driver, or linear/pin-based, which use a pin-into-socket configuration to deliver power. Many of these pin-based products use an external ballast (in the case of fluorescent lamps) or driver (in the case of LED products) to deliver power to the socket, though some linear LED tubes and LED pin-based lamps do contain internal drivers. Multiple fixtures are usually daisy-chained on a distribution circuit, while switches and dimmers are typically hardwired in the circuit. Increasingly, light fixtures are using LED light sources, especially in new construction. Light fixtures and lamps that also incorporate communications and controls are commonly called smart lamps or connected lighting.

**Commercial Lighting**

Lighting is one of the largest electrical loads in the commercial sector, and its use generally coincides with solar generation. Installations tend to be hard-wired, with ceiling mounted fixtures in most spaces. Fluorescent lighting dominates in the commercial sector, although LED fixtures and lamps are becoming common for new installations. Commercial buildings typically power their lighting systems using 277V AC, with some 120V AC installations in smaller commercial buildings. These 120V sources are also common for task or desk lighting. Most commercial lighting systems are manually controlled with wall-mounted switches or dimmers, although many larger buildings have automated controls that adjust zones for occupancy or daylighting or integrated room level motion, occupancy, or light level sensing. Low-voltage DC commonly powers these control systems.

LED/solid-state lighting (SSL) technologies are typically DC-compatible. Solid-state lighting is expected to make up more than 95 percent of sales in the lighting market by 2030, while fluorescent lighting can be made to be DC-compatible and currently has a larger market share than LED lighting in the commercial sector. DC-powered LEDs still require a DC-DC LED driver which potentially can be more efficient than AC-DC drivers.

## Benefits of Direct-Direct Current Distribution

- Direct-DC power distribution to lighting loads can lead to energy savings due to fewer power conversions, especially in commercial settings where PV output is more closely matched with lighting demand.
- Non-energy benefits of DC distribution for lighting applications can include:
    - Easily reconfigurable lighting with the use of low-voltage DC lighting such as PoE. [36]
    - Potential for simpler, and therefore more reliable LED drivers.
    - Additional control and integration options with other DC building systems
    - In the case of PoE, easier communications and controls with the use of the same cable for both power and communications.

## Product Availability

DC LED lamps are available from a number of lighting manufacturers who target primarily the off-grid market (such as Phocos). Larger lighting manufacturers are also developing DC LED lamps and luminaires for building lighting applications (for example, Osram, Acuity, Hubbell, and Philips).

Off-grid/solar powered street and area lighting typically use DC power LEDs paired with either pole- or base-mounted batteries for power. These products have been in the market for several years and are sold by several companies (Carmanah/SOL, Solar Path, Lighting Science, and others).

In recent years, with the emergence of Power over Ethernet (PoE) for lighting applications, an increasing number of companies offer PoE lighting solutions for homes and businesses, including IGOR (distributed by Hubbell), LuxSpace (by Philips), SmartCast (by Cree) NuLEDs, Acuity, Lumencache, Colorbeam, and others. PoE coupled with DC LED lighting has been showcased in several demonstration projects. When this report was prepared, larger installations were being planned and were likely to occur shortly. Efforts to standardize energy performance, operation, and control of PoE lighting systems was also underway. [37]

Cisco is attempting to standardize the DC PoE lighting marketplace with their Cisco Digital Ceiling protocol. [38] This protocol has been used by IGOR, Eaton, Cree, Acuity, Philips, and others in certain PoE products and Cisco now offers lighting specific PoE routers solely focused on DC lighting applications. The Cisco Digital Ceiling concept is part of a larger Cisco Digital building concept (with integrated building management and other sources). Companies like Johnson Controls, Legrand and Molex, and others, which do not make lighting fixtures, are also partners in the Cisco Digital Ceiling concept.

The EMerge Alliance has established a 380V building distribution standard and a 24V DC occupied space standard. Several companies offer compatible 24V DC-ready lighting products (for example, luminaires from Acuity Brands, Osram Sylvania, JLC Tech), and power distribution modules (the DC Flexzone Grid from Armstrong Ceiling Solutions and the Nextek Power Server Module) for commercial applications in high bay, low bay, and outdoor applications.

## Costs and Paybacks

Currently, DC-powered LED products cost more than LEDs with AC drivers, mainly due to their small production scale. However, the energy performance potential for DC LEDs is higher than AC LEDs because the former do not include the additional rectification stage. The rectifiers in AC LEDs, however, are becoming more efficient as well so the energy savings gained by DC LEDs (which are not receiving as much research and development attention since sales are still developing) may or may not be noticeable.

According to manufacturers of PoE lighting systems (Philips, IGOR, Eaton), PoE lighting may lead to reduced installation costs since the low-voltage runs do not require a certified electrician and may require up to 85 percent less mains wiring than conventional wiring systems for lighting. However, these potential savings depend on application and location, so project planners should consider actual savings at the time of project planning. PoE systems do require specialized routers – which may or may not already be installed – so the additional potential costs of these products, and the fact they are always energized and pulling power even when not powering lighting, should also be considered when calculating PoE system savings.

### Challenges and Recommendations

Currently, DC-powered lighting is more costly than AC lighting because of lower production and sales volume. DC lighting may become cost-competitive with AC-powered lighting as volumes increase.

For hardwired lighting installations in commercial buildings, 380V DC lighting systems may be preferred because they can greatly reduce wire size (and cost) and distribution losses. However, the majority of currently available DC LED lighting products accept input voltages of 50V DC or less, so 380V DC products are more difficult to find.

PoE lighting with direct-DC power distribution is becoming more common in the market and has several potential benefits compared to AC lighting. Maximum energy efficiency in PoE installations requires highly efficient DC-DC converters (typically from 380V to 48V or 24V DC) to step-down the main DC bus voltage to feed the low voltage branches.

The lighting industry is changing rapidly with the rapid adoption of LED light sources and "connected" lighting that can be controlled over a communication network. Because of the rapid change in this market, it is likely that new DC-powered lighting products will become more common. Designers and purchasers can stay on top of the latest trends through conferences like LightFair and Strategies in Light, and magazines such as LEDs Magazine.

## Heating, Ventilation, and Air Conditioning Systems

### Description

HVAC accounts for the largest use of electricity in homes and commercial buildings in the United States. Modern air conditioners and heat pumps include variable speed compressors and fan motors with variable frequency drives (VFDs), which require power to go through a DC phase before converting to the desired AC frequency. The most efficient air conditioners use VFDs and DC permanent magnet motors. Variable-speed operation of compressors and fans allows the output of HVAC equipment to be closely matched to the needs of the building occupants, thus improving energy efficiency.

Exhaust, ceiling, and portable fans are used extensively in buildings for ventilation and supplemental cooling. Their small motors and application are well suited for DC permanent magnet motors. Though DC motors are not common for such use today because of costs to production for limited demand, such appliances may be available with DC power.

### Benefits of Direct-Direct Current Heating, Ventilation, and Air Conditioning Systems

- HVAC is a high-energy load, and is relatively well synchronized with solar radiation, especially in commercial settings. Direct-DC distribution to HVAC equipment can therefore lead to meaningful energy savings by avoiding DC-AC and AC-DC power conversions.
- DC-ready HVAC systems and products could be more reliable due to fewer components (for example, elimination of the AC-to-DC VFD rectifier).

- If designed properly, DC-ready HVAC systems could provide a reduced output mode ("fan-only" mode) that could be activated during a grid outage when only PV-generated DC power is available.

## Product Availability

Although the market is moving towards more efficient, DC-internal HVAC products (often designated as "inverter driven" products from manufacturers such as Mitsubishi, Sharp and Daikin), there are a limited number of DC-ready products available in the United States market. These products are highly efficient as they are typically equipped with DC motors. Some examples include:

- Split system air conditioners by Hotspot Energy and Green Energy Innovations (48V).
- Ceiling fans by Nextek Power Systems (24V).
- Radiant heating systems by Warmfloor (24V).

In an existing demonstration DC microgrid project at Fort Bragg, North Caroline that is funded by the United States Department of Defense, Bosch Building Grid Technologies is planning to include a UL-certified 380V rooftop HVAC system.[4] The system will be tied to Bosch's main DC voltage bus, which has a voltage range of 260V-600V DC. For the same project, Bosch has also modified commercial ceiling fans by Big Ass Solutions to accept DC input.[5] [39]

In another demonstration project at the University of Texas, NTT Facilities in collaboration with Japan's New Energy and Industrial Technology Development Organization has developed a DC data center that includes an air conditioning system supplied by 380V DC. [40]

## Costs and Paybacks

- Prices for DC-ready HVAC equipment are expected to be higher in the short term due to engineering and design expenses, but at scale such equipment can have competitive or even lower prices than equivalent equipment with AC input.
- Retrofitting DC-internal air conditioners and heat pumps to include a DC input (that is, to bypass the VFD rectification stage) has been successful in demonstration DC distribution systems at minimal cost. However, such systems are not yet available in factory-built condition, and may therefore require potentially costly on-site UL certification for any field modification.

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[4] The HVAC system will consist of a scalable 5-ton DC compressor unit from Emerson, with Carrier as the packaging unit partner, while Bosch will modify the compressor and other electronics to be DC-ready.

[5] See Big Ass Fan Company, https://www.bigassfans.com/company/.

## Challenges and Recommendations

- Availability of DC-ready HVAC equipment from major manufacturers is limited, and the few products on the market today are marketed for the off-grid and transportation markets.
- For retrofits of existing HVAC units with VFDs, the availability of drop-in, UL-certified, replacement DC VFDs, as opposed to a complete replacement/retrofit of the whole system, is a barrier.
- As the market moves to more efficient DC and AC motors with VFDs, an opportunity for retrofits of DC-internal equipment exists. Centralized space-cooling is a single, large load that is often on a dedicated circuit, which is easier to retrofit than low-voltage loads that require considerable rewiring.
- For new construction, consumers today can install inverter-driven air conditioners and heat pumps and, if they choose to convert to direct-DC, can retrofit their systems to bypass the internal rectification stage. In the future, manufacturers may offer HVAC equipment with the ability to accept both DC and AC power.
- Direct-DC, solar-assisted HVAC systems are available for the off-grid market, and this paradigm can be used for the building sector as well, possibly with the addition of battery storage.
- Ductless heat recovery ventilation systems with DC motors, which can serve as alternatives to ducted heat exchange systems, are available, and use very low power (about 10 watts). These ductless systems, operating internally at 12V DC, optimize indoor air quality and ventilation efficiency, especially for high performance buildings, apartments and smaller homes. In a ZNE setting, these systems could be integrated with low voltage (12V-24V) DC distribution. [41]

# Electronics and Appliances

## Description

### Electronics

Consumer electronics and information technology equipment are the fastest growing load type in the building sector. These end-use loads include solid state components that operate on DC power. Increasingly, they are also “DC-ready” in that they have a DC input through an external power supply that converts AC power to DC. Examples of such products include cell phones, notebook computers, monitors, fire alarm devices, security cameras, network equipment like modems and routers, building management systems, servers, and so on. These products often have network connections, allowing control, monitoring, and communication.

### Appliances

Virtually all electrical end uses in buildings can be DC-compatible because the major appliance components – motors, heating elements, lights, and electronic controls – all are available in designs that can be directly DC powered. [42] Clothes washers, water heating, refrigeration, dishwashing, water pumping, are not only capable of operating internally on DC, but they are also more efficient with the use of permanent magnet brushless DC motors (driving fans, pumps, compressors, and other devices), and variable frequency drives. Most of these end uses are currently powered with AC, at 120V or 240V AC (single phase) in homes, or 208V and 480V AC (3-phase) in business settings. In a DC distribution scheme, high power appliances and equipment would be supplied with 380V DC (hard wired), while low power plug loads would be supplied with lower voltage: 12V, 24V or 48V DC.

## Benefits of Direct-Direct Current distribution

- AC-DC conversion loss avoidance: The power supplies included with DC-internal electronics and appliances have conversion efficiencies that range between 75 percent to 90 percent. A centralized DC-DC converter or AC-DC rectifier in a DC distribution system can reach higher efficiencies (around 95 percent) compared to individual, lower power rectifiers.
- Improved convenience and reduced e-waste due to elimination of external power supplies.
- Better reliability due to fewer appliance power converters.
- Easier communications and controls by transmitting both power and data through the same cable (such as with USB and PoE), thereby allowing for easier deployment of Internet-of-things networks.
- Simplified wiring methods with no concern for load balancing. DC distribution relies only on positive, negative, and ground wiring throughout instead of multi-phase conductors in single and three-phase AC deployments.

## Product Availability

- DC-ready consumer electronics include all notebook computers, tablets, cell phones, and other small electronic appliances with an external power supply. A few offerings are available for monitors (for example, Alphatronics and Niwa) and other larger electronics, but those are typically marketed for the off-grid and recreational vehicle market.
- Several companies offer refrigerators and freezers operating at 12V or 24V (for example, Norcold, Sundanzer, Dometic, Phocos, and others), and some of them include dual (AC or DC) power input. Other end-use appliances (dishwashers, clothes washers and dryers, heat pump water heaters, and so on) are generally not currently available in DC-ready form.
- Many mobile, low-power products such as laptops, computer peripherals, and desktop appliances (external hard drive disks, small monitors, task lights, and fans) may be powered over a universal series bus (USB) connection instead of requiring an external converter. The USB Power Delivery standard specifies powering of devices up to 100 Watts over a USB type C connection at voltage levels of 5V, 9V, 15V, or 20V depending on the device.

- Desk phones, Wi-Fi access points and cameras powered over PoE have long been available.
- For computer servers, using 380V DC distribution systems for data centers is increasingly common. Data centers with DC distribution have been available and operating in commercial settings for more than a decade and have shown energy, reliability, and cost savings. [14]
- Regarding white goods[6] and other end uses, despite the potential for many appliances to operate internally on DC power no manufacturers support appliances operating at voltages higher than 60V DC input because current DC-ready appliances are marketed mostly for the off-grid market. However, a technology developed by Voltserver, inc., allows power distribution ( greater than 1kW) at higher voltages through a relatively thin cable by sending electricity "packets".[7] Voltserver's technology could be applied to power high-power white goods in the foreseeable future.

## Costs and Paybacks

- For DC-ready electronics and appliances, the product cost would be lower than their AC equivalent, since there would be no need for an additional external power supply.
- For DC-internal products that currently include internal power supplies, converting to a DC-ready configuration would reduce material costs, but redesign costs could offset this cost reduction in the short term.
- Direct-DC distribution could lead to tangible operating cost savings due to fewer conversion losses. Supplying appliances with the appropriate voltage and reducing DC-DC conversions can maximize those savings.

## Challenges and Recommendations

- USB power delivery, which now allows up to 100 Watts, can be a standard means of supplying power to DC-ready electronics (and other low power appliances). USB type-C is expected to increase the number of appliances powered by USB-type connectors. DC components and converters interfacing with USB power delivery (for example, USB-C wall socket outlets [43]) would be essential to develop DC distribution systems serving consumer electronics, Another alternative for low power applications is PoE, currently used most often to power networked electronic equipment (such as video cameras and wireless access points) as well as general building lighting applications. However, with the exception of certain prototypes [44], DC plugs and socket outlets for higher power applications (and associated standards) are not widely available.
- Standardizing input voltages for consumer electronics would increase the availability of DC-ready products by allowing converter manufacturers to focus on a smaller number of specifications, which in turn would reduce DC system power conversion losses. The

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[6] White goods typically refers to major household appliances such as refrigerators and stoves.

[7] See http://www.eavesdevices.com/eavesdevices/downloads/voltservernetworkpower_revb.pdf for more information on Voltserver's technology.

EMerge Alliance has developed 24V DC and 380V DC distribution standards that could be used for electronics and higher power end-use loads, respectively.

- The availability of several DC-ready consumer electronics creates an opportunity for development of small, dedicated DC distribution systems in buildings (in retrofit or new construction scenarios). One example is a battery-tied (with optional PV) DC distribution system powering essential electronics in the event of an outage, such as emergency lighting systems, security monitoring, cameras, and so on.
- A potential strategy to speed the introduction of DC-ready appliances and white goods would be to develop dual input (DC and AC) models to accommodate both power delivery options.
- For certain high-power plug loads (such as hair dryers, microwaves, and large appliances), direct powering from 380V DC may not be an appropriate option because of safety concerns and lack of DC plugs and, therefore, such loads are most likely to require AC supply for the foreseeable future. For these products, point-of-use AC inverters (380V DC to 120V AC) may be the most practical option for implementing an all-DC building distribution system.

# Electric Vehicle Charging

## Description

Charging of electric vehicles (EVs) and plug-in hybrid EVs (PEVs) for the residential sector is typically implemented at home, in most circumstances overnight, for one or two vehicles. Charging installations vary between cord-connected and hard-wired chargers, which can be freestanding or wall mounted. These chargers are predominantly single car chargers, but models are available that charge up to four EVs, and most are suitable for indoor and outdoor use. The cord-connected models can be portable. For residential EV owners who want faster charging, additional equipment and professional electrical installation is needed.

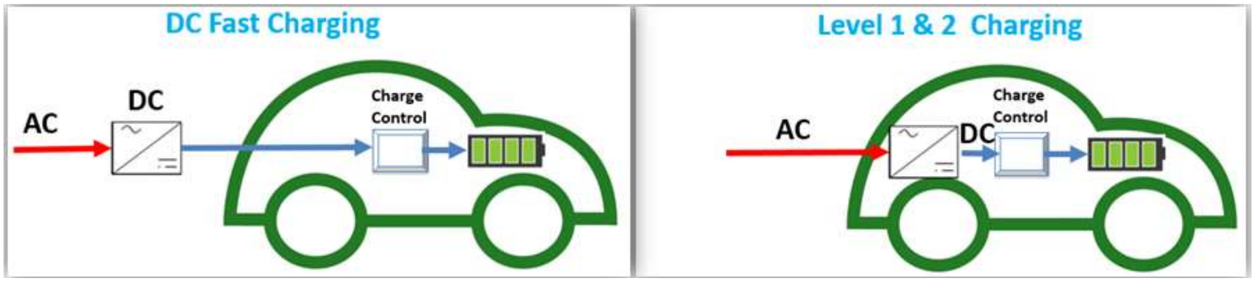
In the commercial sector, charging for EVs and PEVs is typically used to charge multiple vehicles simultaneously for 30 minutes up to a few hours. Installations are hard-wired connections that are either freestanding or wall mounted, although some stations also offer standard connection outlets. These systems can be installed indoors or outdoors and typically charge one to four vehicles simultaneously.

EV charging equipment is generally categorized by the charging rate (in kW):

- Level 1 charging, typically found in residential applications, is provided by 120V AC to the EV, at a charging rate of 1.4 kW, and allows for about 2-5 miles of driving range per hour of charge. Level 2 charging, more common in commercial charging stations, is provided by 240V or 208V AC, at a charging rate of about 3kW-20kW, and allows for about 10-20 miles of driving range per hour of charge.
- DC fast charging is typically used in public and commercial settings and allows for about 100 miles or more of driving range per hour of charge. It is provided at an input

voltage of 208V AC or 480V 3-phase, and a charging rate of about 24kW-100kW. DC fast charging currently includes 3 competing protocols in the United States: CHAdeMO, Combined Charging System (CCS), and the Tesla Supercharger. The CCS allows for all level 1, level 2, and DC fast charging using the same port, while the CHAdeMO is a dedicated DC charging port on the EV that requires a second adjacent AC port for level 1 and 2 charging. The Supercharger is a proprietary charging protocol developed by Tesla, which works for all Tesla vehicle charging options and is most similar to CCS. A fundamental difference between DC and AC charging is that with the latter, a rectifier is included inside the EV, as shown in Figure 15.

**Figure 15: DC Fast Charging versus Level 1 and 2 Charging**



Source: Lawrence Berkeley National Laboratory

Table 3 shows DC fast charging options for several EVs and PEVs available in the market.

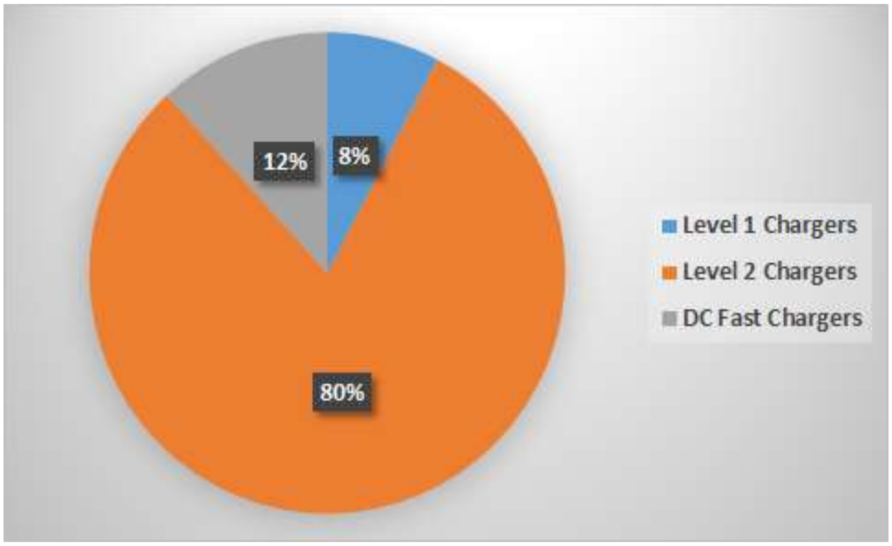
**Table 3: Direct Current Fast Charging Options by Carmaker/Model**

| Carmaker and Model | DC Fast Charging Option |
|---|---|
| BMW i3 | CCS |
| Chevrolet Bolt | CCS |
| Chevrolet Spark EV | CCS |
| Kia Soul EV | CHAdeMO |
| Mitsubishi i-MiEV | CHAdeMO |
| Nissan Leaf | CHAdeMO |
| Tesla Model S | Supercharger |
| Tesla Model X | Supercharger |
| Volkswagen e-Golf | CCS |

Source: http://www.fleetcarma.com/dc-fast-charging-guide.

Figure 16 shows the breakdown of existing commercial charging stations in the United States by charging level as of April 20, 2017.

**Figure 16: Distribution of U.S. Commercial Charging Stations by Charging Level**



Source: http://www.afdc.energy.gov (as of April 20, 2017)

## Benefits of Direct-Direct Current Electric Vehicle Charging

- As battery prices decline and EV sales and charging infrastructure expand in the foreseeable future, EVs are expected to become a large fraction (30 percent to 50 percent) of the native DC loads in buildings; for ZNE homes and businesses, the percentage is expected to be even larger. The large size of the EV load amplifies the potential energy savings from direct-DC distribution.
- Direct-DC charging can provide efficiency and cost savings if charging can occur during peak solar hours. Direct-DC charging, although not currently commercially available, can preclude the need for a large-capacity rectifier, and provide a simpler, more reliable, cost-effective, and efficient fast charging option for future EVs.
- The batteries in EVs not only constitute a large DC load for the building sector, but they can also serve as a DC source which can act as battery storage in a DC distribution system and provide backup during grid outages. Using EVs this way requires vehicles and electric charging equipment that are capable of V2G (vehicle-to-grid) operation. Residential V2G, with bidirectional direct-DC charging interface, does offer an attractive residential solution for utility back-up and resiliency.
- Commercial EV charging stands to benefit the most from direct-DC EV charging, due to better coincidence of EV charging and PV generation. For homes, charging would typically take place in the evening when most people are home from work, and therefore reduce the likelihood of DC charging directly from PV (without the use of stationary battery storage, which incurs energy losses of its own). However, residential community solar installations, due to overall higher PV capacity and diversity of EV charging profiles with a fleet of vehicles, may offer opportunities for direct-DC charging. Several automotive manufacturers (BMW and Nissan have gone public with this, others have ongoing research programs) are looking at “charging appliances” of between 10kW-

20kW DC for residential applications. As on-board battery storage increases, these chargers are likely to be more commonplace. However, this effort seems to be fading in light of a lack of customer interest at this time.

## Product Availability

- Manufacturers that offer DC fast chargers include AeroVironment, ABB, Blink, Eaton, Signet, Efacec, and Schneider Electric, among others.
- eCamion has developed a proprietary DC-DC fast charger that is coupled with their battery system and has indicated willingness to work on a custom solution involving a battery operating at 380V DC.
- Paired Power has commercialized a scalable direct-DC EV charging system, including a PV to EV carport supporting 6 EVs, which does not use maximum power point tracking or charge control but follows the voltage of the PV array. This technology cannot support fast charging due to the capacity of the PV array. [45]

## Costs and Paybacks

- Generally, charging stations increase in cost with the charging voltage, while the per-charger cost for multi-port charging stations is lower compared to single-port chargers.
- Similar to other markets, early adopters of direct-DC chargers will likely face higher costs that could be offset by utility or government incentives. However, consumers entering a more mature market should see comparable or even lower costs for direct-DC EV chargers compared to chargers that use AC power and include a rectifier.
- For systems with high coincidence of EV charging and PV generation, operating cost savings, due to fewer conversion losses from DC to AC and back to DC, may be significant enough to offset a higher capital cost premium.

## Challenges and Recommendations

### Challenges

- PV generation and EV charging do not generally synchronize in home applications. However, for certain end-use cases and use profiles (mostly weekend usage and V2G), direct-DC EV charging can be advantageous for residential consumers.
- As AC-fed DC fast chargers are becoming more prevalent, the largest barrier to their integration with a 380V DC distribution system is the lack of the latter and DC-fed DC fast charging systems in the marketplace.
- It is uncertain which charging protocols and technologies will prevail and how the EV industry will evolve. For example, competing technologies to plug-in EV charging, such as wireless induction charging, could prevail in the future, while direct-DC fast charging protocols are likely to develop separately from AC fast charging protocols. These factors can create additional challenges to DC charging.

- Direct-DC EV charging involves high voltages and fast transfers of power, typically tens of kW. Most residential and small commercial buildings do not have adequate power infrastructure to serve this type of load. Also, direct-DC charging from PV arrays may not be possible at high power rates, as the PV capacity is unlikely to be able to keep up with EV charger demand.

**Recommendations**

- EV charging stations at commercial buildings can be an opportunity for direct-DC applications, because of the coincidence of EV load and PV generation in commercial facilities (for example, workplace charging).
- EV charging stations outside the building sector (for example, on highways, parking lots) may have fewer barriers to implementing direct-DC distribution (such as permitting processes and infrastructure restrictions in buildings). Also, public installations may offer more opportunities for revenues, which would help cover capital cost expenses.
- Direct DC charging, coupled with PV and energy storage could offer an off-grid solution to an evolving EV charging infrastructure.

# Energy Storage Systems

## Description

Energy storage systems (ESS) have been used at commercial and utility scales for some time. Pumped water storage is not an uncommon method for utilities to store excess electricity generation for later use. Both commercial buildings and utilities have used flywheels to store short-term energy, and uninterruptible power supplies (UPS) and telecom backup systems have long used lead acid batteries for backup power. With the continually decreasing price of lithium ion batteries,[8] long-term battery backup systems of all sizes (from residential to utility scale) are becoming more common. Especially for residential and commercial customers, lithium ion batteries represent an efficient and increasingly cost-effective way to store excess renewable generation for use at a later time.[9]

Many companies are beginning to offer different types of battery storage for home use. Both native AC coupled and DC coupled ESS exist in the marketplace. The former tend to be used as an addition to existing systems, while DC-coupled ESS is higher efficiency because the PV-generated can be fed directly to the charge controller without passing through an inverter and rectifier. Even without any DC loads on the system, it is more efficient to connect the renewable generation and the ESS together on a DC bus. However, AC coupled systems persist because the AC components are more common, and the small percentage of additional losses may not be noticeable to a residential customer. On the other hand, commercial systems are often much

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[8] *Cost and Price Metrics for Automotive Lithium Ion Batteries,* DoE EERE publication # DOE/GO-102016-4908, February 2017, https://energy.gov/sites/prod/files/2017/02/f34/67089%20EERE%20LIB%20cost%20vs%20price%20metrics%20r9.pdf.

[9] *Exploring the Potential Cost-Competitiveness of Utility Scale Photovoltaics plus Batteries With Concentrating Solar Power, 2015-2030*, http://www.nrel.gov/docs/fy16osti/66592.pdf.

larger than home systems, so even a small percentage of losses can noticeably add up. For this reason, most commercial-scale systems already couple the PV and ESS on the DC side of the inverter.

## Benefits from Direct Current

- DC-coupling of an ESS increases the system's round-trip efficiency by coupling with renewable generation on the DC bus (compared to AC-coupled systems). [46]
- The use of ESS in building applications enhances the benefits from incorporating a native direct-DC distribution system to DC-ready end uses. These benefits include increased energy savings compared to AC distribution, and better system reliability due to less power conversions.
- Storage of "excess" renewable power from local resources can increase the renewable share of power consumed by a building, thus reducing a building's carbon footprint. Using direct-DC to couple the generation and storage amplifies this effect.
- A home with a direct-DC distribution system and DC loads can see electricity savings of a few percent without an ESS compared to an equivalent building with AC distribution. By installing an ESS, the savings increase even more, to as much as 14 percent. In commercial buildings, direct-DC savings are higher due to higher coincidence of loads and DC generation from PV.

## Product Availability

Some of the energy storage technologies currently available for building applications are listed in Table 4.[10]

## Costs and Paybacks

High upfront costs for systems is the main barrier to the installation of ESS without a strong utility incentive program. A building with an ESS will incur higher capital costs and can experience higher electricity use than one without an ESS due to the round-trip losses in the battery. However, time-of-use rates and demand electricity charges can favorably affect the economics of a battery installation. In addition, as net energy metering programs are phased out for PV systems, it will become increasingly cost-effective to store excess solar production rather than export it to the grid. ESS also include other benefits, such as resiliency during grid outages.

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[10] For a cost and technology comparison across multiple solar battery models, see https://www.solarquotes.com.au/battery-storage/comparison-table/.

**Table 4: Battery Technologies for Building Applications**

| Battery Technology/ Chemistry | Pros | Cons |
|---|---|---|
| Aqueous Hybrid Ion | - Non-toxic<br>- Low cost<br>- Temperature stability<br>- Deep cycling | - Low energy density<br>- Low current density<br>- Lack of Manufacturers |
| Nickel Metal Hydride (NiMH) | - Low cost<br>- Deep cycling<br>- Mature technology | - High self-discharge<br>- Minor memory effect |
| Lithium Titanate (LTO) | - Long cycle life<br>- Temperature stability<br>- Rapid charging<br>- High current density | - Cost<br>- Lower energy density |
| Lithium Iron Phosphate | - Good cycle life<br>- Stable after fault<br>- High discharge power | - Low discharge rate<br>- Lower energy density |
| Other Lithium Ion Technologies | - High energy density<br>- Low self-discharge rate<br>- No memory effects<br>- Competitive manufacturing space | - Low discharge rate<br>- Lower energy density<br>- Insufficient safety |
| Redox Flow | - Stable during fault<br>- Long cycle life<br>- Deep cycling | - New technology<br>- Low energy density<br>- High complexity |
| Lead Acid | - Cost<br>- Proven technology | - Toxic materials<br>- Low energy density<br>- Weight<br>- Requires maintenance<br>- Limited cycle life |

Source: Lawrence Berkeley National Laboratory

## Challenges and Recommendations

- While there are many available battery technology and chemistry choices, relatively few are recommended for use in a home environment. High cost is the primary challenge to implementing ESS in residences.
- For commercial buildings, the high cost of batteries may be offset by using the ESS for load shifting to reduce demand charges. ESS can also be used to participate in utility programs such as demand response, by acting as a distributed energy resource aggregator, or otherwise participating in energy markets.
- As the basis of a DC building distribution system, the ESS should be directly coupled ("DC-coupled") to the DC generation (PV, fuel cell, and so on).

- Many ESS products contain integrated battery inverters so they can accept AC power input, which makes it easier to connect these devices to a standard building with AC distribution. For a DC-coupled system, ensure the ESS products specified do not have integrated inverters.
- Because ESS contain potentially toxic or flammable materials, it is very important to follow all the relevant safety codes in designing, installing, and decommissioning a system. Relevant codes include: NFPA 70 Art. 480 and Art. 690.

# Renewable Energy Integration

## Description

California law requires a reduction of statewide greenhouse gas emissions to 40 percent below 1990 levels by 2030. To achieve this goal, the state has mandated that by 2030, 50 percent of its electricity must be generated by renewable energy sources. In the building sector, the dominant renewable energy source is PV, with California leading the nation in installed capacity at more than 5.6 gigawatts of cumulative installations.[11] An energy landscape centered around renewables requires a highly integrated and interoperable electric grid, with very efficient end uses combined with on-site electricity generation and storage.

## Benefits of Direct Current

- On-site PV and other renewable DC generation such as micro wind turbines [47], coupled through a DC power distribution system to native-DC end uses, ESS, and EVs, can provide an integrating “platform” to help achieve several of California’s energy policy goals including ZNE buildings, zero emission vehicles; customer electricity storage; and customer integrated demand side management.
- DC distribution in buildings with storage and EVs can save electricity and operate during grid power outages, thus maximizing the savings for greenhouse gas reduction goals and the customer. Measured and modeled savings for DC-power integration are higher in systems that include on-site renewable energy systems (about 5 percent to 10 percent), and particularly those that also include ESS (up to 15 percent). Demonstrations by Bosch show that a PV system with DC distribution powering DC loads can lead to 7 percent to 10 percent higher use of on-site generation (and therefore increase system efficiency), compared to equivalent systems with AC distribution.

## Product Availability

- Bosch is demonstrating and testing commercial DC building microgrids and DC end uses in various sites [48]. Nextek Power Systems offers a commercial system for direct distribution of DC from PV systems to DC loads. Traditional electrical equipment suppliers that serve the telecom and data center markets, such as Eaton and Delta

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[11] As of June 2017, according to http://www.californiadgstats.ca.gov/.

Products, also manufacture DC-power components that can be integrated into a building-scale DC power system.

- Multi-port (AC-DC, DC-DC, DC-AC) converters that interface with loads, PV, grid, and battery storage are available by companies such as Ensync, Ideal Power, and others.
- The Alliance for Sustainable Colorado is piloting a retrofit of a 40,000 square foot office building from AC to DC distribution, with the goal of demonstrating the benefits of DC in commercial building retrofits. The building will distribute PV-generated power directly to DC loads and battery storage.

## Costs and Paybacks

- Currently, the capital cost of a direct-DC distribution system compared to an equivalent AC system is higher when converter costs and other soft costs (for example, permitting and installation) are considered. However, DC architectures can provide resiliency benefits that are not typically captured (or easily quantified) in the traditional cost-benefit analyses.
- For new construction, DC distribution in systems with on-site PV and battery storage could be cost effective. For systems without battery storage, the operating cost savings of DC distribution are unlikely to offset capital costs over the system's lifetime.
- For retrofits of buildings with existing PV systems, a DC distribution system is not expected to be cost-effective. However, for buildings undergoing deep retrofit to achieve ZNE, the savings from DC distribution could provide the necessary efficiency gains to reach ZNE status, if additional on-site generation is not possible (for example, due to roof and space constraints for additional PV).

## Challenges and Recommendations

### Challenges

- High capital cost, especially for retrofits.
- Availability of power converters at the right voltage and power level (DC/DC converters, maximum power point trackers (MPPTs), charge controllers, and bidirectional inverters for grid interfacing).
- Certification and permitting issues.
- Lack of communication standards that could enable plug-and-play operation for renewable generation and storage integration, and that can serve as the basis for effective systems for managing local generation, local storage, and DC end-use devices.

### Recommendations

- A centralized multi-port converter that directs power flow and communications from PV to and from the battery, loads, and the grid, may be an efficient and less costly approach, compared to using separate converters. This method is being adopted by the

Bosch DC system configuration, where the maximum power point tracking occurs at the main AC-DC gateway that interfaces with the grid.

- The number of DC-DC power conversions from the PV array to the main DC bus, and battery storage, should be minimized and rely on specific voltages (such as 380V DC). The main DC bus voltage can be used to directly supply high power, hardwired loads such as HVAC.
- For retrofits of existing PV systems, the researchers recommend that DC distribution be implemented in cases where rewiring is not necessary. For systems with battery storage, DC-coupled systems will be easier to retrofit to an all-DC system, compared to AC-coupled.

# CHAPTER 4: Design Guidelines for Home and Business Zero Net Energy Buildings

This chapter provides a structured approach to the integration of DC power in new construction and major building retrofits. The chapter includes recommended system configurations, review of the efficiency gains, technical design considerations, grid integration considerations, and review of economic impacts.

There are many ways to integrate power generation and DC components into a commercial or residential building, but some methods are more practical and cost efficient than others. These design guidelines walk through the design process of three basic system configurations – all-AC, all-DC, and DC-AC hybrid – for integrating solar PV systems, EVs, and battery storage. These guidelines demonstrate the differences between traditional electrical infrastructure, which is predominantly AC, and a DC-coupled system in which direct-DC distribution is better able to serve native DC loads.

## Design Process

A typical ZNE home or commercial building starts with a design that reduces the need for energy in buildings. Among end-use loads, HVAC systems account for a large portion of electricity consumption in both homes and commercial buildings. The need for space heating and cooling can be greatly reduced with well-known energy efficiency and conservation measures installed in the building based on design and orientation; type of walls and insulation; type of windows, window arrangement, and their shading; type of roof and ceiling and its insulation; air-tight building construction with reduced outdoor infiltration; and use of efficient lighting and appliances that use less energy and give off less heat into the indoor environment. Some recent findings for enhanced energy savings show promise from uncommon practices such as locating ducts within conditioned spaces and insulating under the roof instead over the occupied space, as already demonstrated in some ZNE buildings in Southern California.

### Solar Photovoltaics

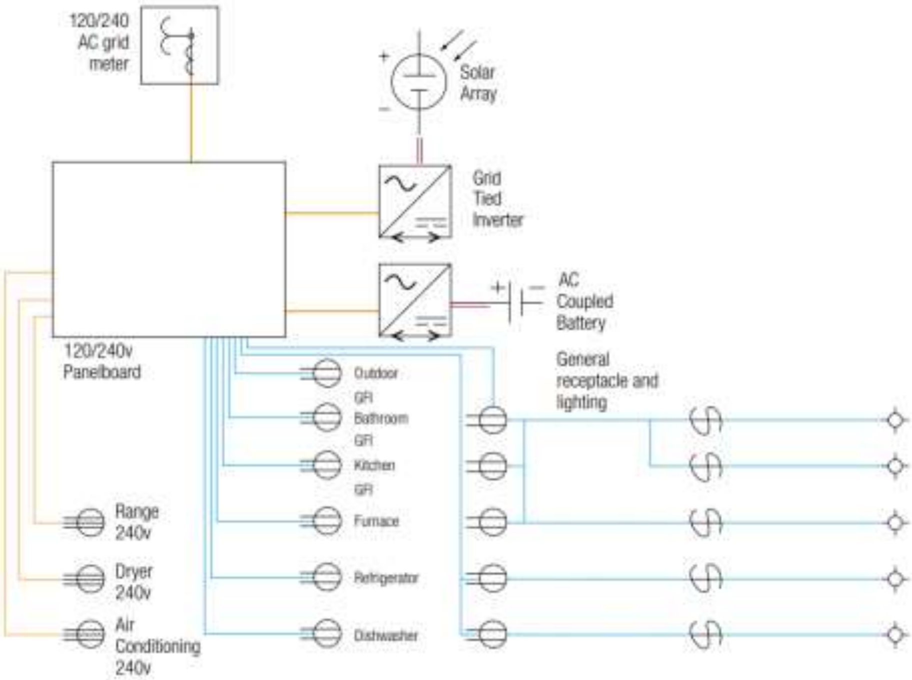
A typical ZNE residential building in CA uses 6,000 kWh to 7,000 kWh per year depending on its size, geographical location, internal equipment, and use behavior. The PV system should be sized to meet the building's annual energy use to be classified as ZNE. With greater interest in lowering carbon emissions associated with transportation, people are choosing to use EVs. Energy use by an EV depends greatly on how it is used, and is typically 3,000 kWh-5,000 kWh a year, which translates to 3 to 4 miles per kWh of charge energy. South facing PV panels at a slope equal to the local latitude is optimal to generate the highest annual electricity. As the building's orientation moves away from the south, annual energy production goes down; for example, 30 degrees away from the south reduces energy production by about 5 percent. Using a building's roof slope is recommended; a 15 degree slope away from the optimal may reduce energy generation by about 5 percent. A 1-kW rated PV panel system typically produces 1,500 kWh to 1,700 kWh of electricity a year, with the amount depending on the PV system's geographic location and the orientation of the PV panels.

## Battery Storage

Battery storage involves round-trip energy losses from the cyclic process to store energy and later recover and use it. Using a net metering option, the battery storage system may not add any economic value. It will also have little or no value if the end use is coincidental with the solar power generation. In residential buildings, however, the end use load is not very coincident with the solar power generation. If the utility rate structure does not reasonably value grid export, it may be cost effective to store locally generated electricity for later use. In commercial buildings, the end use loads are somewhat more coincident with the solar power generation, but time of use tariffs may make storing excess energy economically attractive.

Battery storage systems add resiliency values to the benefit analysis of energy storage systems, and such battery systems can serve critical loads during utility power outages. Since batteries are inherently DC, a DC power distribution system with battery storage can reduce losses from the process used to convert DC back to AC to serve AC loads. Battery storage can also be used to charge EVs without using grid power. DC power distribution and charging of EVs directly with DC can also reduce losses.

**Figure 17: Traditional Alternating Current System, Alternating Current Loads and Direct Current Bus for Distributed Energy Resources**



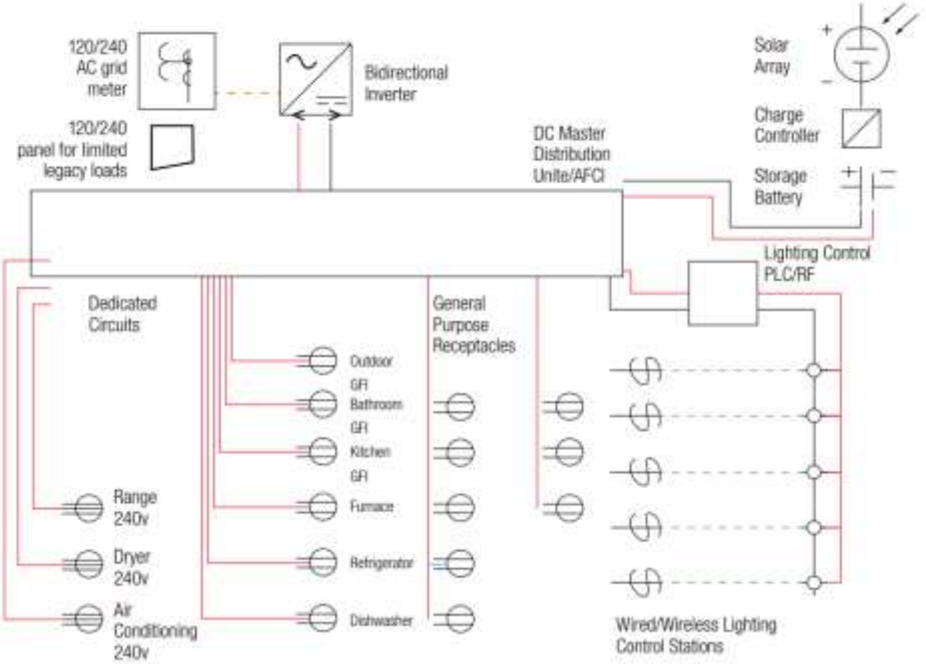
Source: Lawrence Berkeley National Laboratory

## Electrical Distribution Wiring

The AC low-voltage distribution in homes and small-to-medium commercial buildings is a single phase 208V line to line, and 120V line to neutral. The 208V is for large appliances such as HVAC equipment, cooking range, dryers, and so on. Lighting and small appliances are served with 120V. The inherent DC loads have AC-to-DC power converters at the point of use. The AC distribution in medium-to-large buildings, however, is 480V, 3-phase. For DC distribution, 380V DC is used for larger "fixed" loads such as the HVAC equipment, cooking ranges, water heaters, dryers, and so on.

For DC distribution, 380V DC can be used for larger "hard wired" loads such as HVAC equipment, cooking ranges, water heaters, dryers, and so on. For lighting, low voltage 48V DC PoE and 24V DC power distribution is gaining popularity. Low voltage distribution can increase losses. However, DC to DC converters have become very efficient, approaching 99 percent to 100 percent efficiency; therefore, 380V DC distribution coupled with point-of-use conversion will still reduce overall losses. The path to full DC is expected to be gradual, so any DC building will still have need for AC end uses. DC to AC converters are suggested for such applications.

**Figure 18: Potential Future All Direct Current Design**



Source: Lawrence Berkeley National Laboratory

The NEC sets out specific rules for the AC to DC and for DC to AC connection of PV and battery storage systems.

- Article 690 – Solar PV Systems includes important requirements for disconnection, rapid shutdown, grounding and more.

- Article 705 – Interconnected Electric Power Production Sources includes rules for points of connection and electric busbar sizing.
- Article 480 – Storage Batteries includes important requirements for disconnection, overcurrent protection, location requirements, and more.
- Article 706 – Electrical Energy Storage Systems is new article in NEC 2017 that expands on Article 480.

Figure 19 demonstrates possible AC-DC system hybrid configurations. Various DC distribution voltages are shown with their end use load options. Some design options are more suited to residential designs while others are more appropriate for commercial buildings. Figure 20 shows a summary of the current state of DC technologies across end-use categories.

# Residential Designs

The cases shown represent ZNE homes with solar PV systems, EV charging, and battery storage systems. The systems designed and analyzed in this study build up DC components from a system with solar PV only, to a system with solar PV, EV charging, and battery storage. AC power and DC power are differentiated using a red/blue color coding system and areas where conversions between the two (or between voltage levels) occur are labelled with their conversion losses. Design configurations reflect current appliance and equipment availability, standards and regulations, and component costing. At the time of this report, these design recommendations are believed to be best practice for the integration of the distributed energy resources considered for traditional AC distribution systems and their DC distribution counterparts.

## Residential with Photovoltaics

A schematic of a residential building configuration with PV and AC distribution, compared to one with hybrid AC/DC distribution, is shown in Figure 21.

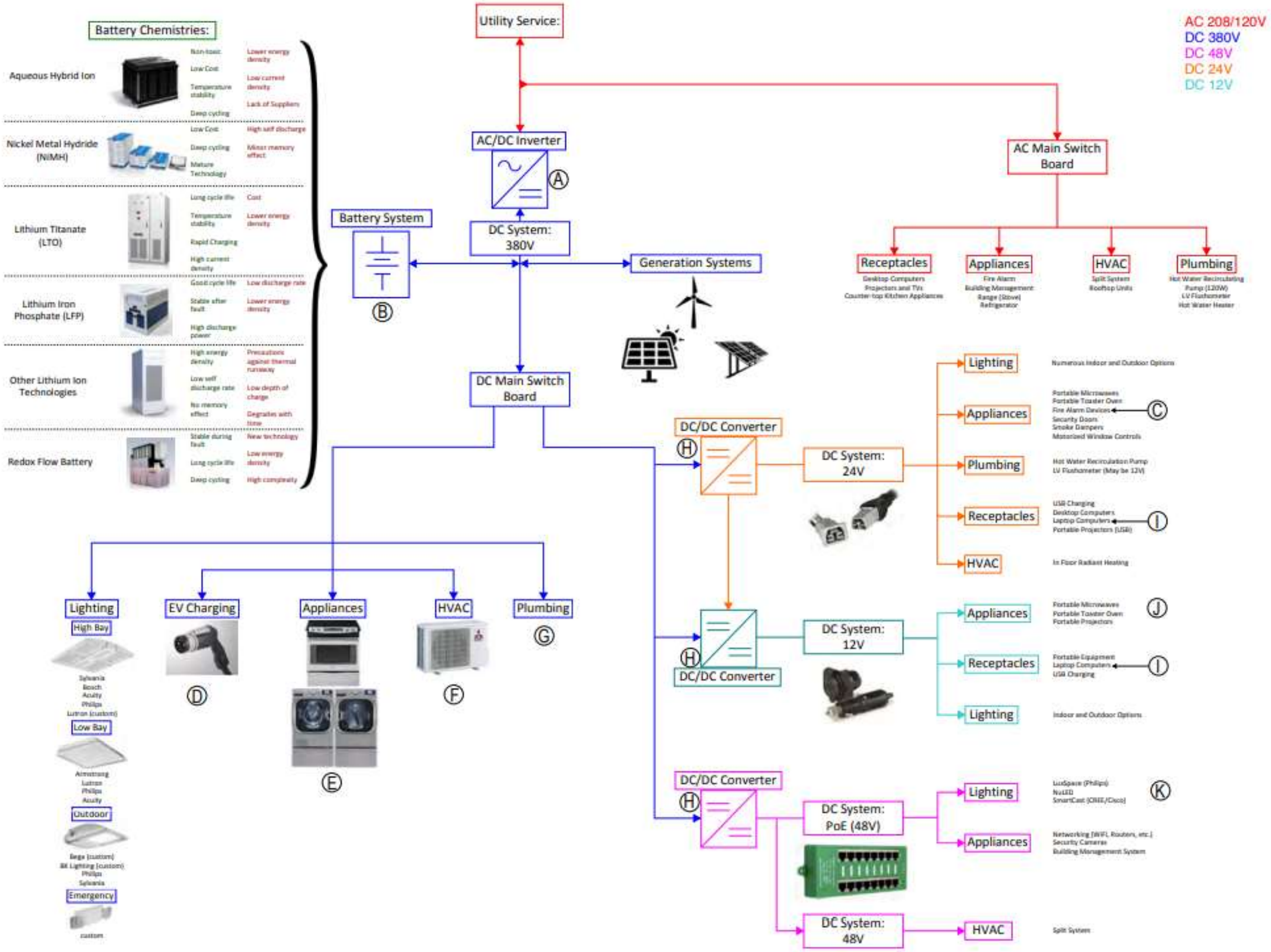
### Alternative Current System

The configuration of the solar PV connection in the AC system is known as “AC coupled,” meaning that the system output is put through an inverter and fed directly into the AC system. This represents the most common residential renewable energy integrated design today. Residential solar PV systems will continue to be a growth market across the United States and these AC coupled systems will continue to represent a large portion of the designs.

### Direct Current Hybrid System

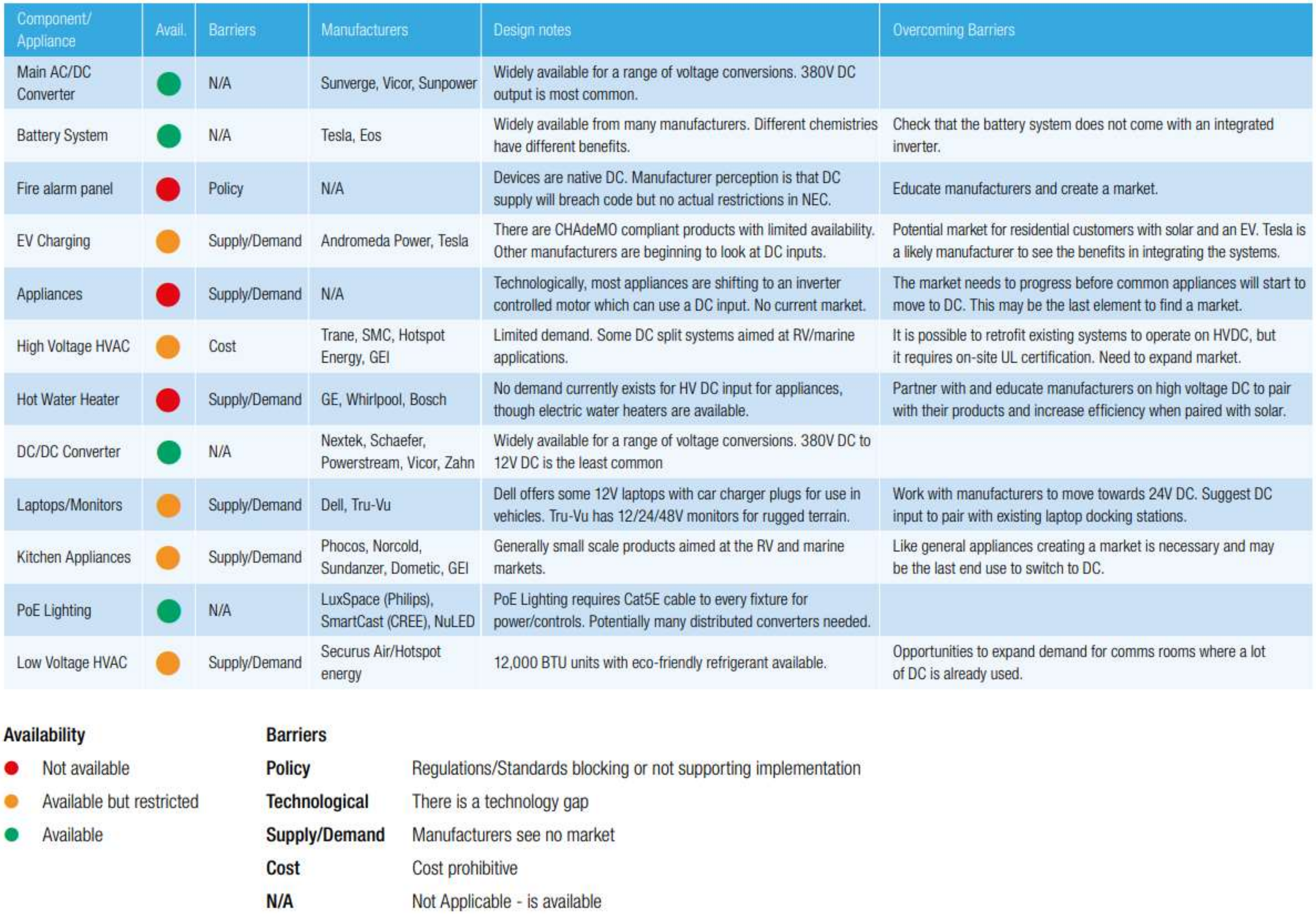
The DC hybrid system introduces a DC bus to integrate the solar PV and serve native DC loads. AC distribution may still be a significant component of the residential hybrid design as DC consumer products (such as hair dryers, washing machines, and so on) are either not produced in mass quantity or not available at all due to limited demand at this time. The DC products that are available are produced primarily for the recreational vehicle market but some may have applications in DC buildings. In the foreseeable future, however, it is very likely that hybrid systems, where some end use loads are DC and some are AC, will become more common.

**Figure 19: Alternating Current/Direct Current Hybrid Distribution System**



Source: Lawrence Berkeley National Laboratory

## Figure 20:  Direct Current Technologies by End-Use Category



| Component/ Appliance | Avail. | Barriers | Manufacturers | Design notes | Overcoming Barriers |
|---|---|---|---|---|---|
| Main AC/DC Converter | 🟢 | N/A | Sunverge, Vicor, Sunpower | Widely available for a range of voltage conversions. 380V DC output is most common. | |
| Battery System | 🟢 | N/A | Tesla, Eos | Widely available from many manufacturers. Different chemistries have different benefits. | Check that the battery system does not come with an integrated inverter. |
| Fire alarm panel | 🔴 | Policy | N/A | Devices are native DC. Manufacturer perception is that DC supply will breach code but no actual restrictions in NEC. | Educate manufacturers and create a market. |
| EV Charging | 🟠 | Supply/Demand | Andromeda Power, Tesla | There are CHAdeMO compliant products with limited availability. Other manufacturers are beginning to look at DC inputs. | Potential market for residential customers with solar and an EV. Tesla is a likely manufacturer to see the benefits in integrating the systems. |
| Appliances | 🔴 | Supply/Demand | N/A | Technologically, most appliances are shifting to an inverter controlled motor which can use a DC input. No current market. | The market needs to progress before common appliances will start to move to DC. This may be the last element to find a market. |
| High Voltage HVAC | 🟠 | Cost | Trane, SMC, Hotspot Energy, GEI | Limited demand. Some DC split systems aimed at RV/marine applications. | It is possible to retrofit existing systems to operate on HVDC, but it requires on-site UL certification. Need to expand market. |
| Hot Water Heater | 🔴 | Supply/Demand | GE, Whirlpool, Bosch | No demand currently exists for HV DC input for appliances, though electric water heaters are available. | Partner with and educate manufacturers on high voltage DC to pair with their products and increase efficiency when paired with solar. |
| DC/DC Converter | 🟢 | N/A | Nextek, Schaefer, Powerstream, Vicor, Zahn | Widely available for a range of voltage conversions. 380V DC to 12V DC is the least common | |
| Laptops/Monitors | 🟠 | Supply/Demand | Dell, Tru-Vu | Dell offers some 12V laptops with car charger plugs for use in vehicles. Tru-Vu has 12/24/48V monitors for rugged terrain. | Work with manufacturers to move towards 24V DC. Suggest DC input to pair with existing laptop docking stations. |
| Kitchen Appliances | 🟠 | Supply/Demand | Phocos, Norcold, Sundanzer, Dometic, GEI | Generally small scale products aimed at the RV and marine markets. | Like general appliances creating a market is necessary and may be the last end use to switch to DC. |
| PoE Lighting | 🟢 | N/A | LuxSpace (Philips), SmartCast (CREE), NuLED | PoE Lighting requires Cat5E cable to every fixture for power/controls. Potentially many distributed converters needed. | |
| Low Voltage HVAC | 🟠 | Supply/Demand | Securus Air/Hotspot energy | 12,000 BTU units with eco-friendly refrigerant available. | Opportunities to expand demand for comms rooms where a lot of DC is already used. |

**Availability**

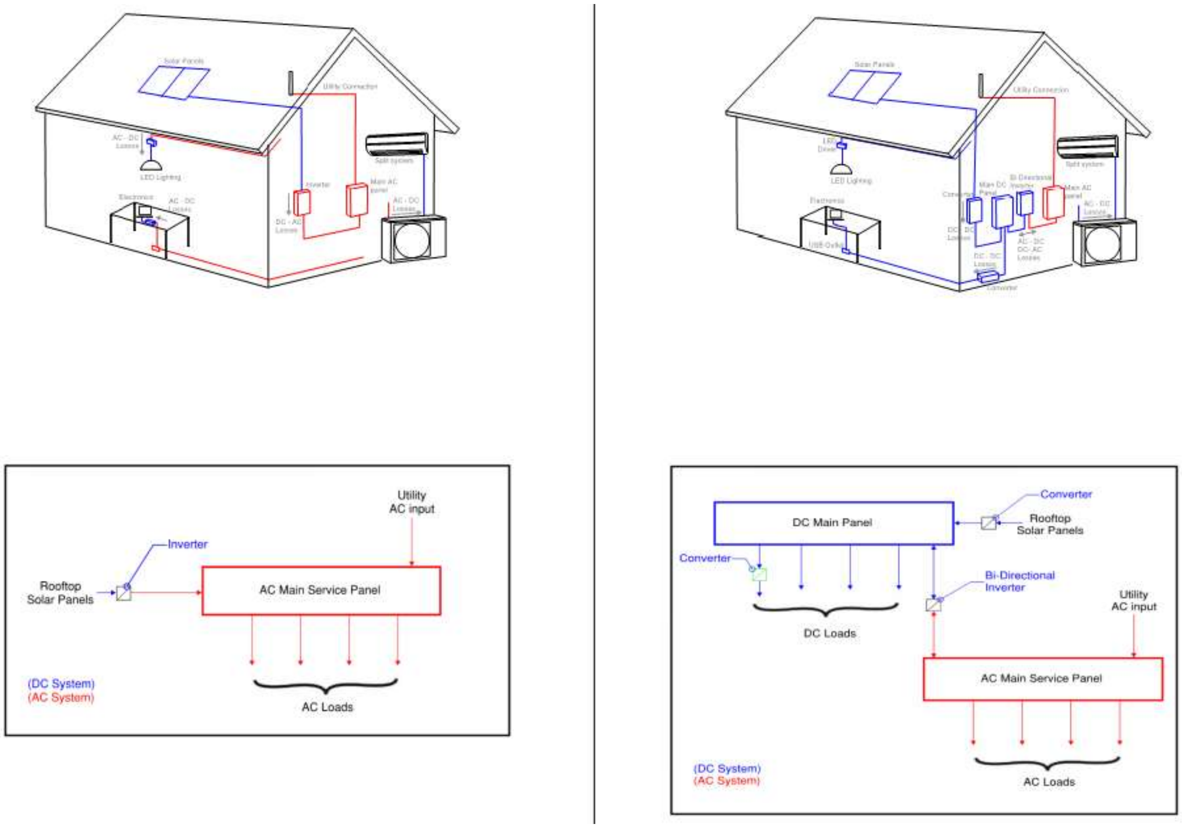
| | |
|---|---|
| 🔴 | Not available |
| 🟠 | Available but restricted |
| 🟢 | Available |

**Barriers**

| | |
|---|---|
| **Policy** | Regulations/Standards blocking or not supporting implementation |
| **Technological** | There is a technology gap |
| **Supply/Demand** | Manufacturers see no market |
| **Cost** | Cost prohibitive |
| **N/A** | Not Applicable - is available |

Source:  Lawrence Berkeley National Laboratory

**Figure 21: Residential Building with Photovoltaics – Comparison of Alternating Current versus Alternating Current/Direct Current Hybrid Distribution**



Source: Lawrence Berkeley National Laboratory

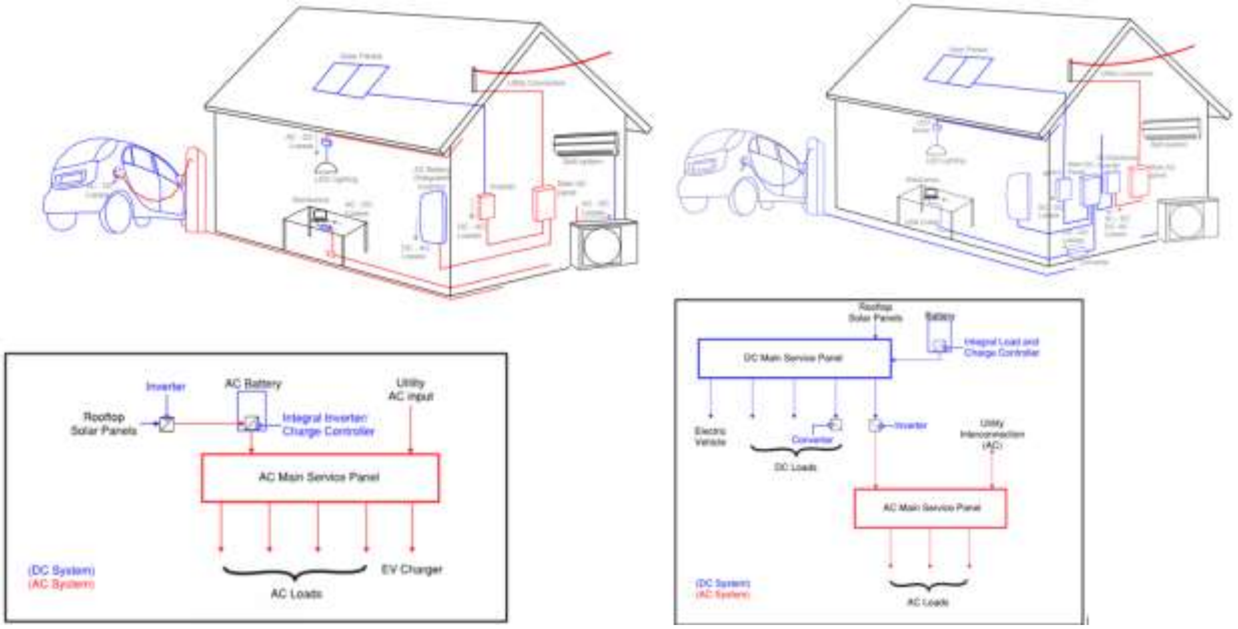
## Residential with Photovoltaics, Electric Vehicles, and Battery Storage

A schematic of a residential building configuration with PV, EV and battery storage and AC distribution, compared to one with hybrid AC/DC distribution is shown in Figure 22.

### Alternating Current System

Installing native DC battery storage on an AC power distribution system can incur AC-DC power conversion losses while charging the battery as well as DC-AC conversion losses during battery discharge, in addition to losses in the battery chemistry. Battery storage also allows a higher use of on-site generated power in some cases so the energy loss aspects need to be carefully considered along with any benefits of load shifting to reduce electricity costs. In existing buildings, it may be more economical to install the battery with AC distribution (AC coupled), but for new buildings it is preferential to design for a DC-coupled battery. This is advantageous particularly where there are large DC end use loads such as EVs that can be directly charged from the battery storage.

**Figure 22: Residential Building with Photovoltaics, Electric Vehicles, and Battery Storage – Comparison of Alternating Current versus Alternating/Direct Current Hybrid Distribution**



Source: Lawrence Berkeley National Laboratory

### Direct Current Hybrid System

The residential DC plus PV, EV charging, and battery storage design represents a scenario which may become more common in the future as distributed energy resources and EVs penetrate the market. The presence of large DC loads from EVs can significantly reduce losses from inherently efficient DC-DC converters while charging from the storage batteries. Currently, there are no direct-DC residential EV charging systems available, although some manufacturers have considered producing battery coupled DC-DC EV chargers. As EV adoption increases and battery costs decrease, this configuration may become viable in purpose-built ZNE homes.

Energy modelling of this DC hybrid system showed that the use of battery storage with a DC-coupled EV reduced electricity conversion and delivery losses by 8 percent to 15 percent compared to the AC-coupled system. Reduced losses are helpful in achieving ZNE for homes and minimizing the size of the PV system required. With three-story single-family homes gaining traction in metropolitan areas and therefore a smaller roof area relative to internal square footage, any efforts to reduce energy use and losses are helpful in achieving ZNE goals.

# Commercial Designs

## Commercial with Photovoltaics

### Alternating Current System

In commercial buildings, systems with AC distribution and PV represents the most common commercial renewable energy integrated design today. DC components such as battery storage and EVs integrated with PV in commercial buildings are starting to become more common;

however, there will continue to be new and retrofitted AC buildings with PV as the sole DC asset. Large footprint, low-rise buildings may generate a surplus of energy for grid export. However, small footprint, high-rise buildings generally do not produce enough power to meet the on-site building loads. The on-site DC power generated by PV in this situation must always be converted to AC before distribution and incurs conversion losses in the inverter. Additional power conversion losses occur when AC is supplied to native DC loads where the power conversion devices tend to be inefficient.

### Direct Current Hybrid System

The commercial DC plus solar PV design introduces a DC backbone to accept DC power from the solar PV system and serve native DC loads. The main DC panel at 380V can directly supply fixed loads such as mechanical equipment and lighting. Additional converters step down the voltage to PoE at 48V, and 24V and 12V to supply electronics. An AC panel is still required to serve loads which are not currently available in DC. Commercial environments such as offices have many more devices that use DC internally such as laptops and monitors. These electronics also have the highest availability of DC-ready products. The advantages to DC distribution in commercial buildings are again related to power use reduction. In commercial buildings, DC distribution can reduce power conversion losses even further than in residential buildings since more of the end use loads are coincident with the local PV generation.

Without energy storage, this system is limited to on-site consumption and immediate grid export. The disadvantage of not having energy storage is that any DC loads will need to be supplied via the AC supply and a bidirectional inverter when solar PV generation is not adequate. Though typically the commercial demand curve means that most of the generated DC solar power will be used locally, some will still need to be converted from DC to AC and exported onto the grid (for example, on weekends), and additional losses will be introduced to serve the DC loads from grid imported power outside of PV generating hours.

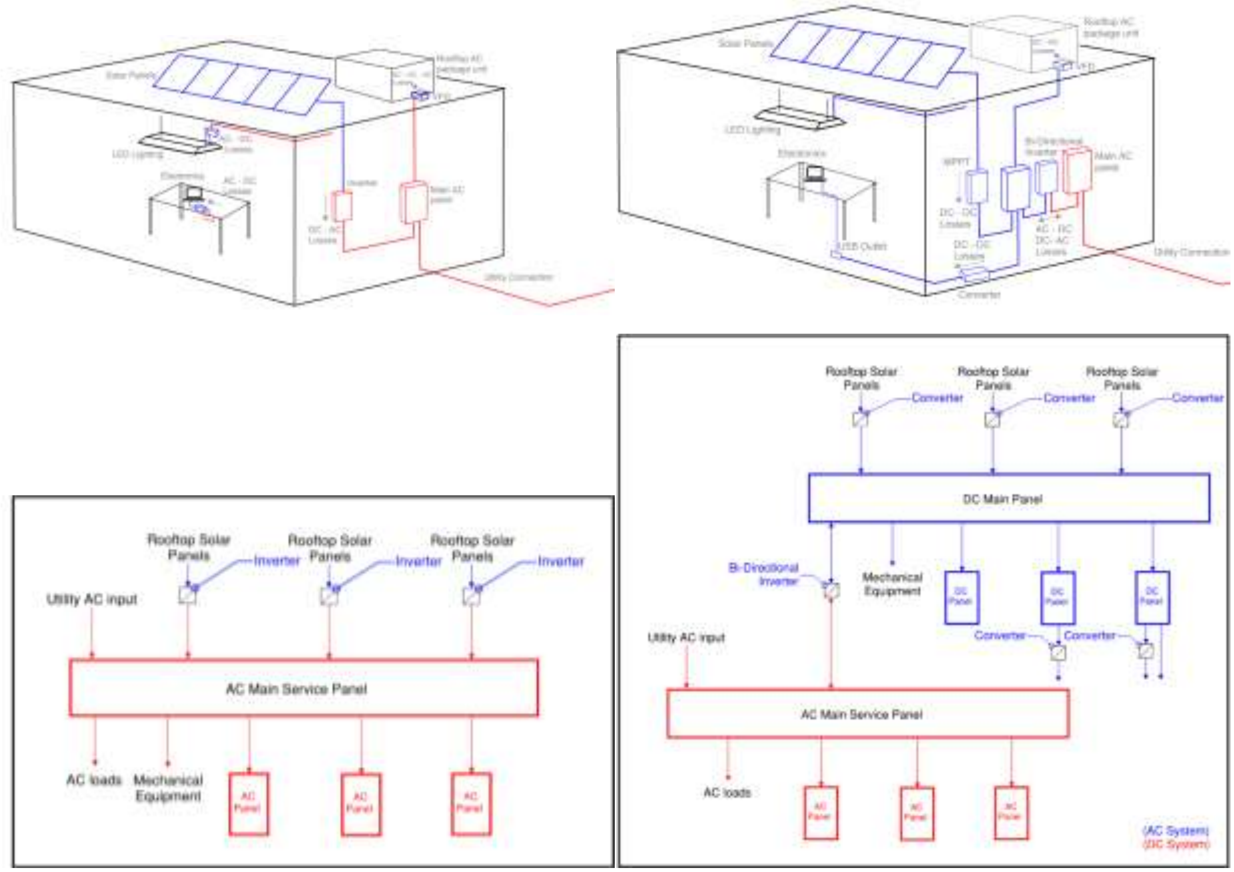
## Commercial with Photovoltaics, Electric Vehicles, and Battery Storage

### Alternating Current System

The commercial AC design for solar PV, EV charging, and battery storage represents a less common system set up. Though the cost of batteries has come down significantly – nearly 50 percent in the last decade – and continues to come down, costs per kWh are still high. Introducing battery storage systems may allow buildings to participate in demand response markets, as well as the ability to shift excess PV production to cover evening loads when electricity prices are expected to be high. This can increase the use of on-site generation and improve system economics, especially where net metering is not in effect. This system represents the most likely path for upgrading buildings with PV systems that wish to participate in demand response markets or incorporate resiliency.

Shifting of utility time-of-use peak rates from the middle of the day towards the evening (immediately after sunset) in the future provides additional economic incentive for integrating battery storage into existing building systems. However, the addition of a battery may also increase energy usage by upwards of 15 percent due to losses in the battery and converters, but the electricity rate changes may still mean there is an economic case.

**Figure 23: Commercial Building with Photovoltaics – Comparison of Alternative Current versus Alternating/Direct Current Hybrid Distribution**



Source: Lawrence Berkeley National Laboratory

Installing native DC battery storage on an AC power distribution system can incur AC-DC power conversion losses while charging the battery as well as DC-AC conversion losses during battery discharge and losses in the battery chemistry. Battery storage also allows a higher use of on-site generated power in some cases so energy losses need to be carefully considered along with any benefits of load shifting to reduce electricity costs. In existing buildings, it may be more economical to install the battery with AC distribution (AC coupled), but for new buildings it is preferential to design for a DC-coupled battery.

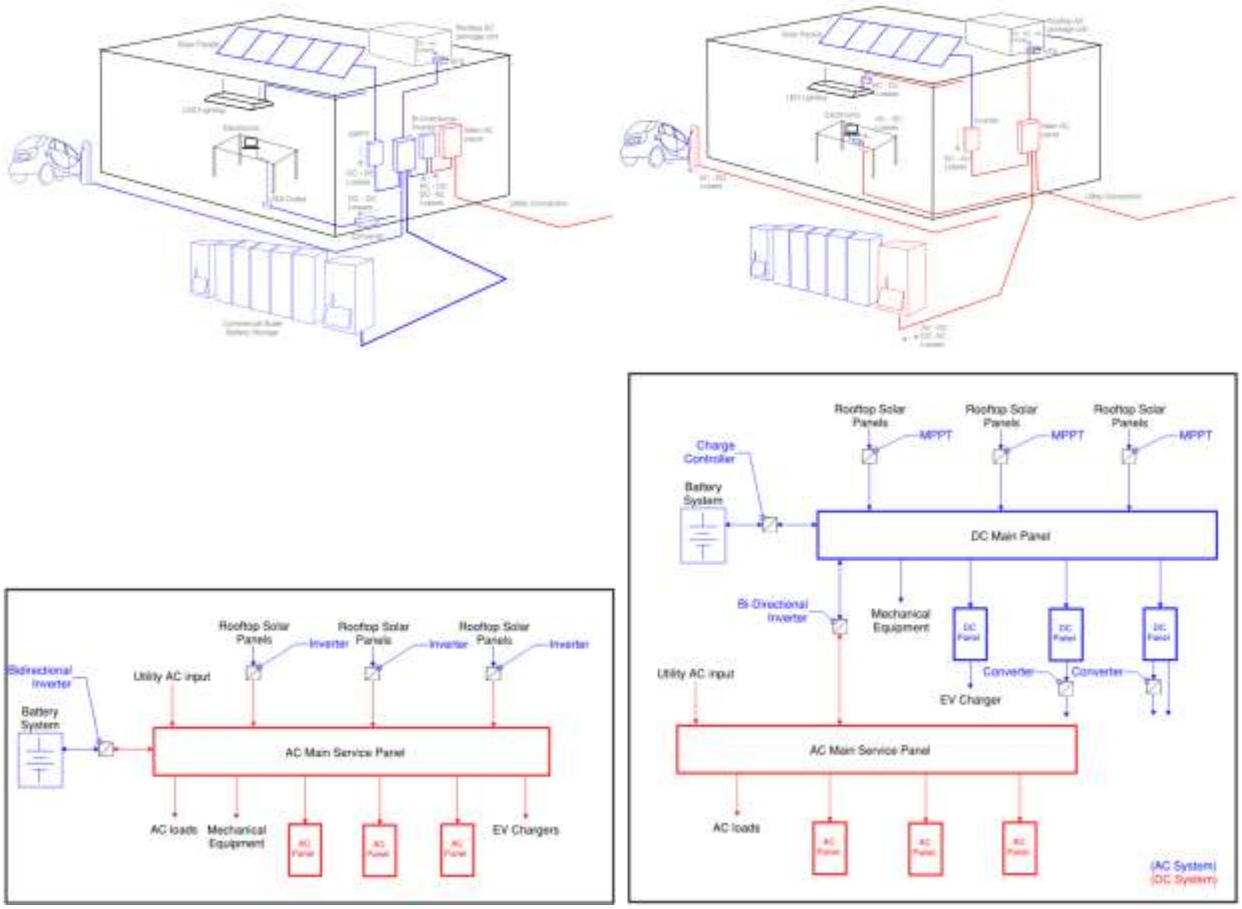
### Direct Current Hybrid System

The commercial DC distribution design for solar PV, EV charging and battery storage represents the ideal scenario for DC component integration. This offers the advantages of locating a large DC load on the DC side of the system with the added benefit of having energy storage to provide additional power outside of daylight hours. With the addition of battery storage to pick up any DC load outside of solar PV generation hours it may be possible to reduce the size of the AC system components since the grid may not be required to support the EV load. This would be a trade-off between the sizing of the battery and PV system.

This system has the potential for the greatest energy savings and this was reflected in the energy modelling analysis. It also provides the ability to achieve maximal energy cost savings and improve the economic performance of a DC distribution system where excess PV is generated during the day.

Considerations for sizing systems, electric distribution and future proofing are summarized in the following section.

**Figure 24. Commercial Building with Photovoltaics, Electric vehicles, and Battery Storage – Comparison of Alternative Current versus Alternating/Direct Current Hybrid Distribution**



Source: Lawrence Berkeley National Laboratory

## Systems Loss Analysis

A systematic simulation study was conducted to better estimate power distribution losses using Modelica, a power simulation tool. The end use load profile and PV generation data for a residential home were modeled after the ZNE Meritage Homes in Fontana, California. The commercial end use load profile and data were sourced from a ZNE electrical training center in San Leandro, California.

Figure 25. The Zero Net Energy Training Center (left) and the Zero Net Energy Meritage Homes (right)

Source: Lawrence Berkeley National Laboratory

Although the Fontana ZNE homes do not currently have EVs, annual electricity consumption of 3,000 kWh (representing 10,000 miles of driving per year) were added for the residential building. Residential EV charging was assumed to occur at night using charge rates of 3.7 kW from 12 a.m. to 2 a.m., and 1 kW from 2 a.m. to 3 a.m. in the simulation. For the commercial building, the team used EV metered charging data from 4 EV chargers in a commercial office building in Palo Alto, California.

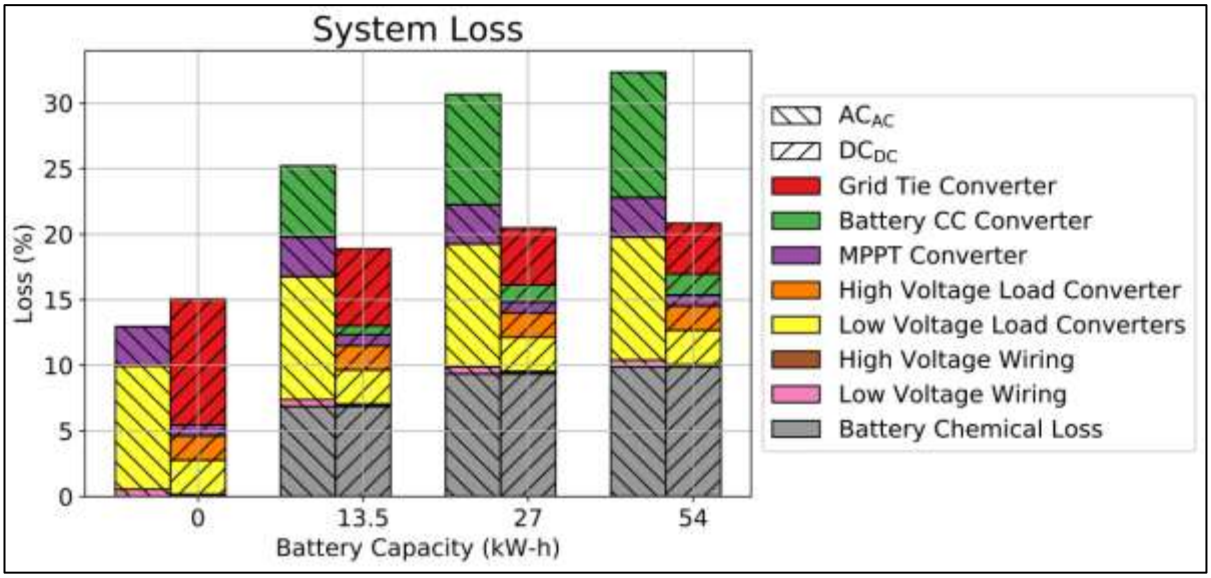
Battery storage for both building types was assumed to have a 90 percent charging efficiency (81 percent roundtrip), and maximum depth of discharge was assumed to be 75 percent (up to 25 percent state of charge). Battery charging was also assumed to occur when PV generation exceeded total building load demand. For the residential buildings, battery storage was modeled with one, two, and four Tesla Powerpack batteries, each with 13.5 kWh storage capacity for both AC and DC homes. The larger capacity was selected to be able to store all locally generated power without dispatching any to the grid. With a single battery Powerpack, there are times when power is exported to the grid and times when power is imported.

All electrical loads in the commercial building are assumed to be DC-internal, while for the residential building, some loads are assumed to include a resistive element (such as water heaters, ovens, and dryers), which operates on AC. In the DC distribution systems, high power loads (such as HVAC and motors) are assumed to be hard wired at 380V DC, and other low power equipment and plug loads require a 380V-24V DC-DC converter. Converter efficiency curves are based on median market efficiency data.

The energy losses in a ZNE home and commercial building for three scenarios (with PV; with PV and EV; with PV, EV, and battery storage) are modeled with both AC and DC configurations discussed above. For the ZNE home with PV only, losses with AC distribution are about 13 percent of the total electricity consumption, whereas with DC distribution, losses are slightly larger at 15 percent. This is primarily because PV generation and electricity demand are not coincident, requiring AC power from the grid to be converted to DC for distribution to end-use loads.

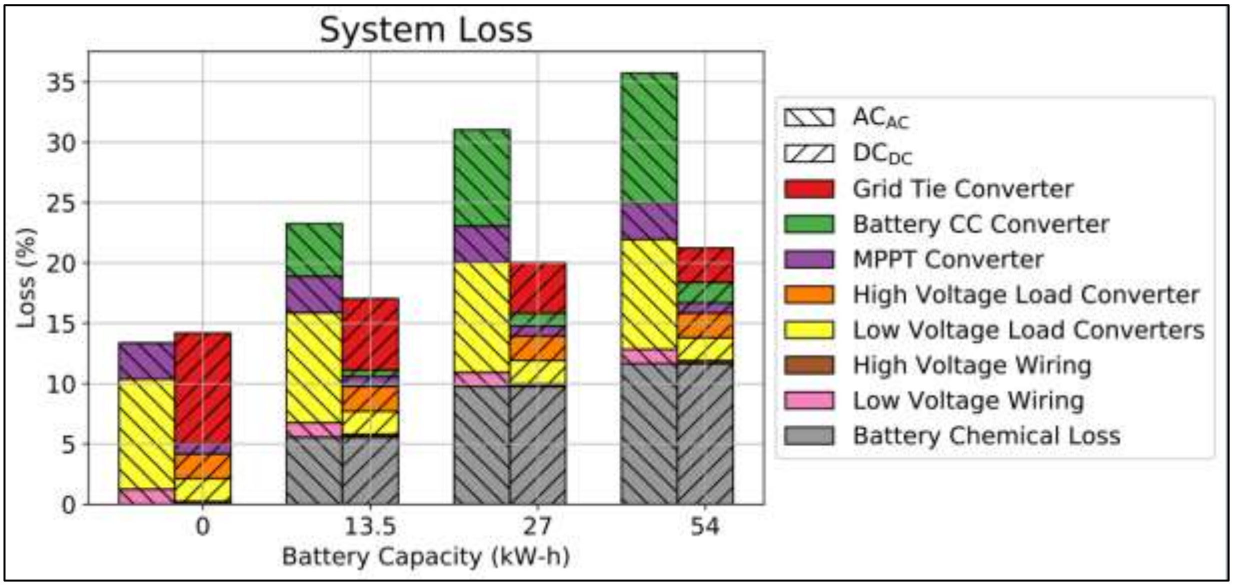
For the ZNE home with EV and battery, losses are plotted side-by-side for the AC and DC topologies and for different sizes of battery storage without EV, and with EV. The total losses increase with the use of battery packs with both AC and DC topologies, but the increase is smaller for DC versus the AC. A DC configuration saves 6 percent, 10 percent and 12 percent respectively with one, two and four Powerpacks. The overall losses are slightly more with the EV loads. A DC configuration saves 6 percent, 11 percent and 15 percent respectively with one, two and four power packs.

**Figure 26: System Loss for the Residential System with Photovoltaics and Various Battery Sizes**



Source: Lawrence Berkeley National Laboratory

**Figure 27: System Loss for the Residential System with Photovoltaics, Electric vehicles, and Various Battery Sizes**

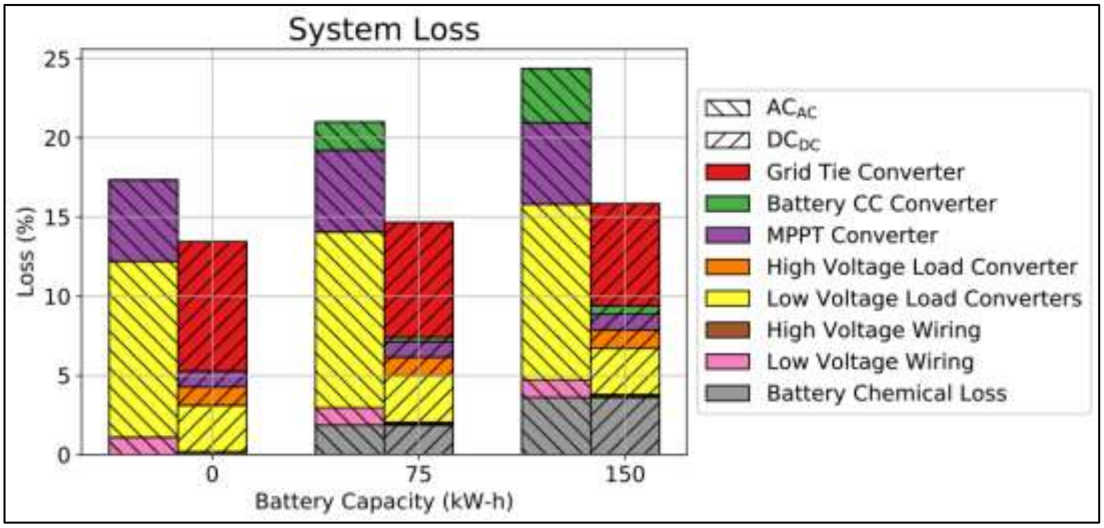


Source: Lawrence Berkeley National Laboratory

Similarly, losses from three scenarios for ZNE commercial buildings versus battery sizes are modeled and the results are presented. For commercial buildings, the project team selected five battery sizes – 75 kWh, 150 kWh, 250 kWh, 500 kWh, and 750 kWh – for simulation.

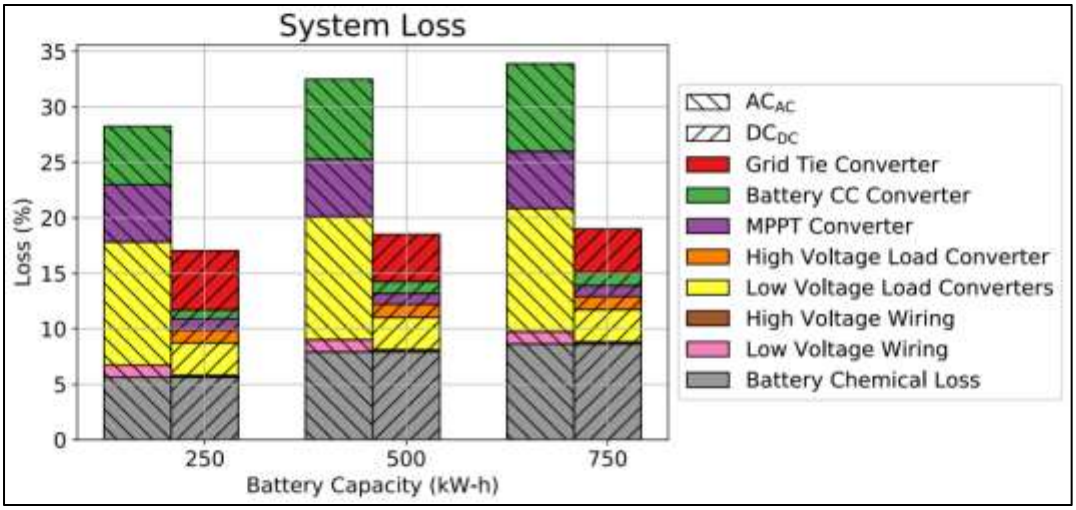
The solar PV system for the commercial building is sized for 150 kilowatts peak. The battery size of 250 kWh represents energy required for 4 hours immediately after the sunset when power demands and utility rates may be still high. Since batteries are expensive, a battery size of 75 kWh was simulated as the baseline. The larger battery sizes (150 kWh, 250 kWh, 500 kWh, and 750 kWh) were selected to simulate cases when the grid export tariff is low enough to justify the extensive use of storage. These sizes are also relevant if islanding is desired.

**Figure 28: System Loss for the Commercial System with Photovoltaics, Electric vehicles, and 0 kWh – 150 kWh Battery Sizes**



Source: Lawrence Berkeley National Laboratory

**Figure 29: System Loss for the Commercial System with Photovoltaics, Electric vehicles, and 250 kWh – 750 kWh Battery Sizes**



Source: Lawrence Berkeley National Laboratory

## Economic Analysis

The team conducted an economic analysis to determine the cost premium of the DC distribution systems and to understand if the higher costs could be recovered through ongoing energy cost savings. For simplicity, only incremental cost differences between the AC and DC systems were considered. This allowed the researchers to find the cost premium for the DC system. PV, EV chargers, and batteries were not factored into the costing as they represent a similar cost in both the AC and DC systems.

The project team calculated the energy cost savings using yearly grid import values determined through the modelling exercise. Researchers used current Pacific Gas and Electric Company electricity rates to calculate the energy costs of each kWh for the AC and the DC systems.

The capital cost assessment demonstrated that there is a significant cost premium involved with installing a DC hybrid distribution system. This cost summary shows a comparison of total system costs including component and installation cost for system components which are unique to each system. The DC premium represents the total additional cost of construction for the DC hybrid design. The cost estimations are based on material costs and labor rates from the San Francisco, California area.

Panelboards consistently represent the highest portion of cost in the AC systems. The DC systems contain more components that make up the premium for DC systems. The additional DC panelboard means that panels also make up the majority of the cost followed by the connecting inverter and then the additional DC/DC converters. When the size of the inverter increases with the addition of battery storage this new larger inverter accounts for almost half the DC premium.

### Residential

For the residential case, all of the infrastructure included in the standard Meritage home design is adequately sized to incorporate an EV charger, therefore there is no cost difference between those two scenarios. On the DC side, those two scenarios require a lot more equipment, two panel boards as opposed to one for the AC system, along with additional converters. To cater for the EV charger, the panels and some cables are upsized. The addition of battery storage requires only additional cabling and a small inverter to the AC system resulting in minimal increased cost. For the DC system, costs increase due to the need for a larger converter between AC and DC systems to allow for simultaneous charging of batteries and the EV.

### Commercial

On the commercial side, the AC systems are assumed to be the same in terms of components, whether EV charging is present or not. As with the residential cases, the corresponding DC designs require additional DC panels, DC/DC converters and additional cabling. The AC panelboard can be reduced in size, offsetting a small portion of the DC system's additional cost. When batteries are added to the AC system there is additional cost for the battery inverter. On the DC system the bidirectional inverter between AC and DC panels is increased to allow simultaneous charging of batteries and the EV.

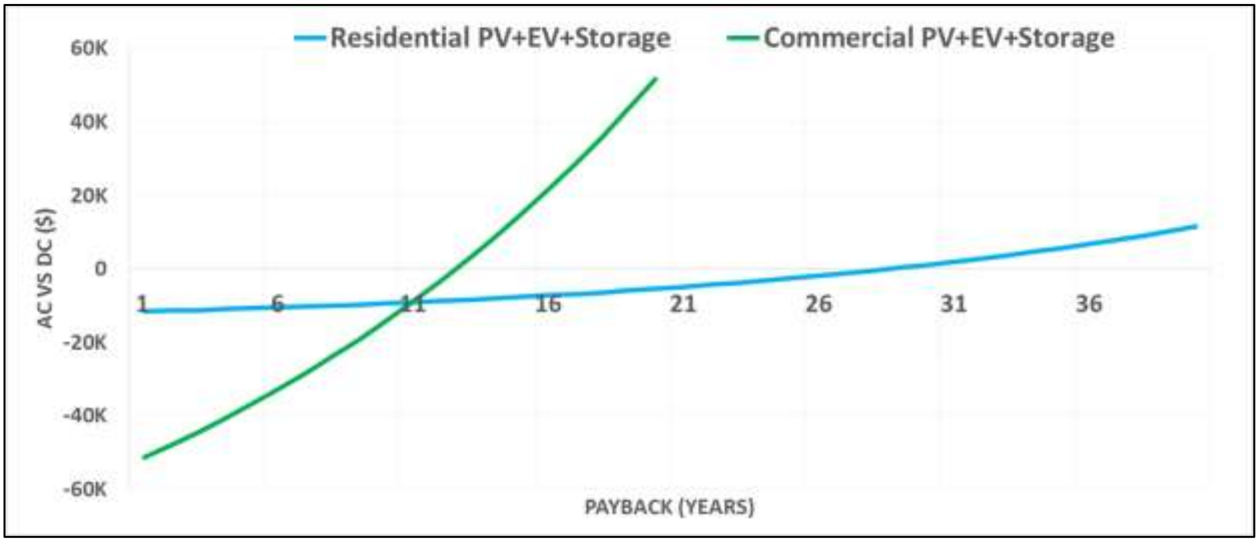
## Return on Investment

The return on investment has been calculated based on the capital costs and the yearly energy savings. Maintenance costs were not considered in this assessment due to the negligible additional maintenance requirements of the DC components such as the DC/DC converters.

A 40-year projection of the residential systems shows that only when a battery is included in the DC-coupled system will the costs of the DC infrastructure be recovered within the analysis timeline. The rate at which this happens is very slow however and the system costs will not be recovered within the life of the system. Therefore, residential applications offer no payback period for the DC hybrid systems regardless of whether the system includes EV charging or battery storage.

A 20-year projection of the commercial systems shows that the introduction of a large DC load, such as EV charging has the potential to increase the viability of the DC hybrid system. A DC system with only PV and limited small DC loads can still achieve a payback period, though 13 years would be unacceptable for many developers. A system with battery storage shows the most promise economically. Correct sizing of the battery system is crucial to achieving the optimal efficiency from the system and maximizing energy savings to accelerate returns.

**Figure 30: Hybrid Direct Current System Return on Investment for Commercial Buildings with Photovoltaics, Electric Vehicles, and Battery Storage**



Source: Lawrence Berkeley National Laboratory

Overall, the economic review of the systems suggests the following:

- DC does not provide a return on investment within the lifetime of the equipment in any of the scenarios studied.
- Return on investment for a commercial system is more promising but still outside the range of most minimum rates of return.
- DC systems are far more economical with the addition of DC-coupled battery storage.

- Increased DC load through EVs or other means marginally improves economic performance.
- Costs of the DC system are mainly inflated due to the requirements for both an AC and DC backbone due to the lack of native DC appliances.

## Adoption Pathways for Direct Current and Hybrid Alternating/Direct Current

This section discusses scenarios (or applications) in buildings that seem most appropriate for market adoption of DC and hybrid AC/DC systems. These applications can be thought of as adoption pathways, building on the work that CLASP has done on DC power in residences [11]. For residential buildings, CLASP described seven potential adoption paths for DC power distribution in homes. The study team started with these residential pathways and extended them to cover commercial buildings. For commercial buildings, the most appropriate adoption pathways tend to involve either high-densities of native DC equipment or applications that require high power reliability. Table 5 on the following page summarizes these residential and commercial pathways.

### Table 5: Potential Residential and Commercial Adoption Paths

| Adoption Path | Description | Primary Motivation | Key System Components* | Full / Hybid DC Solution | Targeted DC Devices |
|---|---|---|---|---|---|
| AP1: Clusters & Hubs | Clusters of DC-powered devices (mostly electronics), usually involving a combination of power and data transfer. | Convenience<br>Reduced cabling and power supplies<br>First cost savings | PV [O]<br>Storage [O] | Hybrid | Home entertainment system, office equipment, electronics charging station |
| AP2: Emergency backup power | A dedicated DC power distribution system to power the home's essential loads during grid disturbances | Energy resilience<br>Safety and security | PV [R]<br>Storage [R] | Hybrid | Small electronics, TV, chargers, subset of lights, well pump, fridge, essential medical equipment, security devices |
| AP3: DC garage or warehouse | Dedicated DC power distribution for EV charging and other battery-powered vehicles and garage equipment | Solar-powered vehicle<br>Fuel cost savings | PV [R]<br>Storage [R]<br>EV [R] | Hybrid | EV, forklift, power tools, spare fridge/ freezer |
| AP4: Energy independent living | Off-grid or otherwise grid-independent homes whose only source of electricity is DC | Grid independence<br>Resilience | PV [R]<br>Storage [R]<br>EV [O] | Full | All |
| AP5: ZNE/NZNE homes | ZNE or near-ZNE buildings that use DC to power some or all loads and to increase the value of on-site generation | ZNE attainment<br>Clean tech pioneer | PV [R]<br>Storage [R]<br>EV [O] | Full or Hybrid | All (Full DC) or subset of available DC products (i.e., electronics, lighting, appliances) |
| AP6: Load matching to on-site generation | HVAC and other loads run when on-site generation is high | Optimize use of on- site generation<br>Reduce electricity costs during peaks | PV [R] | Hybrid | HVAC, commercial lighting, water heater, dishwasher, clothes washer/dryer |
| AP7: Energy saving retrofit | Run DC circuits for key end uses such as electronics and lighting solely for power conversion efficiency benefits | Energy savings | PV [O]<br>Storage [O] | Hybrid | Lighting, electronics |

***[O]=optional, [R]=required**

Source: CLASP 2016 [11], and LBNL analysis.

# CHAPTER 5:
# Benefits to California

This chapter uses the system loss analysis results along with estimates of PV penetration, electricity demand, pricing, and growth rates for the residential and commercial sectors in California to generate the potential energy, operating cost, and carbon dioxide ($CO_2$) emissions savings from DC distribution systems. Table 6 lists the inputs and assumptions used, as well as the results of this analysis for a 10-year period (years 2021 to 2030). Figure 31 shows cumulative PV capacity projections in California for the residential and commercial sectors for PG&E, Southern California Edison (SCE), San Diego Gas & Electric (SDG&E), Los Angeles Department of Water and Power (LADWP), and Sacramento Municipal Utility District (SMUD) ratepayer areas.

**Table 6: Statewide Impacts Input Parameters**

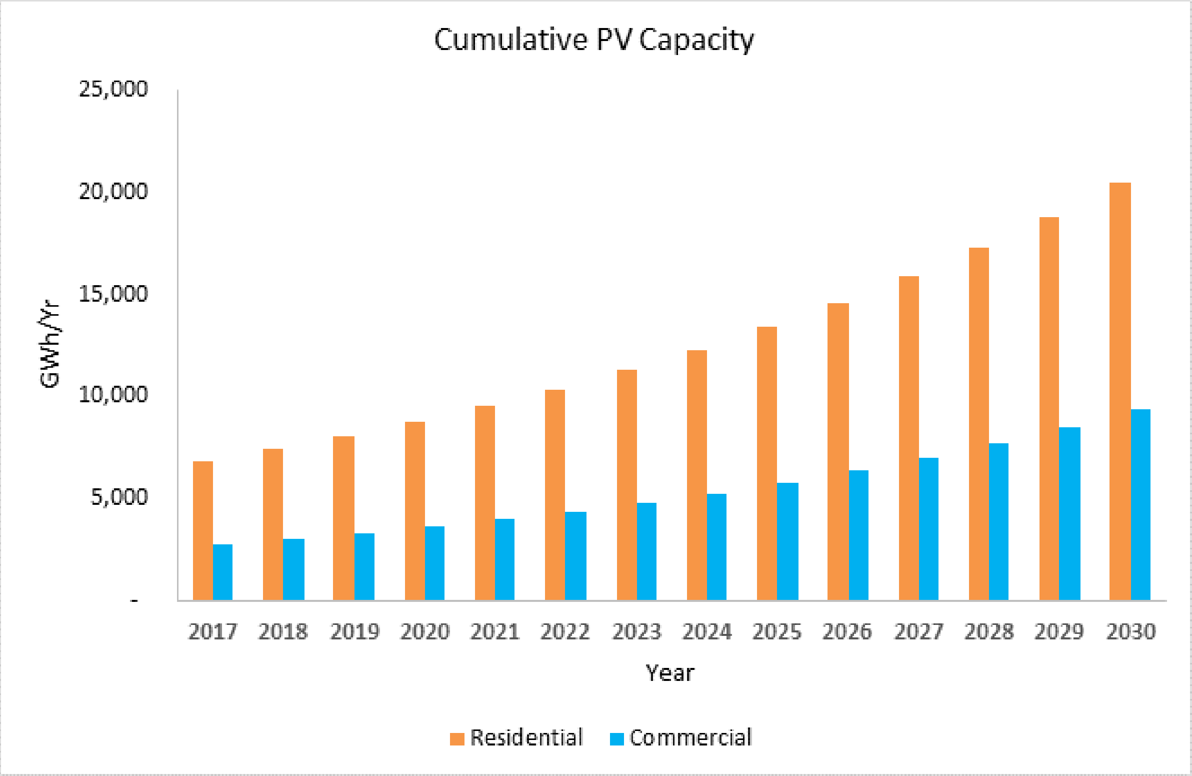
| Parameter | Residential | Commercial | Source |
|---|---|---|---|
| PV capacity in 2017 (MW)* | 4,023 | 1,700 | [49] |
| PV capacity in 2030 (MW)* | 11,640 | 5,453 | [49] |
| Weighted-average PV capacity growth* | 8.5% | 9.2% | [49] |
| PV generation in 2017 (GWh)* | 6,808 | 2,731 | [49] |
| PV generation in 2030 (GWh)* | 20,498 | 9,374 | [49] |
| Weighted-average PV generation growth | 8.7% | 9.7% | [49], calculated |
| CA electricity prices ($/kWh) in 2017 | 0.19 | 0.18 | [50] |
| CA electricity consumption (GWh/year) in 2016 | 90,886 | 104,986 | [51] |
| Electricity consumption growth rate (2016–2030) | 2.0% | 1.3% | [51] |
| DC energy savings, no storage** | 0.0% | 4.0% | Systems loss analysis |
| DC energy savings with storage** | 6.3% | 14.0% | Systems loss analysis |
| Fraction of systems with storage versus no storage | 25% | 50% | Assumption |
| Discount rate | 3% | 7% | Assumption |

*** Mid-case scenario for PG&E, SCE, SDG&E, LADWP, and SMUD ratepayer areas.**

**** Reflects results for cases with EV, and assumes a 13.5 kWh and 500 kWh battery capacity for the residential and commercial system, respectively.**

Source: Lawrence Berkeley National Laboratory

**Figure 31: Cumulative Photovoltaic Capacity Projections in California**



Source: California Energy Demand 2018-2030 Forecast (Table 2. CED 2017 Mid Energy Demand) (https://efiling.energy.ca.gov/getdocument.aspx?tn=223244)

Table 7 presents the results of this analysis, showing cumulative energy savings, operating cost savings, and $CO_2$ emissions reduction for 10 years (2021–2030) in California. The following results are based on the input assumptions shown earlier, as well as the following assumptions:

- DC distribution systems are assumed to be installed in buildings with behind-the-meter PV systems.
- All electric loads in buildings with DC distribution are assumed to be DC-internal (i.e., directly served by the DC distribution).

**Table 7: Statewide Impacts from DC Distribution**

| Parameter | Residential | Commercial |
|---|---|---|
| Cumulative energy savings 2021–2030 (GWh) | 2,245 | 5,680 |
| Cumulative operating cost savings 2021–2030 ($million) | 418 | 925 |
| Cumulative $CO_2$ emissions* reduction 2021–2030 (million metric tons) | 0.6 | 1.6 |
| Energy savings fraction of total electricity sales 2021–2030 | 0.2% | 0.5% |

***Assuming 0.28 kilogram/kWh $CO_2$ emissions factor**

Source: Lawrence Berkeley National Laboratory

# CHAPTER 6:
# Technology Transfer Activities

This EPIC project examined the feasibility, cost effectiveness, market barriers, customer needs, and savings potential for DC and hybrid DC-AC systems, to power ZNE residences and commercial buildings, subdivisions, and communities. The results of the research were documented in a technical report summarizing the technical and market status of DC power in buildings [52], as well as a guidebook documenting the current best practices in implementing DC power for individual building end-uses and whole-building integrated design. Table 8 lists the target audiences for the results of this research and their information needs.

**Table 8: Target Audiences for Research Results**

| Audience | Information Needs |
|---|---|
| Architects and electrical designers | Design templates and guidelines to provide guidance for how to incorporate DC power distribution into projects they design. |
| Production homebuilders who do their own architectural design | Design templates and guidelines on how to incorporate DC power into new ZNE homes |
| Electrical product manufacturers | Potential product gaps that need to be filled |
| CA utilities | The potential savings and other benefits from DC power in buildings, to design efficiency programs |
| Title 20 officials | Information about product-level standards or test procedures that need to be created or updated to better promote DC power |
| Title 24 officials | Information about enhancements to building codes to promote DC power |

Source: Lawrence Berkeley National Laboratory

## Dissemination Channels

With the target audience in mind, the research team identified several key information distribution channels that are most effective at reaching those audiences. These included:

- Technical Advisory Committee – The TAC was composed of representatives from utilities, manufacturers, architectural and engineering firms, and non-profits. All of these TAC members are key influencers in the DC power community, either through the form of products, standards, design methods, or advocacy. The TAC had access to the earliest results from the project and provided advice on technology transfer strategies, as well as being consumers of the study findings themselves.

- Project activities – Several phases of this project involved interaction with stakeholders in the DC power community and served as a technology transfer mechanism to make them aware of the research and its findings. These included:
    - Stakeholder workshop – the research team held a workshop with approximately 60 participants to solicit feedback on the initial literature review and brainstorm with stakeholders about additional issues in the DC power market. These discussions led to a refined sense of how the DC power market functions, and the best targets for technology transfer.
    - Stakeholder interviews - as part of Task 2, the study team conducted in-depth interviews with about a dozen key players in the DC power industry. These interviews informed these stakeholders about the goals of this project and some of the expected results.
    - Project design review - as part of Task 3, the study team held an in-person review of the preliminary DC-power design templates, which served as another opportunity to spread the findings of our study to stakeholders. This design review was particularly important in formulating a strategy to reach the architect and designer target audiences, with the input of project team member Arup (a design and engineering firm).
- Conference presentations and papers – The research team presented the findings of this research at several conferences, including:
    - A poster at the 2018 EPIC Symposium, titled "DC Power as an Integrating Technology for Zero-Net Energy Buildings,"
    - A paper presented at the 2016 ACEEE Summer Study and published in the conference proceedings [53]. In addition, the research team helped convene an informal session on the topic of DC power in buildings at the Summer Study, co-organized with the non-profit CLASP. The informal session was attended by 20-30 people in the buildings energy efficiency field.
    - Findings from this study were presented at a March 2017 workshop convened by Legrand (an electrical equipment supplier), with participation from engineering firms, DC equipment suppliers, non-profits, and researchers.
    - The energy-savings modeling results from this study were presented in a paper at the 2017 IEEE International Conference on DC Microgrids (ICDCM) [54].
    - A paper presented at the 2017 EEDAL (Energy Efficient Domestic Appliances and Lighting) conference and published in the conference proceedings [55].
- EMerge Alliance - The EMerge Alliance is a DC-power industry organization that was a partner on this project. The Executive Director of the EMerge Alliance was a member of the TAC, and participated in the workshop and the design review. Lessons learned from this project were used to inform future revisions of the EMerge Alliance's DC power

standards, which serve as the basis for interoperability of DC-powered equipment. The EMerge Alliance also participates in a number of tradeshows, and distributed information about this EPIC project at the 2017 GreenBuild conference, which is a gathering of designers and builders of sustainable, energy-efficient buildings.

- Title 20 and Title 24 – Staff from the Energy Commission's codes and standards program participated in the TAC for this project and also attended the final project meeting. Research findings were presented in a way that was relevant to informing future standards efforts.
- EPIC Investment Plan – The research team provided a distillation of research recommendations that resulted from this study, as comments officially submitted to Energy Commission for the 2018-2020 EPIC Triennial Plan,
- Websites – LBNL created a web site for this DC power project (http://dc.lbl.gov/epic-research-project) that contains information about the project, access to work products, and links to and information about the project partners including CIEE, EPRI, EMerge Alliance and LA ETI. This web site will be maintained on an ongoing basis.

# CHAPTER 7:
# Conclusions and Future Research

## Conclusions

Based on the project team's review of previous studies and the energy modeling conducted in this study, there is a general consensus in the research community that DC power can save significant energy in buildings. This is especially true for buildings in which the power generated by on-site DC sources is immediately used for the building's own power needs, either to power end-use equipment or to charge battery storage for later use to power on-site equipment. The candidate buildings with the most energy savings potential are commercial buildings with PV and battery storage because the PV generation profile coincides with the profile of power demand, either for direct-DC loads or battery charging. On the lower end of the savings continuum are homes with PV only, because their building power demands tend not to coincide with daytime solar production, thus requiring conversion of the power to AC for "storage" in the grid and conversion back to DC for on-site consumption. Adding battery storage to a residence to store the PV-generated power significantly increases the energy savings from DC distribution (compared to an all-AC house with batteries). The scenarios examined for the design guidelines in this study show that DC power can be an integrating platform to efficiently connect multiple behind-the-meter distributed energy resources.

Based on the market and product survey presented in Chapter 2, the study team concluded that no technology breakthroughs are needed to make DC power distribution a viable option for ZNE buildings. There are, however, many barriers to the adoption of DC power, with product availability and cost being the most significant. There also is a general unfamiliarity with DC power in the building community, from designers, code officials, contractors, tradespeople, maintenance staff, building owners, occupants, and policy makers. The study team found a real need for DC-power market development in the form of product standards and building and fire codes that explicitly account for DC systems, DC-specific design practices, improved trade familiarity, and a wider variety of DC-ready products in a range of product categories, feature sets, capacities, and so on.

As discussed in Chapter 2, and based on survey and interview feedback, DC systems have the potential of having the same, or even a lower, first cost compared to AC systems in buildings, primarily due to simpler circuitry and the use of fewer components. However, this would require the appropriate economies of scale. For the current market, certain end-use applications where DC power is starting to see significant adoption, such as DC data centers and PoE lighting, may be better suited for commercialization. Overall, first cost is one of the main barriers for developers, designers, specifiers, manufacturers, and end users to implement DC systems in buildings.

From a research perspective, the few studies that address DC system costs follow for the most part a qualitative approach, primarily due to the lack of data on DC appliances, converters, and actual installed systems. However, bottom-up approaches (that is, estimating costs from components to systems), as well as top-down (based on data from demonstration projects) could be employed to estimate the current and future costs of DC systems.

Another observation from this study is that DC power systems can produce benefits that go well beyond energy savings, to include improved power quality, extended component lifetime, and improved power reliability. However, these benefits are difficult to quantify and may accrue to different stakeholders in the power system life-cycle, which makes it hard to comprehensively evaluate the cost-benefit tradeoff when building owners and managers consider adoption of DC power systems. For this reason, a systems approach is needed to adequately evaluate the benefits of DC power in the context of designing a building or purchasing electrical equipment.

A final observation is that the entire topic of DC power in buildings would not be receiving the attention it is if not for the rapid proliferation of behind-the-meter distributed energy resources, such as rooftop PV, on-site battery storage systems, and home and workplace EV charging, all of which are native DC. The rapid market adoption of these distributed energy resources is stimulating increased interest in DC power distribution, as a way to better manage the energy produced and consumed on-site. It is very possible that as these native-DC distributed resources become more commoditized, with shrinking profit margins due to competition, the industries that produce and install these resources will turn to DC power distribution as a "value-added" service that can improve the overall attractiveness of an integrated package. This will ultimately prove the premise of this research study, that DC power distribution can serve as a platform for integrating several distributed energy resources within a ZNE building.

## Future Research

Direct distribution of DC power in buildings offers energy, reliability, and other benefits over AC power, but the buildings industry lacks sufficient experience and commercial products for wide use of this technology. To overcome these barriers, several research activities are needed:

- Conduct controlled testing of side-by-side, DC versus AC buildings to quantify cost, energy and operational savings, along with non-energy benefits such as power quality and resilience. These tests should cover the scenarios outlined in the design guidelines (PV, EV, and battery storage systems) for all building end-uses.
- Demonstrate DC power distribution in the field in new construction and retrofits for ZNE and near-ZNE buildings to determine practical barriers to deployment, integration issues, and energy savings under actual use.
- Conduct techno-economic evaluation of DC power systems in buildings, using updated performance data from lab and field tests, and updated product cost data (first-cost, installation, maintenance, repair, and soft costs such as design and permitting costs).
- Develop and standardize key interoperability features that will make DC a plug-and-play option in buildings (particularly at voltages greater than 48V DC). Standards should be

international where possible, building on the rapid penetration of off-grid DC solar systems in the developing world. Areas to standardize include: voltages, connectors, and communication protocols for power control.

- Develop and test DC electrical components that are missing or not widely available today, including: DC electrical protection devices, such as circuit breakers and switches, dual-input DC and AC appliances, power converters such as bidirectional AC/DC converters, DC EV chargers, DC battery chargers, and turnkey solutions for directly connecting PV systems to battery storage. Offer an award or competition program for DC-powered products that meet key performance criteria (similar to the Global LEAP[12] competition, but for typical California building equipment).
- Develop an industry-wide DC building-design resource center to serve as an information hub to raise awareness and help designers and planners. The hub should include updated retrofit and new construction templates, best practice guidelines, product databases, measured data on DC system performance, and other information resources. To the extent possible, information should be based on actual data from DC power demonstrations and lab testing.
- Demonstrate small DC microgrids for collections of buildings, such as multifamily developments and community-scale solar systems, to quantify energy and cost savings at a larger scale.
- Conduct lab and field tests of re-using existing AC wiring in buildings for DC retrofit.
- Develop a DC "power hub" for distribution and storage of power from small-scale solar systems directly to DC loads such as consumer electronics, especially in small residential settings such as apartments.

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[12] The Global LEAP program is the Clean Energy Ministerial's energy access initiative. Its programs and initiatives support the growth of sustainable commercial clean energy access markets throughout the developing world. http://globalleap.org/.

# GLOSSARY AND ACRONYMS

| Term/Acronym | Definition |
|---|---|
| AC | Alternating current |
| AC-DC driver | Power conversion device that converts alternating current to direct current, typically for powering LED lights |
| Battery storage system | Energy storage system consisting of chemical batteries and a battery management system for delivering power to the batteries |
| Behind-the-meter | Energy equipment owned by a utility customer and powered from the customer's side of the utility meter |
| CCS | Combined Charging System |
| Coincident | Loads that coincide with the utility peak load |
| DC | Direct current |
| DER | Distributed Energy Resource |
| EPIC | Electric Program Investment Charge |
| ESS | Energy storage systems |
| EV | Electric vehicle |
| Flywheel | An energy storage system that stores energy in a rotating mass |
| HVAC | Heating, ventilation, and air conditioning |
| Interoperability | The ability of components in a system to exchange data for purposes of coordinating their operation |
| Inverter | Power conversion device that converts direct current to alternating current |
| Islanding | The ability of a power system to disconnect from the utility grid while maintaining operation and serving loads |
| kW | Kilowatt |
| LED | Light emitting diode |
| Level 1/Level 2 charging | Refers to the power level and charging rate of an electric vehicle charger. Level 1 is limited to approximately 1.8 kW, while Level 2 is limited to approximately 7kW. |
| Luminaire | Light fixture |
| Microgrid | A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that |

| Term/Acronym | Definition |
|---|---|
| | acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode. (per DOE) |
| MPPT | Maximum power point tracker |
| Nanogrid | A single domain of power, defined by the voltage and characteristics of the power delivered |
| Native load | Electrical equipment or devices that use DC power internally to operate their primary components |
| Net metering | A billing system that allows residential and commercial customers who generate their own electricity from solar power to feed electricity they do not use back into the grid. (per SEIA) |
| NFPA | National Fire Protection Association |
| Non-energy benefits | Benefits from using an energy efficient product, other than reduced energy use |
| Overcurrent protection | Circuitry in an electrical device that prevents excessive current flow |
| PEV | Plug-in electric vehicle |
| PoE | Power over Ethernet |
| PV | Photovoltaic |
| Rectifier | Power conversion device that converts alternating current to direct current |
| Solid-state lighting | Lighting systems with semiconductor-based light sources, typically LED or organic LED |
| Time of use tariffs | Electricity prices that vary over short periods, such as hourly |
| UPS | Uninterruptible power supplies |
| USB | Universal series bus |
| V | Volt |
| V2G | Vehicle-to-grid |
| VFD | Variable frequency drive |
| ZNE | Zero net energy |

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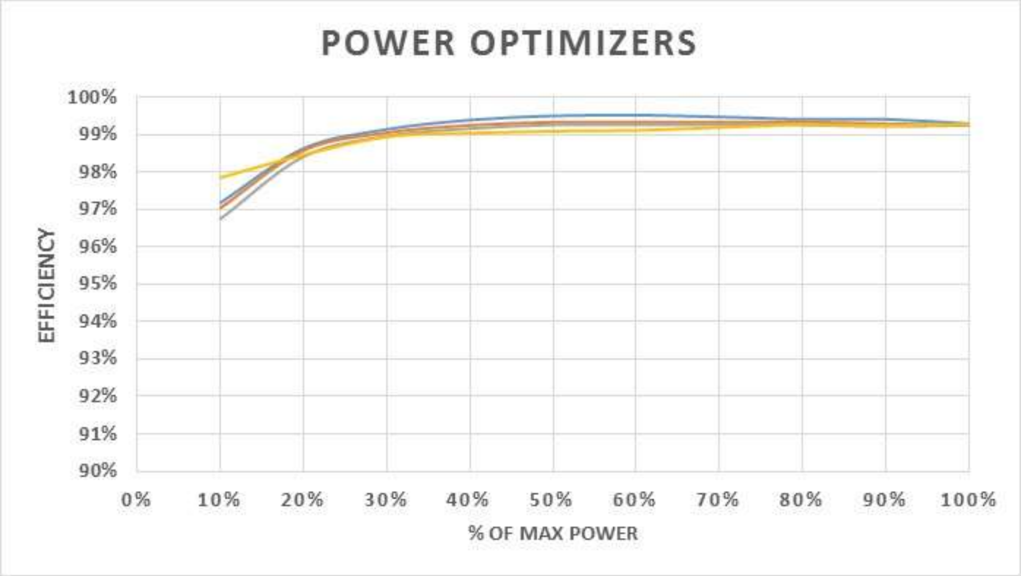
# APPENDIX B: Converter Efficiency Curves

This appendix addresses efficiencies of power converters used in power distribution systems in buildings with AC and DC distribution, based on market surveys. The study team collected efficiency, power, and voltage data from various sources, including manufacturer websites, product spec sheets, and online databases. The following sections provide brief descriptions of the power converters used in the building distribution systems, and present efficiency curves (efficiency as a percentage of converter max power) for each surveyed converter. Converters surveyed include DC/DC converters and Maximum Power Point Trackers (MPPTs), AC/DC rectifiers, DC/AC inverters, for different input and output voltage levels, and power ratings.

## Power Optimizers

Power optimizers are DC/DC converters, typically connected to individual PV modules, with the purpose of maximizing PV power output using MPPT. Power optimizers are relatively new PV system components that replace the PV junction box. They can be used both with AC and DC building distribution systems. Power optimizer manufacturers include SolarEdge, BlackMagic, eIQ, Pika Energy, and others. Figure B-1 shows efficiency curves for power optimizers with power ratings less than 1 kW.

**Figure B-1: Efficiency Curves for Power Optimizers ($V_{in}$<125 VDC, $V_{out}$=48 VDC, $P_{max}$<1 kW)**

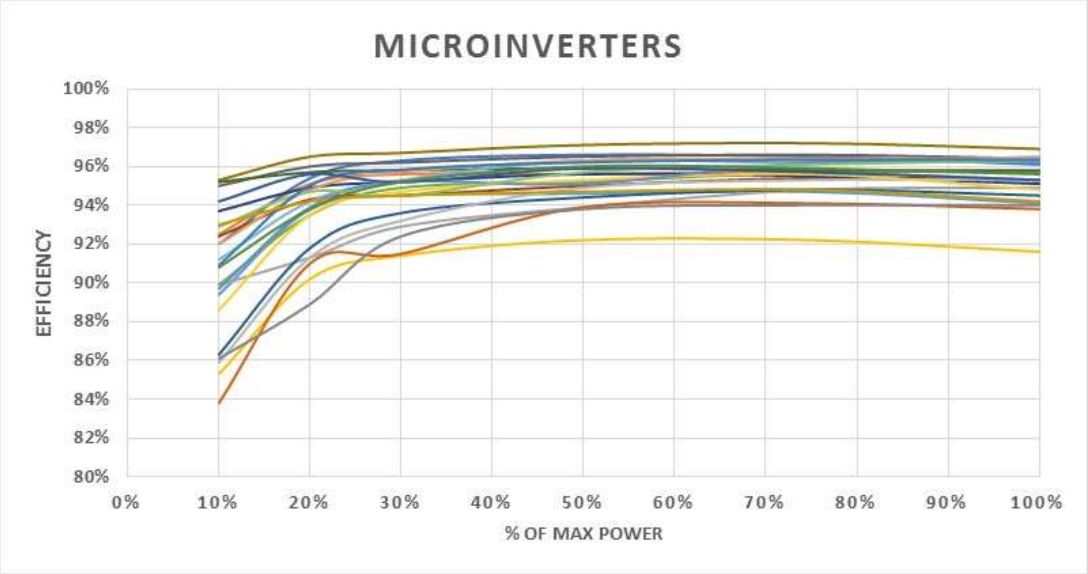


Source: Lawrence Berkeley National Laboratory

## Microinverters

Microinverters convert DC power from the PV modules to AC power that is typically synchronous to the grid. They include MPPT and are connected to individual PV modules to maximize power output from each module. Microinverter manufacturers include Altenergy, Enphase, ABB, SMA, SolarBridge, Petra, LeadSolar, and others. Figure B-2 shows efficiency curves for microinverters with power ratings less than 1 kW.

**Figure B-2: Efficiency Curves for Microinverters ($V_{in}$<65 VDC, $V_{out}$=120/240 VAC, $P_{max}$<1 kW)**

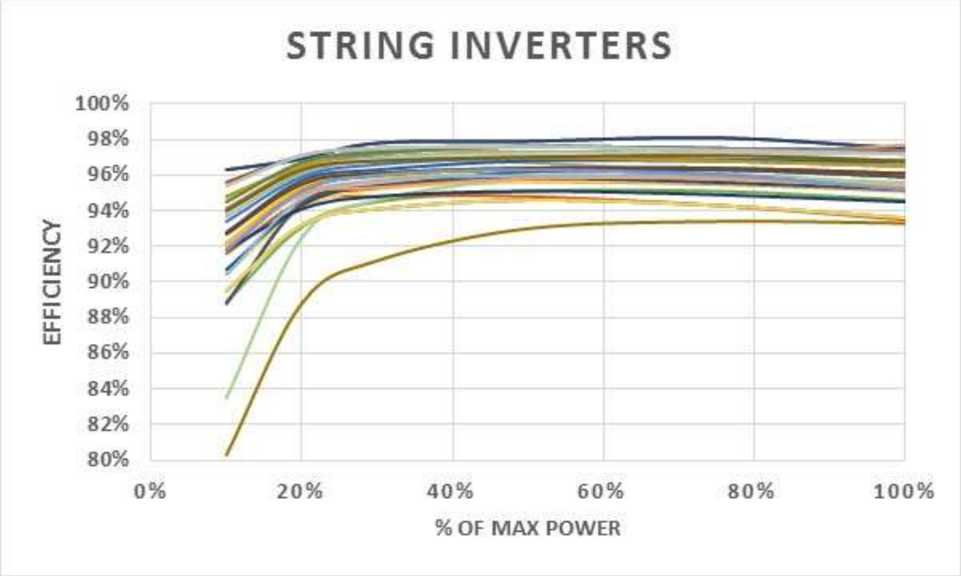


Source: Lawrence Berkeley National Laboratory

## String Inverters

Figure B-3 shows efficiency curves for string inverters with power ratings less than 10 kW.

**Figure B-3: Efficiency Curves for String Inverters ($V_{in}$<600 VDC, $V_{out}$=240/208 VAC, $P_{max}$<10 kW)**



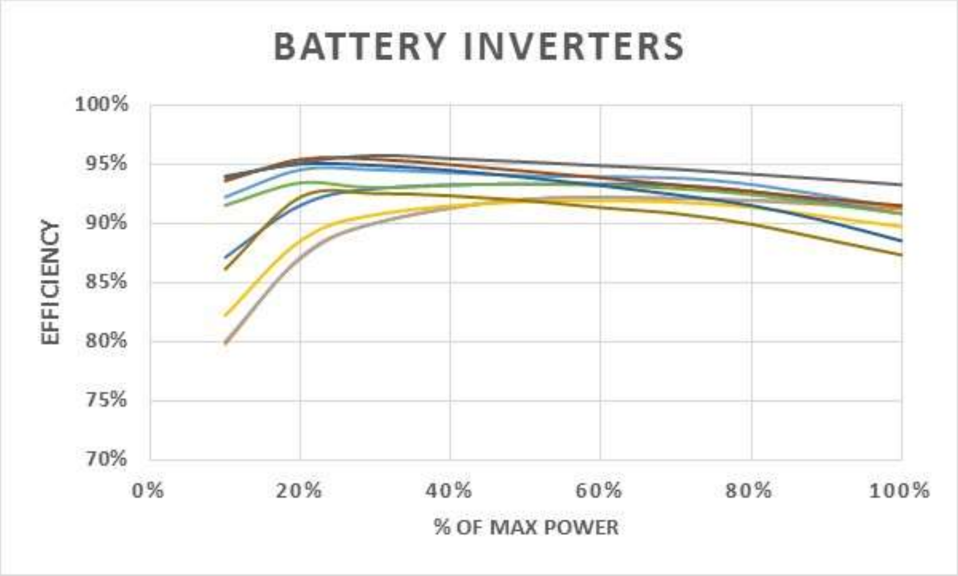
Source: Lawrence Berkeley National Laboratory

String inverters have a similar function as microinverters. They typically include MPPT and convert DC from the PV array into AC synchronous to the grid. They are more widespread than microinverters, and their main difference is that instead of connecting to each PV module, they connect to strings of PV modules (i.e., modules connected in series). String inverter manufacturers include SMA, Fronius, Schneider Electric, ABB, Solectria, and many others. Power ratings, input and output voltages vary for string inverters depending on the building type (residential or commercial, voltage service type (single phase, or three-phase, and the load served by the PV system.

## Battery Inverters

Battery inverters convert DC power coming from the building battery storage system, or directly from the PV array, to AC power that is sent to the loads or to the grid. Battery inverters include a built-in rectifier to convert AC grid-power to DC, as required for battery charging, but they typically do not include MPPT, as this function is generally performed by an upstream located charge controller. The battery inverter market is smaller compared to the non-battery backup inverter market (i.e., the market for string inverters and microinverters). Manufacturers of battery inverters include Schneider Electric, SMA, Outback, Sigineer, Samlex, and others. Figure B-4 shows efficiency curves for battery inverters with power ratings less than 10 kW.

**Figure B-4: Efficiency Curves for Battery Inverters ($V_{in}$<64 VDC, $V_{out}$=120 VAC, $P_{max}$<10 kW)**

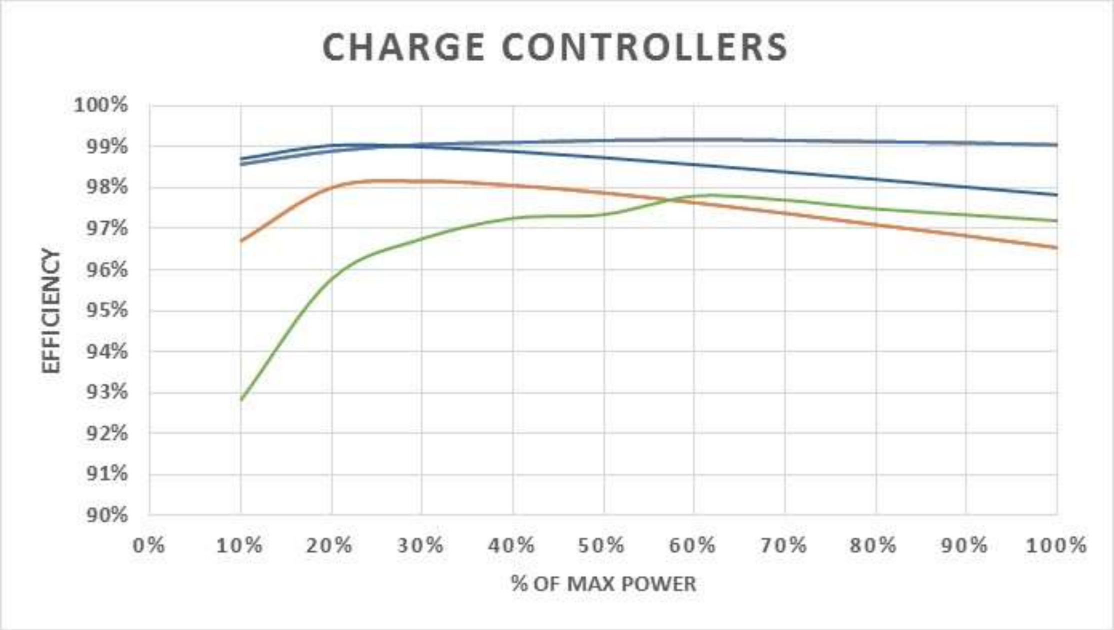


Source: Lawrence Berkeley National Laboratory

## Charge Controllers

Charge controllers are used in battery backup systems to regulate the current sent to, or coming from, the battery, and typically include MPPT. Charge controller manufacturers include Outback, Morningstar, Schneider Electric, SMA, Midnite Solar, and others. Figure B-5 shows charge controller efficiency curves for charge controllers with MPPT, with power ratings between 1-5 kW.

**Figure B-5: Efficiency Curves for Charge Controllers ($V_{in}$<600 VDC, $V_{out}$=48 VDC, $P_{max}$: 1-5 kW)**



Source: Lawrence Berkeley National Laboratory

## Direct Current/Direct Current Converters

DC/DC converters convert DC power from one voltage level to another. They are predominantly used in low-power, low-voltage applications and are found in appliances with electronic circuits. DC/DC converter manufacturers include Vicor, Emerson, Synqor, Eltek, and others. High power DC/DC converters are typically more efficient than lower power models. Figure B-6 shows efficiency curves for step down DC/DC converters with power ratings less than 5 kW but more than 1 kW.

## Light Emitting Diode Drivers

AC LED drivers typically convert AC power to a lower voltage DC. They also regulate voltage and current through the LED circuit. DC LED drivers operate similarly to their AC counterparts, but do not require rectification. Manufacturers of LED drivers include Philips, Delta Electronics, Meanwell, and others. Figure B-7 shows efficiency curves for AC LED drivers with power ratings less than 500 W and input voltage at 120V.[13]

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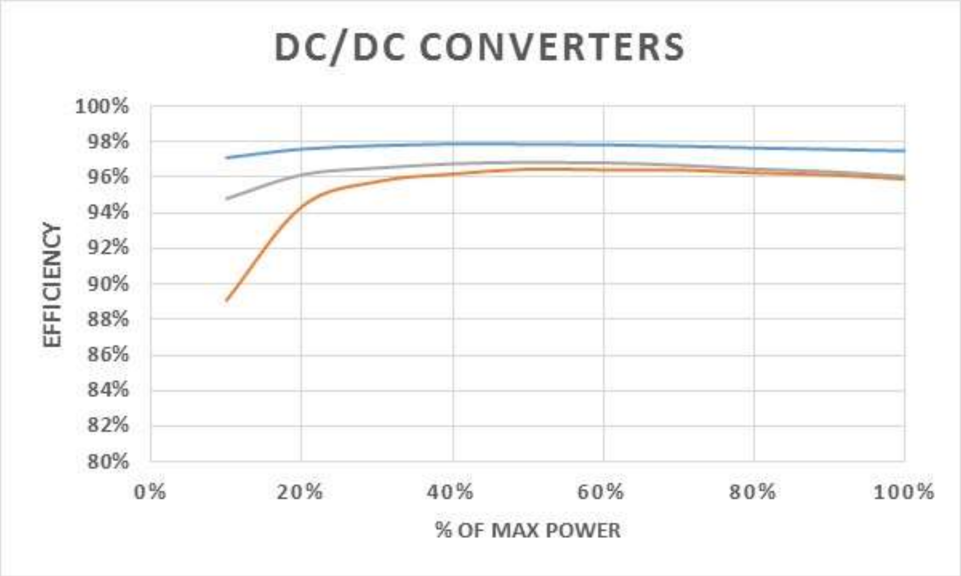
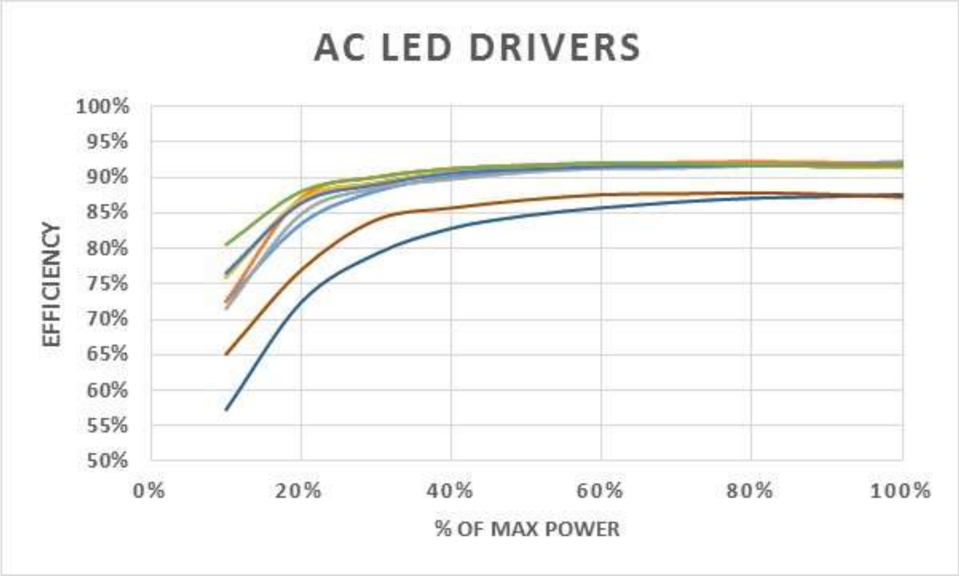
[13] Note that although the study team was not able to obtain efficiency curves for DC LED drivers, their peak efficiencies were higher than those for AC LED drivers.

**Figure B-6: Efficiency Curves for DC/DC Converters ($V_{in}$<140-400 VDC, $V_{out}$=48 VDC, $P_{max}$: 1-5 kW)**



Source: Lawrence Berkeley National Laboratory

**Figure B-7: Efficiency Curves for AC LED Drivers ($V_{in}$=120 VAC, $V_{out}$=48 VDC, $P_{max}$<500 W)**

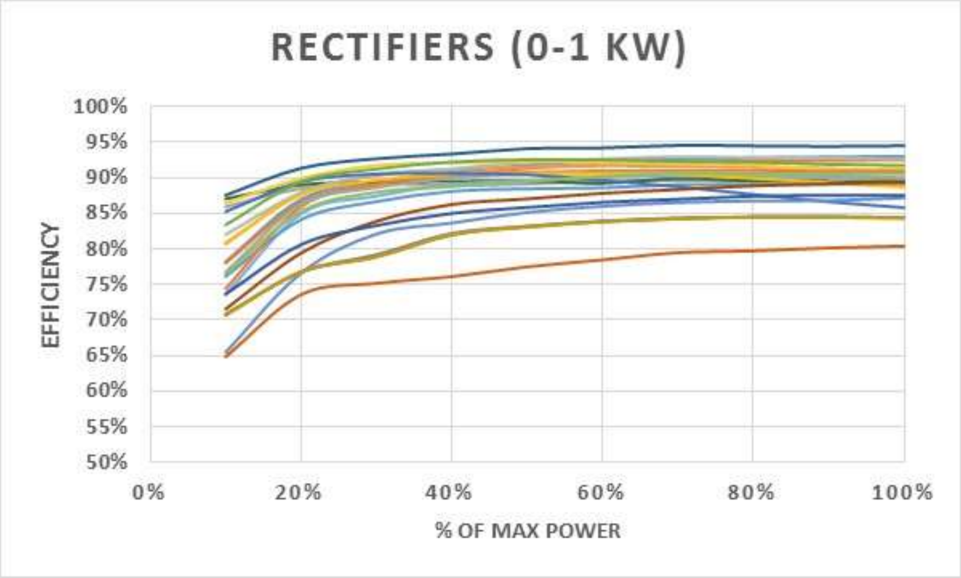


Source: Lawrence Berkeley National Laboratory

## Rectifiers

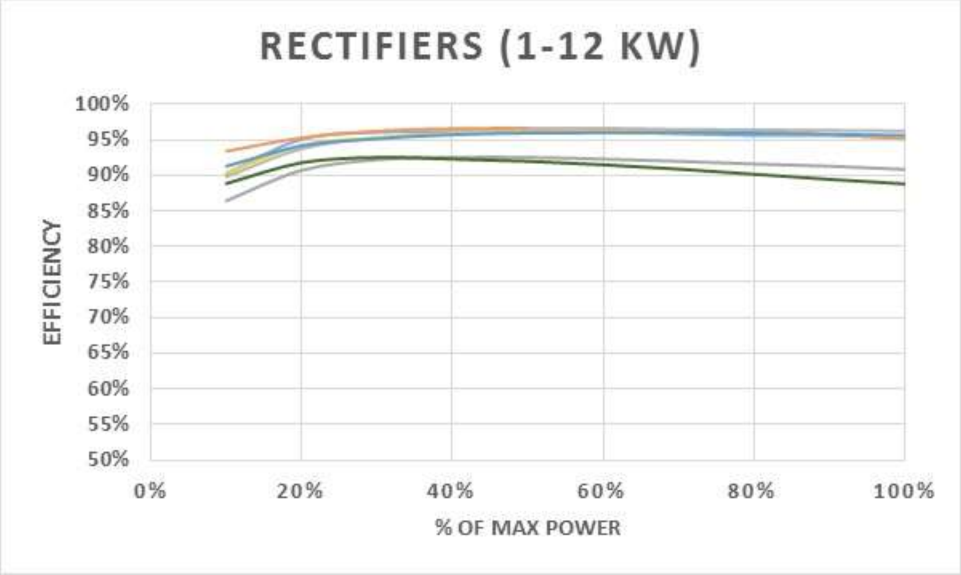
Rectifiers are used to convert AC power to DC. In the AC distribution system, rectifiers are used in DC-internal appliances. In the DC distribution system, one or more higher power rectifiers can be used to convert AC power from the grid to DC when power from the PV system or the battery is not sufficient for the building loads. Manufacturers for rectifiers include Eltek, Delta Electronics, Murata, XPPower, Emerson, and others. Figure B-8 and Figure B-9 show efficiency curves for rectifiers rated at 0-1 kW, and 1-12 kW, respectively. As shown in the figures, higher power rectifiers are more efficient than those rated at lower power.

**Figure B-8: Efficiency Curves for Rectifiers ($V_{in}$=120 VAC, $V_{out}$=48 VDC, $P_{max}$≤1 kW)**



Source: Lawrence Berkeley National Laboratory

**Figure B-9: Efficiency Curves for Rectifiers ($V_{in}$=120/277/480 VAC, $V_{out}$=48 VDC, Pmax: 1-12 kW)**



Source: Lawrence Berkeley National Laboratory

# APPENDIX C:
# Stakeholder Workshop

The research team held a workshop on direct current as an integrating and enabling platform in zero net energy buildings on March 15, 2016 at the Los Angeles Electrical Training Institute in the City of Commerce, California. The workshop was funded by the California Energy Commission EPIC program, as part of the LBNL/EPRI/CIEE joint research project on “Direct Current as an Integrating and Enabling Platform.”

The workshop solicited input and advice on the technology, policy, and market development needs for adoption of DC and AC-DC hybrid systems in residential and commercial buildings, focusing on zero net energy (ZNE) buildings with PV, battery storage, and EV charging. The workshop agenda is shown below, followed by a summary of the workshop comments.

## Workshop Agenda

| | |
|---|---|
| 9:00am - 9:30am | Introductions |
| 9:30am - 10:15am | Overview of EPIC research project and findings to date |
| 10:15am - 11:00am | “Quick pitch” updates from partners |
| 11:00am - 11:15am | Break |
| 11:15am - 12:15pm | Breakout session: “What’s needed to maximize the opportunities and overcome the barriers for DC power in these areas?”<br>• Technology<br>• Policy<br>• Market Development |
| 12:15pm - 1:15pm | Lunch and tour of zero-net energy features of ETI building |
| 1:15pm - 1:45pm | Report out and discussion from morning breakout session |
| 1:45pm - 2:00pm | Review end-use applications for DC and AC-DC hybrid power |
| 2:00pm - 3:00pm | Breakout session: “What factors* affect ZNE designs today for our end-use applications?”<br>• Small loads (lighting, electronics, fans, …)<br>• Larger loads (HVAC, water heating, motors, EVs, …)<br>• ZNE integrated systems (PV, storage, EV charging, power infrastructure)<br>*e.g., product availability, building codes, interoperability standards, etc. |
| 3:00pm - 3:30pm | Report out and discussion from breakout session |
| 3:30pm - 4:00pm | Concluding session: feedback and discussion |

# Codes and Standards

*Brian Patterson, EMerge Alliance*

- There are thousands of related codes and standards. Standards get translated into codes centered on safety, not efficiency.
- Most standards bodies treat DC categorically: high, medium, low. Power systems are being treated, not products.
- Fire code is revised every three years. There is more interest in DC-related topics.
- Most current standards written with AC in mind. Most standard-setting bodies are composed of AC experts. Most standards focus on equipment, safety, or testing; NOT system standards.
- The standards are not explicit about the technical requirements for DC. (For example, a code inspector doesn't know what you are talking about when you start talking about interpolating tables.)
- DC is currently only addressed in specific end uses – transport (railway), marine, telephony (DC used for > 50 years). Transmission of water is DC - i.e., Three Gorges in China, also Europe.
- Heavy commercialization waits for standards definition.
- EMerge is rewriting standards to accelerate the process for DC or hybrid systems. In Germany in particular and Europe in general, more work has been done with renewables.
- EMerge focuses on standards definition, in preparation for international standards bodies taking this up (what Patterson calls a "vanguard" organization). Vanguard organizations like EMerge do the coordination work to get initial versions of standards, then work with others to spread adoption, share info, etc. Industry needs to lead the effort if rapid change is desired; then products can be built around the new standards: technical operations, safety standards, building energy codes, performance codes (not green standards).

# "Quick Pitch" Updates

*Rajendrah Singh, Clemson University*

- Disagrees with much said; driver is the carbon issue; utility to decentralized power generation; electrification of the transport sector. Not in favor of working with existing systems – just go to DC power.
- Savings can go up to 30 percent–50 percent. There are 25 percent losses in AC-DC conversion if below peak power. Part load inverter efficiency is 30 percent–40 percent
- Use experience curves for future prices of batteries and PV. We will need factories to produce at large scale to decrease unit prices.

*Peter May Ostendorp / Steve Pantano, CLASP*

- Current research focused on identifying the likely paths for DC in homes; conduct gap analysis to address shortcomings.

- CLASP convening a group “Demand DC.”
- Look at end-points - appliances, etc.; how to incentivize these value propositions.
- Adoption paths: In the next decade, what are the most likely clusters of products in the home – entertainment, home office, garage, others?
- What is doable in a year?
- Focusing on non-energy benefits; energy efficiency won't motivate the change to DC with consumers. Probably PV + storage is stronger incentive; 1/3 of what is in home is DC-compatible, and this percentage is rising.
- Market transformation – what will it take? How should we be motivating this transition? There are unique opportunities – vertical integrators make multiple end points possible.

*Pete Horton, Wattstopper - Legrand & Alliance to Save ENergy*

- Legrand is a $6B global enterprise – U.S., Europe, India.
- Alliance to Save Energy - DC is one of the largest working groups in Alliance. Spent twelve months looking at system efficiencies for lighting, HVAC, multi-system effects in building level DC.
- Creating a draft document on system efficiency, which will be out next month.
- Alliance is focusing on DOE carbon neutral target. What does carbon neutral home/building look like in the future? Considering both savings and cost, also transactional markets. Who are early adopters? How can we get there?
- EVs will help bring down battery costs. Efficiency won’t get us there.
- Codes and standards – develop enough to get going.

*Henry Lee, ADC Energy*

- DC energy deteriorates the minute it is generated. ADC offers two applications:
    - AC and DC transmission on existing wire;
    - Permits long distance transmission without deterioration.

*Dave Geary, DC Fusion and Alliance for Sustainable Colorado*

- Denver Alliance for Sustainable Colorado: In 2016, the DC Microgrid Project is converting The Alliance Center from alternating current AC to a self-contained DC system. Stamped drawing in permitting now. 360 Engineering. Optimize what we can do tomorrow.
- DC-Fusion joining Power Analytics. Model DC in software, same as AC. Evolve this from design to control; then evolve to transactional market participation.
- DC-Nexus Website tracking current events. http://dc-nexus.com

*Dan Lowe, Voltserver*

- Voltserver makes high voltage DC safe to touch. Senses energy leakage of current, and shuts off current; while checking system for safety, can simultaneously send control data.

- Waiting for DC products is not necessary.
- SBIR Phase 2, energy efficiency up to 99 percent. Focusing on mobile communications. In residential 30 percent–40 percent overall savings.

*Brian Patterson, EMerge Alliance*

- EMerge has new board members; partnered with IEEE.
- EMerge is writing standard for Residential DC; draft in one month, final in one year.
- EMerge is coordinating demonstrations:
    - GreenCon on DC Enernet
    - LightFair Cava DC as a network technology
    - IECS EG4 - Low voltage DC
    - Solar Power International, Las Vegas - demo two microgrids in Smart Community Pavilion; most rapid growth at solar show is storage exhibits. Marriage of renewable and storage is critical.
    - Greenbuild LA – Large draw of DC microgrid, also hybrid.

**Breakout Session 1: "What's needed to maximize the opportunities and overcome the barriers for DC power in these areas?"**

*A. Technologies*

*Key takeaways:*
Direct-DC technologies are emerging in certain areas like motors, pumps, ceiling fans, PoE applications for charging, lighting and other uses; hybrid AC and DC electric outlets allowing more PoE applications; for lighting and heat pumps, computer servers and electric vehicle charging. DC power advantages for emergency backup lighting, resiliency, islanding from the grid may be "Trojan-horses" for introducing DC microgrids into residential and commercial buildings especially for ZNE buildings. There is also a need for revenue-grade two-way net metering for DC microgrids and for better modeling programs for designing DC systems.

- Available Technologies:
    - PoE devices and applications are expanding significantly with the current ability to have 50 watts per channel, which is expected to go to 90 watts later this year.
    - DC motors and pumps – size, control, efficiency and cost of ownership advantages (need larger volume to bring prices down.
    - Ceiling fans: DC motors with LED lights now available
    - DC Lighting: Samsung DC smart lighting platform; CREE Smartcast
- Technology gaps and other barriers:
    - Improved bidirectional inverters
    - Revenue grade metering and two-way net metering for DC
    - System operation and control management – analysis and modeling
    - Agreement on residential DC voltage

  - AC/DC dual options built-in by manufacturers on home and office appliances
  - Performance and demo data plus UL and other listings
  - Improved DC system design modeling software
- Barriers can be addressed in demos
- "Trojan Horses" for DC power:
  - E.g.: Emergency lighting: Transforms dead asset to active management
  - UPS systems
  - Audiovisual equipment
  - Cell phone towers (as DC microgrid test beds)

*B. Policies*

*Key takeaways:*

- Energy savings: Perception in the policy community that there are not enough energy savings
- There is no "home" currently for DC
- Non-energy benefits:
  - Bipartisan support can potentially be drawn from non-energy benefits such as resilience and reliability (e.g., the ability for buildings to switch to "resilient mode").
  - Our existing codes and standards network does not take into account factors such as resiliency and reliability
  - Interoperability: DC enables communications
- Title 24-California: Energy Commission looks at feasibility and cost-effectiveness (life-cycle cost)
- For utilities, the important aspects of DC would be functionality and first cost savings. (e.g., can DC make that heat pump cheaper?)
- Need metrics to compare buildings on all factors. For example, for transformers, the current metric used is "watts lost"
- DC also enables water measures: Reduces water desalination plant costs
- Government incentives are need for manufacturers to make DC-ready appliances
- Convergence is needed on voltage standards to 24, 48, and 380VDC
- Potential policy for voluntary standards: Providing a credit for DC-readiness, or the golden carrot incentive
- Sandy-microgrid-PSE&G
- DC Products: Look at products in the developing world
- Storage: There are benefits to the utility providers.

*C. Market Development*

*Key takeaways:*

- Retrofit challenges come from:
  - Unavailability of DC infrastructure/DC power
  - Lack of training/education (design, construction/installation, operation)
  - Lack of retrofit transformational scheme
  - Power distribution challenges; no one likes existing wall tearing
  - Potential ROI/payback
  - Defer initial costs: Incentives/rebates from utilities/government; Multiple stakeholders, consumers/utilities/regulators
- Energy Savings
  - What are the energy savings? More research is needed (claims range from 3 percent–30 percent)
  - Consider total cost of ownership, not just energy savings
- Product Availability
  - DC products availability/awareness limited
  - Competitive, cost-effective products needed
  - Make "hip"/cool products, e.g., Tesla to drive market
  - Distribution products (e.g., plugs, switches, circuit breakers) needed
- Worldwide standards
  - DC-specific standards are required
  - Standards would greatly increase volume/reduce costs
- Ability to achieve ZNE
  - Common definition of ZNE is desired
  - How to address sharing of community-scale renewables?
  - Need to articulate consumer drivers
  - Drive demand (through incentives, regulations, etc.)
- Integration
  - DC is easier to integrate than AC
  - No frequency regulation requirement
- Safety
  - Emerging issues depend upon voltage and current
  - Safety needs to be addressed along with standards

### Breakout Session 2: "What factors* affect ZNE designs today for our end-use applications?"

*A. Small Loads*

Most small loads, especially plug load appliances, are already digital devices and have AC/DC converters that provide the required DC voltage to the digital appliance. This includes adjustable speed motors, fans, and pumps, as well as electronic ballasts and LED lighting. For plug loads, dual AC or DC power inputs from the manufacturers or DC networks that can integrate the devices like PoE systems are needed for market adoption. The efficiency, reliability, interoperability, and controllability of DC motors provide important features for ZNE buildings.

*Key takeaways:*

- Plug loads – some key issues are:
  - How to connect to ZNE building system and smart grid
  - How to optimize the energy use for clusters of DC devices for entertainment and workstations.
- Heat pumps
  - Key technology for HVAC in ZNE buildings
  - Products: Carrier - PV powered heat pump system; Japan - Mitsubishi, Sharp residential DC mini split
- Lighting
  - PoE
  - Armstrong 24V microgrid ceiling system
  - Cove, task lighting, etc. – already DC for low voltage lighting provide target applications
- Need improved DC systems design and analysis tools for manufacturers and for engineering of ZNE buildings.
- DC VSD motors
- Need to have standard DC voltages and standard DC designs for appliances, plug load devices, and other small electric loads
- Major appliance designers need to provide DC/AC capabilities
- Demand response (DR) can improve with DC networks and easier control and Internet of Things (IoT) access
- Load-balancing DR, with "grid-friendly" appliances is possible and has been demonstrated to be effective, but manufacturers need to be motivated to add these controls – most likely by legislation.
- DC networked entertainment and electronics/office systems cluster networks are being developed – some under the EPIC 15-310 and 15-311 grants

*B. Larger Loads*

*Key takeaways:*

- Potential loads
    - Water heating: Heat pump water heater
    - HVAC: Split system heat pump
    - Pumps and fans: DC motors

- Issues with DC Motors
    - Does the OEM or the motor manufacturer assemble the e.g., compressor assembly? How easy is it going to be for the product to be converted to DC-ready?
    - From the utility's perspective, you want to have most of the dispatchable loads on the microgrid
    - What is the DC voltage that DC motors run on? Is 380V the right voltage?
    - Part-load efficiencies should be accounted for (both for AC and DC systems)

- Electric vehicles
    - Fast charging direct at 600V taking 380V from DC and boosting to 600V
    - What is the voltage at the input of the charge controller? Is it 380V?
    - PV to EV coincidence: Does it make sense in the residential case study?

*C. ZNE integrated systems (PV, storage, EV charging, power infrastructure)*

*Key takeaways:*

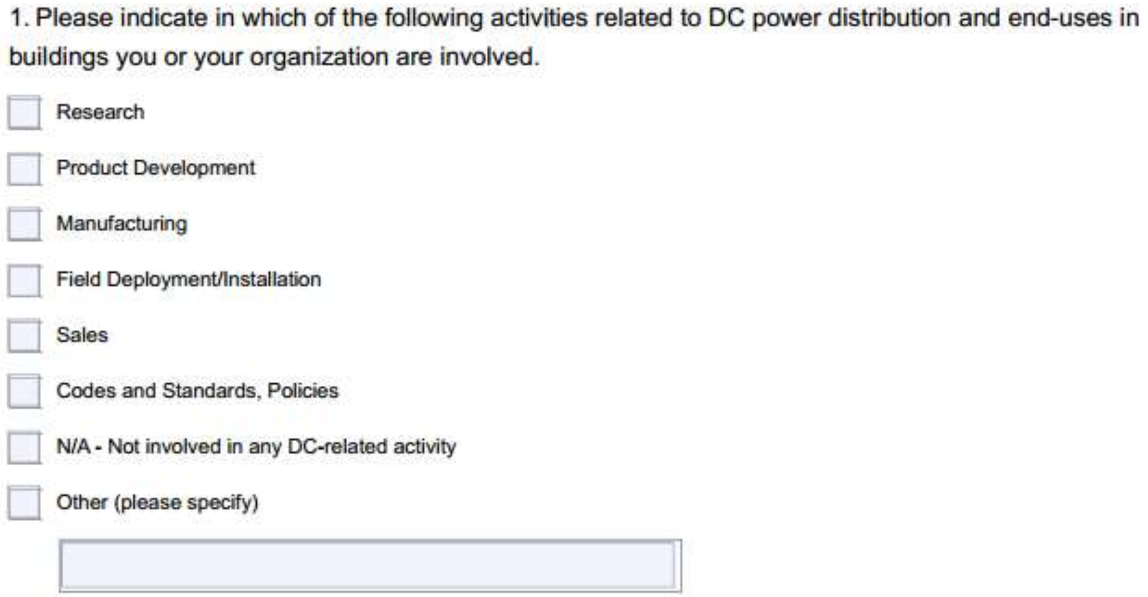
- Load requirements
    - Fixed loads
    - Variable loads/miscellaneous
    - Automobile

- Issues
    - Sizing of PV
    - Space limitation
    - Virtual net metering for shared PV allocation
    - Building – passive, low consumption, efficient
    - Storage/battery to stabilize afternoon load Integration of power system components: Inverters, rectifiers, circuit breakers, DC-DC converters, etc.

- Supply voltages (standardization)
    - 380V DC
    - 24/48V DC
    - 125/250V (currently used in industrial applications)

# APPENDIX D:
# Survey and Interview Questions

## Survey Questions



1. Please indicate in which of the following activities related to DC power distribution and end-uses in buildings you or your organization are involved.

☐ Research

☐ Product Development

☐ Manufacturing

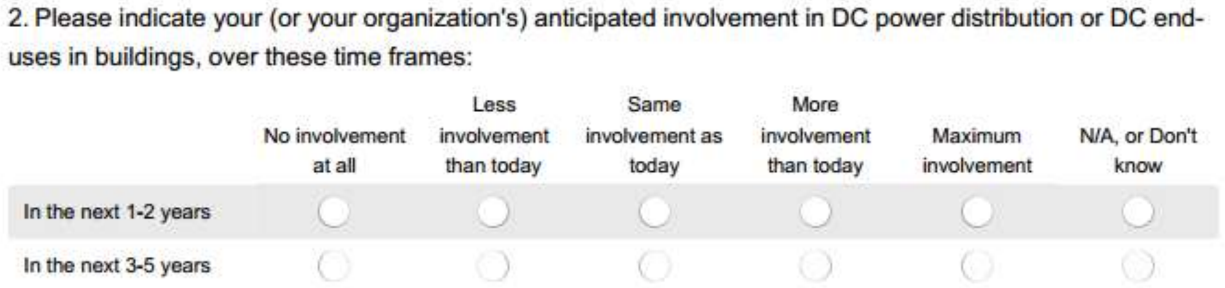
☐ Field Deployment/Installation

☐ Sales

☐ Codes and Standards, Policies

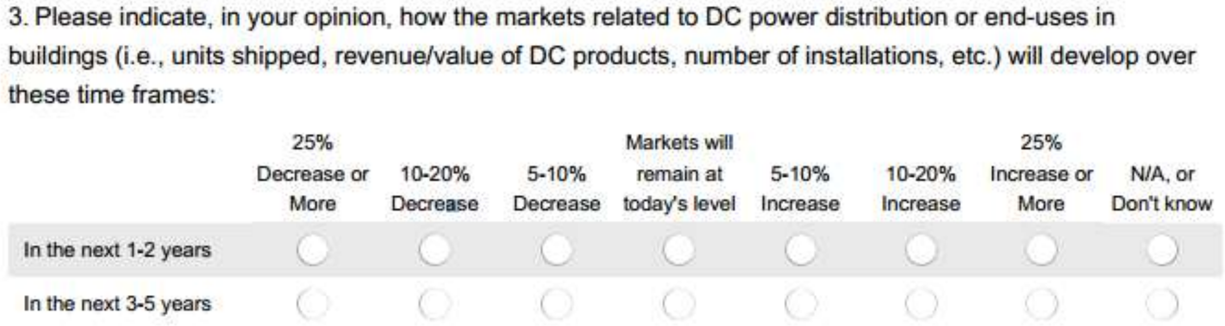
☐ N/A - Not involved in any DC-related activity

☐ Other (please specify)



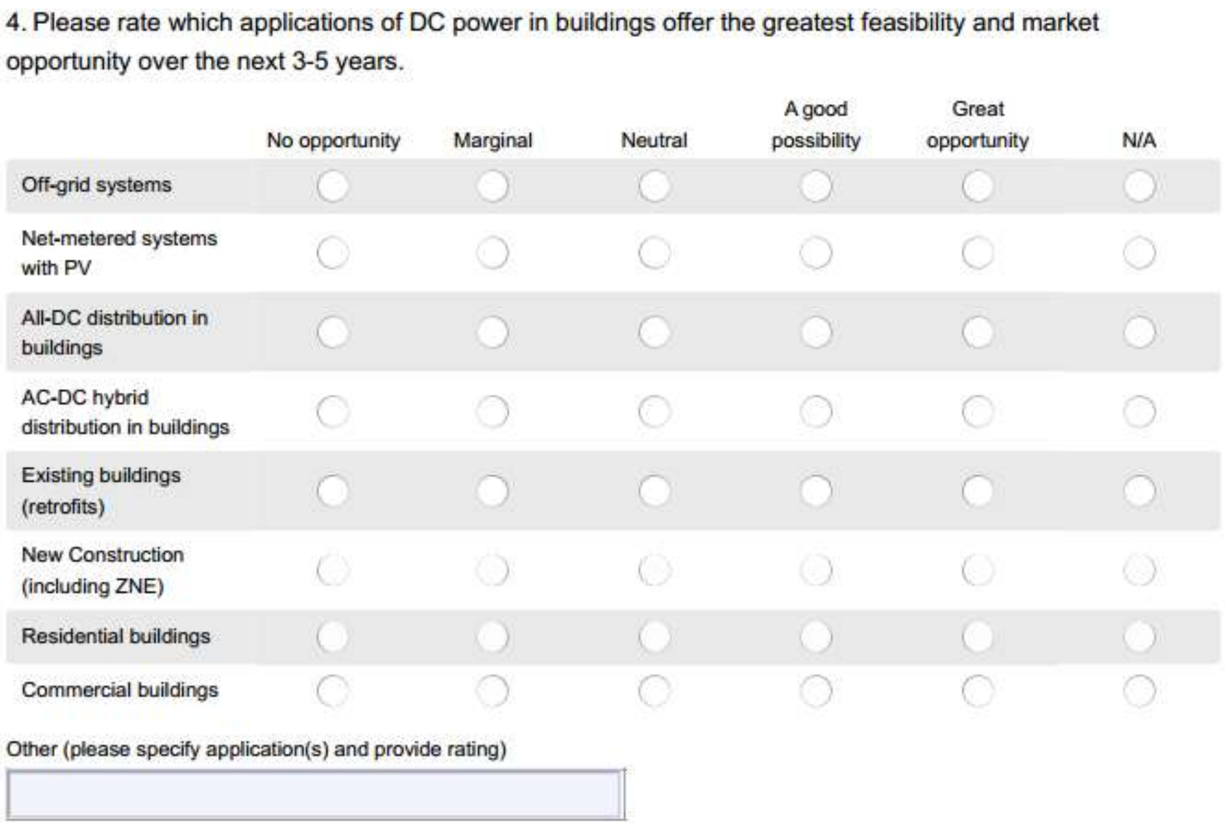
2. Please indicate your (or your organization's) anticipated involvement in DC power distribution or DC end-uses in buildings, over these time frames:

| | No involvement at all | Less involvement than today | Same involvement as today | More involvement than today | Maximum involvement | N/A, or Don't know |
|---|---|---|---|---|---|---|
| In the next 1-2 years | ○ | ○ | ○ | ○ | ○ | ○ |
| In the next 3-5 years | ○ | ○ | ○ | ○ | ○ | ○ |



3. Please indicate, in your opinion, how the markets related to DC power distribution or end-uses in buildings (i.e., units shipped, revenue/value of DC products, number of installations, etc.) will develop over these time frames:

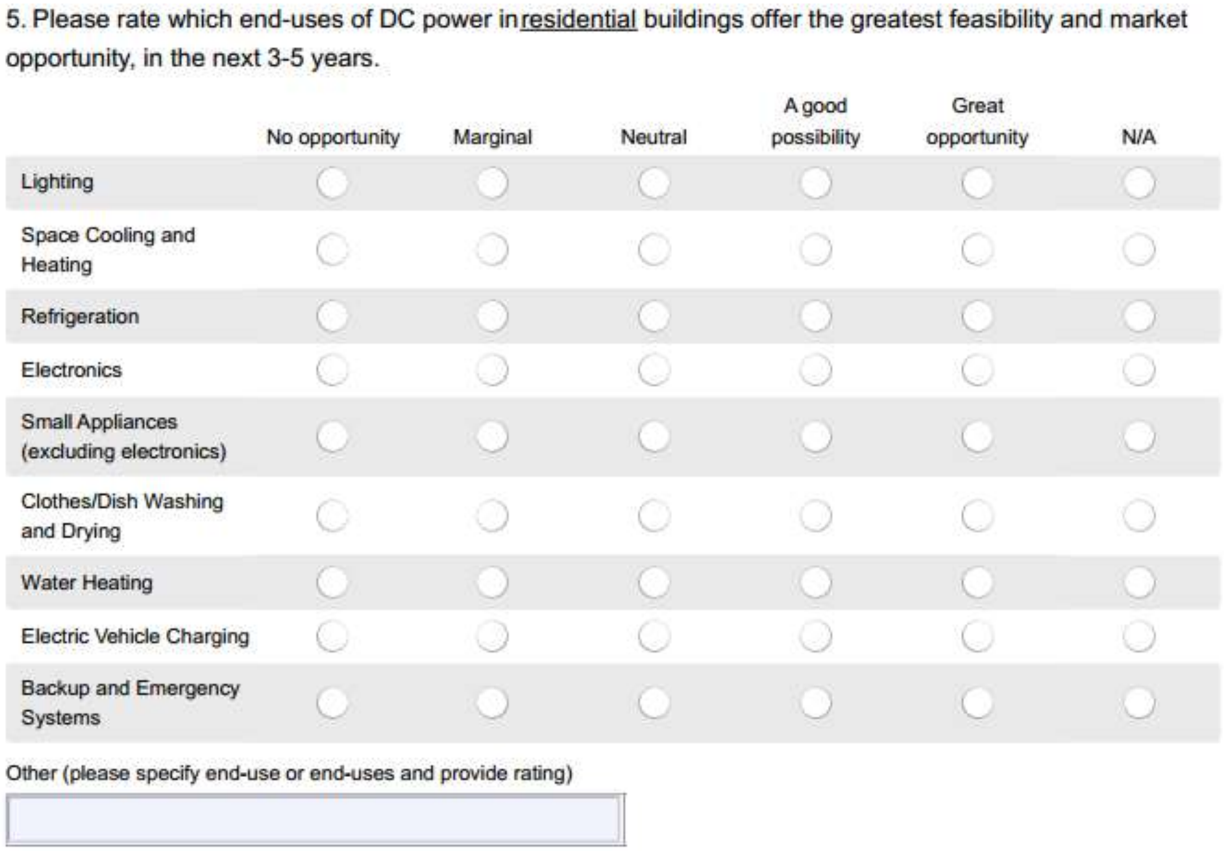
| | 25% Decrease or More | 10-20% Decrease | 5-10% Decrease | Markets will remain at today's level | 5-10% Increase | 10-20% Increase | 25% Increase or More | N/A, or Don't know |
|---|---|---|---|---|---|---|---|---|
| In the next 1-2 years | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| In the next 3-5 years | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |



4. Please rate which applications of DC power in buildings offer the greatest feasibility and market opportunity over the next 3-5 years.

| | No opportunity | Marginal | Neutral | A good possibility | Great opportunity | N/A |
|---|---|---|---|---|---|---|
| Off-grid systems | ○ | ○ | ○ | ○ | ○ | ○ |
| Net-metered systems with PV | ○ | ○ | ○ | ○ | ○ | ○ |
| All-DC distribution in buildings | ○ | ○ | ○ | ○ | ○ | ○ |
| AC-DC hybrid distribution in buildings | ○ | ○ | ○ | ○ | ○ | ○ |
| Existing buildings (retrofits) | ○ | ○ | ○ | ○ | ○ | ○ |
| New Construction (including ZNE) | ○ | ○ | ○ | ○ | ○ | ○ |
| Residential buildings | ○ | ○ | ○ | ○ | ○ | ○ |
| Commercial buildings | ○ | ○ | ○ | ○ | ○ | ○ |

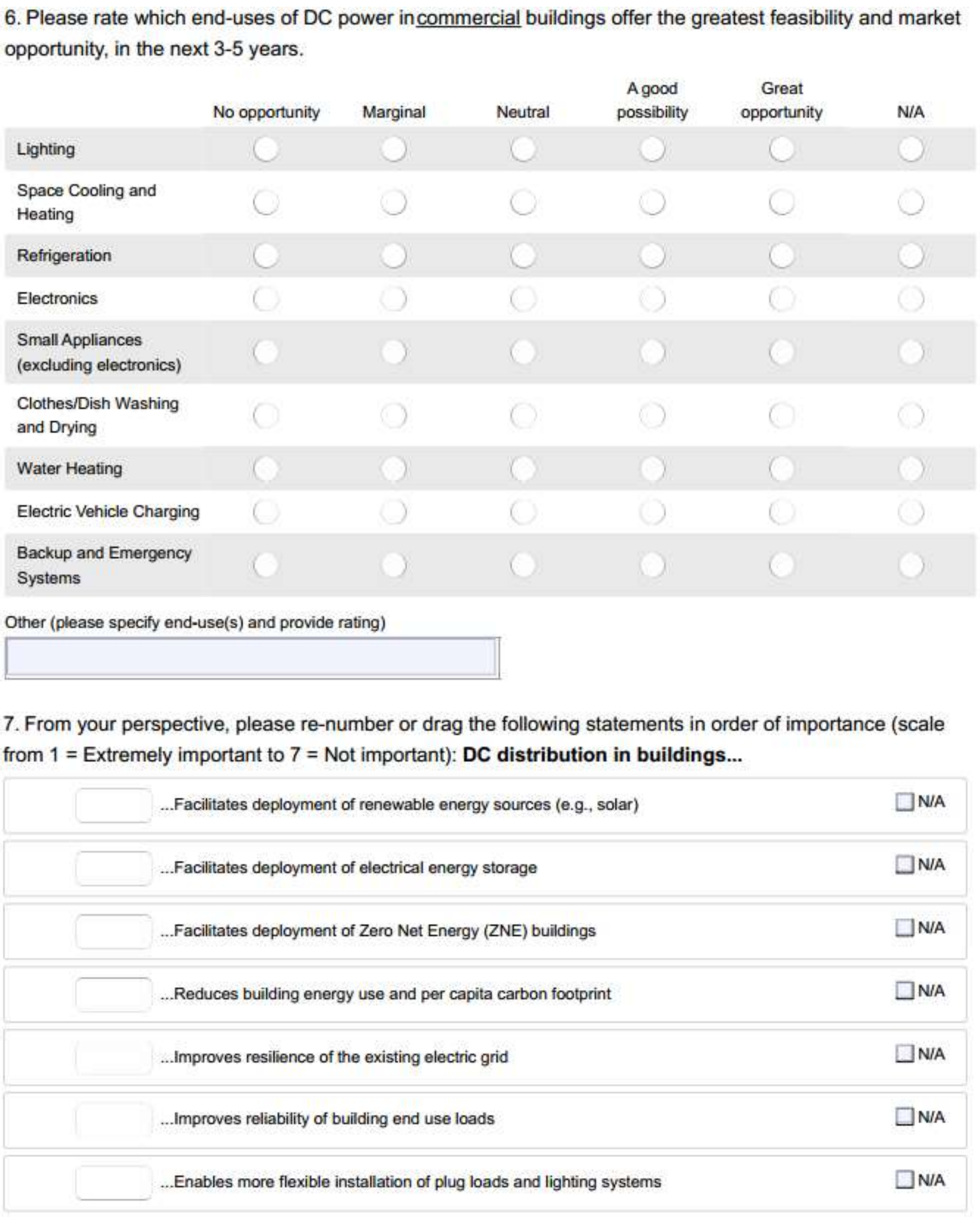
Other (please specify application(s) and provide rating)



5. Please rate which end-uses of DC power in residential buildings offer the greatest feasibility and market opportunity, in the next 3-5 years.

| | No opportunity | Marginal | Neutral | A good possibility | Great opportunity | N/A |
|---|---|---|---|---|---|---|
| Lighting | ○ | ○ | ○ | ○ | ○ | ○ |
| Space Cooling and Heating | ○ | ○ | ○ | ○ | ○ | ○ |
| Refrigeration | ○ | ○ | ○ | ○ | ○ | ○ |
| Electronics | ○ | ○ | ○ | ○ | ○ | ○ |
| Small Appliances (excluding electronics) | ○ | ○ | ○ | ○ | ○ | ○ |
| Clothes/Dish Washing and Drying | ○ | ○ | ○ | ○ | ○ | ○ |
| Water Heating | ○ | ○ | ○ | ○ | ○ | ○ |
| Electric Vehicle Charging | ○ | ○ | ○ | ○ | ○ | ○ |
| Backup and Emergency Systems | ○ | ○ | ○ | ○ | ○ | ○ |

Other (please specify end-use or end-uses and provide rating)



6. Please rate which end-uses of DC power in commercial buildings offer the greatest feasibility and market opportunity, in the next 3-5 years.

| | No opportunity | Marginal | Neutral | A good possibility | Great opportunity | N/A |
|---|---|---|---|---|---|---|
| Lighting | ○ | ○ | ○ | ○ | ○ | ○ |
| Space Cooling and Heating | ○ | ○ | ○ | ○ | ○ | ○ |
| Refrigeration | ○ | ○ | ○ | ○ | ○ | ○ |
| Electronics | ○ | ○ | ○ | ○ | ○ | ○ |
| Small Appliances (excluding electronics) | ○ | ○ | ○ | ○ | ○ | ○ |
| Clothes/Dish Washing and Drying | ○ | ○ | ○ | ○ | ○ | ○ |
| Water Heating | ○ | ○ | ○ | ○ | ○ | ○ |
| Electric Vehicle Charging | ○ | ○ | ○ | ○ | ○ | ○ |
| Backup and Emergency Systems | ○ | ○ | ○ | ○ | ○ | ○ |

Other (please specify end-use(s) and provide rating)

7. From your perspective, please re-number or drag the following statements in order of importance (scale from 1 = Extremely important to 7 = Not important): **DC distribution in buildings...**

...Facilitates deployment of renewable energy sources (e.g., solar) ☐ N/A

...Facilitates deployment of electrical energy storage ☐ N/A

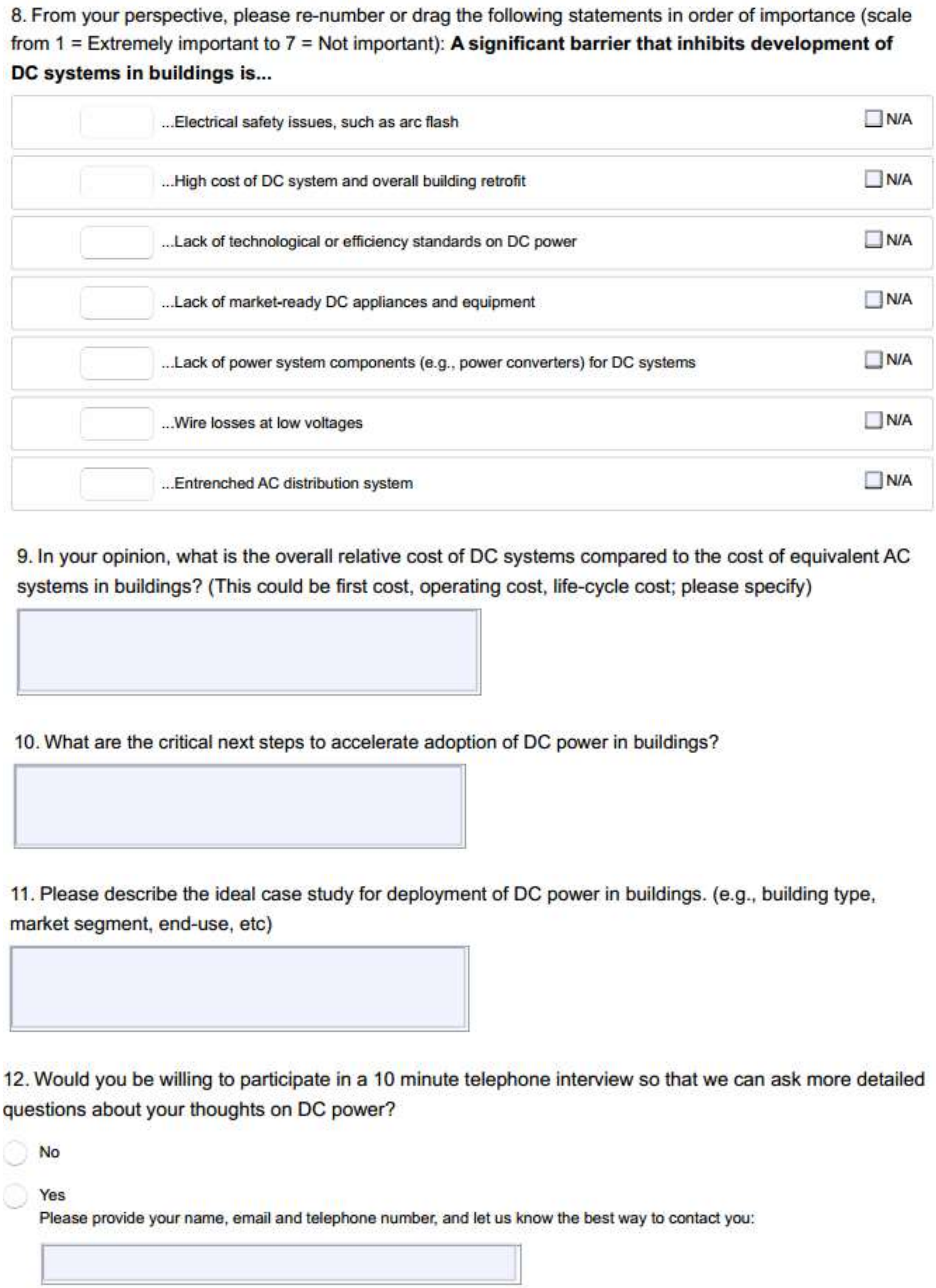
...Facilitates deployment of Zero Net Energy (ZNE) buildings ☐ N/A

...Reduces building energy use and per capita carbon footprint ☐ N/A

...Improves resilience of the existing electric grid ☐ N/A

...Improves reliability of building end use loads ☐ N/A

...Enables more flexible installation of plug loads and lighting systems ☐ N/A



8. From your perspective, please re-number or drag the following statements in order of importance (scale from 1 = Extremely important to 7 = Not important): **A significant barrier that inhibits development of DC systems in buildings is...**

| | | |
|---|---|---|
| | ...Electrical safety issues, such as arc flash | ☐ N/A |
| | ...High cost of DC system and overall building retrofit | ☐ N/A |
| | ...Lack of technological or efficiency standards on DC power | ☐ N/A |
| | ...Lack of market-ready DC appliances and equipment | ☐ N/A |
| | ...Lack of power system components (e.g., power converters) for DC systems | ☐ N/A |
| | ...Wire losses at low voltages | ☐ N/A |
| | ...Entrenched AC distribution system | ☐ N/A |

9. In your opinion, what is the overall relative cost of DC systems compared to the cost of equivalent AC systems in buildings? (This could be first cost, operating cost, life-cycle cost; please specify)

10. What are the critical next steps to accelerate adoption of DC power in buildings?

11. Please describe the ideal case study for deployment of DC power in buildings. (e.g., building type, market segment, end-use, etc)

12. Would you be willing to participate in a 10 minute telephone interview so that we can ask more detailed questions about your thoughts on DC power?

○ No

○ Yes

Please provide your name, email and telephone number, and let us know the best way to contact you:

## Interview Questions

### Initial Questions for All

- Feedback on questions from electronic survey: Request further comment, discuss clarifications on responses.
- What is the most exciting new development that you know about DC power in buildings?
- What is your current involvement in DC power and components?

### Researchers:

- What are the most pressing research questions that should be addressed?
- Could you name the "top" (3-5) papers in the field? (with regard to energy savings, benefits and barriers of DC distribution systems at the building level). Can you summarize the major findings of these papers and send us links?
- Please summarize your past, current, and future research findings on DC distribution in buildings. Can you send us pdfs/links?

### Industry (DC Hardware and Appliance Manufacturers):

- What components/appliances do you currently manufacture or sell (by component type: end-use equipment, distribution equipment, generation/storage/conditioning equipment).
- What factors do they consider when deciding to participate/expand in the market? (i.e., market demand, standards, profitability, etc.) What key signs would you need to see to participate in the DC market?
- What components/appliances are currently under development? Do you have any future plans that you would like to share?
- At what scale will DC production become competitive with AC?
- At what scale will hybrid AC-DC become competitive with AC?

### A&E Firms & Contractors (Architects, Engineers, Electrical Contractors, Security Systems, Telecom/Network Installers):

- Do you have any plans to design/install/construct a DC system at the building level?
- Imagine for you next project you were asked to design a dc system. What will be your biggest challenges and opportunities? In designing/installing/constructing a DC system, what are the most important considerations that should be taken into account?
- How do you think DC power can be used most effectively in ZNE buildings?
- What would keep you from putting DC in your next building? What is the typical profile of a client who would be interested in DC? What is your perception of how your clients respond to DC systems (safety, convenience, availability, etc.)?
- At scale do you think DC will be more/less/equally expensive as DC?
- Do you have any cost data?

### Utility Staff and Utility Regulators

- What are your upcoming and long-term plans for DC power on the customer side of the meter?
- What role does DC power play in any ZNE programs you have?

- Do you think that DC applications and deployment could help in improving the resilience and reliability of the existing grid, and, if so, how?
- How would an integrating technology, like DC power, be treated in programs?
- Are there any other projects that we should be aware of?

**Environmental Organizations**

- What's the most effective way to accelerate DC uptake? (policy and market development, etc)
- What are the environmental pros and cons with DC power in buildings (air quality, toxics, EMF)? What are potential mitigations?

**Close-out Questions for All**

- Is there anything you would like to add, or tell us about?
- Are there any other projects that we should be aware of or talk to?
- Would you like us to use your name if we quote you?

# APPENDIX E:
# EMerge Alliance Reference List for Direct Current Codes and Standards

| **MANDATORY STANDARDS - apply to all electrical installations** | | | |
|---|---|---|---|
| **Standard** | **Description** | **Region** | **Status** |
| NFPA 70 | US National Electrical Code Addresses fundamental principles of protection for safety. Applies to LVDC (under 1000V). | US | 2014 version released |
| Article 250 Section VIII | Grounding & Bonding - Direct Current Systems - Articles 250.160-250.169 | US | 2014 version released |
| Article 393 | Low-Voltage Suspended Ceiling Power Distribution Systems | US | 2014 version released |
| Article 408 | Switchboards, Switchgear, and Panellboards | US | 2014 version released |
| Article 480 | Storage Batteries | US | 2014 version released (2017 revisions) |
| Article 690 | PV Systems over 600 Volts | US | 2014 version released (2017 revisions) |
| NFPA 70E | Standard for electrical safety in the workplace - Includes LVDC. | US | 2014 version released |
| NFPA 70B | Recommended practice for electrical equipment maintenance. | US | 2014 version released |
| **GENERAL APPLICATION STANDARDS** | | | |
| **Standard** | **Description** | **Region** | **Status** |
| EMerge Occupied Space V. 2.0 | DC power distrib. Req'mts for commercial bldg. interiors | Global | Released |
| EMerge Residential V1.0 | DC power distrib. Req'mts for residential bldgs. | Global | Scheduled Release 2016 |
| EMerge Commercial Bldg. V1.0 | DC power distrib. Req'mts for commercial bldg. and Campus | Global | Scheduled Release 2016 |

| | | | |
|---|---|---|---|
| USB-PD | Extra Low Voltage DC for Desktop and Personal Electronics | Global | Released |
| PoE | Extra Low Voltage DC for ICT Equipment 24 & 48V DC; 35 Watts | Global | Released |

| EUROPEAN AND GLOBAL STANDARDS | | | |
|---|---|---|---|
| **Standard** | **Description** | **Region** | **Status** |
| DIN VDE 0100-100:2009-06 | Low-voltage electrical installations – Part 1: Fundamental principles, assessment of general characteristics, definitions | Europe | Released |
| DIN VDE 0100-410:2007-06 | Low-voltage electrical installations – Part 4-41: Protection for safety - Protection against electric shock | Europe | Released |
| DIN VDE 0100-530:2011-06 | Low-voltage electrical installations – Part 530: Selection and erection of electrical equipment – Switchgear and controlgear | Europe | Released |
| DIN VDE 0100-540:2012-06 | Low-voltage electrical installations – Part 5-54: Selection and erection of electrical equipment – Earthing arrangements and protective conductors | Europe | Released |
| DIN EN 61557-2:2008-02 | Electrical safety in low voltage distribution systems up to 1000 V a.c. and 1500 V d.c. – Equipment for testing, measuring or monitoring of protective measures, Part 2: Insulation resistance | Europe | Released |
| DIN EN 61557-8:2007-12 | Electrical safety in low voltage distribution systems up to 1000 V a.c. and 1500 V d.c. – Equipment for testing, measuring or monitoring of protective measures Part 8: Insulation monitoring devices for IT systems | Europe | Released |
| DIN EN 61557-9:2009-11 | Electrical safety in low voltage distribution systems up to 1000 V a.c. and 1500 V d.c. – Equipment for testing, measuring or monitoring of protective measures Part 9: Equipment for insulation fault location in IT systems | Europe | Released |
| IEC 60050-614 | International Electrotechnical Vocabulary - Part 614: Generation, transmission and distribution of electricity - Operation | Global | Released |
| IEC 60034-1 | Rotating electrical machines - Part 1: Rating and performance | Global | Released |

| Standard | Description | Region | Status |
|---|---|---|---|
| IEC 61362 | Guide to specification of hydraulic turbine governing systems | Global | Released |
| IEC 60308 | Hydraulic turbines - Testing of control systems | Global | Released |
| IEC 61992 | DC switchgear | Global | Released |
| IEC 60038:2009 | Standard Voltages | Global | Released |
| IEC 62848-1 | DC Surge arresters | Global | Released |
| IEC 62924 | Stationary energy storage system for DC traction systems | Global | Released |
| IEC 62053-41/Ed1 | ELECTRICITY METERING EQUIPMENT (DC) - PARTICULAR REQUIREMENTS | Global | Released |
| IEC 61378-3 Edition 1.0 (2006-04-27) | Converter transformers | Global | Released |
| IEC 62620 | Performance of lithium ion batteries for industrial apparatus (unit battery/ battery pack) | Global | Released |
| IEC/TS 62735-2 | D.C. Plugs and socket-outlets to be used in indoor access controlled areas<br>- Part 2: Plug and socket-outlet system for 5,2 kW | Global | Released |
| IEC 61869-14 | Specific Requirements for DC Current Transformers (CDV) | Global | Released |
| IEC 61869-15 | Specific Requirements for DC Voltage Transformers (CDV) | Global | Released |
| IEC 61180 /Ed1 | HIGH-VOLTAGE TEST TECHNIQUES FOR LOW-VOLTAGE EQUIPMENT<br>Definitions, test and procedure requirements, test equipment | Global | Released |
| IEC 60947-2 | Low-voltage switchgear and controlgear – Part 2: Circuit-breakers | Global | Released |
| IEC 60947-3 | Low-voltage switchgear and controlgear - Part 3: Switches, disconnectors, switch-disconnectors and fuse-combination units. | Global | Released |

| | | | |
|---|---|---|---|
| IEC 61439-X | LOW-VOLTAGE SWITCHGEAR AND CONTROLGEAR ASSEMBLIES –Part X: Assemblies for photovoltaic installations | Global | Released |
| **TELECOM AND DATA CENTERS** | | | |
| **Standard** | **Description** | **Region** | **Status** |
| ETSI EN 300 132-3-0 | Power supply interface at the input to telecommunications and datacom (ICT) equipment | Europe | Released |
| ETSI EN 3061605 | Earting and bonding for 400VDC systems | Europe | Released |
| ITU -T L.1200 | Specification of DC power feeding interface | Global | Released |
| EMerge Data/Telecom V.1.1 | DC power distribution requirements in data centers/telecom | Global | Released |
| YD/T2378-2011 | 240VDC systems | China | Released |
| YD/T XXXX-201X | 336V direct current power supply systems for telecom | China | Approval process |
| ATIS - 0600315.01.2015 | Voltage levels for 400VDC systems | US | Released |
| IEC 62040-5-3 | DC UPS test and performance standard | Global | Scheduled release 2016 |
| IEC 62040-5-1 | Safety for DC UPS | Global | Work started |
| IEC TS62735-1 | 400VDC plug & socket outlet | Global | Released |
| YD/T 2524-2015 | 336V HF switchmode rectifier for telecommunication | China | Approval process |
| **ELECTRICAL VEHICLE CHARGING** | | | |
| **Standard** | **Description** | **Region** | **Status** |
| CHAdeMO | DC fast charging | | Released |
| SAE/CCS | DC charging | | Released |