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Review of DC Power Distribution in Buildings: A Technology and Market Assessment

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Disclaimer

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1. Introduction and Background

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, 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, our power systems need to integrate resources and loads that are natively DC: distributed generation, storage (batteries), and end-use devices (electronics, DC motors with variable-speed drives, etc.). DC 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, thus helping California meet its ZNE and global climate change goals.

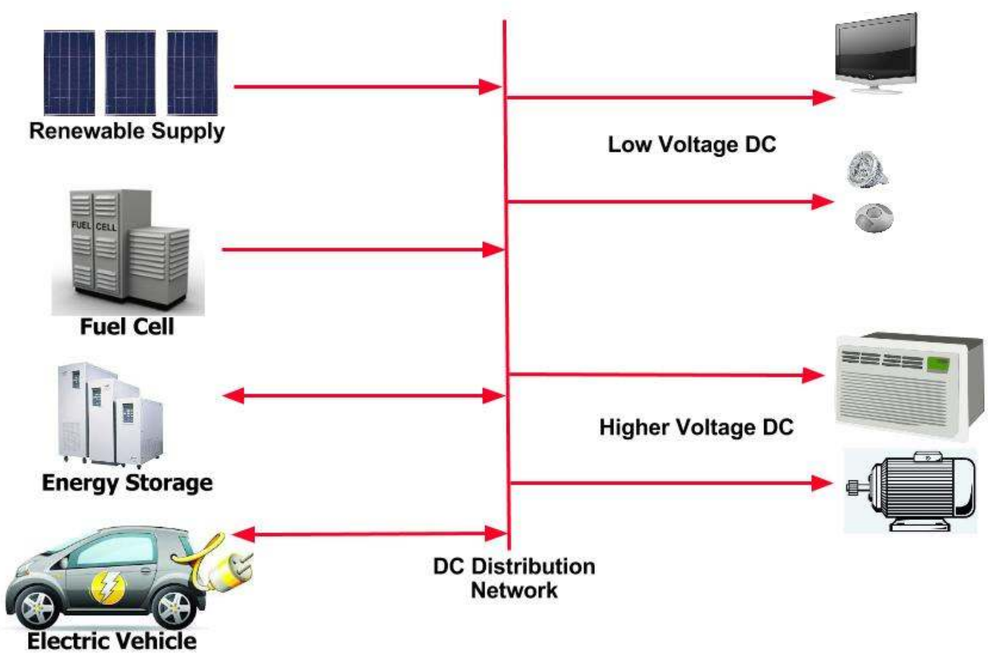

Figure 1. Direct Integration of DC Generation and End-Use Loads

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 (HVDC) transmission systems used in the United States, Europe, and Asia. However, there is very little performance information on DC systems in U.S. residential or commercial buildings.

This report first starts with a review of existing academic and market literature on 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. The report concludes with a summary of the findings and suggested next steps based on all the information compiled and collected.

2. Literature Review and Information

The research team conducted a review and analysis of recent existing literature on DC power distribution in both entirely and hybrid AC-DC buildings. The literature review, consisting of approximately 200 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, we 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 our main literature review findings related to these topics of interest. See appendix A for a list of the references used in this study. [1]

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. The presence of battery storage, which is a DC source, and EVs in the commercial sector (primarily because EVs are large DC loads that synchronize well with PV generation in a commercial building), can increase savings. We also note that modeling studies produce a wider range of energy savings compared to experimental studies. This range in savings estimates is due primarily to the actual or assumed power system component efficiencies (AC/DC, DC/DC, DC/AC converters), which, to a large extent, determine the energy savings potential. However, other system parameters, such as system configuration, DC voltage, and coincidence of PV and building loads are also important factors for 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). We note that converter efficiencies are dependent both on voltage conversion levels, as well as converter power ratings.

[1] These references are also publicly available at the project's webpage: http://dc.lbl.gov/epic-research-project/reference-list

Table 1. DC 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.) No battery storage	5% residential 8% commercial [2]
	All-DC residential building	5% w/o battery 14% w/ battery [3]
	All-DC residential building	5.0% conventional building 7.5% smart bldg. (PV-load match) [4]
Experimental	LED** DC system (no battery storage)	2% measured 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 EV, No battery storage	2.7%–5.5% daily energy savings [8]

*All scenarios include a local DC source, (typically PV). ** 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.

Table 2. Power System Component Peak[2] 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) 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

*MPPT = maximum power point tracker

[2] 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.

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:

1. *Bosch*, in collaboration with the California Lighting Technology Center (CLTC), is developing a demonstration project in Chino, California, funded by the California 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 PV powered, direct-DC, 380V distribution system powering lighting and forklift chargers. [9]
2. *The Alliance for Sustainable Colorado* is developing a retrofit of a 40,000 square foot commercial building from AC to DC distribution inside the building. The building will be fed by PV power and other renewable DC sources, will include battery storage, and will be capable 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. [10]
3. *NextHome in Detroit*, Michigan, is a demonstration DC test bed developed by NextEnergy, featuring PV-supplied direct-DC power for LED lighting, ceiling fans, a DC computing center, floor heating, home appliances, battery storage, and bi-directional EV charging. The Next Home features a PV 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. [11]
4. *Aquion Energy*, an energy storage company, and *Ideal Power*, a power converter manufacturer, have partnered to install a microgrid showcasing their technologies at Stone Edge Farm, an organic winery in Sonoma, CA. The system includes a 32 kW PV array, a 350 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. [12]
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 kilowatt (kW) PV array powering 44 DC induction lights, 4 DC ceiling fans, and a 100 kW lithium-ion (Li-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. [13] 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, and is expected to be completed by 2018.

7. *Philips* is developing a 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. [14]
8. *ARDA Power* has designed a DC microgrid which 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 bi-directional inverter, AC and DC loads. [15]
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* (BUCEA) 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. [16]
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 bi-directional inverter and battery storage, and that a hybrid DC-AC building distribution system would be more suitable for today’s commercial buildings. [17]
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. [18]

We note that 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.

Figure 2. Worldwide DC Case Studies

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 bi-directional rectifier for the DC system was not accounted for in the cost calculation.
Another study by Foster Porter et al. [19] 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. [20], 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 [21] report that electricians typically charge by the number of receptacles in the residential sector and state that due to 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. [22] 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 [23], 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 [24]. Similarly, Eaton claims that their PoE DC lighting systems can lead to a 40 percent reduction in materials and installations costs [25].

Non-Energy Benefits and Barriers

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], [26]–[29]. Sannino et al [30] 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 [31] claim that, by eliminating power distribution units and the inverter on the output of the uninterruptible power supply (UPS) system, data centers using a 380V DC distribution system are 200 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. [32] 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 bi-directional DC/DC converters.

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 [19], [26], [28] 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.

3. Stakeholder Input

A. 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 photovoltaics (PV), battery storage, and electric vehicle (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. Then, as demand for DC products grows, economies of scale will result in reduced costs to consumers.
- Stakeholders need to reach agreement on DC voltages, so that products can be designed around international DC standards. Common voltage levels are 24 volt (V), 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" (e.g., 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.
- Power over Ethernet (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[3], the energy use requirements for ZNE over the building's lifetime, the sizing of battery storage (i.e., initial requirement versus likely requirement over the life of the building), and the allocation of shared renewables in community-scale projects.

[3] We note that a report on this specific issue (A Common Definition for Zero Energy Buildings) was published in 2015.
https://energy.gov/sites/prod/files/2015/09/f26/bto_common_definition_zero_energy_buildings_093015.pdf

- 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 (e.g., 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 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 National Electrical Code (NEC). These standards have been developed in the last 10 years, with the EMerge Alliance leading the way in North America.

B. Highlights of Stakeholder Surveys and Interviews

As one part of this research effort, we 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.

Online Surveys

We 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).[4] We received 39 survey responses, of which four 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

[4] The survey questionnaire is available in Appendix D

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. (See Figure 3.)

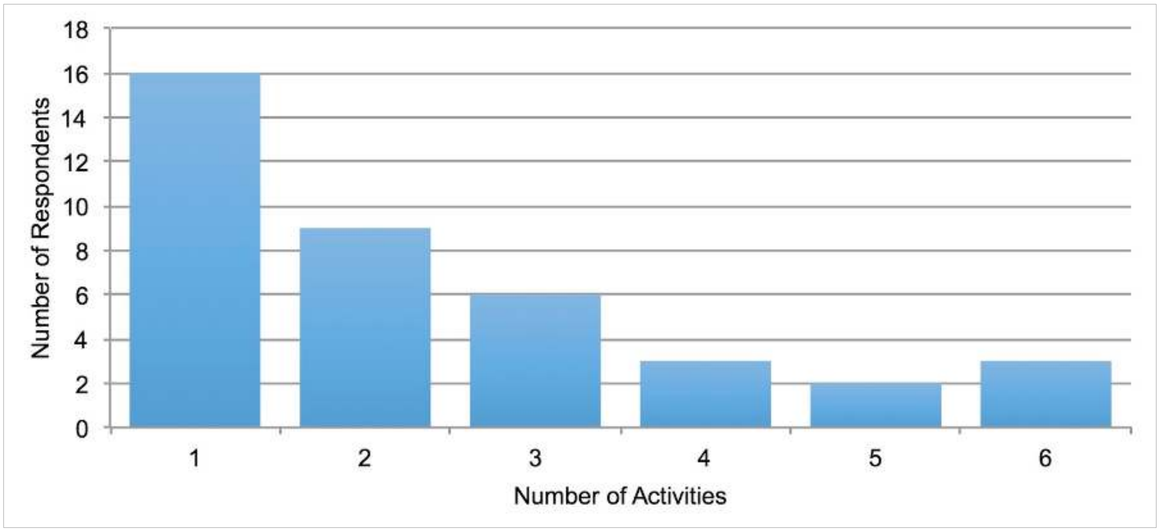

Figure 3. Number of Respondent Activities (Q1)

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.

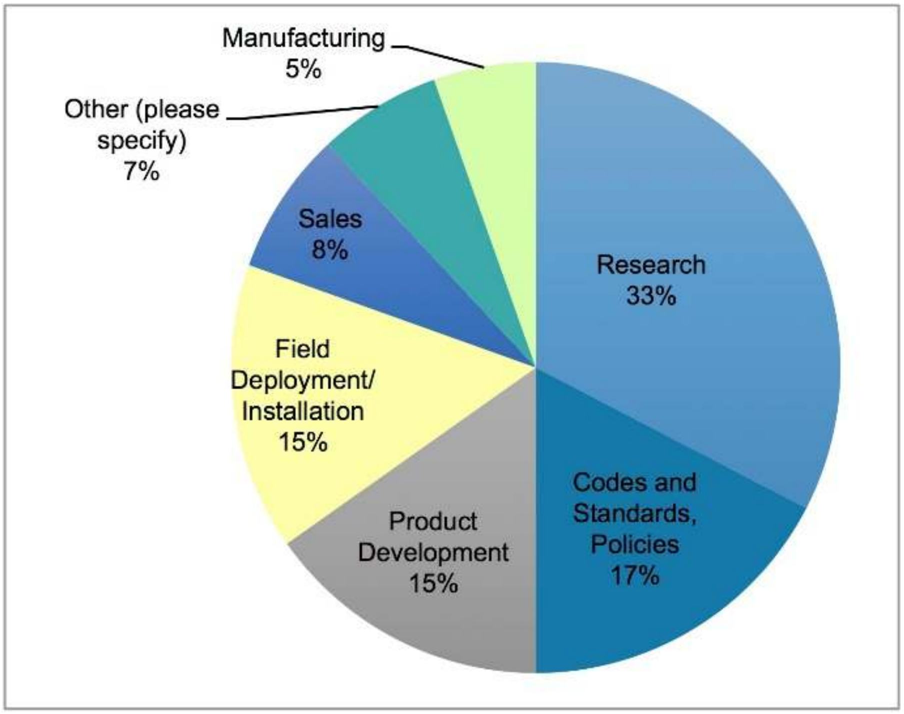

Figure 4. Types of Respondent Activities (Q1)

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.

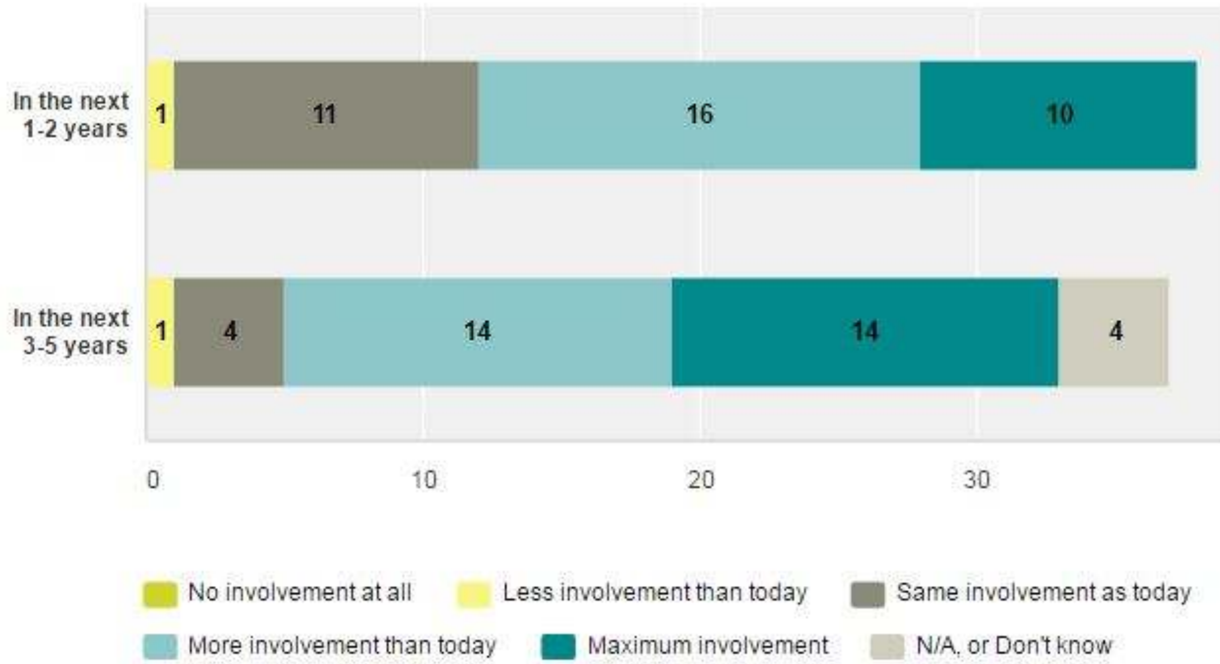

Figure 5. Respondents' Anticipated Involvement in DC Power in the Foreseeable Future (Q2)

- Question 3 Responses: In the next one to two years, 30 percent of respondents anticipate a 10 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.

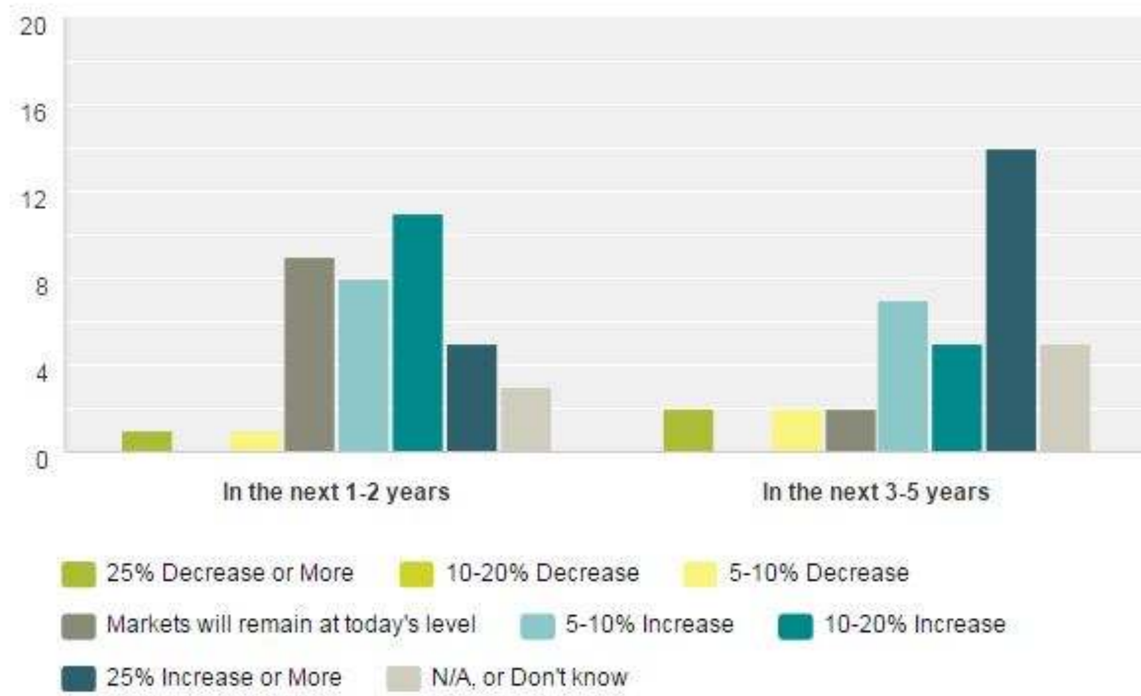

Figure 6. Respondents' Anticipated Market Development of DC Power in the Foreseeable Future (Q3)

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.

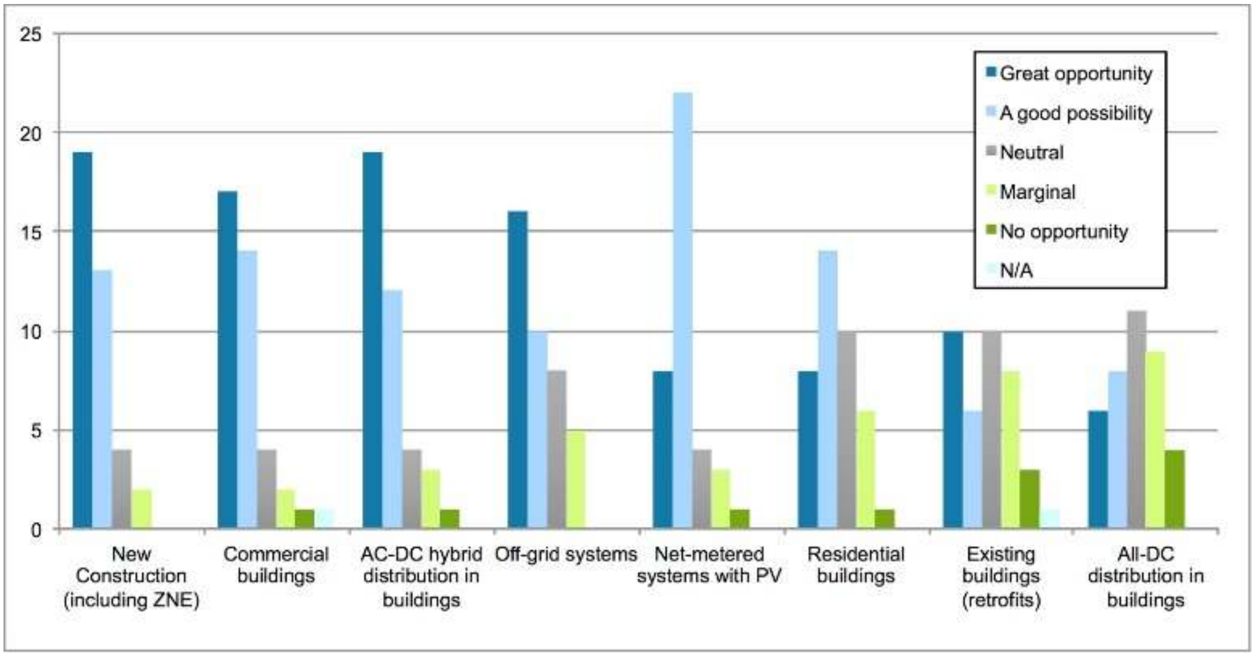

Figure 7. Respondents' Rating for Applications of DC Power in Buildings for the Next 3–5 Years (Q4)

- 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/dish washing and drying, and water heating were last.

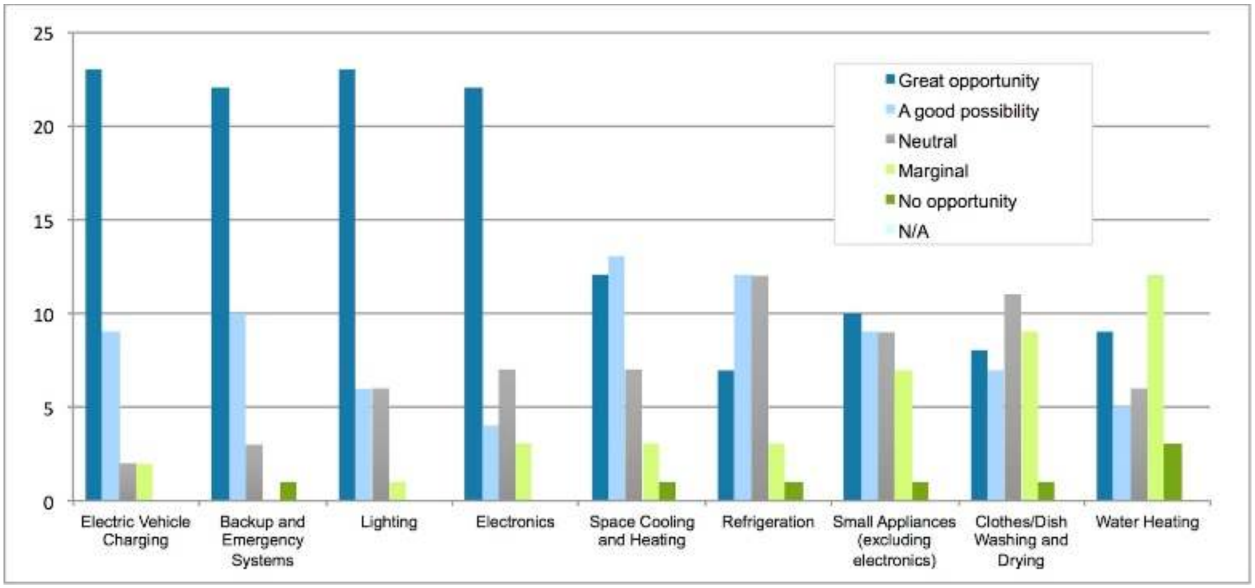

Figure 8. Respondents' Rating for End Uses of DC Power in Residential Buildings for the Next 3–5 Years (Q5)

- 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 dish/clothes washing and drying were last.

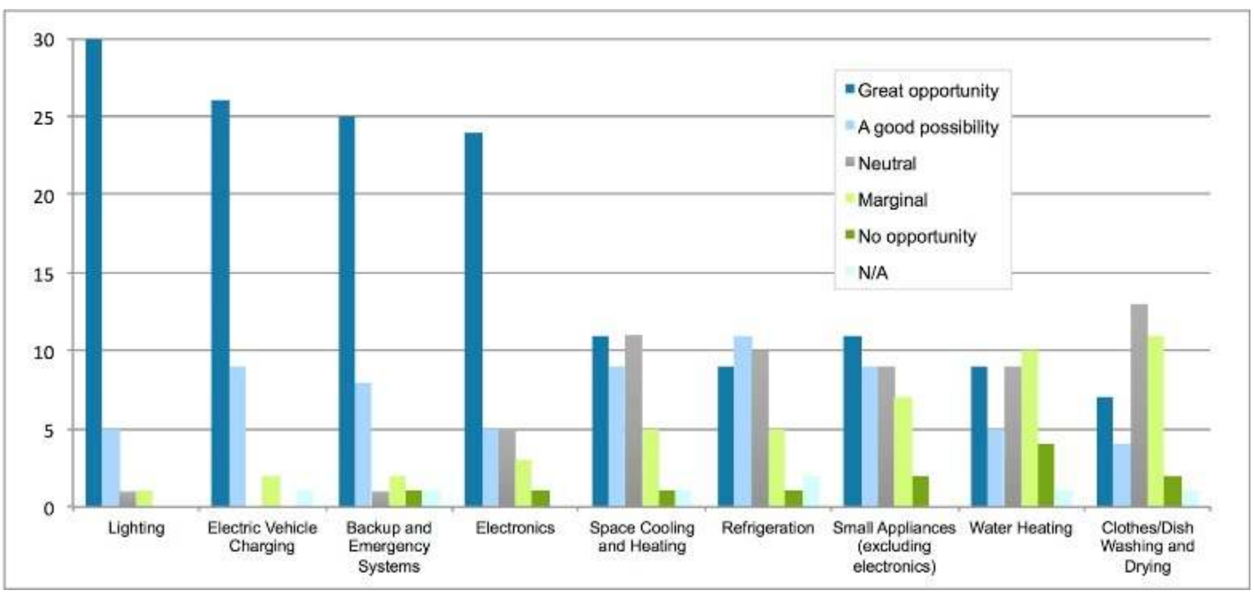

Figure 9. Respondents' Rating for End Uses of DC Power in Commercial Buildings for the Next 3–5 Years (Q6)

- 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.

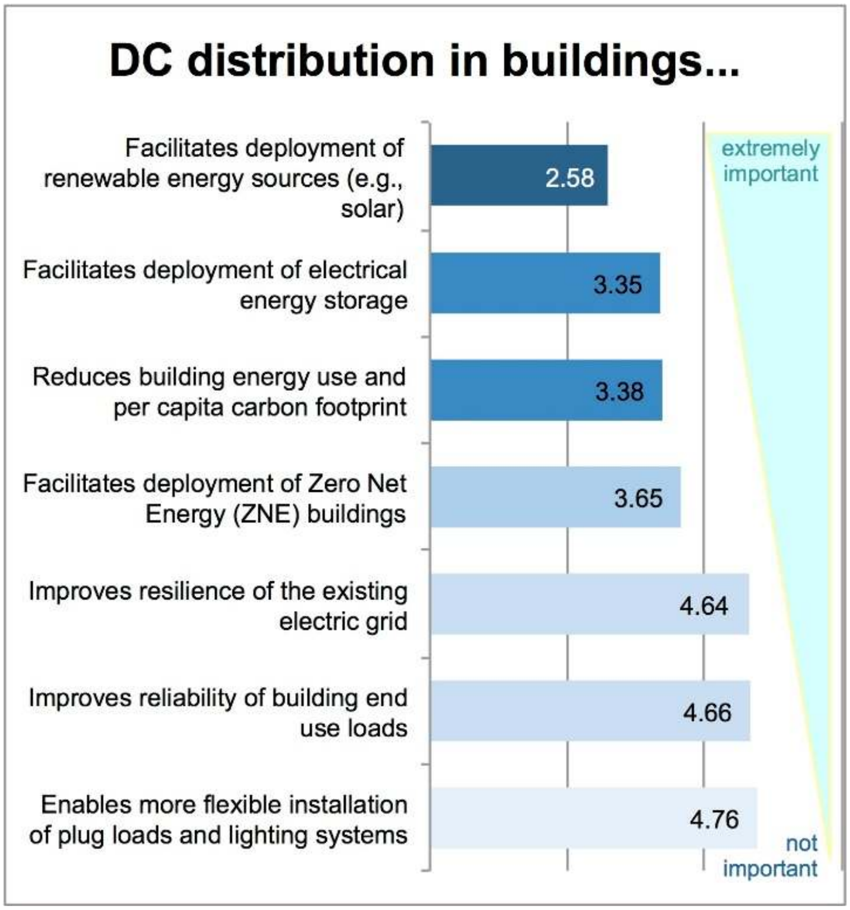

Figure 10. Respondents' Rating of Benefits Associated with DC Distribution in Buildings (Q7)

- 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.

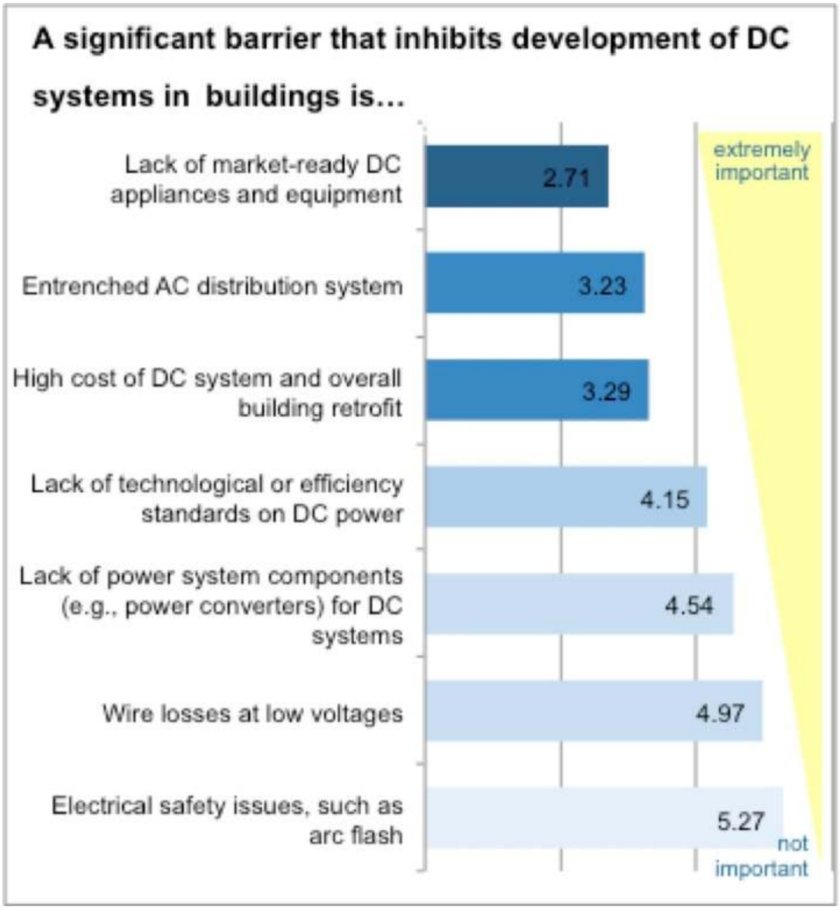

Figure 11. Respondents' Rating of Barriers Associated with DC Distribution in Buildings (Q8)

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. See Figure 12 for details.

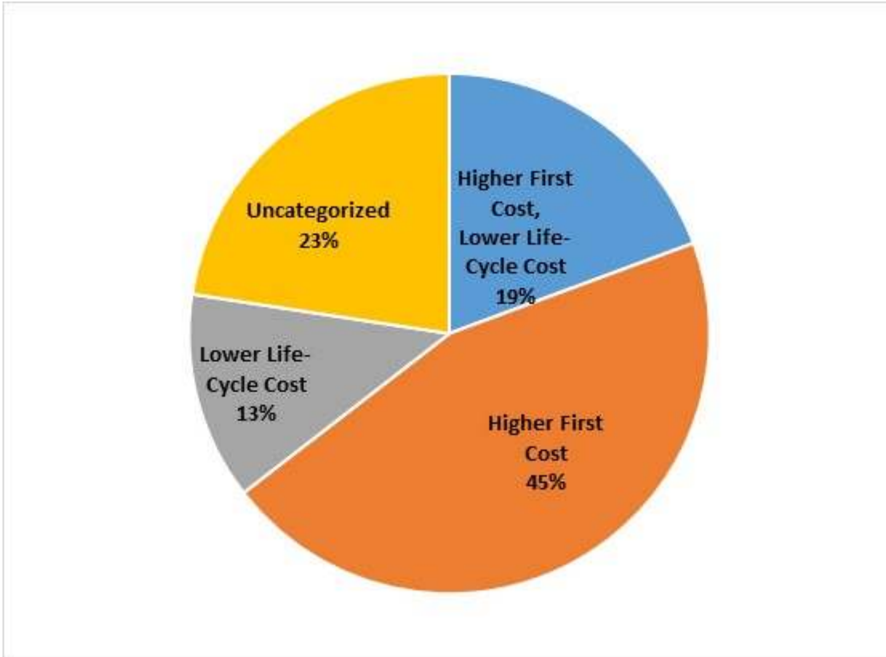

Figure 12. Respondents' Rating of DC System vs. AC System Cost (Q9)

- Question 10 Responses: Regarding the next critical steps to accelerate adoption of DC power in buildings, we received 31 responses. The top categories were the development of DC –ready products and codes & 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. See Figure 13.

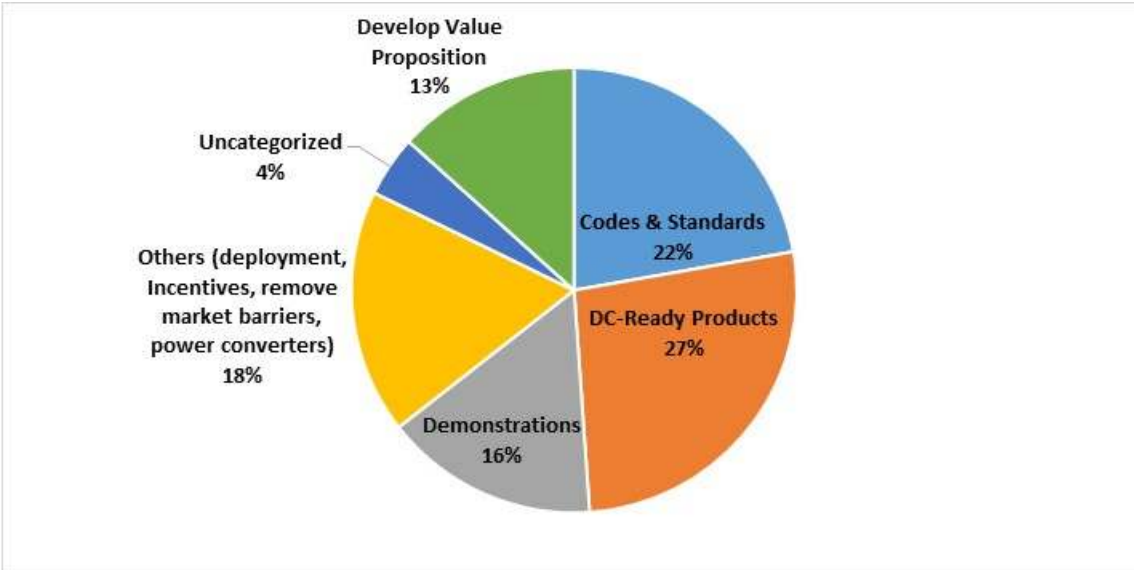

Figure 13. Categorization of the Critical Next Steps to Accelerate Adoption of DC Power in Buildings, based on Respondents' Feedback (Q10)

- 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 & plug loads. Note that PV integration was an overarching theme throughout responses.

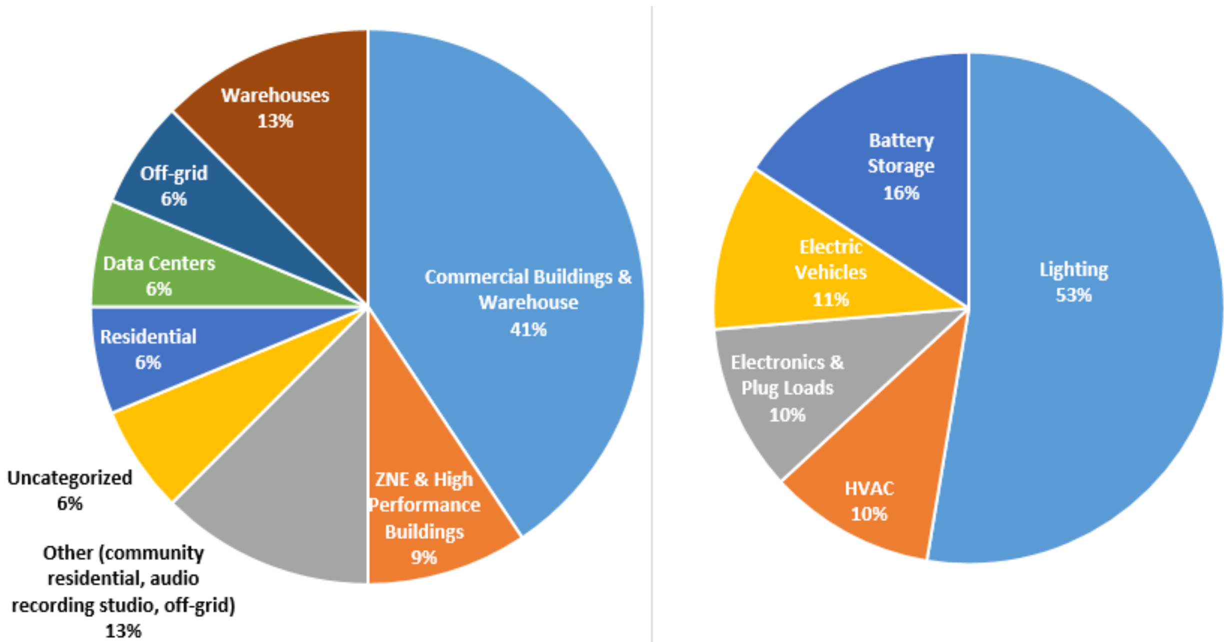

Figure 14. Respondents' Ranking the Ideal Case Studies for DC in Buildings Categorized by Building Type (left) and End-Use Application (Q11)

Telephone Interviews

At the end of the survey questionnaire, participants were provided a further option to participate in an in-depth telephone interview.[5] From the individuals who elected to be considered for a telephone interview, we selected 10 respondents, 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, in order 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.

[5] 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 (NREL) noted that DC can have a cascading effect on the energy used by HVAC systems.

4. Summary and Discussion

This study focuses on how DC power can help meet the AB 32 and related California goals for ZNE residential and small commercial buildings with battery storage and EV charging. For these types of ZNE buildings, a DC infrastructure can save energy and may have other, non-energy, benefits, such as increased resiliency, reliability, and power quality, and better integration of communications and controls. In evaluating these benefits, it is critical to understand the full picture of energy and non-energy benefits, cost-effectiveness, market and technological barriers, and current market adoption of DC distribution in buildings. This section discusses our findings on these topics, based on our research to date, through review of the literature, conclusions from the stakeholder workshop, and feedback from electronic surveys and interviews.

Market Adoption

Although DC power is often perceived as a radical departure from mainstream electricity distribution, DC power systems have been widely used for a long time in vehicles and boats. DC also has long powered traditional telephone service, and more recently USB (universal serial bus) and PoE in buildings. The number of native DC sources and end uses has been on the rise in the past few years, with the proliferation of PV systems [35], battery storage [36], LED lighting [37], and consumer electronics. These developments have spurred renewed interest in DC and AC-DC hybrid distribution systems in buildings. As discussed in Chapter 2, an increasing number of various DC case studies and demonstration projects are underway and under development in the United States and worldwide. Concurrently, DC systems are being commercially implemented in data centers and for lighting systems in commercial buildings, primarily with PoE. Several international and domestic organizations (e.g., EMerge Alliance, Alliance to Save Energy, Passive House Institute, CLASP, and others in the United States) are advocating for DC, spurring research and raising awareness.

However, 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 following:

- A lack of cost-competitive, market-ready DC-ready appliances and power distribution system components, including DC system protection schemes.
- A lack of mature and DC-explicit standards and guidelines (e.g., for electrical protection, physical connectors, etc.).
- Limited awareness of DC systems and their potential benefits among potential specifiers and purchasers.
- High capital costs of retrofitting legacy AC systems, which present a particularly large barrier for such applications.

Discussions with stakeholders have revealed that these barriers are interdependent. For example, manufacturers are less likely to develop DC-ready appliances when comprehensive standards are not available. Utilities and regulatory bodies are less likely to support and incentivize DC systems when their potential benefits have not been substantiated by sufficient research and demonstration projects. On a bright note, the amount of research, the number of demonstration projects worldwide and in the United States, the increasing involvement of appliance and converter manufacturers entering this field in the past one to two years, and the widespread installation of on-site PV systems may lead to a critical mass for widespread adoption of DC systems in buildings in the future.

Energy Savings

One of the main arguments in favor of DC distribution in buildings is the potential for energy savings. Our literature review reveals a significant variance in energy savings, which is more prominent in modeling studies than in experimental findings. As discussed in Chapter 2, calculated energy savings from modeling studies range between 2 and 14 percent, whereas in experimental studies savings range between 2 and 8 percent.

The following factors 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 currently occur in a typical AC system with PV and battery storage.
- **Coincidence of PV output and load:** When power demand occurs during solar PV generation, DC can be fed directly from the PV array to DC-ready appliances in the building. At the same time, a direct-DC system with high coincidence of PV and load usage 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 (i.e., efficiencies of inverters and power supply/rectifier efficiencies at the appliance level)—can determine energy savings. In the foreseeable future potential increased demand and R&D 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 (and more so in systems with battery storage), and are therefore expected to keep their theoretical efficiency advantage.
- **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.

Non-Energy Benefits and Barriers

According to several studies, DC power distribution in buildings has important non-energy benefits compared to AC power. DC systems allow for easier integration of power, communications, and controls with certain DC standards (PoE and USB). Expanded use of renewables also reduces greenhouse gas emissions, extending the energy savings of DC power in this critical dimension. In addition, 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 (i.e., to be islanded from the grid) can improve resiliency, an increasingly valuable characteristic as utilities and government agencies are addressing disaster mitigation. Furthermore, 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 from 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.

Cost

As discussed in Chapter 2, and based on survey and interview feedback, DC systems have the *potential* of having a lower first cost compared to AC systems in buildings, primarily due to the use of less components and simplicity of circuitry. 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 systems cost 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 (i.e., 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.

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 (IT) standards—namely PoE and 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 [38], 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. Those include the following:

- Standardization for DC voltages, including voltage variation, particularly for application with battery storage.
- Standardization of 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.

5. Conclusions and Future Research

To summarize the state of the industry for DC power in buildings, we have drawn on several information sources, including a review of the academic and industry literature, a stakeholder workshop, a stakeholder survey, and in-depth stakeholder interviews.

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. Currently, these elements are lacking. 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 (e.g., energy savings) when deciding to promote and incentivize a specific technology. However, the strategic value of DC power requires a *systems* approach—encompassing the easier integration of on-site renewable generation with digital building controls, battery storage, and EV charging, to energy savings from reduced power losses, to the potential for increased resiliency and reliability.

For this reason, and as expressed by stakeholders during the workshop, surveys, and interviews, additional field demonstrations of DC power distribution in low-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. These demonstrations should include multiple vendors' systems so the results can be generalized to advance our overall knowledge of DC power in buildings.

The domestic market for DC power in buildings can look to advancements and lessons learned from the international market. Japan, China, and several European countries have invested in DC power and have developed numerous case studies and demonstration projects, with a focus on energy efficiency, renewables, and resiliency. Review of international case studies compared to the U.S. market shows a convergence on the types of benefits and barriers to DC power; however, the selection and recommendation of DC distribution voltages and configurations can vary between projects in different countries. Clearly, at this early stage of development, DC power distribution in buildings would benefit from a coordinated effort to standardize voltage levels— not only to facilitate standards development, but also to concentrate the market of power converters and DC-ready appliances and facilitate manufacturers in standardizing product offerings and reaching economies of production scale.

Another key market from which DC can benefit is the off-grid market; and specifically the off-grid solar PV market for the developing world and rural applications. There is currently a large number of direct-DC appliances and solutions for direct coupling with PV [39], which are supported by international and U.S. programs, such as the Global LEAP initiative led by the U.S.

Department of Energy (DOE) [40], the Power Africa initiative managed by the United States Agency for International Development (USAID) [41], and the World Bank's Energy Sector Management Assistance Program (ESMAP). [42] The success of those programs, and the involvement of manufacturers in this field, can have a spillover effect to the developed-world off-grid market, and further to the grid-connected building sector.

With the proliferation of distributed DC generation, battery storage, EVs, and efficient DC-internal 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. The next phase of this project will focus on creating such end-use design recommendations for a small number of case-study DC powered buildings and on analyzing the energy and cost impacts of these designs.

References

[1] S. Backhaus *et al.*, “DC Microgrids Scoping Study—Estimate of Technical and Economic Benefits,” Los Alamos National Laboratory, LA-UR-15-22097, Mar. 2015.

[2] D. Denkenberger, D. Driscoll, E. Lighthiser, P. May-Ostendorp, B. Trimboli, and P. Walters, “DC Distribution Market, Benefits, and Opportunities in Residential and Commercial Buildings,” Pacific Gas & Electric Company, Oct. 2012.

[3] V. Vossos, K. Garbesi, and H. Shen, “Energy savings from direct-DC in U.S. residential buildings,” *Energy Build.*, vol. 68, Part A, pp. 223–231, Jan. 2014.

[4] S. Willems and W. Aerts, “Study and Simulation Of A DC Micro Grid With Focus on Efficiency, Use of Materials and Economic Constraints,” University of Leuven, Leuven, Belgium, 2014.

[5] U. Boeke and M. Wendt, “DC power grids for buildings,” in *2015 IEEE First International Conference on DC Microgrids (ICDCM)*, 2015, pp. 210–214.

[6] D. Fregosi *et al.*, “A comparative study of DC and AC microgrids in commercial buildings across different climates and operating profiles,” in *2015 IEEE First International Conference on DC Microgrids (ICDCM)*, 2015, pp. 159–164.

[7] M. Noritake, K. Yuasa, T. Takeda, H. Hoshi, and K. Hirose, “Demonstrative research on DC microgrids for office buildings,” in *Telecommunications Energy Conference (INTELEC), 2014 IEEE 36th International*, 2014, pp. 1–5.

[8] R. Weiss, L. Ott, and U. Boeke, “Energy efficient low-voltage DC-grids for commercial buildings,” in *2015 IEEE First International Conference on DC Microgrids (ICDCM)*, 2015, pp. 154–158.

[9] S. Ravula, “Direct Current Based Power Distribution Architectures for Commercial Buildings,” presented at the Bosch DC Microgrid Project: EPC 14-053, 12-Nov-2015.

[10] Alliance for Sustainable Colorado, “DC Project.” [Online]. Available: http://www.sustainablecolorado.org/what-we-do/building-innovation/dc-project/. [Accessed: 31-Jul-2016].

[11] NextEnergy, “NextHome,” *NextEnergy*. .

[12] E. Pond, “Aquion & Ideal Power Part of Hybrid Microgrid Design at Sonoma Winery,” *Aquion Energy*, 26-Apr-2016. .

[13] L. Roose, “Moku o Lo’e DC Microgrid,” Honolulu, HI, 27-Mar-2015.

[14] BusinessWire, “Philips Unveils First Lighting Installation That Leverages Power over Ethernet on Major University Campus as Part of Clemson University’s Watt Family Innovation Center | Business Wire,” 21-Jan-2016. [Online]. Available: http://www.businesswire.com/news/home/20160121005196/en/Philips-Unveils-Lighting-Installation-Leverages-Power-Ethernet. [Accessed: 22-Jan-2016].

[15] ARDA Power, “Burlington DC Microgrid Project Configuration,” *ARDA Power*, 2016. [Online]. Available: http://www.ardapower.com/configuration.html. [Accessed: 19-Apr-2016].

[16] BUCEA, “DC micro-grid photovoltaic power generation efficiency simulation analysis reports (Unpublished Manuscript),” Beijing University of Civil Engineering and Architecture, Oct. 2015.

[17] F. Zhang *et al.*, “Advantages and challenges of DC microgrid for commercial building a case study from Xiamen university DC microgrid,” in *2015 IEEE First International Conference on DC Microgrids (ICDCM)*, 2015, pp. 355–358.
[18] E. Rodriguez-Diaz, J. Vasquez, and J. Guerrero, “Intelligent DC Homes in Future Sustainable Energy Systems: When efficiency and intelligence work together.” *IEEE Consumer Electronics Magazine*, vol. 5, no. 1, pp. 74–80, Jan-2016.
[19] S. Foster Porter, D. Denkenberger, C. Mercier, P. May-Ostendorp, and P. Turnbull, “Reviving the War of Currents: Opportunities to Save Energy with DC Distribution in Commercial Buildings,” ECOVA, 2014.
[20] E. Planas, J. Andreu, J. I. Gárate, I. Martínez de Alegría, and E. Ibarra, “AC and DC technology in microgrids: A review,” *Renew. Sustain. Energy Rev.*, vol. 43, pp. 726–749, Mar. 2015.
[21] D. King and J. Brodrick, “Residential DC Power Bus. Opportunities for Savings?,” *ASHRAE Journal*, pp. 73–77, Sep-2010.
[22] B. Glasgo, I. Azevedo, and C. Hendrickson, “Understanding the potential for electricity savings and assessing feasibility of a transition towards DC powered buildings,” 2015.
[23] Armstrong Ceiling Solutions, “DC FlexZone Grid.” [Online]. Available: https://www.armstrongceilings.com/commercial/en-us/suspension-systems/ceiling-grid/dc-flexzone.html [Accessed: 23-Jan-2017].
[24] Philips, “Philips shines light on opening of the office of the future – the Edge in Amsterdam,” *Philips*, Jun-2015. [Online]. Available: http://www.philips.com/a-w/about/news/archive/standard/news/press/2015/20150625-Philips-shines-light-on-opening-of-the-office-of-the-future-the-Edge-in-Amsterdam.html. [Accessed: 06-May-2016].
[25] M. Wright, “Eaton demonstrates distributed DC power for LED lighting at LFI,” *LEDs Magazine*, 04-May-2016.
[26] B. T. Patterson, “DC, Come Home: DC Microgrids and the Birth of the ‘Enernet,’” *IEEE Power Energy Mag.*, vol. 10, no. 6, pp. 60–69, Nov. 2012.
[27] K. George, “DC Power Production, Delivery and Utilization: An EPRI White Paper,” 2006.
[28] S. Pantano, P. May-Ostendorp, and K. Dayem, “Demand DC. Accelerating the Introduction of DC Power in the Home,” CLASP, May 2016.
[29] D. E. Geary, “Phasing out AC - Directly,” in *2012 IEEE Energytech*, 2012, pp. 1–6.
[30] A. Sannino, G. Postiglione, and M. H. J. Bollen, “Feasibility of a DC network for commercial facilities,” *IEEE Trans. Ind. Appl.*, vol. 39, no. 5, pp. 1499–1507, Sep. 2003.
[31] G. AlLee and W. Tschudi, “Edison Redux: 380 Vdc Brings Reliability and Efficiency to Sustainable Data Centers,” *IEEE Power Energy Mag.*, vol. 10, no. 6, pp. 50–59, Nov. 2012.
[32] S. Whaite, B. Grainger, and A. Kwasinski, “Power Quality in DC Power Distribution Systems and Microgrids,” *Energies*, vol. 8, no. 5, pp. 4378–4399, May 2015.
[33] M. Monadi, M. Amin Zamani, J. Ignacio Candela, A. Luna, and P. Rodriguez, “Protection of AC and DC distribution systems Embedding distributed energy resources: A comparative review and analysis,” *Renew. Sustain. Energy Rev.*, vol. 51, pp. 1578–1593, Nov. 2015.
[34] L. Hardesty, “Direct Current Powers Building,” *Energy Manager Today*, 29-Jul-2015. [Online]. Available: http://www.energymanagertoday.com/direct-current-powers-building-0114185/. [Accessed: 15-Apr-2016].

[35] Solar Energy Industries Association, "Solar Market Insight Report 2016 Q4," *SEIA.org*. [Online]. Available: http://www.seia.org/research-resources/solar-market-insight-report-2016-q4. [Accessed: 24-Jan-2017].

[36] GTM Research, "U.S. Energy Storage Monitor: Q4 2016 Executive Summary," GTM Research, Dec. 2016.

[37] Navigant Consulting, Inc., "Energy Savings Forecast of Solid-State Lighting in General Illumination Applications," U.S. Department of Energy, DOE/EE-1133, Aug. 2014.

[38] IEC, "Implementing the standardization framework to support the development of Low Voltage Direct Current and electricity access: Final report IEC Systems Evaluation Group 4 - Low Voltage Direct Current Applications, Distribution and Safety for use in Developed and Developing Economies," International Electrotechnical Commission, Edition 1.0, Oct. 2016.

[39] H. Olk and J. Mundt, "Photovoltaics for Productive Use Applications. A catalogue of DC-Appliances," Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, Jan. 2016.

[40] Global LEAP, "The State of the Global Off-Grid Appliance Market," Feb. 2016.

[41] U.S. Agency for International Development, "Power Africa." [Online]. Available: https://www.usaid.gov/powerafrica. [Accessed: 24-Jan-2017].

[42] ESMAP, "Energy Sector Management Assistance Program." [Online]. Available: https://www.esmap.org/. [Accessed: 24-Jan-2017].

Appendix A: Reference List

Date	Author	Title	Publication Title	URL
2015	Aarstad, Cassidy; Kean, Andrew; Taufik	Arc Fault Circuit Interrupter Development for Residential DC Electricity		
2012	ABB	ABB solves 100-year-old electrical puzzle – new technology to enable future DC grid		http://www.abb.com/cawp/seitp202/65df338284e41b3dc1257aae0045b7de.aspx
2007	ABB	ABB Circuit-Breakers for Direct Current Applications		http://www04.abb.com/global/seitp/seitp202.nsf/0/6b16aa3f34983211c125761f004fd7f9/$file/vol.5.pdf
2016	ADC Energy, Inc.	ADC Energy, Inc.		http://www.adcenergy.org/
	Adelman, Jacob	Softbank, Bloom Energy Team Up in Japanese Fuel Cell Venture	Bloomberg.com	http://www.bloomberg.com/news/articles/2013-07-18/softbank-bloom-energy-team-up-in-japanese-fuel-cell-venture
2014	Afamefuna, David; Chung, Il-Yop; Hur, Don; Kim, Ju-Yong; Cho, Jintae	A Techno-Economic Feasibility Analysis on LVDC Distribution System for Rural Electrification in South Korea	Journal of Electrical Engineering & Technology	http://www.kpubs.org/article/articleDownload.kpubs?downType=pdf&articleANo=E1EEFQ_2014_v9n5_1501
2011	Ahn, Jung-Hoon; Koo, Keun-Wan; Kim, Dong-Hee; Lee, Byoung-kuk; Jin, Hyun-Cheol	Comparative analysis and safety standard guideline of AC and DC supplied home appliances	2011 IEEE 8th International Conference on Power Electronics and ECCE Asia (ICPE ECCE)	
2012	AlLee, G.; Tschudi, W.	Edison Redux: 380 Vdc Brings Reliability and Efficiency to Sustainable Data Centers	IEEE Power and Energy Magazine	
	Alliance for Sustainable Colorado	DC Project		http://www.sustainablecolorado.org/what-we-do/building-innovation/dc-project/
	Ambibox	Ambibox. Technical Information		https://www.ambibox.de/downloads/ambibox_techinfo.pdf
2011	Amin, M.; Arafat, Y.; Lundberg, S.; Mangold, S.	Low voltage DC distribution system compared with 230 V AC	2011 IEEE Electrical Power and Energy Conference (EPEC)	
2016	ARDA Power	Burlington DC Microgrid Project Configuration	ARDA Power	http://www.ardapower.com/configuration.html
2016	ARDA Power	ARDA Battery DC-DC Converter	ARDA Power	http://www.ardapower.com/battery-dc-dc-converter.html
	Armstrong Ceiling Solutions	DC FlexZone Grid		https://www.armstrongceilings.com/commercial/en-us/suspension-systems/ceiling-grid/dc-flexzone.html
2015	Asia Pacific Economic Cooperation Secretariat	APEC Smart DC Community Power Opportunity Assessment		
2015	Asmus, Peter; Elberg, Richelle	Direct Current Distribution Networks		https://www.navigantresearch.com/wp-assets/brochures/DCDN-15-Executive-Summary.pdf

2015	Backhaus, Scott; Swift, Gregory W.; Chatzivasileiadis, Spyridon; Tschudi, William; Glover, Steven; Starke, Michael; Wang, Jianhui; Yue, Meng; Hammerstrom, Donald	DC Microgrids Scoping Study—Estimate of Technical and Economic Benefits		http://www.energy.gov/sites/prod/files/2015/03/f20/DC_Microgrid_Scoping_Study_LosAlamos-Mar2015.pdf
2015	Boeke, U.	Deliverable: D 4.5.1. Demonstration of Industrial Application		http://dcgrid.tue.nl/files/D4_5_1_Demonstration_of_Industrial_Application_v1.0.pdf
	Boeke, U.	Low voltage DC power grid system and applications		http://dcgrid.tue.nl/files/2014-04-03_Boeke-DCCG_Project-Low_Voltage_DC_Power_Grids.pdf
2014	Boeke, U.; Ott, L.	Impact of a 380V DC Power Grid Infrastracture on Commercial Building Energy Profiles		http://dcgrid.tue.nl/files/2014-04-28_DCC+G-White_Paper-Building_profiles_and_impact_by_DC_grids.pdf
2015	Boeke, U.; Wendt, M.	DC power grids for buildings	2015 IEEE First International Conference on DC Microgrids (ICDCM)	
2016	Brenguier, J.; Vallet, M.; VAILLANT, F.	Efficiency gap between AC and DC electrical power distribution system	2016 IEEE/IAS 52nd Industrial and Commercial Power Systems Technical Conference (I CPS)	
2016	Brocade	Brocade	Brocade	http://www.brocade.com/en.html
2015	BUCEA	DC micro-grid photovoltaic power generation efficiency simulation analysis reports (Unpublished Manuscript)		
2016	BusinessWire	Philips Unveils First Lighting Installation That Leverages Power over Ethernet on Major University Campus as Part of Clemson University's Watt Family Innovation Center | Business Wire		http://www.businesswire.com/news/home/20160121005196/en/Philips-Unveils-Lighting-Installation-Leverages-Power-Ethernet
2010	BusinessWire	World's First DC-Powered, Ductless Mini-Split Air Conditioner Unveiled by Solar Panels Plus		http://www.businesswire.com/news/home/20100120006248/en/World%E2%80%99s-DC-Powered-Ductless-Mini-Split-Air-Conditioner-Unveiled
2017	Cacciato, M.; Nobile, G.; Scarcella, G.; Scelba, G.	Real-Time Model-Based Estimation of SOC and SOH for Energy Storage Systems	IEEE Transactions on Power Electronics	
2015	Cal Poly State University	The DC House Project		http://www.calpoly.edu/~taufik/dchouse/index.html
2015	Capasso, Clemente; Veneri, Ottorino	Experimental study of a DC charging station for full electric and plug in hybrid vehicles	Applied Energy	http://www.sciencedirect.com/science/article/pii/S030626191500495X
2016	Cardwell, Diane	A Suburban Experiment Aims for Free	The New York Times	http://www.nytimes.com/2016/06/04

		Energy		/business/energy-environment/solar-power-energy-efficient-net-zero.html
2016	Centre for Solar Energy and Hydrogen Research (ZSW)	Number of Electric Cars Worldwide Climbs to 1.3 Million		http://www.zsw-bw.de/uploads/media/pr05-2016-ZSW-DataE-Mobility.pdf
2014	Chauhan, R.K.; Rajpurohit, B.S.	DC distribution system for energy efficient buildings	Power Systems Conference (NPSC), 2014 Eighteenth National	
2015	Chen, Fang; Burgos, R.; Boroyevich, D.	Efficiency comparison of a single-phase grid-interface bidirectional AC/DC converter for DC distribution systems	2015 IEEE Energy Conversion Congress and Exposition (ECCE)	
2014	Chiltrix	Ultra Efficient Chiller Technology - How It Works		http://www.chiltrix.com/chiller-technology.html
	Cho, Bo-Hyung	DC Microgrid Project in SNU		http://microgrid-symposiums.org/wp-content/uploads/2014/12/tianjin_bo-hyung-cho.pdf
2015	Cho, J.; Kim, J-H; Chae, W.; Lee, H.; Kim, J.	Design and Construction of Korean LVDC Distribution System for Supplying DC Power to Customer	CIRED 2015	http://cired.net/publications/cired2015/papers/CIRED2015_0604_final.pdf
2016	Cisco Blogs	Cisco UPoE Powers Cutting Edge Retail Experience At The Dandy Lab	blogs@Cisco - Cisco Blogs	http://blogs.cisco.com/enterprise/cisco-upoe-powers-cutting-edge-retail-experience-at-the-dandy-lab
2014	Clover, Ian	Microinverters vs. Optimizers	PV Magazine	http://www.pv-magazine.com/archive/articles/beitrag/microinverters-vs-optimizers-_100016637/618/#axzz4KvGiZR3P
2016	CUI, Inc.	Power Quick Guide | CUI Inc		http://www.cui.com/catalog/resource/power-quick-guide.pdf
	Dell'Oro Group	Ethernet Switch — Layer 2+3	Dell'Oro	http://www.delloro.com/products-and-services/ethernet-switch
2012	Denkenberger, Dave; Driscoll, Debbie; Lighthiser, Erica; May-Ostendorp, Peter; Trimboli, Brendan; Walters, Philip	DC Distribution Market, Benefits, and Opportunities in Residential and Commercial Buildings		http://www.xergyconsulting.com/wp-content/uploads/2013/09/Dc-Distrib_Final-Report_FINAL_30Oct2012.pdf
	Department of Defense	DC Microgrid Building Energy Management Platform for Improved Energy Efficiency, Energy Security, and Operating Costs EW-201352	DOE SERDP and ESTCP programs	https://www.serdp-estcp.org/Program-Areas/Energy-and-Water/Energy/Microgrids-and-Storage/EW-201352
2015	Díaz, E. R.; Su, X.; Savaghebi, M.; Vasquez, J. C.; Han, M.; Guerrero, J. M.	Intelligent DC Microgrid living Laboratories - A Chinese-Danish cooperation project	2015 IEEE First International Conference on DC Microgrids (ICDCM)	
2015	Diaz, Enrique Rodriguez; Firoozabadi, Mehdi Savaghebi; Quintero, Juan Carlos Vasquez; Guerrero, Josep M.	An Overview of Low Voltage DC Distribution Systems for Residential Applications	5th IEEE International Conference on Consumer Electronics-Berlin 2015	http://vbn.aau.dk/ws/files/219724154/2015_ICCE_An_Overwiew_of_LVDC_Distribution_systems_for_Residential_Applications.pdf

2016	Direct Current BV	DC System Innovation and System Transition		http://www.directcurrent.eu/en/
2016	Direct Current BV	DC in utility building becomes reality		http://www.directcurrent.eu/en/news/news-archive/82-dc-in-utility-building-becomes-reality
2012	Diversified Technologies, Inc.	PowerMod MVDC Conversion & Transmission Systems		http://www.divtecs.com/data/File/papers/PDF/MVDC%20Final.pdf
2016	DKE	GERMAN STANDARDIZATION ROADMAP: Low Voltage DC, Version 1		
2016	Downey, Kyle	Microgrids: The Future of Smarter Grid Design and Energy Stability - Law Street (TM)	Law Street (TM)	http://lawstreetmedia.com/issues/energy-and-environment/microgrids-smarter-grid-energy-stability/
2014	E2SG	e2sg-project.eu		http://www.e2sg-project.eu/
	Eascor	EASCOR | About Us		http://eascor.net/about/about.html
	Eaton	Eaton Highlights Broad Array of Connected Lighting Capabilities at LIGHTFAIR 2016		http://www.eaton.com/Eaton/OurCompany/NewsEvents/NewsReleases/PCT_1930713
2016	Ehrlich, Brent	The Death and Rebirth of DC Power	BuildingGreen	https://www.buildinggreen.com/feature/death-and-rebirth-dc-power
2015	Elsayed, Ahmed T.; Mohamed, Ahmed A.; Mohammed, Osama A.	DC microgrids and distribution systems: An overview	Electric Power Systems Research	http://www.sciencedirect.com/science/article/pii/S0378779614003885
2015	Emerson Network Power	400V DC Resource Center		http://www.emersonnetworkpower.com/fr-EMEA/Brands/Netsure/ensys-400v-dc/Pages/resource-center.aspx
	EmotorWerks	DC Charging Systems		https://emotorwerks.com/index.php/store-juicebox-ev-charging-stations/dc-charging-systems/product/listing
2006	Engelen, K.; Leung Shun, E.; Vermeyen, P.; Pardon, I.; D'hulst, R.; Driesen, J.; Belmans, R.	The Feasibility of Small-Scale Residential DC Distribution Systems	IECON 2006 - 32nd Annual Conference on IEEE Industrial Electronics	
2016	Ethernet Alliance	2016 Ethernet Roadmap		http://www.ethernetalliance.org/wp-content/uploads/2015/03/Ethernet-Roadmap-2sides-29Feb.pdf
2008	Fortenbery, Brian; Ton, My; Tschudi, William	DC power for improved data center efficiency		http://energy.lbl.gov/ea/mills/HT/documents/data_centers/DCDemoFinalReport.pdf
2014	Foster Porter, Suzanne; Denkenberger, Dave; Mercier, Catherine; May-Ostendorp, Peter; Turnbull, Peter	Reviving the War of Currents: Opportunities to Save Energy with DC Distribution in Commercial Buildings		http://w.greenercars.org/files/proceedings/2014/data/papers/3-817.pdf
2015	Frank, Stephen M.; Rebennack, Steffen	Optimal design of mixed AC–DC distribution systems for commercial buildings: A Nonconvex Generalized Benders Decomposition approach	European Journal of Operational Research	http://www.sciencedirect.com/science/article/pii/S0377221714008121

	Fraunhofer IISB	DC/DC Converters	Fraunhofer Institute for Integrated Systems and Device Technology IISB	http://www.iisb.fraunhofer.de/en/research_areas/vehicle_electronics/dcdc_converters.html
2015	Fregosi, D.; Ravula, S.; Brhlik, D.; Saussele, J.; Frank, S.; Bonnema, E.; Scheib, J.; Wilson, E.	A comparative study of DC and AC microgrids in commercial buildings across different climates and operating profiles	2015 IEEE First International Conference on DC Microgrids (ICDCM)	
	Frey, Lothar	Power Electronics for DC Grids		http://www.artemis-ioe.eu/events/presentations/25.09.2014_NESEM_2014_Erlangen_L.Frey_FhG_IISB_Power_Electronics_DC_grids.pdf
2010	Fujitsu Component	Development of DC plugs and socket outlets for smart grid and data center		http://www.fujitsu.com/jp/group/fcl/en/resources/news/press-releases/2010/20101109-1.html
2011	Garbesi, Karina; Vossos, Vagelis; Shen, Hongxia	Catalog of DC Appliances and Power Systems		http://eetd.lbl.gov/publications/catalog-dc-appliances-and-power-systems
2012	Geary, D.E.	Phasing out AC - Directly	2012 IEEE Energytech	
2006	George, K.	DC Power Production, Delivery and Utilization: An EPRI White Paper		http://www.netpower.se/documents/EPRI_DCpower_WhitePaper_June_2006.pdf
2016	Glasgo, Brock; Azevedo, Inês Lima; Hendrickson, Chris	How much electricity can we save by using direct current circuits in homes? Understanding the potential for electricity savings and assessing feasibility of a transition towards DC powered buildings	Applied Energy	http://www.sciencedirect.com/science/article/pii/S0306261916309771
2015	Glasgo, Brock; Azevedo, Inês; Hendrickson, Chris	Understanding the potential for electricity savings and assessing feasibility of a transition towards DC powered buildings		http://www.usaee.org/usaee2015/submissions/OnlineProceedings/USAEE%202015%20Paper_Glasgo.pdf
2016	Global LEAP	The State of the Global Off-Grid Appliance Market		http://www.cleanenergyministerial.org/Portals/2/pdfs/Global_LEAP_The_State_of_the_Global_Off-Grid_Appliance_Market.pdf
	Green Energy Innovations	Green Energy Innovations		http://www.geinnovations.net/
2014	Grillo, S.; Musolino, V.; Piegari, L.; Tironi, E.; Tornelli, C.	DC Islands in AC Smart Grids	IEEE Transactions on Power Electronics	
2016	GTM Research	U.S. Energy Storage Monitor: Q4 2016 Executive Summary		
2014	Guerrero, Josep M.	DC Microgrids		
	Halper, Mark	Cisco, Philips add a showcase Power over Ethernet lighting installation in the UAE		http://www.ledsmagazine.com/articles/2016/04/cisco-philips-add-a-showcase-power-over-ethernet-lighting-installation-in-the-uae.html
	Halper, Mark	Digital SSL's mega disruptor will be Power		http://www.ledsmagazine.com/article

		over Ethernet (MAGAZINE)		s/print/volume-12/issue-11/features/networks-power/digital-ssl-s-mega-disruptor-will-be-power-over-ethernet-magazine.html
2007	Hammerstrom, D.J.	AC Versus DC Distribution Systems. Did We Get it Right?	IEEE Power Engineering Society General Meeting, 2007	
2015	Hardesty, L.	Direct Current Powers Building	Energy Manager Today	http://www.energymanagertoday.com/direct-current-powers-building-0114185/
2013	Hirose, Keiichi; Reilly, J. T.; Irie, H.	The sendai microgrid operational experience in the aftermath of the tohoku earthquake: a case study		https://www.smart-japan.org/english/vcms_cf/files/The_Operational_Experience_of_Sendai_Microgrid_in_the_Aftermath_of_the_Devastating_Earthquake_A_Case_Study.pdf
	Hoshi, Hidekazu; Yajima, Hiroya; Babasaki, Tadatoshi; Hirose, K.; Matsuo, H.; Noritake, M.; Takeda, T.	Development of Equipment for HVDC Power Supply Systems		https://www.ntt-review.jp/archive/ntttechnical.php?contents=ntr201503fa8.pdf&mode=show_pdf
2010	Hotspot Energy	DC Air Conditioner		http://www.hotspotenergy.com/DC-air-conditioner/
2014	Houseman, Doug.	DC@Home General Meeting		http://workspaces.nema.org/public/LVDC/Shared%20Documents/DC%20at%20Home%20-%20GM%20Main%20presentation.pdf
2015	Hummel, Michael; Grant, Galen; Benton, Byron; Kuetter Desmond, Kim	Working Example	High Performance Buildings	http://www.hpbmagazine.org/attachments/article/12211/15Su-Zero-Net-Energy-Center-San-Leandro-CA.pdf
2016	IEC	Implementing the standardization framework to support the development of Low Voltage Direct Current and electricity access: Final report IEC Systems Evaluation Group 4 - Low Voltage Direct Current Applications, Distribution and Safety for use in Developed and Developing Economies		
2015	IEEE Standards Association	IEEE and EMerge Alliance Sign Memorandum of Understanding (MoU) to Allow Collaboration in Hybrid AC/DC Microgrid Power Standardization		http://standards.ieee.org/news/2015/emerge_mou.html
	IEEE Standards Association	P2030.10 - Standard for DC Microgrids for Rural and Remote Electricity Access Applications		https://standards.ieee.org/develop/project/2030.10.html
2015	IET Standards	Code of Practice for Low and Extra Low Voltage Direct Current Power Distribution in Buildings		http://www.theiet.org/resources/standards/lvdc-cop.cfm
2016	IGOR	Power Over Ethernet Lighting | POE Lighting Control	IGOR	http://www.igor-tech.com/

	Illinois Institute of Technology	Ribbon Cutting Ceremony for First Hybrid AC-DC Nanogrid at the Illinois Tech Microgrid		http://engineering.iit.edu/events/2016/aug/17/ribbon-cutting-ceremony-first-hybrid-ac-dc-nanogrid-illinois-tech-microgrid
	Innovative Lighting	Innovative Lighting PoE Power Over Ethernet Lighting Installation		https://www.youtube.com/watch?v=IDsSsXvv_10
2015	Innovative Lighting	PoE LED Lighting	GENISYS PoE Lighting Systems	http://www.innovativelight.com/commercial-industrial-led-lighting/poe-led-lighting/
2015	Iyer, S.; Dunford, W.G.; Ordonez, M.	DC distribution systems for homes	2015 IEEE Power Energy Society General Meeting	
	Jacobson, Julie	Colorbeam's LVDC Lighting System Delivers Power, Control over Single Cat 5 Cable		http://www.cepro.com/article/colorbeams_lvdc_lighting_system_delivers_power_control_over_single_cat_5_ca
2013	Justo, Jackson John; Mwasilu, Francis; Lee, Ju; Jung, Jin-Woo	AC-microgrids versus DC-microgrids with distributed energy resources: A review	Renewable and Sustainable Energy Reviews	http://www.sciencedirect.com/science/article/pii/S1364032113002268
2007	Kaipia, Tero; Salonen, Pasi; Lassila, Jukka; Partanen, Jarmo	Application of low voltage DC-Distribution system–A Techno-economical Study	19th International Conference on Electricity Distribution	http://www.cired.net/publications/cired2007/pdfs/CIRED2007_0464_paper.pdf
2015	Kann, Shayle; Shiao, MJ; Honeyman, Cory; Kimbis, Tom; Baca, Justin; Rumery, Shawn; Jones, Jade; Cooper, Leandra	U.S. Solar Market Insight Q1 2015 Executive Summary		http://www.seia.org/sites/default/files/resources/Y3pV3Vn7QKQ12015SMI_0.pdf
2015	Kaur, P.; Jain, S.; Jhunjhunwala, A.	Solar-DC deployment experience in off-grid and near off-grid homes: Economics, technology and policy analysis	2015 IEEE First International Conference on DC Microgrids (ICDCM)	
2015	Keles, Cemal; Karabiber, Abdulkerim; Akcin, Murat; Kaygusuz, Asim; Alagoz, Baris Baykant; Gul, Ozan	A smart building power management concept: Smart socket applications with DC distribution	International Journal of Electrical Power & Energy Systems	http://www.sciencedirect.com/science/article/pii/S0142061514005195
2010	King, Darrell; Brodrick, James	Residential DC Power Bus. Opportunities for Savings?	ASHRAE Journal	
	LEDs Magazine	Goldeneye linear LED lighting can be integrated into architecture		http://www.ledsmagazine.com/articles/2016/05/goldeneye-linear-led-lighting-can-be-integrated-into-architecture.html
	LEDs Magazine	Lighting industry progresses on DC-power grids that pair well with LEDs (MAGAZINE)		http://www.ledsmagazine.com/articles/print/volume-10/issue-6/features/lighting-industry-progresses-on-dc-power-grids-that-pair-well-with-leds-magazine.html
2012	Lee, J.; Han, B.; Cha, H.	Development of hardware simulator for DC micro-grid operation analysis	2012 IEEE Power and Energy Society General Meeting	

2014	Lennox	Sunsource Home Energy System		http://resources.lennox.com/FileUploads/SunSource_Home_Energy_System.pdf
2014	Liu, Zifa; Li, Mengyu	Research on Energy Efficiency of DC Distribution System	AASRI Procedia	http://www.sciencedirect.com/science/article/pii/S2212671614000328
2014	Locment, F.; Sechilariu, M.	DC microgrid for future electric vehicle charging station designed by Energetic Macroscopic Representation and Maximum Control Structure	2014 IEEE International Energy Conference (ENERGYCON)	
2015	LUX	Can power over Ethernet transform how we control lights in the workplace?		http://www.luxreview.com/article/2015/06/when-power-meets-intelligence
2015	Mackay, L.; Hailu, T.; Ramirez-Elizondo, L.; Bauer, P.	Towards a DC distribution system - opportunities and challenges	2015 IEEE First International Conference on DC Microgrids (ICDCM)	
2015	Madduri, Achintya	A Scalable DC Microgrid Architecture for Rural Electrification in Emerging Regions		http://www.eecs.berkeley.edu/Pubs/TechRpts/2015/EECS-2015-240.html
2015	Makdessian, Alec; Huynh, Thong	PoE technology for LED lighting delivers benefits beyond efficiency (MAGAZINE)		http://www.ledsmagazine.com/articles/print/volume-12/issue-8/features/dc-grid/poe-technology-for-led-lighting-delivers-benefits-beyond-efficiency.html
2015	Maly Lisy, S.; Smrekar, M.	Three Case Studies of Commercial Deployment of 400V DC Data and Telecom Centers in the EMEA Region		http://www.emergealliance.org/portals/0/documents/events/intelec/TS01-2.pdf
2013	McCluer, Stephen	NFPA 70E's Approach to Considering DC Hazards		http://ecmweb.com/safety/nfpa-70e-s-approach-considering-dc-hazards
	Microgrid Projects	DC Microgrids	Microgrid Projects	http://microgridprojects.com/dc-microgrids/
	Microgrid Projects	Kalkeri Sangeet Vidyalaya DC Microgrid	Microgrid Projects	http://microgridprojects.com/microgrid/kalkeri-sangeet-vidyalaya-dc-microgrid/
	Microgrid Projects	Stone Edge Farm Winery Microgrid	Microgrid Projects	http://microgridprojects.com/microgrid/stone-edge-farm-winery-microgrid/
	Mitsubishi Electric	Mitsubishi Electric to Build DC Development and Demonstration Facility at Power Distribution System Center in Marugame, Japan		http://www.mitsubishielectric.com/news/2015/0914-b.html
2015	Monadi, Mehdi; Amin Zamani, M.; Ignacio Candela, Jose; Luna, Alvaro; Rodriguez, Pedro	Protection of AC and DC distribution systems Embedding distributed energy resources: A comparative review and analysis	Renewable and Sustainable Energy Reviews	http://www.sciencedirect.com/science/article/pii/S1364032115006607
2016	Murata Power Solutions	Latest products for power solutions in industrial applications		http://www.murata-ps.com/data/catalogs/industrial_app_products.pdf
2014	Naud, Paul S.	Smoothing the Effects of Renewable Generation on the Distribution Grid	eScholarship	http://escholarship.org/uc/item/3nr053m8
2014	Navigant Consulting, Inc.	Energy Savings Forecast of Solid-State Lighting in General Illumination		http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/energysavingsf

		Applications		orecast14.pdf
2016	New Energy and Industrial Technology Development Organization	NEDO Demonstration Project Aims for 15% Energy Savings with a High-Voltage Direct Current (HVDC) Feeding System		http://www.nedo.go.jp/english/news/AA5en_100103.html
	Nextek Power Systems	Fort Belvoir Direct Coupling® DC Microgrid	Nextek Power Systems	http://www.nextekpower.com/fort-belvoir-direct-coupling-dc-microgrid/
	NextEnergy	NextHome	NextEnergy	https://www.nextenergy.org/nexthome-dc-distribution-system/
2015	NFPA	NFPA 850: Recommended Practice for Fire Protection for Electric Generating Plants and High Voltage Direct Current Converter Stations		http://www.nfpa.org/codes-and-standards/document-information-pages?mode=code&code=850
2015	Nordman, B.; Christensen, K.	The need for communications to enable DC power to be successful	2015 IEEE First International Conference on DC Microgrids (ICDCM)	
2015	Nordman, Bruce; Christensen, Ken	DC Local Power Distribution with microgrids and nanogrids	DC Microgrids (ICDCM), 2015 IEEE First International Conference on	http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=7152038
2014	Noritake, M.; Yuasa, K.; Takeda, T.; Hoshi, H.; Hirose, K.	Demonstrative research on DC microgrids for office buildings	Telecommunications Energy Conference (INTELEC), 2014 IEEE 36th International	
2013	Noritake, Masatoshi; Hoshi, Hidekazu; Hirose, Keiichi; Kita, Hiroyuki; Hara, Ryoichi; Yagami, Masaki	Operation algorithm of DC microgrid for achieving local production for local consumption of renewable energy	Telecommunications Energy Conference 'Smart Power and Efficiency' (INTELEC), Proceedings of 2013 35th International	
	Northerntool.com	GPI GPRO 12 Volt Commercial Grade Fuel Transfer Pump		http://www.northerntool.com/shop/tools/product_200665169_200665169
	NTT Group	High-voltage Direct Current System : NTT HOME		http://www.ntt.co.jp/ntt-tec/e/high-tec/10034.html
2015	nuLEDs	Nuleds - Led Lighting		http://www.nuleds.com/
2016	Ode, Mark	Not Your Average DC | EC Mag		http://www.ecmag.com/section/not-your-average-dc
2016	Olk, Harald; Mundt, Juliane	Photovoltaics for Productive Use Applications. A catalogue of DC-Appliances		https://collaboration.worldbank.org/docs/DOC-20766
2015	Pande, A.; Goebes, M.; Barkland, S.	Residential ZNE Market Characterization		http://calmac.org/publications/TRC_Res_ZNE_MC_Final_Report_CALMAC_PGE0351.01.pdf
2016	Pantano, Stephen; May-Ostendorp, Peter; Dayem, Katherine	Demand DC. Accelerating the Introduction of DC Power in the Home		http://clasp.ngo/Resources/Resources/PublicationLibrary/2016/DemandDC
2012	Patterson, B.T.	DC, Come Home: DC Microgrids and the Birth of the "Enernet"	IEEE Power and Energy Magazine	
2014	Patterson, Brian	DC: The Power to Change Buildings		http://www.constructioncanada.net/d

				c-the-power-to-change-buildings/
	Pellis, J.	The DC Low-Voltage House		http://alexandria.tue.nl/extra1/afstversl/E/501233.pdf
2010	Philips	Philips PoE - ColorDial Pro		http://download.p4c.philips.com/l4bt/3/326814/colordial_pro_326814_ess_aen.pdf
2016	Philips	LuxSpace PoE	Philips Lighting	http://www.lighting.philips.com/main/prof/indoor-luminaires/downlights/luxspace/luxspace-poe
2015	Philips	Philips shines light on opening of the office of the future – the Edge in Amsterdam	Philips	http://www.philips.com/a-w/about/news/archive/standard/news/press/2015/20150625-Philips-shines-light-on-opening-of-the-office-of-the-future-the-Edge-in-Amsterdam.html
2016	Pika Energy	Smart Batteries: A New Standard in Distributed Storage		
2015	Planas, Estefanía; Andreu, Jon; Gárate, José Ignacio; Martínez de Alegría, Iñigo; Ibarra, Edorta	AC and DC technology in microgrids: A review	Renewable and Sustainable Energy Reviews	http://www.sciencedirect.com/science/article/pii/S1364032114010065
	Preparedness.com	Portable Power Centers		http://preparedness.com/powercenters.html
	Princeton Power Systems	Demand Response Inverter (4 Port) - Princeton Power Systems		http://www.princetonpower.com/products/demand-response-inverter-4-port.html
	PV-Tech	Indian PV projects suffering from poor selection of DC cables	PV-Tech	http://www.pv-tech.org/news/multiple-indian-pv-projects-suffering-from-poor-selection-of-dc-cables
2012	Radio-Electronics.com	Understanding Power Supply Reliability		http://www.radio-electronics.com/articles/power-management/understanding-power-supply-reliability-56
2015	Rajaraman, V.; Jhunjhunwala, A.; Kaur, P.; Rajesh, U.	Economic analysis of deployment of DC power and appliances along with solar in urban multi-storied buildings	2015 IEEE First International Conference on DC Microgrids (ICDCM)	
2015	Ravula, S.	Direct Current Based Power Distribution Architectures for Commercial Buildings		http://www.energy.ca.gov/research/epic/documents/2015-12-03_symposium/presentations/Session_1A_4_Sharmila_Ravula_Robert_Bosch.pdf
2016	Reiner, Mark	dc Project—Alliance for Sustainable Colorado WHITE PAPER: 1		http://www.sustainablecolorado.org/wp-content/uploads/2015/05/dc-Project-White-Paper-1.pdf
2016	Rodriguez-Diaz, E.; Vasquez, J.; Guerrero, J.	Intelligent DC Homes in Future Sustainable Energy Systems: When efficiency and intelligence work together.	IEEE Consumer Electronics Magazine	

2015	Roose, Leon	Moku o Lo'e DC Microgrid		http://www.hnei.hawaii.edu/sites/www.hnei.hawaii.edu/files/CoconutIsland%20SPIDERS%20Luncheon%20HNEI%20L.Roose%20(8.27.15).pdf
2014	Saber, Jim	IEEE Power and Energy Society General Meeting: NextHome		http://workspaces.nema.org/public/LVDC/Shared%20Documents/DC%20at%20home%20-%20DC%20house%20project.pdf
2007	Salomonsson, D.; Sannino, A.	Low-Voltage DC Distribution System for Commercial Power Systems With Sensitive Electronic Loads	IEEE Transactions on Power Delivery	
2003	Sannino, A.; Postiglione, G.; Bollen, M.H.J.	Feasibility of a DC network for commercial facilities	IEEE Transactions on Industry Applications	
2015	Sasidharan, Nikhil; Madhu M., Nimal; Singh, Jai Govind; Ongsakul, Weerakorn	An approach for an efficient hybrid AC/DC solar powered Homegrid system based on the load characteristics of home appliances	Energy and Buildings	http://www.sciencedirect.com/science/article/pii/S0378778815302358
2010	Savage, Paul; Nordhaus, Robert R.; Jamieson, Sean P.	DC microgrids: benefits and barriers	From Silos to Systems: Issues in Clean Energy and Climate Change	
	Schneider Electric	DC Rated Circuit Breakers - Schneider Electric USA		http://www.schneider-electric.us/en/product-subcategory/50370-dc-rated-circuit-breakers/?parent-category-id=50300
2011	Seo, Gab-Su; Baek, Jongbok; Choi, Kyusik; Bae, Hyunsu; Cho, Bohyung	Modeling and analysis of DC distribution systems	2011 IEEE 8th International Conference on Power Electronics and ECCE Asia (ICPE ECCE)	
2015	Seyedmahmoudian, M.; Arrisoy, H.; Kavalchuk, I.; Oo, A. Maung; Stojcevski, A.	Rationale for the use of DC microgrids: feasibility, efficiency and protection analysis	Energy and Sustainability V: Special Contributions	https://books.google.com/books?hl=en&lr=&id=h6nkBgAAQBAJ&oi=fnd&pg=PA69&ots=iBxDqiMw_7&sig=lodizWuH4GXn7oRJ9jhzixPt-0w
	SMAP	Energy Sector Management Assistance Program		https://www.esmap.org/
2008	Starke, M.R.; Tolbert, L.M.; Ozpineci, B.	AC vs. DC distribution: A loss comparison	Transmission and Distribution Conference and Exposition, 2008. T #x00026;D. IEEE/PES	
2014	Strategen Consulting; ARUP Group	Direct-Current Scoping Study: Opportunities for direct current power in the built environment.		
2015	Tamaki, Hisashi	Nushima Project. An Experimental Study on a Self-Sustainable Decentralized Energy System for an Isolated Island		http://microgrid-symposiums.org/wp-content/uploads/2015/09/a-Tamaki_20150819.pdf
2012	Teratani, Tatsuo	Current Status and Future View of EV/PHEV with Charging Infrastructure in Japan		http://www.oecd.org/futures/Current%20Status%20and%20Future%20View%20of%20EV%20PHEV%20with%20Charging%20Infrastructure%20in%20Jap

				an.pdf
2012	Thomas, Brinda A.; Azevedo, Inês L.; Morgan, Granger	Edison Revisited: Should we use DC circuits for lighting in commercial buildings?	Energy Policy	http://www.sciencedirect.com/science/article/pii/S0301421512001656
	Tikkanen, Dave	The Benefits of Low-Voltage DC Power Distribution for LED Lighting		http://www.lumastream.com/sites/default/files/specsheets/lumastream_low-voltage_whitepaper-2.pdf
	U.S. Agency for International Development	Power Africa		https://www.usaid.gov/powerafrica
2011	Uesugi, Takehiro	Quantitative Simulation of energy saving impacts through DC power supply at residential sector		
	University of Arkansas	NSF Grant Will Help Researchers Change Power for Data Centers from AC to DC	University of Arkansas News	http://news.uark.edu/articles/33784
2015	University of Pittsburg	Direct Current Architecture for Modern Power Systems (DC-AMPS)		http://www.engineering.pitt.edu/Sub-Sites/Labs/Electric-Power-Systems/_Content/Research/Current/DCAMPS/
	University of Pittsburg	DC HEART		http://dcpower.pitt.edu/
2015	University of Texas	University of Texas, Japan Collaborate on Next-Generation Energy Efficient Data Center	UT News | The University of Texas at Austin	https://news.utexas.edu/2015/08/11/ut-japan-collaborate-on-energy-efficient-data-center
2015	Vicor	New BCM Bus Converter Modules with Unprecedented Performance	Vicor PowerBlog	http://powerblog.vicorpower.com/2015/10/new-bcm-bus-converter-modules-with-unprecedented-performance/
2015	Vicor	BCM® Bus Converter		http://www.vicorpower.com/documents/datasheets/ds-BCM380P475T1K2A30.pdf
	Virginia Tech.	CPES Research Areas | Center for Power Electronics Systems | Virginia Tech		http://www.cpes.vt.edu/areas/Sustainable%20Building%20Initiative
2015	Voltserver	VoltServer technology - the dawning of digital power		http://www.voltserver.com/Technology.aspx
2014	Vossos, Vagelis; Garbesi, Karina; Shen, Hongxia	Energy savings from direct-DC in U.S. residential buildings	Energy and Buildings	http://www.sciencedirect.com/science/article/pii/S0378778813005720
2013	Webb, Victor-Juan Eli	Design of a 380 V/24 V DC Micro-Grid for Residential DC Distribution		https://etd.ohiolink.edu/ap/10?0::NO:10:P10_ACCESSION_NUM:toledo1355247158
2015	Weiss, R.; Ott, L.; Boeke, U.	Energy efficient low-voltage DC-grids for commercial buildings	2015 IEEE First International Conference on DC Microgrids (ICDCM)	
2015	Whaite, Stephen; Grainger, Brandon; Kwasinski, Alexis	Power Quality in DC Power Distribution Systems and Microgrids	Energies	http://www.mdpi.com/1996-1073/8/5/4378
2014	Willems, Simon; Aerts, Wouter	Study and Simulation Of A DC Micro Grid With Focus on Efficiency, Use of Materials and Economic Constraints		http://www.dehaagsehogeschool.nl/xmsp/xms_itm_p.download_file?p_itm_id=94657
2016	Wills, R.	DC Microgrids Gain Popularity in	ei, The Magazine of	http://www.nxtbook.com/ygsreprints

		Commercial Buildings	the Electroindustry	/NEMA/g59228_nema_mar16/#/18
2016	Wright, Maury	Eaton demonstrates distributed DC power for LED lighting at LFI	LEDs Magazine	http://www.ledsmagazine.com/articles/2016/05/eaton-demonstrates-distributed-dc-power-for-led-lighting-at-lfi.html
2016	Wright, Maury	Low-voltage scheme trivializes installation of LED lighting and supports controls (MAGAZINE)	LEDs Magazine	http://www.ledsmagazine.com/articles/print/volume-13/issue-8/features/dc-power/low-voltage-scheme-trivializes-installation-of-led-lighting-and-supports-controls.html
2014	Wunder, B.; Ott, L.; Szpek, M.; Boeke, U.; Weis, R.	Energy efficient DC-grids for commercial buildings	Telecommunications Energy Conference (INTELEC), 2014 IEEE 36th International	
2013	Wunder, Bernd	380V DC in Commercial Buildings and Offices		http://dcgrid.tue.nl/files/2014-02-11%20-%20Webinar%20Vicor.pdf
	XICATO	The Case for a 48VDC Lighting System		http://www.xicato.com/sites/default/files/documents/The%20Case%20for%2048VDC_0.pdf
2015	Yeager, K.	DC Microgrid Performance Excellence in Electricity Renewal	2015 IEEE First International Conference on DC Microgrids (ICDCM)	
2012	YMGI Group	Solar DC Inverter Mini System: PV Powered/Boosted Mini Split Wall Mount		http://www.ymgihvacsupply.com/index.php?option=com_content&view=article&id=2&Itemid=103
2014	Yu, Xiaoyan; Yeaman, P.	A new high efficiency isolated bi-directional DC-DC converter for DC-bus and battery-bank interface	2014 Twenty-Ninth Annual IEEE Applied Power Electronics Conference and Exposition (APEC)	
2015	Zhang, Fengyan; Meng, Chao; Yang, Yun; Sun, Chunpeng; Ji, Chengcheng; Chen, Ying; Wei, Wen; Qiu, Hemei; Yang, Gang	Advantages and challenges of DC microgrid for commercial building a case study from Xiamen university DC microgrid	2015 IEEE First International Conference on DC Microgrids (ICDCM)	
	Zimmerman, Scott; Liesay, William; Evans, William	DC-powered modular SSL delivers efficiency and flexibility	LEDs Magazine	http://www.ledsmagazine.com/articles/print/volume-13/issue-6/features/dc-modular-lighting/dc-powered-modular-ssl-delivers-efficiency-and-flexibility.html

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. We 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 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)

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.

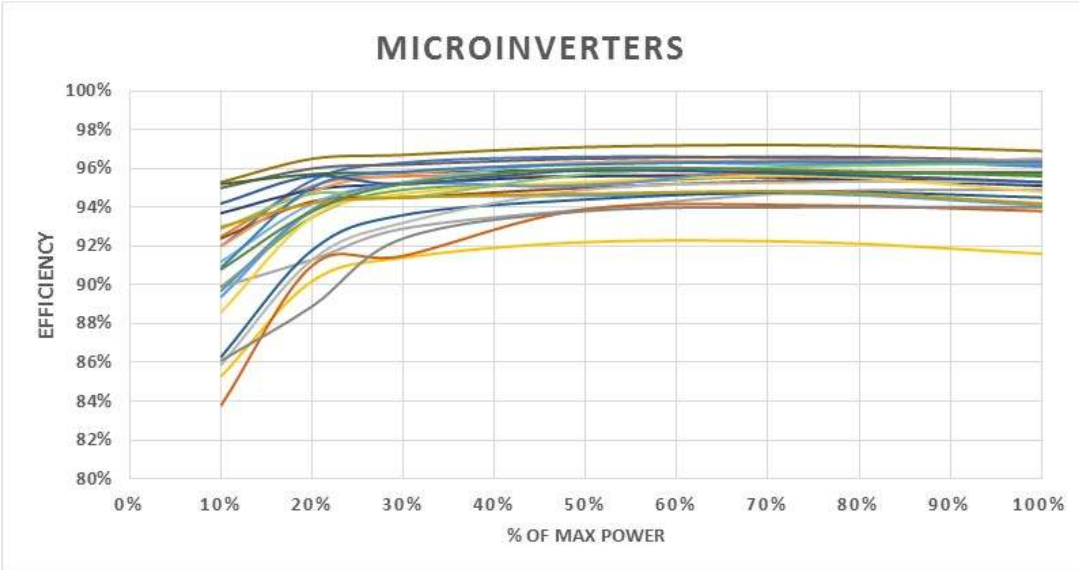

Figure B.2. Efficiency Curves for Microinverters (V_{in}<65 VDC, V_{out}=120/240 VAC, P_{max}<1 kW)

String Inverters

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

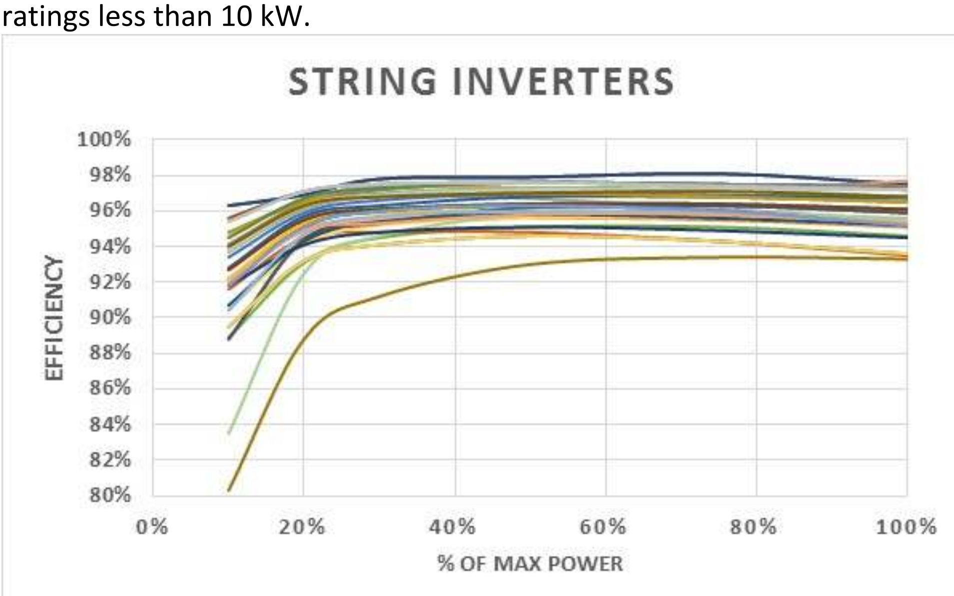

Figure B.3. Efficiency Curves for String Inverters (V_{in}<600 VDC, V_{out}=240/208 VAC, P_{max}<10 kW)

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.

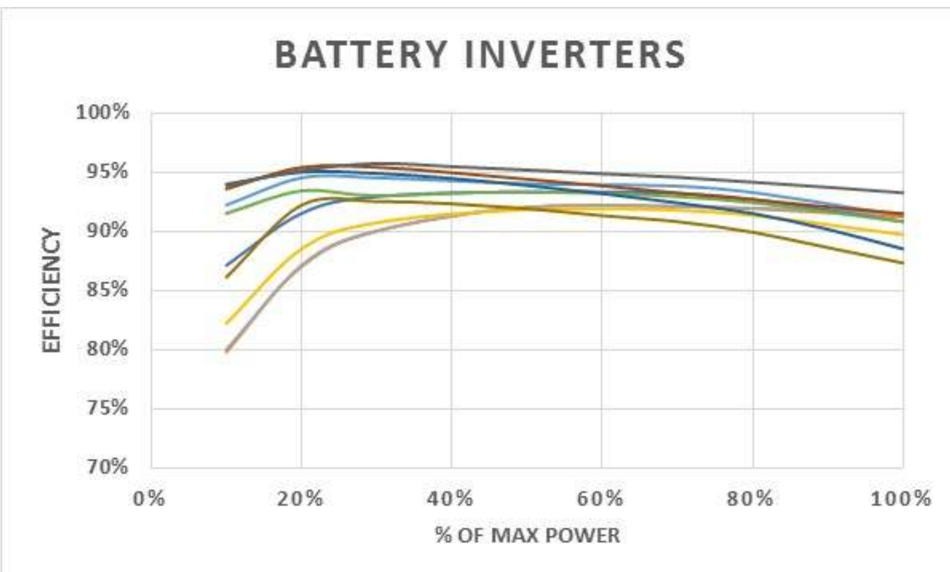

Figure B.4. Efficiency Curves for Battery Inverters (V_{in}<64 VDC, V_{out}=120 VAC, P_{max}<10 kW)

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.

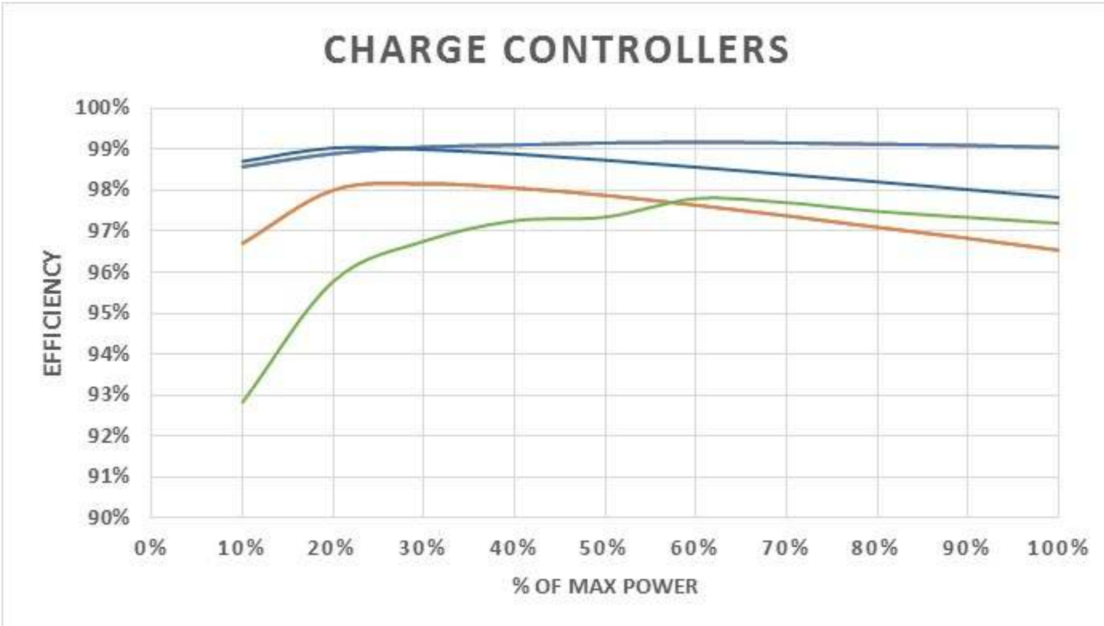

Figure B.5. Efficiency Curves for Charge Controllers (V_{in}<600 VDC, V_{out}=48 VDC, P_{max}: 1-5 kW)

DC/DC 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.

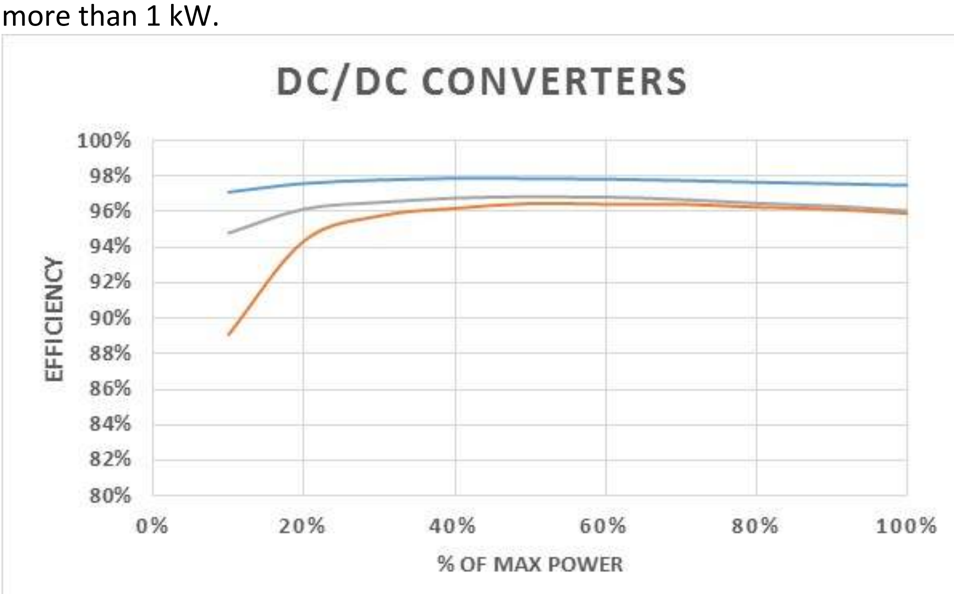

Figure B.6. Efficiency Curves for DC/DC Converters (V_{in}<140-400 VDC, V_{out}=48 VDC, P_{max}: 1-5 kW)

LED 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.6 shows efficiency curves for AC LED drivers with power ratings less than 500 W and input voltage at 120V.[6]

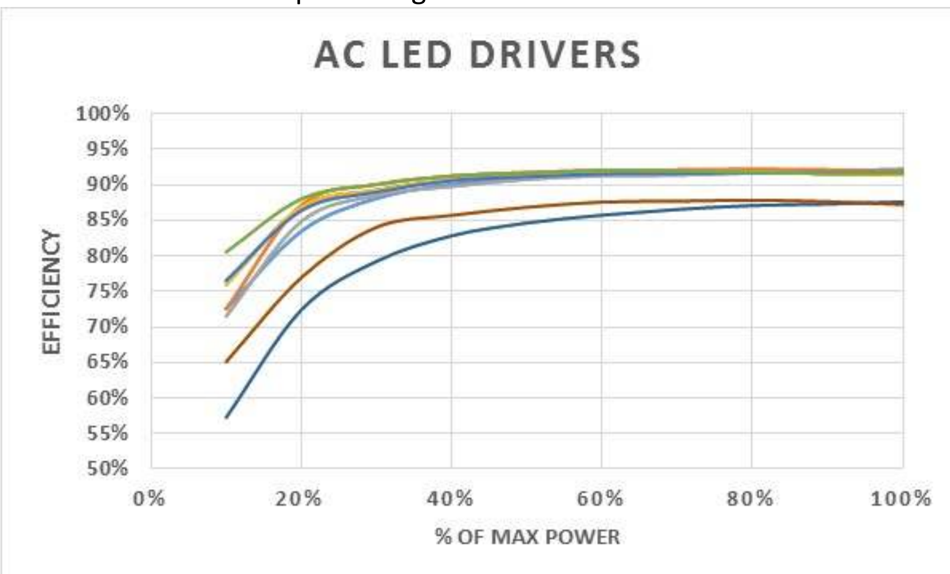

Figure B.7. Efficiency Curves for AC LED Drivers (V_{in}=120 VAC, V_{out}=48 VDC, P_{max}<500 W)

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.

[6] We note that although we did not obtain efficiency curves for DC LED drivers, their peak efficiencies were higher than those for AC LED drivers.

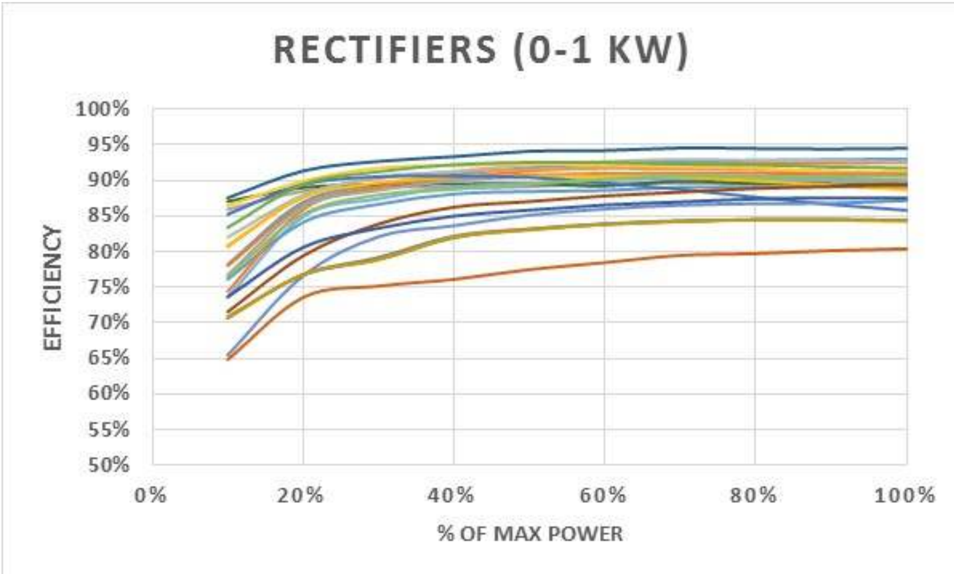

Figure B.8. Efficiency Curves for Rectifiers (V_{in}=120 VAC, V_{out}=48 VDC, P_{max}≤1 kW)

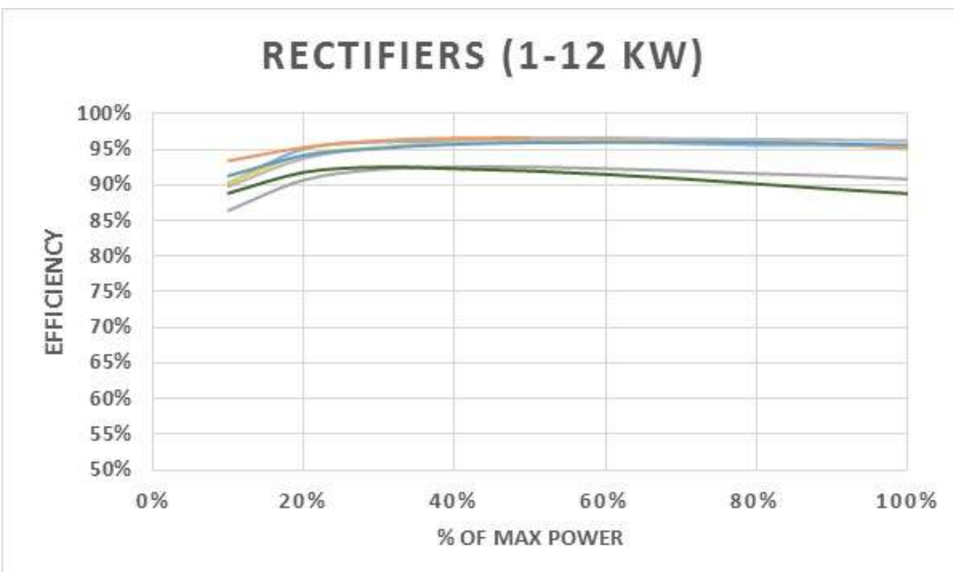

Figure B.9. Efficiency Curves for Rectifiers (V_{in}=120/277/480 VAC, V_{out}=48 VDC, Pmax: 1-12 kW)

Appendix C: Stakeholder Workshop

Workshop on Direct Current as an Integrating and Enabling Platform in ZNE Buildings
March 15, 2016

Los Angeles Electrical Training Institute (ETI)
6023 S. Garfield Ave., City of Commerce, CA 90040

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.

Workshop Agenda

8:30am - 9:00am	Check-in and networking
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?" • Technology • Policy • 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?" • Small loads (lighting, electronics, fans, …) • Larger loads (HVAC, water heating, motors, EVs, …) • ZNE integrated systems (PV, storage, EV charging, power infrastructure) *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

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."

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%–50%. There are 25% losses in AC-DC conversion if below peak power. Part load inverter efficiency is 30%–40%
- 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%. Focusing on mobile communications. In residential 30%–40% 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 bi-directional 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: CEC 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%–30%)
  - 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.

<u>Key takeaways:</u>

- 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

<u>Key takeaways:</u>

- 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 <u>commercial</u> 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 DC 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			
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	Global	Released

	DC; 35 Watts		

EUROPEAN AND GLOBAL STANDARDS			
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
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 - 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 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			
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			
CHAdeMO	DC fast charging		Released
SAE/CCS	DC charging		Released