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# Direct Current as an Integrating Platform for ZNE Buildings with EVs and Storage: DC Direct Systems – A Bridge to a Low Carbon Future?

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**ABSTRACT**

Cost effective zero net energy (ZNE) schemes exist for many types of residential and commercial buildings. Yet, today's alternating current (AC) based ZNE designs may be as much as 10% to 20% less efficient, more costly, and more complicated than a design based on direct current (DC) technologies. An increasing number of research organizations and manufacturers are just starting the process of developing products and conducting research and development (R&D) efforts. These early R&D efforts indicate that the use of DC technologies may deliver many energy and non-energy benefits relative to AC-based typologies. DC ZNE schemes may provide for an ideal integrating platform for natively DC-based onsite generation, storage, electric vehicle (EV) charging and end-use loads. Emerging empirical data suggest that DC end-use appliances are more efficient, simpler, more durable, and lower cost. DC technologies appear to provide ratepayers a lower cost pathway to achieve resilient ZNE buildings, and simultaneously yield a plethora of benefits.

This paper draws from the current research effort entitled "Direct Current as an Integrating and Enabling Platform," co-led by the Lawrence Berkeley National Laboratory (LBNL), the California Institute for Energy and the Environment (CIEE), the Electric Power Research Institute (EPRI) and funded under the California Energy Commission's Energy Program Investment Charge (CEC EPIC). The first phase of this EPIC research is focused on assembling and summarizing known global performance information on DC and DC-AC hybrid end-use appliances and power systems. This paper summarizes the information and insights gained from this research effort.

## Introduction

DC power is often perceived as a radical departure from mainstream electricity distribution. In fact, DC power systems have been widely used for a long time in vehicles and boats; DC has long powered traditional telephone service (and more recently USB and power over Ethernet (PoE)) in buildings. The number of native DC end-uses is on the rise too, with the proliferation of LED lighting and consumer electronics. Nearly all office equipment -- monitors, computers, copiers, and servers -- are now natively DC. A large and growing number of DC-based appliances provide compelling reliability, power quality, and efficiency reasons for directly using DC power from renewable energy systems or batteries, rather than converting first to AC and then back to DC. With both building-sited photovoltaic (PV) power and DC-based product usage rapidly growing, and given the critical need for improved energy efficiency, it is time to adopt DC power for mainstream applications.

In evaluating any of these emerging DC solutions, it is critical to understand the full picture of both energy and non-energy benefits: strategic value, installation factors, customer needs, safety, potential costs and benefits, controllability, interoperability, integration with smart grid connections, reliability, resiliency, market barriers, and others. The next step is to focus on use of DC solutions in residential and light commercial building applications. This paper provides an overview of the existing DC and hybrid technologies, systems, market information, performance data, case studies, research, codes and standards, market barriers, costs, benefits, and adoption pathways.

**DC and Hybrid Systems Have Major Integration Advantages for ZNE Buildings with EVs and Battery Storage**

The state of California is the leader in greenhouse gas reduction through landmark legislation AB 32, the California Global Warming Solutions Act of 2006, and its more recent amendment, SB 32. Attaining these targets will require electrification of end-uses, including our transportation system, and conversion to renewable generation, much of it onsite in ZNE buildings. Virtually all renewable generation, battery, EV loads, and an increasing fraction of energy efficient appliances require DC. Thus, the strategic value of an integrated DC system has the potential for significant energy savings beyond the existing ZNE best practices. Initial research also shows many other potential benefits for DC power, such as increased reliability, reduced materials and space savings, improved controllability and interoperability, and lower cost of ownership (George 2006; Strategen Consulting, and ARUP Group 2014).

**Evolutionary and Revolutionary Change Needed for DC and Hybrid Building Systems**

There are many fundamental and systemic barriers hindering the market transformation to DC and hybrid electric systems. The AC platform served as the foundation for most electric power systems, beginning with power plants, through transmission networks, to appliances. The digital revolution, combined with utilizing PV and other renewable energy sources, has already shifted the majority of end-use technologies to digital designs requiring DC power. The rapidly growing PoE and Internet of Things (IoT) products, systems, and networks are trends that propel DC power systems into the market; traditional building products companies with networked DC solutions are now competing with information and telecommunications companies (Halper 2016). The ZNE and EV goals will also drive the use of DC systems, in particular, EV rapid charging via DC. Even with all of these clear and growing trends for DC-based technologies, there are many multi-layered barriers to market adoption of DC and hybrid systems. Demonstrations, performance documentation, and DC and hybrid AC/DC guidelines can work to dissolve these barriers.

**Existing Buildings**

One of the key challenges to attaining a low carbon future is to retrofit existing buildings with optimal efficiency, renewable power, battery storage, EV charging, and smart grid interconnections. The second and third tasks in this research project address both retrofit and new construction end-use applications and ZNE building system designs. A fundamental issue for retrofits is whether the existing AC wiring system can be used for DC retrofits. Preliminary estimates show that in some cases this may be feasible for DC, because the new digital

technology may use only 10 to 20% of the designed power. Current electrical codes and standards allow an engineer to calculate the DC loads and show that the proposed design meets the existing requirements, however the expense of this custom design process along with the resistance of code officials to check the analysis create significant barriers. Emerging technologies enable the use of existing AC building power lines to supply energy both AC and DC end-uses simultaneously (ADC Energy, Inc. 2016). Retrofitting existing buildings to meet ZNE goals will be a major challenge and the research and demonstration of the emerging DC retrofit systems as a part of the solution is vital to showing the field performance and breaking through the market transformation barriers.

## Overview of DC and DC-AC Hybrid End-Use Systems for Residential and Commercial Buildings

An increasing number of end-use building products and systems are comprised of solid state componentry that require DC power to operate. Typically, each device has an individual AC/DC converter. Most digital products also have an Internet Protocol (IP) address, which allows digital control, monitoring, and communication via the IoT, thus leading to greater inter-operability and systems integration. The emerging PoE technology integrates the digital power communications, sensors, and controls on a DC power platform using USB cables, creating DC micro-grids. Older PoE cable carried only 30 watts but Universal PoE now has 60 watts per port, while the new version, expected in 2016, will provide 80 to 100 watts. According to market research, PoE worldwide annual shipments for 2015 are estimated at 100 million powered devices, with an annual increase rate of about 60% (Dell'Oro Group 2016). PoE systems with this higher power and IoT controls may be a "game changer" for DC systems in buildings. When buildings are powered by renewable power and/or use storage and EV-charging, these DC end-use microgrids can provide significant advantages.

In 2014 the U.S. Department of Energy (DOE) sponsored the Direct Current Scoping Study, which identified the following opportunities for DC power in buildings: 1) replace existing end-uses with high efficiency DC motors; 2) use variable frequency drives for air conditioning and refrigeration loads, and 3) use wide band gap semiconductors for equipment power supplies along with native-DC lighting -- already well underway (Strategen Consulting and ARUP Group 2014).

Lighting is in the midst of a transformation to LED solid-state lighting sources, controls, sensors, and communication -- all requiring DC power. According to a recent study, LEDs will cover 99% of the general service lighting market share by 2030 (Navigant Consulting, Inc. 2014). DC-powered lighting systems breaking into the market include the 24V DC commercial ceiling grid, DC-powered fluorescent ballasts, low voltage DC lighting, retrofit of existing AC wiring for DC lighting, DC building distribution and lighting systems, and PoE lighting systems. Philips, Cisco, and NuLEDS and many others are partnering in emerging lighting PoE systems with occupancy, daylighting, temperature, and other controls (BusinessWire 2016). There are a number of PoE lighting demonstrations; one of the largest is the Edge Building in New Amsterdam, designed by Philips. According to Philips, PoE lighting can lead to a 25% reduction in installation cost due to 87.5% less mains wiring compared to conventional wiring systems for lighting (Philips 2015).

## DC & DC/AC Hybrid ZNE Building Microgrid Systems

The renewably powered electrification of buildings and transportation will be required to meet California goals and will require re-design of the energy infrastructure by 2050. Thus combining the buildings with storage and EV charging is a very likely scenario and DC power is an essential enabler platform for this systems integration, interoperability, reliability, and resiliency. There are numerous emerging products and demonstrations for DC systems in buildings and community microgrids.

The EMerge Alliance is a nonprofit organization working for the rapid adoption of DC microgrids in commercial buildings through developing DC designs and demonstrations for both high voltage 380 V DC and low voltage 24 V DC systems. In addition, the Alliance is working to create national and international standards for DC systems. Figure 1 shows one example of an EMerge Alliance microgrid that includes lighting, lighting controls, security, IT and audio-visual (AV) devices, onsite generation of DC electricity, and heating, ventilation, and air conditioning (HVAC) controls. One case study is the NextEnergy Center building and DC testing labs in Detroit, which received grant funding from the State of Michigan for the conversion of the NextEnergy facilities from AC to a DC power distribution system. The 45,000 sf building in Detroit's Tech Town encompasses eight laboratories, a showroom/atrium, an auditorium, and office/meeting space. The project included demonstration of a unique solar panel that produces both thermal heating and PV power. Working with NextEnergy Center and Power Panel, Nextek successfully converted lab and office space ceiling, lighting, and fan systems to DC, rectified AC grid power to 380 VDC, and installed motion sensing and wireless lighting controls. In each of the eight lab spaces, lighting retrofits achieved a 43% energy savings on the lighting system while providing more and better distributed light.

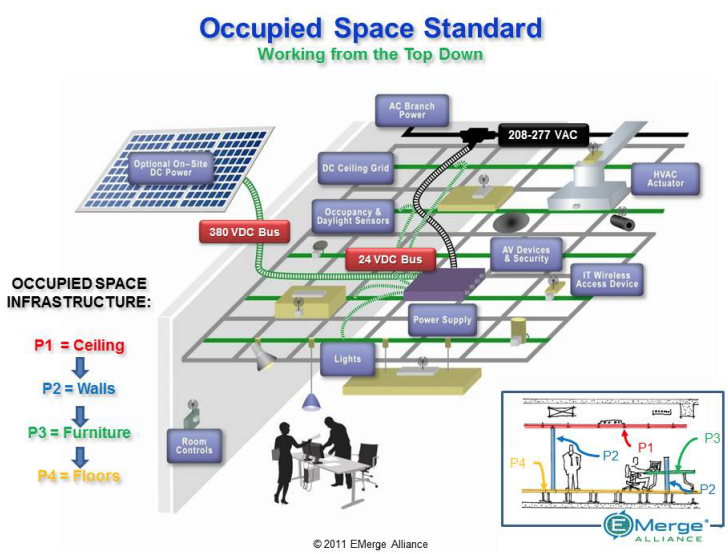


Fig. 1: EMerge Alliance Occupied Space Standard. *Source*: Reprinted with permission from EMerge Alliance.

A few examples of demonstration sites worldwide are described in Table 1 and shown in Figure 2 below.

Table 1. Description of Demonstration Sites for DC Distribution in Buildings

| Site | Description |
|---|---|
| NextHome Detroit, MI | NextHome (Detroit, MI) is a demonstration DC test bed developed by NextEnergy. The NextHome features PV generation and supplies direct-DC power for LED lighting, ceiling fans, floor heating, home appliances, and includes battery storage and bi-directional EV charging. (NextEnergy 2015) |
| Chino, CA | Bosch, in collaboration with the California Lighting Technology Center (CLTC), is developing a demonstration project in Chino, CA, funded by the CEC EPIC program. The project's goal is to demonstrate the benefits of DC distribution in commercial buildings, by implementing a PV powered, direct DC, 380 Volt distribution system powering lighting and forklift chargers. (Ravula 2015) |
| Fort Bragg, NC | Bosch has implemented a DC microgrid demonstration project, funded by the U.S. Department of Defense, in Fort Bragg, NC, which includes a 15kW PV array powering 44 DC induction lights, 4 DC ceiling fans, and a 100 kW Li-Ion battery storage system. A side-by-side equivalent AC system reportedly uses 8% 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 performed directly after the PV array, but rather at the AC/DC gateway converter, allowing for higher system efficiency. (Fregosi et al 2015) |
| Eindhoven HTC Netherlands | 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% electricity savings and 5% potential savings for the DC system. (Boeke and Wendt 2015) |
| Fraunhofer Institute Germany | 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 at about 2.7%-5.5% over an equivalent AC system. (Weiss, Ott, and Boeke 2015) |
| BUCEA China | 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% savings from shifting to an all-DC system from the current AC-system (BUCEA 2015). |
| Hokkaido, Japan | 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% electricity savings compared to the same system powered by AC. (Noritake et al 2014) |
| Xiamen University China | A DC microgrid has been implemented at Xiamen University in China. The direct-DC system consists of a 150kW PV array, 30kW air conditioning system, 40kW EV charging station, and 20kW 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. (Zhang et al 2015) |

Figure 2. Worldwide Demonstration Sites for DC Distribution in Buildings

## Energy Savings

Several recent studies are available for savings from DC power 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. Table 2 presents the findings of these studies.

Table 2. DC System Energy Savings Estimates

| Study | Study Type | Scenario* | Electricity Savings |
|---|---|---|---|
| Backhaus et al 2015 | Modeling | Battery Storage | 2 – 3% |
| Boeke and Wendt 2015 | Experimental | LED DC system<br>No battery storage | 2% measured<br>5% potential |
| Denkenberger et al. 2012 | Modeling | All DC building<br>Residential & commercial<br>No battery storage | 5% Residential<br>8% Commercial |
| Fregosi et al 2012 | Experimental | LED DC system<br>No battery storage | 6-8% (modeled) |
| Noritake et al 2014 | Experimental | All DC office building<br>Battery storage and EV | 4.2% |
| Fortenbery, Ton, and Tschudi 2008 | Modeling | Data Center | 20% or more |
| Vossos, Garbesi, and Shen 2014 | Modeling | All DC Building<br>Residential | 5% w/o battery<br>14% w/ battery |
| Weiss, Ott, and Boeke 2015 | Experimental | All DC Building<br>Battery storage and EV | 2.7% - 5.5% daily savings |

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

As shown in Table 2, energy savings from DC distribution in buildings may vary. Evidently, the presence of battery storage (and EVs in the commercial sector) can increase savings, as battery storage favors the DC system, and EVs are relatively large DC loads. Perhaps less obvious is the fact that the presence of an EV for residential buildings may not be beneficial in all cases, since charging typically occurs during the night, thus rectified AC-to-DC may be used to charge EVs. It should also be noted that modeling studies produced a range of energy savings -- both at the low and high ends of the spectrum. This range in savings estimates is due primarily to the power system component efficiency assumptions. On the other hand, experimental savings measurements are more consistent, in the 4-8% range, depending on the presence of battery storage, system configuration, and component efficiencies. Table 3, below, summarizes the power system component efficiencies found in recent literature.

Table 3. Power System Conversion Efficiencies

| **Component** | **Efficiencies** |
|---|---|
| AC-DC Central Rectifier | 93.0[1], 96.5[2], 96.9[3], 97.0[4,5] |
| DC-AC Inverter | 95.0[1], 96.9[4], 97.6[2] |
| DC-DC Converter (380V @ 24V) | 95.0[1, 4, 6],96.0[2] |
| DC-DC Converter (24V @ Lower Voltage) | 95.0[6] |
| MPPT & Charge Controller | 97.4%[5], 97.6[2, 3], 98.0[1] |
| Appliance AC-DC Converter (high power loads) | 90.0[1], 94.2[3], 96.5[2] |
| Appliance AC-DC Converter (low power loads) | 87.0[1], 87.9[6], 91.7[3], 95.0[2] |
| LED Driver | 93.3[6], 94.9[3], 97-98%[4] |
| EV Charger | 96.0[6], 97.2[3] |

1: (Vossos, Garbesi, and Shen 2014); 2: (Backhaus et al 2015); 3: (Weiss, Ott, and Boeke 2015); 4: (Fregosi et al 2015); 5: (Boeke and Wendt 2015); 6: (Noritake et al 2014)

**DC Policy Issues**

The key policy drivers for California are AB32 and SB32 focused on greenhouse gas reductions, the CPUC Energy Efficiency Strategic Plan, along with the variety of other renewable energy, energy efficiency, demand response and transportation policies and goals. To meet these policies and goals, electrification of both buildings and transportation will be needed, powered by PV, wind, water and other renewable energy resources by 2020, 2030, and 2050. This massive and disruptive shift will also require a new sustainable energy infrastructure, and DC power systems will play an essential role in this transition. The entire legacy AC power systems will need to be redesigned -- beginning with ZNE buildings as microgrids with storage and EV charging, outward to community grids, to Smart Grids that reduce our GHG footprint by 50% by 2030 and 80% by 2050. Thus the overarching policy question is how to create an integrated set of market transformation policies and goals for the end-uses, buildings, transportation, electric infrastructure, electric transmission and renewable power generation. Below are a few examples of important policy issues that could spur the transformation needed to meet California goals:

1. Shift the CPUC and CEC benefit analysis from energy-based cost avoidance to lifecycle greenhouse gas reduction impacts. This removes the existing contradictions in economic results using energy metrics that show gas versus electricity-use paybacks without properly crediting the full life-cycle value of the GHG reductions.
2. Integrate renewables, customer storage, Integrated Demand Side Management (IDSM) and EV policies that provide system and infrastructure requirements and incentives for DC building microgrids.
4. Eliminate the CPUC and CEC restrictions on fuel shifting from petroleum-based fuels to electric sources. This is a basic conflict with the CEC definition of ZNE buildings and provides a substantial barrier for ZNE retrofits.
5. Provide planning, permitting, and financing incentives to commercial and residential developers for sustainable infrastructure and smart-grid technologies.
6. Develop specific pathways to DC and hybrid building technologies and designs for policy

development and provide demonstration funds for these systems.

**Standards and Codes**

Changing the AC-centric electrical standards is a long process and can be a barrier to DC power applications and new technologies, while providing significant momentum for legacy products and paradigms. Many new standards for DC power have been developed in the last ten years and many are in process with the goal of creating international standards for DC power systems and applications. The main goal of the EMerge Alliance is to help create DC standards directly, or by catalyzing standards creation through other organizations like IEC, IEEE, NFPA, etc. 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, as to make them extremely difficult and unlikely to be used for DC. Thus explicit DC and AC-DC hybrid electrical standards and codes are vital for widespread market adoption. Another key factor is that the emerging PoE systems are merging Information Technology (IT) with electric power systems as DC products or microgrids.

In spite of the need for improvements, many key DC standards and demonstrations now exist such as: 24-volt DC ceiling grids, low voltage DC standards, 380-volt DC standards, DC fast chargers for EVs, and DC building microgrid standards, and others (Emerge Alliance 2016).

**Market Adoption**

The barriers to replace the existing AC electrical system with the adoption of DC electrical systems requires strategic, interconnected, and systematic analysis to show the integrating and performance benefits of a hybrid DC and AC system in meeting our California goals. In some areas specific end-use DC end-use solutions offer significant non-energy benefits; for example, fast charging 380V DC for EVs reduces the charging time to under one hour, instead of five to 11 hours on AC charging systems. PoE systems combine the power with the communications, monitoring and controls in one digital system. Even though DC-internal appliances are typically more expensive than AC counterparts, market adoption is expanding rapidly because DC appliances are more efficient, smaller, and reliable, and enable the IoT for easier control and interoperability. Thus the market transformation will likely occur on different fronts: whole building or community system integrating aspects of DC power, and the new benefits from innovative DC products, services and networked systems. The new paradigm of a digital world with buildings and transportation powered by renewable DC power requires a new vision, design, and replacement of existing infrastructure and products. The key to market deployment of DC and hybrid building products, systems and infrastructure replacements will require sustained market facilitation, demonstrations, education, and documented benefits of integrated DC and hybrid systems. Below are some examples of market barriers beyond the typical emerging technology challenges.

- Lack of market-ready DC equipment and appliances.
- Technology and efficiency standards for DC systems are lacking, and companies are then reluctant to embark on product development.
- Explicit codes and standard changes take a long time and the legacy of AC power negatively impacts both the availability of DC products, designers, installers and owners

- For retrofit applications the legacy AC system presents a particularly large barrier. PoE systems and using the existing building AC wiring for DC power are pathways to surmount the legacy barriers.

## Lessons Learned & Conclusions

The key lessons learned and conclusions for DC and hybrid power systems to date in this study is that the strategic value of DC power requires a systems approach integrating onsite renewable generation, digital building systems, battery storage EV charging and smart grid controls. Working backwards from the ZNE and low carbon goals requires this strategic analysis to support the replacement of the existing electrical system with a sustainable power system. Some particular points are:

- Lab and field performance data on DC systems is very limited at this time. Our literature review showed a large increase in publications on DC power systems starting in 2012 indicating a surge in interest.
- More demonstrations and lab studies are critically needed for ZNE buildings with battery storage and EV charging to validate the performance, costs, resiliency, GHG savings, integration with the smart grid, digital networks and other overall electric system benefits.
- There are significant multi-layered barriers to DC building systems especially for retrofits.
- Improved efficiencies of 10 to 15% may be feasible with an integrated system design, synergy, optimization and networked controls. Additional improvements up to 20% efficiencies may be realized through 1) DC system power component efficiencies can only improve with increased R&D (e.g., MPPT efficiency can reach 99.5%); 2) ZNE buildings achieve better coincidence of load and PV synergy of energy savings because of lower heating/cooling loads required by whole building.
- DC and hybrid electrical systems or micro-grids provide a better design platform for integrating and controlling ZNE buildings, renewable power, electric transportation, smart grid management which may be key to meeting the California AB 32 goals and create a low carbon future.
- The digital revolution is generating a wave of emerging PoE systems and IoT applications for lighting, plug loads, office workstations, device charging and other applications. The continued growth of PoE and IoT systems create a new market dynamic for DC applications, products and services with IT and networking companies like Cisco entering these markets with disruptive technology combining power and controls.

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