Pacific Gas and Electric Company

Zero Net Energy Program

DC Distribution Market, Benefits, and Opportunities in Residential and Commercial Buildings

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TABLE OF CONTENTS

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EXECUTIVE SUMMARY

As high-performance building designs move toward zero net energy (ZNE) and the electric consumption of those buildings is increasingly dominated by plug loads and lighting, the alternating current (AC) current of today's electric grid is less and less appropriate for the building electrical systems of the future. Both the distributed generation resources (mainly photovoltaic panels) and many of the electrical loads in today's buildings fundamentally produce and consume direct current (DC). The solution for decades has been for each device to convert AC into low-voltage DC current through power supplies, lighting ballasts, and motor drives. Our estimates show that today's commercial office buildings waste about 13% of their electricity every year simply distributing and converting power from the utility meter down to the point where it can power equipment.

As an alternative to today's AC distribution paradigm, we envision "microgrids" of DC power within our broader AC grid. These DC "islands"—a building, a neighborhood, or a community—would use DC power for certain end uses that favor it. Native DC generation sources, like PV panels, could be more directly coupled to modern lighting systems and office equipment, avoiding some conversion losses from AC electricity distribution. As an ancillary benefit, many consumer electronics products could jettison the power adapters that now clutter the power strips behind our desks and televisions in favor of a standard DC power connection.

We may be years away from realizing this vision for a mature DC microgrid solution. This report instead examines the near-term benefits, barriers, and opportunities for implementing DC distribution systems in residential and commercial buildings, with special consideration for zero net energy (ZNE) buildings that use on-site generation to offset energy use. Our major findings show that:

- Although the market for DC systems is extremely nascent, industry-led efforts are spurring the development of near-term applications, particularly in commercial buildings. The EMerge Alliance, an industry consortium of electrical system, lighting, modular furniture, solar PV, and other manufacturers is developing standards to enable safe distribution of DC power in commercial buildings. Early applications focus on suspended ceiling grids mainly to power overhead lighting.
- Several encouraging field studies of DC distribution exist, with varying degrees of monitoring data to demonstrate energy savings impacts. Projects to date are predominantly commercial and include data centers, manufacturing facilities, and office buildings. Further demonstrations are needed to demonstrate the benefits of new applications, like DC-powered office equipment, residential buildings, and retrofit projects.

- The main barriers to DC power distribution in buildings are market-oriented rather than technological. Challenges include driving down the cost of new DC infrastructure components that are currently produced in low volume and ensuring that DC alternatives exist for mass-market products like computers, mobile phones, and task lighting. These market barriers are best mitigated by continued standardization activities on the part of EMerge Alliance and could be aided by market transformation efforts from electric utilities and energy efficiency advocates.
- DC distribution provides several important benefits beyond simply reducing distribution and conversion losses in buildings. For overhead lighting, it can enable greater flexibility and configurability, because licensed electricians are not required to move fixtures. For plug loads, it could allow lighter weight, more compact, less expensive designs by eliminating the need for AC-DC power supplies. Fewer power supplies in electronics would also translate into less electronic waste at end-of-life. DC distribution could also enable simpler, less expensive variable speed drives (VSD) in larger motorized equipment like HVAC pumps and fans, potentially leading to greater adoption of VSD technology and significant additional energy savings.
- DC distribution presents compelling energy savings, particularly in ZNE buildings. By eliminating redundant conversion steps and smaller, less efficient power conversion devices, commercial office buildings with full DC distribution could shave their electric consumption by 2% to 8%, depending on whether they are “code-built” construction or ZNE. Savings increase to 11% to 23% when one includes savings that might be enabled by greater use of VSDs.
- Residential buildings also present a sizeable savings opportunity for DC systems, although current industry standardization and product development efforts focus more heavily on the commercial sector. Fully DC homes could save 5% to 6% of their electricity use.
- The most cost-effective end-use applications for DC power, in order of greatest cost-effectiveness, are small electronics (less than 100W), lighting, and large motor loads (e.g. HVAC equipment). DC is most cost-effective for ZNE buildings or other facilities with on-site power generation that is natively DC (i.e. photovoltaic panels), because they can use DC power directly without the need for multiple AC-DC conversion steps. In many cases, a DC distribution system can actually reduce overall system costs (including power conversion, distribution, and end-use equipment).
- Near-term solutions are available to provide DC power to overhead lighting systems, data center equipment, and large motorized equipment like HVAC, but additional standardization will be required to provide DC power to consumer electronics and other office equipment.

THE EMERGING DC OPPORTUNITY

This report addresses a debate as old as the electric grid itself: what is the best way to transmit electric power: as alternating current (AC) or direct current (DC)? During the early electrification of the United States, the "founding fathers" of the modern electric grid grappled with this very question. George Westinghouse and several European competitors advocated for a grid standard based on AC electricity, whereas Thomas Edison pushed a DC model.[1] AC electricity eventually won these so-called "Current Wars" due to the ease of transmitting AC power over long distances.[2] By the turn of the century, most leading industrialized nations and heavy industrial firms (Westinghouse, General Electric, Siemens, etc.) adopted AC power as the de facto standard for distributing electricity. Today, AC power is so ubiquitous that it is almost synonymous with the concept of the electric grid itself.

The grid's founding fathers chose a very sensible electrical distribution standard for the time, because the early grid largely powered incandescent lamps and motors, both of which are perfectly compatible with AC power. However, today's grid powers an increasing number of electronics that fundamentally operate on DC power. Semiconductor devices—from microprocessors to memory chips to liquid crystal displays—all require DC voltage. Even traditional end uses like lighting have been making a steady migration first to fluorescent and now to light emitting diode (LED) technology, both of which run on DC. This "natively DC" portion of our electric grid is steadily growing and may soon surpass traditional electric end uses like HVAC equipment (Figure 1). As a result, billions of products—ranging from sophisticated data center servers to light bulbs—are produced with a built-in AC-DC power supply to convert AC grid power into DC power required by the device's electronic components.

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[1] Thomas Edison held a substantial number of patents on DC electric distribution infrastructure and therefore had a significant financial stake in the success of DC. Westinghouse had similarly large investments in AC, having licensed technologies related to AC motors and three-phase AC power distribution.

[2] Transformer technology at the time made it much easier and efficient to up-convert AC power for high-voltage transmission compared to DC power.

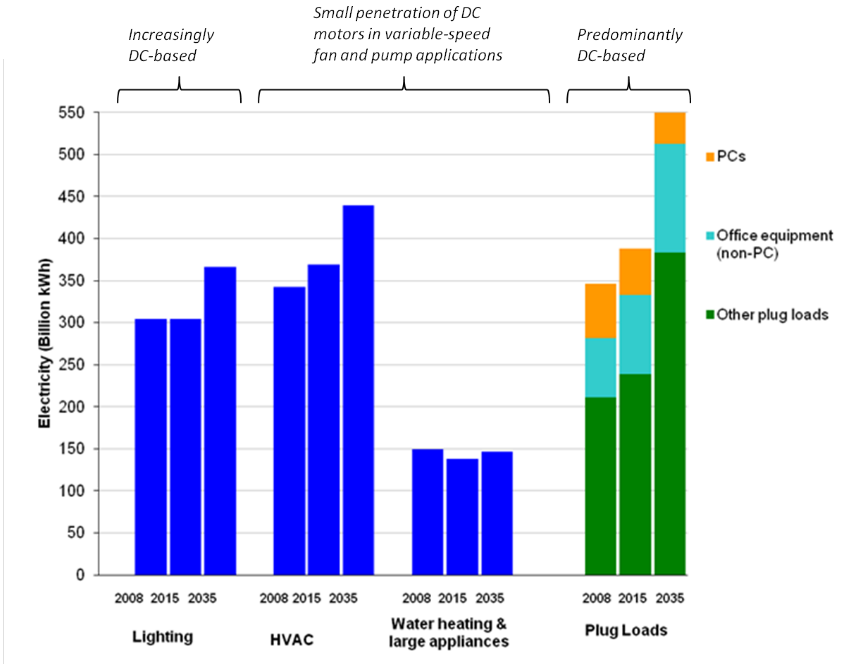


Figure 1: Commercial electric end uses over time. Source data: (DOE-EIA, 2011).

Converting AC to DC comes with a cost. Power supplies, lighting ballasts, and motor drives turn billions of kilowatt-hours of useable electricity into heat every year. Our estimates show that commercial office buildings waste about 13% of their electricity every year simply distributing and converting power from the utility down to the point where it can do useful work (Figure 2). Furthermore, conversion components add to the stream of physical waste generated by short-lived consumer products.

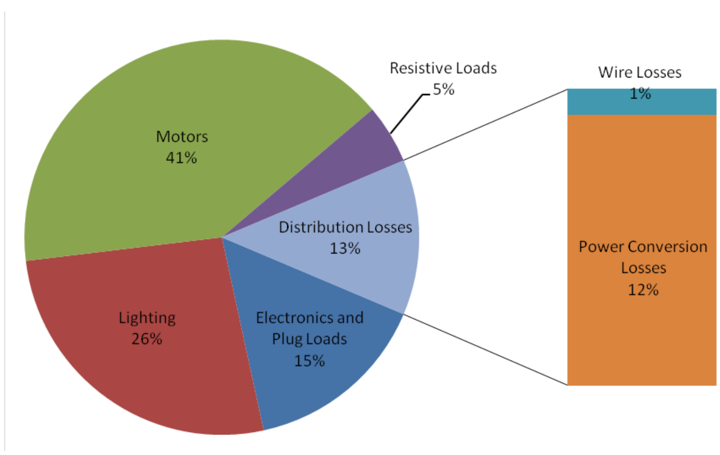


Figure 2: Losses in a typical commercial office building compared to end-use consumption

The same semiconductor technology that spawned modern lighting and electronics also created a fundamentally different source of power not envisioned when the grid was first deployed: photovoltaic (PV) panels. PV and a host of other distributed generation and storage technologies (fuel cells, high energy density batteries) are making significant inroads on today's electric grid. U.S. solar PV capacity, for example, is expected to triple by 2017 (Pike Research, 2012).

Coincidentally, this next wave of energy generation technology is also natively DC. Today's PV systems must convert their power from DC to AC in order to feed wiring infrastructure and end uses. Ultimately, that AC electricity is destined to encounter a power supply before it can be used—in a compact fluorescent lamp, a cell phone charger, or a computer—and undergoes yet another conversion step from AC *back* to DC. These redundant conversions are unavoidable in today's zero net energy (ZNE) buildings, many of which rely on grid-tied PV panels to offset site energy use. The result is that a third of the energy produced on site may be lost in conversions before it reaches the DC device it powers (Figure 3).

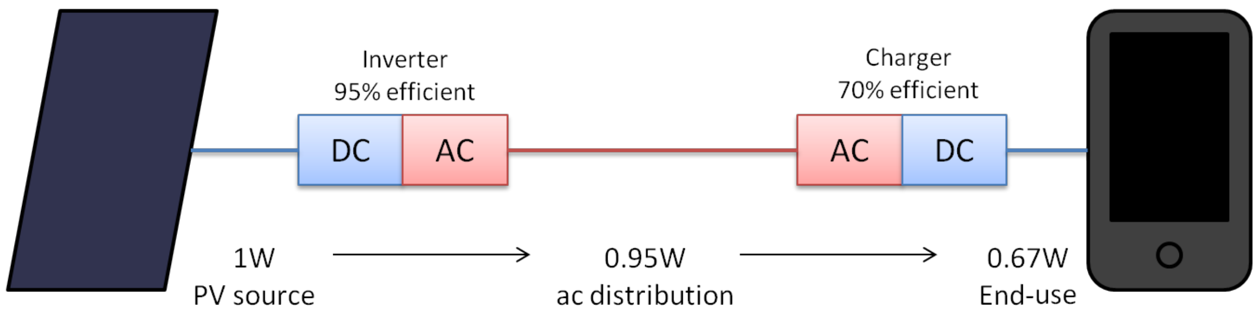


Figure 3: Conversion of 1 watt of electricity from PV panel (left) delivers 0.67 W of usable power to consumer electronics (right)

If the future load on our grid is increasingly DC, and most of the up-and-coming distributed generation solutions are DC as well, the current AC paradigm may no longer be the optimal choice for distributing power in buildings. Instead, we envision "microgrids" of DC power within our broader AC grid.[3] These DC "islands"—a building, a neighborhood, or a community—would use DC power for certain end uses that favor it. Native DC generation sources, like PV panels, could be married with modern lighting systems and office equipment, avoiding some of the conversion losses illustrated in Figure 3. As an ancillary benefit, many consumer electronics products could jettison the power adapters that now clutter the power strips behind our desks and televisions in favor of a standard DC power connection.

[3] It should be noted that high-voltage DC power transmission from DC generation sources like wind farms are starting to crop up in Europe, Asia, and to some degree North America.

We may be years away from realizing this vision for a mature DC microgrid solution. This report instead examines the near-term benefits, barriers, and opportunities for implementing DC distribution systems in residential and commercial buildings, with special consideration for zero net energy (ZNE) buildings that use on-site generation to offset energy use. Our research shows that, in general, DC systems would be highly cost-effective and provide meaningful energy savings in ZNE buildings, particularly commercial facilities whose load coincides more with daytime hours, when PV panels supply electricity. Near-term solutions are available to provide DC power to overhead lighting systems, data center equipment, and large motorized equipment like HVAC, but additional standardization will be required to provide DC power to consumer electronics and other office equipment.

THE STATE OF LOCAL DC DISTRIBUTION

Although DC power is an extreme minority when it comes to today's transmission and distribution of electricity, people have been designing and using DC power systems for years.[4] With increasing pressures to lessen the energy impacts of buildings and growing interest in distributed generation, nascent interest and development of DC power systems continues to build. This section provides an overview of the current state of DC distribution in buildings and provides a snapshot of the emerging market for DC power systems. We also highlight some existing analyses of the energy savings potential associated with DC and provide some brief case studies from several early adopter facilities.

DC STANDARDIZATION EFFORTS

At first glance, it might seem that the solution to the distribution problem posed in Figure 3 would be to simply connect the DC output of the PV panels to the DC input of the connected devices. Of course in reality, building power systems are far more complicated. For both AC and DC, power must be supplied at voltages that are appropriate to the capacity of the equipment being powered in order to reduce resistive losses (and heat buildup) in building wiring. In today's AC buildings, plug loads draw on 120 V_{AC}. We refer to these devices, powered at 120 V and below, as "low voltage," or LV for the purposes of this report. Devices powered at greater than 120 V are called "high voltage," or HV. For example, larger appliances in residences (e.g. electric stoves, pool pumps, water heaters) draw on 240 V_{AC}. High-power loads in commercial buildings typically operate on a 277 V_{AC} three-phase power system.

The voltage requirements of natively DC equipment differ vastly from the standard voltages at which we typically provide AC power today. For example, plug load devices can require anywhere from 5 V_{DC} for a cell phone charger up to 48 V_{DC} for certain telecommunications equipment (Figure 4). No one DC voltage dominates. This creates a challenge for anyone designing a DC distribution system, because one must eventually standardize on one or two voltages to supply to the building's equipment. Fortunately, industry-led efforts are beginning to tackle these difficult issues to ease the transition to building-level DC distribution.

[4] As recently as 2007, ConEdison was still providing a limited group of customers in Manhattan with DC power from the Pearl Street power plant, a DC generator originally developed by Thomas Edison.

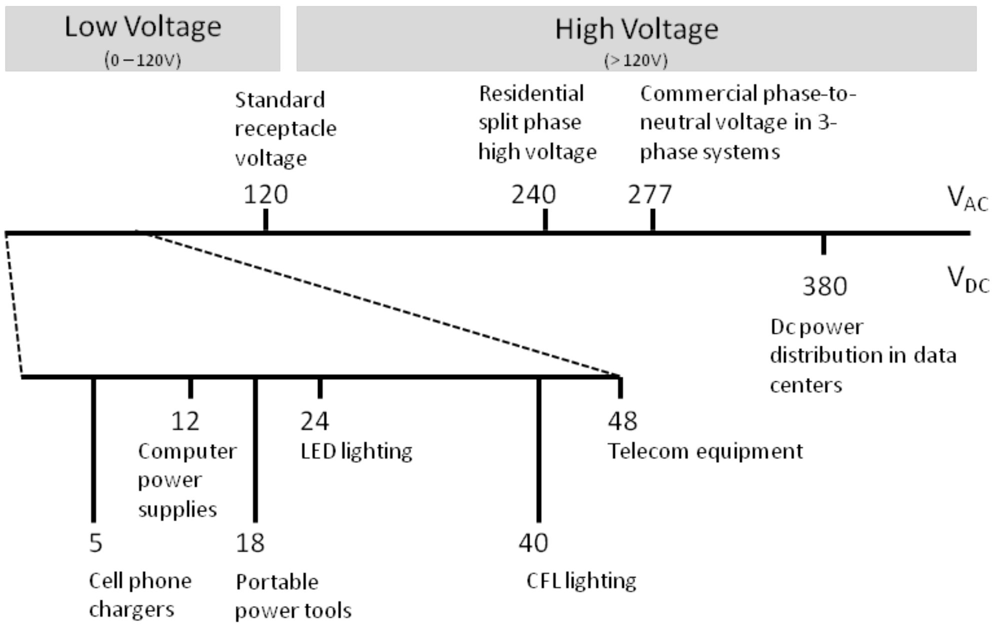


Figure 4: Common AC and DC voltages in high and low voltage products

Infrastructure Standards

The EMerge Alliance is an association of industry and research institute members aiming to accelerate adoption of DC power through standards development (EMerge Alliance, 2012). EMerge has thus far developed a 24 V_{DC} standard for commercial buildings and plans to release a 380 V_{DC} standard for DC data centers in October 2012. Member companies of the EMerge Alliance are beginning to develop mainstream DC products that meet the EMerge standards (discussed in subsequent sections). These products include both DC end-uses as well as power distribution and conversion equipment.

The EMerge Alliance's first standard is the 24 V_{DC} Occupied Space Standard (Figure 5). This standard creates an integrated, open platform for power, interior infrastructures, controls and peripheral devices to facilitate the hybrid use of AC and DC power within commercial buildings. Companies developing DC products can then use these standards to inform product design. Under the Standard, conversion of AC power occurs in one central power supply in each room. Low-voltage DC then flows via conductors in the suspended ceiling grid to power lights and other DC loads. If PV is available, its DC output can be connected directly to the power supply, eliminating need for an inverter and avoiding unnecessary power conversion steps.

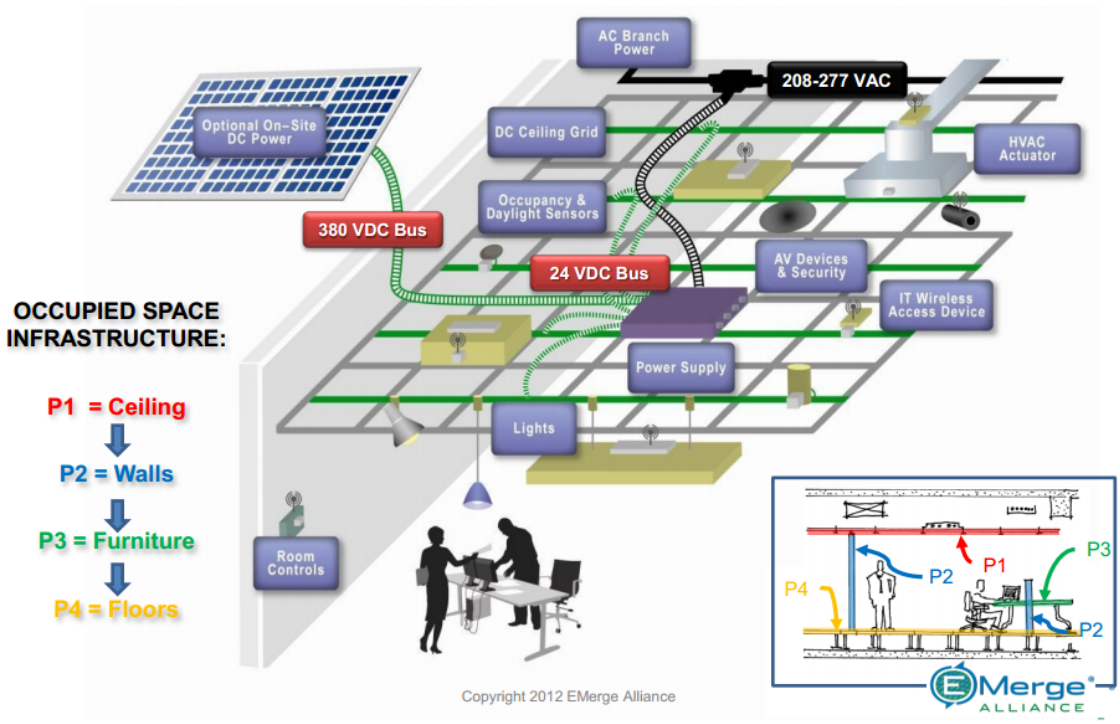
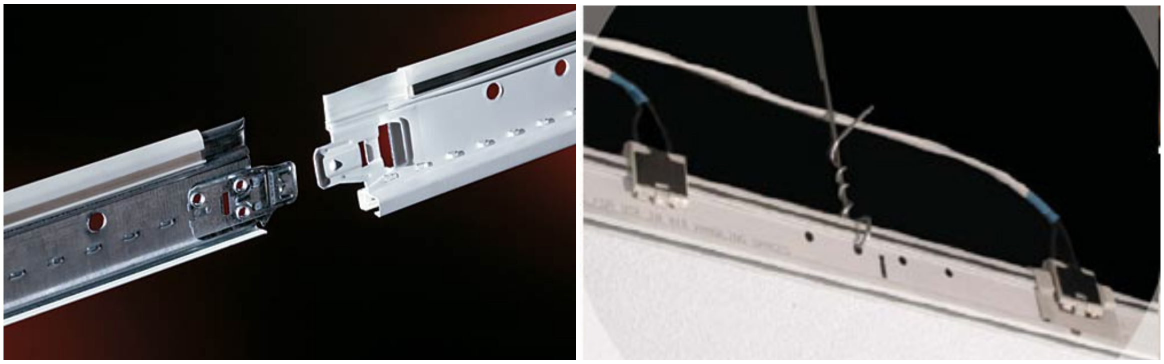


Figure 5. The EMerge Alliance 24 VDC Occupied Space Standard (Courtesy of EMerge Alliance, 2012)

The EMerge Alliance continues to update the Occupied Space standard and released version 1.1 in early October 2012. The next step in the standards development process for commercial buildings will be to address plug load equipment—task lighting, computers, monitors, and cell phone chargers—so that office users can power these devices with DC power at their desks. This will be done by integrating DC power into walls, furniture, and floors in addition to suspended ceilings (Figure 5). According to the Alliance's Brian Patterson, the Occupied Space standard version 1.1 has paved the way for near-term development of a Task-Level/Furniture component led by office furniture manufacturers Steelcase and Hermann Miller. These developments help ensure some degree of industry consensus around basic DC infrastructure in the near future. National codes and standards bodies such as the National Electric Manufacturers Association (NEMA) are also investigating DC power standards, although our understanding is that their efforts are nascent.

DC-Ready Products

The EMerge Alliance registers products that are compatible with their Occupied Space Standard. A growing number of manufacturers produce infrastructure, power, peripherals and controls that operate on 24 V_{DC}. Armstrong created the first key infrastructural component based on this standard: a ceiling suspension system called DC FlexZone (Figure 6). The grid has two sets of integrated electrical conductors to distribute low-voltage DC to lighting fixtures, sensors, and other electrical devices in the ceiling.



Pictured: DC FlexZone Suprafine T-bar and Silhouette Grid Systems (left), and TE Connectivity cable assemblies (right)

Figure 6. Armstrong DC FlexZone Ceiling (Architectural Record, 2012)

Currently, lighting is the most mature product category among possible end-uses that could connect to a DC ceiling grid. EMerge-registered products in this category include LED and fluorescent lighting, switches and dimmers. There are still some notable end-uses missing from the EMerge registry that are required in an office, such as plug loads and HVAC. We provide a summary of EMerge-registered products by category in Table 1.

Table 1. Products Registered by the EMerge Alliance that Integrate with 24 VDC

Category (Manufacturers[1])	Products[2]
End Uses (Osram Sylvania, Cooper, Nextek, Focal Point)	LED and fluorescent lights Lighting ballasts Ceiling fans
Power Conversion and Communication (Nextek, Roal)	Power supplies Converters Wireless gateways
Infrastructure (Armstrong, TE Connectivity)	DC ceiling grid Power cable assemblies System connectors
Controls (Crestron, Osram Sylvania)	Control processors (for lighting, audio-visual, HVAC and security, etc.) Wireless gateways Photocells

	Wireless keypads Occupancy sensors Energy control units Switches Dimmers

[1]Some manufacturers provide more than one product in a given category

[2]Product registry with the EMerge Alliance does not guarantee availability

EARLY IMPLEMENTATION EFFORTS

At this writing, only a few early adopters have made use of DC distribution in their buildings; for example, a few data centers and a handful of commercial office buildings with DC ceilings. Similarly, use of DC in residential buildings is limited to custom off-grid homes and grid-tied projects for demonstration purposes. In the sections to follow, we discuss recent implementations of DC in three building classes—data centers, commercial buildings, and residences—and note estimates of energy savings where available. A list of stakeholders contacted while investigating certain case studies is provided in the Appendix.

Data Centers

Though not the subject of this paper, the opportunity for energy savings in data centers is likely more compelling than in any other type of facility. DC data centers demonstrate clear efficiency gains over AC from the elimination of multiple conversion steps in the delivery of DC power to the server hardware. For example, in a typical data center, AC power is converted to DC at the uninterruptible power supply (UPS) only to be switched back to AC before it is finally converted to DC at each server's power supply unit. Therefore, a data center with DC distribution eliminates many power conversions, leading to substantial energy savings.

In a 2008 demonstration by Lawrence Berkeley National Laboratory (LBNL), Electric Public Research Institute (EPRI) and Ecos Consulting, researchers compared two 380 V_{DC} delivery systems with two 208-120 VAC delivery systems (Ton, Tschudi and Fortenbery, 2008). In both cases, the DC delivery system showed a minimum of 5% to 7% efficiency gains over "best in class", efficient AC systems. Compared to standard AC equipment, savings can be as high as 28%. Similar results, yielding savings estimates of 7% to 20%, were obtained in a recent demonstration at a Duke Energy data center (EPRI, 2011).

These measured energy efficiency gains did not include reductions in cooling loads and space requirements, which provide additional opportunities for cost and energy savings. In another demonstration comparing 400 V_{DC} to a 480-208 V_{AC} design in a 5.5 MW data center, Aldridge *et al.* (2007) estimated that fewer conversion steps and components of a DC data center result in 33% floor space reduction and 15% capital cost savings. For the risk-averse IT industry, perhaps the most compelling advantage of DC data centers is a 200% reliability improvement due to the reduction in system components and conversions. Since reliability is a key element in any data center operation, these results make DC distribution appealing for the reliability benefits alone (Aldridge et al. 2007). Table 2 lists DC data center projects and associated savings estimates.

Table 2. Examples of DC Building Case Studies with Monitoring Data

Application	Details	Benefits
Duke Data center	Savings from eliminating conversion losses	7%-20% energy savings, dependent on baseline
SUN Microsystems Newark, CA Data center	Savings from eliminating conversion losses	5%-28% energy savings, dependent on baseline
US Intel Corporation Data center	400 VDC design for a 5.5 MW data center that also was able to reduce cost, required space and improve reliability	7%-8% energy savings over best practice AC system, 15% cost savings, 33% space savings, 200% reliability improvement

Commercial Office Buildings

Commercial office buildings provide some of the best near-term usage cases for DC distribution, and yet a fully DC office building is still a distant vision. We list some proof-of-concept examples of implementation of DC infrastructure in Table 3. Unfortunately, these DC commercial buildings are not currently monitored for energy performance.

Table 3. List of DC Lighting Projects Based on EMerge Alliance Standards

Organization and Building	Project Details
Southern California Edison Utility Services Office Irwindale, CA	Fluorescent lighting fixtures with DC ballasts. SCE plans to connect solar to the DC system in the next phase.
Pittsburgh National Corporation(PNC) Financial Headquarters Pittsburg, PA	DC lighting and “smart ceiling”. Space repurposed twice since installation. PNC plans on using this system in other branch banks, and is considering solar for banks in southern regions.
University of California Davis California Lighting Technology Center Davis, CA	PV-powered DC LED lighting system
UC San Diego Sustainability Center San Diego, CA	DC fluorescent lighting system with integrated solar panels. LEED Gold certified.
US Green Building Council. Headquarters Washington D.C.	DC lighting. LEED Platinum with infrastructure in place to add solar panels.
L.A. Community College District Los Angeles, CA	Trade and Technology College with DC lighting system. The building is a repurposed single story high-bay multiuse building part of a large, publicly funded sustainable building program. Solar power will be connected to the DC lighting system in future phases.
Nextek Power Systems Detroit, MI	DC lighting in a one-story mixed use commercial office/lab/factory building.

	Solar planned for future phases.
Armstrong World Industries Lancaster, PA	DC lighting in two-story mixed use commercial office/factory building. This system is connected to PV as the primary power source, and uses AC as a back-up.
Frito-Lay Distribution Warehouse Rochester, NY	This LEED Gold-rated facility is equipped with a lighting system that uses DC fluorescent ballasts and roof-integrated solar panels. Nextek power routers allow the DC to be used by lighting systems directly.
Optima Engineering Charlotte, NC	Nation's first use of DC-based solar energy to drive LED lighting and controls based on the EMerge standards. LEED Platinum.
Integral Group Oakland, CA	DC lighting LEED Platinum office building.
Pacific Gas and Electric, Pacific Energy Center San Francisco, CA	A DC ceiling is in place, but currently there are not any lights connected to it. When funding becomes available, the PEC plans to install a DC lighting system connected to onsite solar panels.
Virginia Tech Center for Power Electronic Systems Blacksburg, VA	Developed a power supply that interfaces directly with a residential PV system and provides 380 VDC to building loads.

Many of the listed projects have a number of common elements, including:

- 24 V_{DC} suspended ceiling conforming to the EMerge Alliance Occupied Space Standard with accompanying overhead light fixtures (Figure 7)
- DC power supplies (sometimes confusingly referred to as "servers") that can either be powered by grid AC electricity or DC electricity from onsite solar
- DC-powered touch-panel control interface

Figure 7. Armstrong Industries DC Lighting Infrastructure (Courtsey of Armstrong, 2009)

Below we provide more detail on two of these DC pilot projects in commercial buildings.

Integral Group. Integral Group is a green architectural engineering firm known for its design of zero net energy buildings. For demonstration purposes, the firm installed an Armstrong FlexZone ceiling lighting system in their Oakland, Calif. office. (Figure 8). The building's other DC grid-compatible components include power supply modules by Nextek Power Systems, cabling by TE Connectivity, LED and fluorescent fixtures from Lunera Lighting and Focal Point, and lighting controls from Creston. Integral demoed the system because they believe DC to be a promising technology for high-performing buildings. So far, they are pleased with the system's performance (Smith, 2012).

Figure 8. Integral Solutions FlexZone LEED Platinum Project (Courtesy of Armstrong, 2012)

PNC Financial Headquarters. In addition to energy savings, one of the key advantages of a DC ceiling infrastructure is flexibility. Under the current EMerge Alliance Occupied Space Standard, a DC ceiling grid can be reconfigured without rewiring, a key advantage in today's evolving open office environments. The PNC Financial headquarters in Pittsburg, Penn. was an early implementation of a DC ceiling. Since the initial installation in 2002, PNC reconfigured the office space twice. Office reconfigurations normally require licensed electricians to move light fixtures, but DC-powered ceiling grids fall into the Class 2 regime of the National Electric Code (NEC), meaning that electricians are not required. A maintenance staffer with a ladder should be able to safely reconfigure an entire ceiling grid. "We were able to simply snap pendant fixtures into the grid wherever needed" said Mike Gillmore, PNC Director of Design and Construction Services (Armsrong, 2012)..

Figure 9. PNC Financial Headquarters in Pittsburg, PA (Courtesy of Armstrong, 2012)

Based on discussions with partners in the EMerge Alliance, we have some evidence that early adopters are pleased with their investment in DC infrastructure and are expanding their systems. This may be due to some inherent non-energy benefits associated with DC, such as configurability, power quality, and easier coupling with renewables. Due to the success of the PNC Financial pilot project, the bank decided to deploy similar systems in a number of branch banks. They also plan to build a ZNE bank branch in 2013 in Fort Lauderdale, Fl. that uses a DC ceiling. This willingness to incorporate additional elements of a DC system solution is some indication that building operators are not dissuaded by the lack of DC-ready products—a possible sign of coming growth in this market. However, early adopters have been eager to share positive experiences, but reluctant to discuss barriers, implementation issues, and concerns (some of these barriers are discussed later in the report).

Residential

Compared to the commercial sector, the concept of residential DC infrastructure is even more nascent. There are currently no residential DC infrastructure standards (although the EMerge Alliance plans to develop them), and DC-ready residential equipment is limited. There are a few products (e.g. refrigerators, televisions, coffee makers) available from lesser-known manufacturers (e.g. SunDanzer, Sundance, Avanti). However, these products are designed for off-grid solar-powered homes and recreational vehicles. We are not aware of any mainstream manufacturers that make DC-ready residential products.

A number of analytical models have demonstrated energy savings potential in DC residences. As compared to data centers and commercial buildings, less energy is saved in the DC house because due

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to the lower load density and low coincidence between onsite energy supply (daytime) and demand (morning and evening). Garbesi *et al.* (2011) modeled net-metered PV residences and estimated they could save 14% of total electricity if they switch to DC and include energy storage. Without storage, savings are a more modest 5%. Although these figures may seem small compared to commercial numbers, the overall savings can be significant. Savage, Nordhaus and Jamieson (2010) estimated the overall energy savings that can be achieved by replacing appliance AC-DC converters with a more efficient centralized rectifier and using DC distribution within a house to power native DC loads. They estimated that DC could generate overall savings up to 25%, corresponding to a 3% reduction in *national* electric load.

Internationally, Japan and Korea have made the most progress with actual implementations of residential DC infrastructure. Korea appears to be farthest along, having completed a large residential DC demonstration project in 2009 (a 30KW project by Samsung C&T Corp). Japan's New Energy and Industrial Technology Organization (NEDO) modeled the potential energy savings of DC, engaging Panasonic in the assessment and development of DC appliance prototypes (Baek et al. 2011). Japanese home electronics company Sharp is also testing DC-enabling technologies and equipment, having completed a solar-assisted DC-powered home (Sharp, 2011).

MITIGATING BARRIERS TO BROADER ADOPTION

Despite the many benefits of a DC system, transforming in-building distribution from the historical standard of AC to DC is no easy task. As long as the larger generation, transmission, and distribution grid is based on AC, fundamental barriers to DC electric distribution will remain in grid-tied buildings. We examined these barriers through a combination of qualitative engineering analysis, literature review, and stakeholder outreach, summarized the largest issues, and identified solutions where appropriate.

Market Barriers

Lack of DC-ready products. Perhaps the single largest barrier to widespread adoption of DC is the lack of DC-ready products. Although DC alternatives to common commercial and residential equipment are entirely feasible from a technical perspective, the market for DC-powered equipment is nascent. As an example, one of the most straightforward product categories to power with DC is electronics because the devices ultimately use DC. However, effectively all electronics today require an AC power source (the one exception being smaller devices that can be powered or charged directly from USB). The manufacturers that offer DC products designed for niche applications such as large data centers, off-grid homes and mobile residences may not be familiar to most consumers. EMerge Alliance-registered products, although growing in number and from mainstream manufacturers, are currently limited to lighting and ceiling fans.

The EMerge Alliance is trying to overcome the product availability barrier in part by registering DC-ready products that are compatible with their commercial building standards. The number of commercial products is growing slowly, probably in step with the dozen or so DC data centers and office buildings in the United States. These installations represent the experimentation of innovators and early adopters, and doubt remains as to whether this market will be able to “cross the chasm” into mainstream adoption given the chicken-and-egg nature of re-engineering part of our electrical system (Figure 10). Continued standardization efforts will be crucial to coax end-use product manufacturers, building design professionals, and building owners and operators into fully embracing DC technology and catalyzing market transformation.

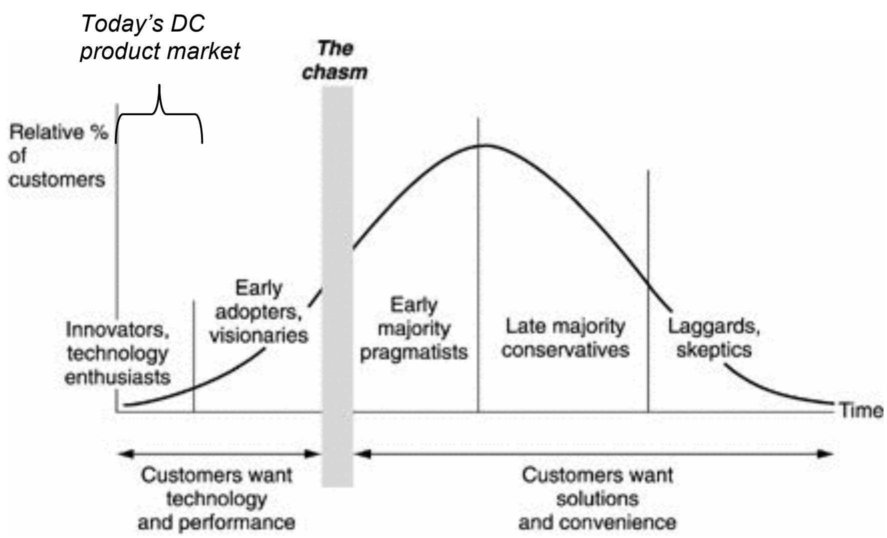

Figure 10. The early DC-powered products market and the chasm toward mainstream market acceptance (Crossing the Chasm, 1999)

Cost barriers. In the near term, DC distribution will generally not be cost-effective from a purely energy efficiency standpoint because of low production volume of DC components and end-uses. There will be added cost associated with building- and room-level converters, none of which are produced in the same quantities as inexpensive commodity power supplies. An exception may be EMerge-listed lighting products, which require fewer components to run off DC, and therefore may be more cost-effective to manufacture than the AC equivalent.

The primary way to address this barrier is to identify applications with compelling DC advantages. One of these is off-grid or islanded villages where AC power distribution is very expensive, common in rural areas and less-developed countries. Using DC in microgrid applications would increase production volume for certain end uses. Another compelling application is high-reliability data centers. DC distribution eliminates several conversion steps, increasing reliability because there are fewer components that can fail. Again, this is limited to certain end use devices. A medium-term application of DC distribution would be a zero net energy office building where most of the electricity from PV can be used directly by DC devices. In the US, this is only likely to become common after 2030 when new commercial buildings must be ZNE in California. We discuss the most cost-effective applications for homes and offices in the Benefits section of this report.

Design and Safety Considerations

High-voltage DC safety. To limit line losses in both AC and DC electric distribution systems, one generally tries to bring high voltages as close to the load as possible, while maintaining safety. Unfortunately, compared with high-voltage AC, high-voltage DC (e.g. 380V) is much more prone to dangerous arc flash. Without the appropriate connector design, DC loads can remain energized even after the user physically “disconnects” a load. For this reason, high-voltage DC is not appropriate for plug loads or easily accessible light fixtures—pulling a plug from the wall could draw an electric arc out of the socket, keeping the appliance energized and directly exposing users to current.

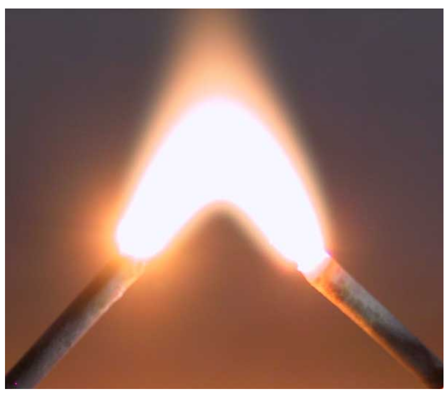

Figure 11. Example of Arc Flash Between Two Conductors (Grochowski, 2008)

To mitigate the risk of arc flash, lighting, plug loads and other commonly moved devices should be on low voltage circuits. Using the EMerge Alliance 24 V_{DC} standard, lighting and plug loads are safe to disconnect because the voltage is insufficient to maintain the current arc through the air between the device and source.

Potential for single points of failure. Without redundant power supplies, system-level outages may be more common in a DC infrastructure than in AC. Instead of a power supply on each device, DC buildings use large, room-level AC-DC or DC-DC power supplies. These DC power supplies contain active electronic components, which are less reliable than passive AC transformers. Thus, there is a higher probability of an electronic malfunction affecting the entire downstream system in a DC building. For example, in AC buildings, lightning can blow out a television or computer, but in a similar DC system, an electric surge could cause a failure in a building- or room-level converter, cutting power to all lighting or plug loads in a given area of the building.

The natural solution to this problem is to use redundant building-level AC-DC converters. Redundant converters provide a parallel path for energy to power loads (Figure 12). If one converter fails, the other is available to assume the full load. However, redundancy decreases power conversion efficiency and increases the cost and complexity of the building's electrical system.

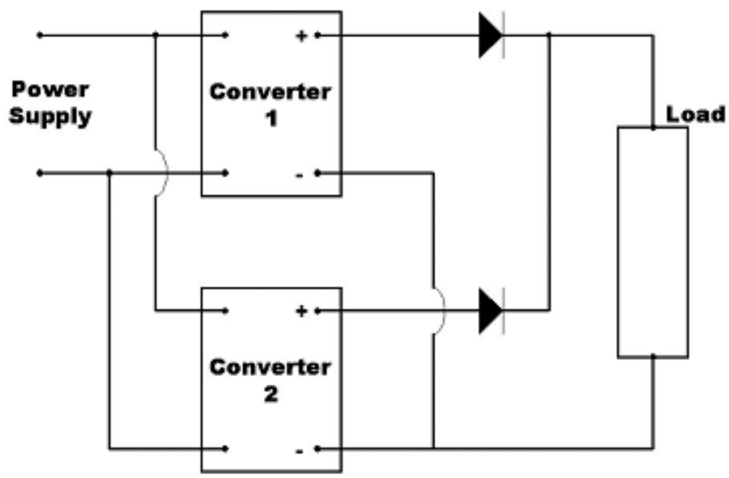

Figure 12. Redundant Converters

Project-specific design considerations. Although not barriers per se, there are a number of design considerations that currently must be addressed on a project-by-project basis. For example, there is the consideration of where to convert high voltage to lower voltage DC within the building. The lower the voltage, the thicker the gauge of wire required to move current (see a more thorough discussion of this topic in the Appendix). Converting grid AC to low-voltage DC (e.g. 24V) at the building level would require thicker and vastly more expensive conductors to limit line losses (as discussed previously in this report).

The EMerge Alliance currently envisions a more localized AC-DC conversion solution (see Figure 5), which saves money on copper wiring through shorter runs but requires a larger number of converters. Although the Alliance presents a potential solution, in the current market this decision needs to be made on a case-by-case basis depending on the type of building and the current prices of copper and converters. Lacking tested cases and rules of thumb, designers likely face greater scrutiny in justifying these system choices.

Offering hybrid AC and DC distribution. In the early phases of a transition to DC power, it would be necessary to have both AC as well as DC power available in buildings to service the large number of "legacy" AC devices. This will require new codes, standards and coordination between a number of electrical standards agencies. The requirement of running parallel AC and DC distribution systems for plug loads also naturally incurs additional cost.

In buildings where AC and DC loads must coexist , the cost of installing parallel infrastructure could be significantly reduced through structured wiring systems. Video, network and communication systems currently reduce material and labor requirements by incorporating the wires for multiple systems into a common cable jacket to reduce wire-pulling labor (Figure 13). Similar cable that incorporates AC and DC power distribution would reduce the labor of installing cable to power outlets.

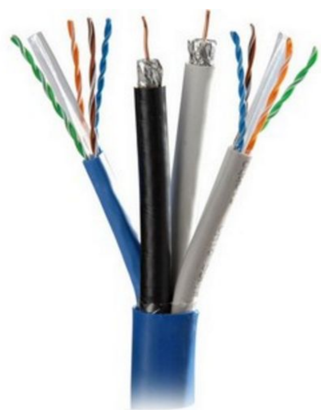

Figure 13. Example of Structured Wiring with Power and Network Cabling Housed in Same Jacket (Surveillent Security, 2012)

Grouping multiple systems into the same outlet box would further reduce material and labor costs. Boxes designed to keep AC and DC distribution systems separated are available from manufacturers such as Arlington. These boxes have an insulating divider between sections to comply with existing code requirements. It would therefore be possible with suitable insulation and barriers to have AC and LV DC power available at the same outlet, as illustrated by the USB-equipped AC outlet shown in Figure 14.

Figure 14. Example outlet providing both standard AC and DC USB connectors (Think Geek, 2012)

With further standards development, research and funding, most technical and safety barriers—even those described above—can be overcome. However, standards can only do so much to influence the court of public opinion. When the incumbent technology is generally reliable and time-tested, perceived technical and safety concerns could remain an obstacle. Advocates of DC power have seen some success in promoting the concept among data center operators who are notoriously risk-averse. This experience suggests that DC power should be able to overcome similar perception issues in the broader marketplace.

Through our discussions with stakeholders[5] the transition to DC distribution seems inevitable, particularly in data centers, load-dense commercial buildings, or microgrids with onsite generation resources; however, getting there will probably be slow. Fully leveraging cost savings in DC will take time and economies of scale and the transition will need to be motivated by clear benefits.

[5] See Appendix for full list of stakeholders contacted.

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BENEFITS

One of the core motivations for this work was to clearly establish the benefits of DC distribution in buildings. Energy efficiency is arguably the single largest benefit touted by proponents of the technology, and to this end, this section mostly explores the energy savings and accompanying cost impacts of using the technology. However, DC can provide many other benefits, including improved power quality, ease of integration with renewable energy, and even convenience. We qualitatively address these non-energy benefits toward the end of this section.

ENERGY AND COST MODELING METHODOLOGY

In order to quantify the potential benefits of building-level DC distribution, it was necessary to understand the physical differences between AC and DC distribution schemes and how those differences impacted building-level energy consumption. Since the shift to DC infrastructure significantly alters a building's electrical system from the point electricity enters the building right down to the loads, we considered the costs associated with DC distribution upgrades in order to determine their relative cost effectiveness. Ecova developed side-by-side energy and cost models, described below. Detailed assumptions are provided in the Appendix.

Scenarios Considered

We examined the potential energy savings of switching from AC to DC distribution in typical buildings (i.e. those built to meet building energy codes like California's Title 24). In addition, we also identified synergies associated with implementing DC in "zero net energy[6]" (ZNE) buildings, where both loads and on-site generation can directly tie into the DC system. We modeled both commercial and residential cases, resulting in the four scenarios summarized in Table 4, using typical electric load assumptions from large surveys and case studies (see Appendix for details).

[6] "A zero net energy building is one that produces as much clean, renewable, grid-tied energy on-site as it uses when measured over a calendar year." We interpret this definition to include offsetting on-site natural gas consumption. http://www.pge.com/myhome/saveenergymoney/energysavingprograms/znepilotprogram/

Table 4: Scenarios Considered for Energy and Cost Models

	T24 construction	ZNE construction
Commercial	• Baseline commercial case • 50,000 sf office building built to 2008 Title 24 compliance	• "Best practice" commercial case • 50,000 sf office building built to ZNE definition • Source energy offset by onsite generation
Residential	• Baseline residential case • 2,000 sf single-family home built to 2008 Title 24 compliance	• "Best practice" residential case • 2,000 sf single-family home built to ZNE definition • Source energy offset by onsite generation

Accounting for Energy Losses

Our model captures the basic conversion and loss mechanisms present in typical building electrical systems today. Figure 15 illustrates some of the key distinctions between AC and DC distribution systems that impact energy loss. The most fundamental difference is the consolidation of AC-DC conversion stages into a single "building-level" converter that interfaces between the building's electric distribution system and the AC grid. We also eliminated all AC loads in the DC distribution topology to examine the impact of a fully DC system. We provide a more detailed discussion of distribution and power conversion assumptions in the Appendix.

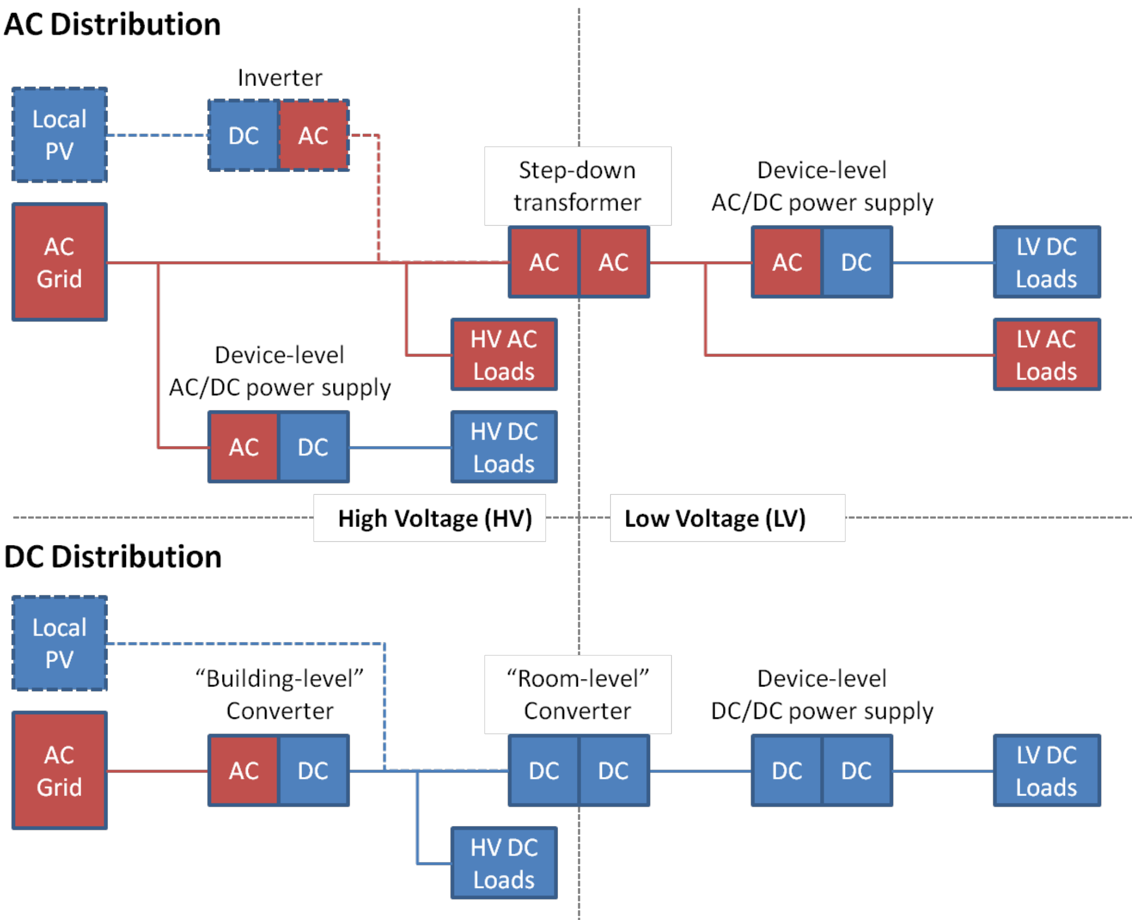

Figure 15. Energy flow diagram illustrating AC and DC distribution topologies

Cost Model

Our cost model examines the basic operational and capital expenses associated with the electric distribution, power conversion, and power generation equipment in our model buildings. We assumed a retail cost of electricity of $0.16/kWh, reflecting bundled rates reported by the PUC for PG&E's territory (CPUC, 2011). In the ZNE case, we developed an equivalent price of electricity to reflect the added cost of on-site PV and power conversion equipment ($0.25 to $0.30/kWh for commercial cases and $0.35 to $0.40/kWh residential cases). We also assumed that ZNE buildings participate in net metering programs, with credit for PV production given at retail rates. We used a National Renewable Energy Laboratory PV model to establish PV sizing based on Sacramento, CA typical solar conditions.

Our economic analysis took a lifecycle approach to evaluating DC distribution opportunities, including the capital cost of replacing equipment and operational costs associated with powering that equipment (and its inherent losses). We use a 5% discount rate and an assumed 5% annual reduction in inflation-adjusted product prices in accounting for the present value of future costs/savings.

COMMERCIAL OFFICE BUILDINGS

Energy Savings Potential

The primary energy savings proposition of DC systems has been the ability to cut losses in the distribution and conversion of electricity as it travels through a building to end-uses. Figure 16 illustrates the primary types of electric energy losses that occur between the electric service entry and end-uses in a representative commercial office building. Losses attributable directly to the distribution infrastructure include wire and conversion losses. Power conversions are further broken out based on their location in the system. Building-level conversions are needed in DC buildings to convert incoming AC electricity into DC or in ZNE buildings to invert onsite PV energy; HV to LV conversions occur when HV electricity must be stepped down to safer levels used with plug-in devices; and device-level conversion occurs near the end-use in power supplies, ballasts, or motor drives. Replacing the building's AC distribution system with a DC distribution system reduces losses in the building's distribution system by 2% in the baseline T24-compliant case and 8% in the best-practice ZNE construction case.

In the ZNE cases, we also show conversion losses for energy that is exported to the grid in purple. The PV system will frequently produce more energy than can be used on-site, so the remainder must be exported to the grid through an inverter, with some conversion losses in the process. Since we use a zero source energy definition, our system also needs to offset natural gas usage. All of electricity generated to offset the natural gas must be exported to the grid.

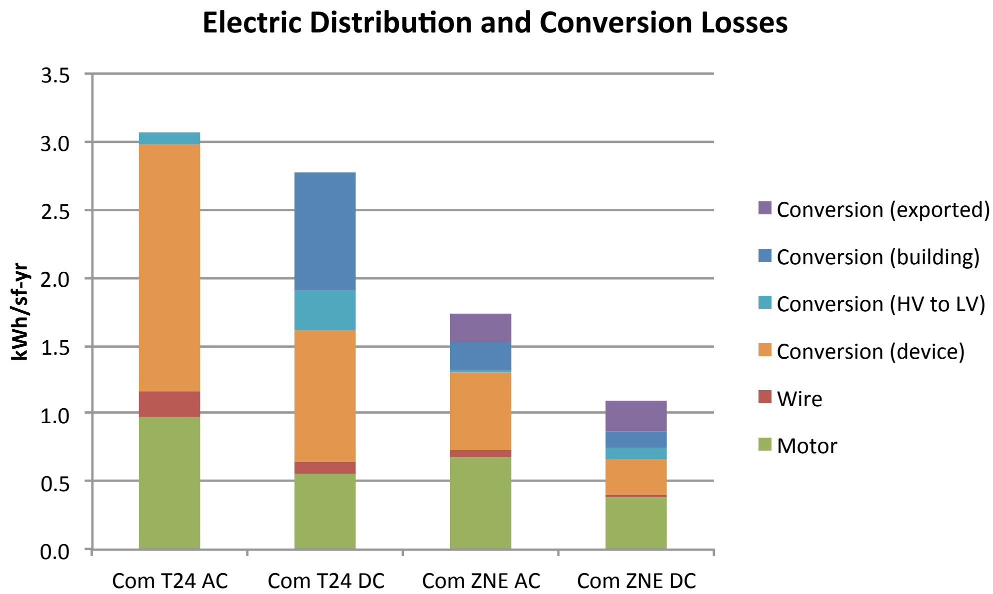

Figure 16. Electric distribution and conversion losses in commercial office buildings

Although our results show a net reduction in losses, it also clearly shows that there can be tradeoffs. For example, device-level conversion losses are significantly reduced in the T24 DC distribution case by eliminating the AC-DC front ends of power supplies in electronic products, of ballasts in lighting products, and of motor drives. However, this is offset by increases in upstream conversion losses, because even in a DC building, power must travel through several power conversion stages before it reaches its destination. Only certain loads with low device-level power conversion efficiencies (e.g. smaller electronics) can really benefit. Our T24 building would actually use slightly *more* energy to distribute and convert electricity and only achieve a net savings of 2% by switching to more efficient DC motors.

A much larger energy savings opportunity exists when we examine some of the indirect benefits of a DC electric system. DC systems will make it easier and cheaper to integrate variable speed drives (VSDs) into large motor-driven systems (compressors, fans, pumps, etc.) in commercial buildings, because the typical AC-DC conversion and power factor correction stages required in current VSDs would not be required.[7] When taking into account the indirect benefits of using larger amounts of VSDs, savings for a T24 office building actually increase to 11% or nearly six times the savings realized in the distribution system by itself (Figure 17).

[7] Variable speed drives can draw current in very distorted, "noisy" patterns, which is typically mitigated by using power factor correction circuitry on the AC side of the drive. This circuitry adds cost and complexity to the system.

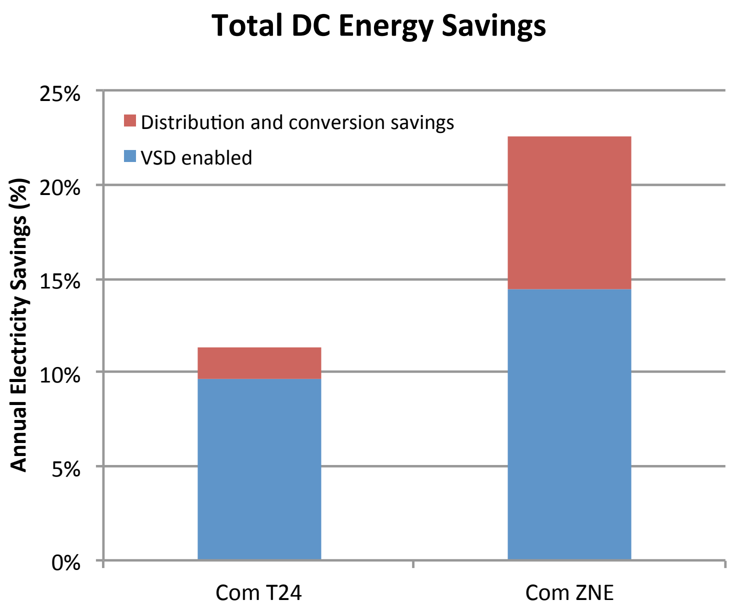

Figure 17. Source of electric energy savings in both T24 and ZNE commercial office buildings

A DC ZNE building represents about double the energy savings opportunity on a percentage basis compared to T24 new construction. This is because more of the loads can be met using DC energy produced on-site without importing that energy from the grid and passing it through multiple conversion stages.

Although we analyzed scenarios where an entire building would run on DC, this of course would not be possible today due to a lack of DC-powered products. Even if it were possible, our analysis showed that certain end-uses can generate more savings than others. In T24 new construction, motor loads account for a majority of the direct savings from distribution loss reduction, followed by electronic loads as shown in Figure 18. Note that some end-uses such as lighting and large electronic loads (greater than 100W) are represented as negative segments in Figure 18, because they actually *increase* distribution losses in the DC T24 case. Smaller electronic loads (less than 100W) use inefficient power supplies, so DC distribution actually improves system efficiency, but we expect that larger electronics like computers will already have relatively efficient power supplies. As a result, DC distribution cannot really generate net savings for these larger plug loads and is actually expected to slightly increase losses. All end-uses contribute energy savings in the ZNE case with motor loads providing the most significant amount.

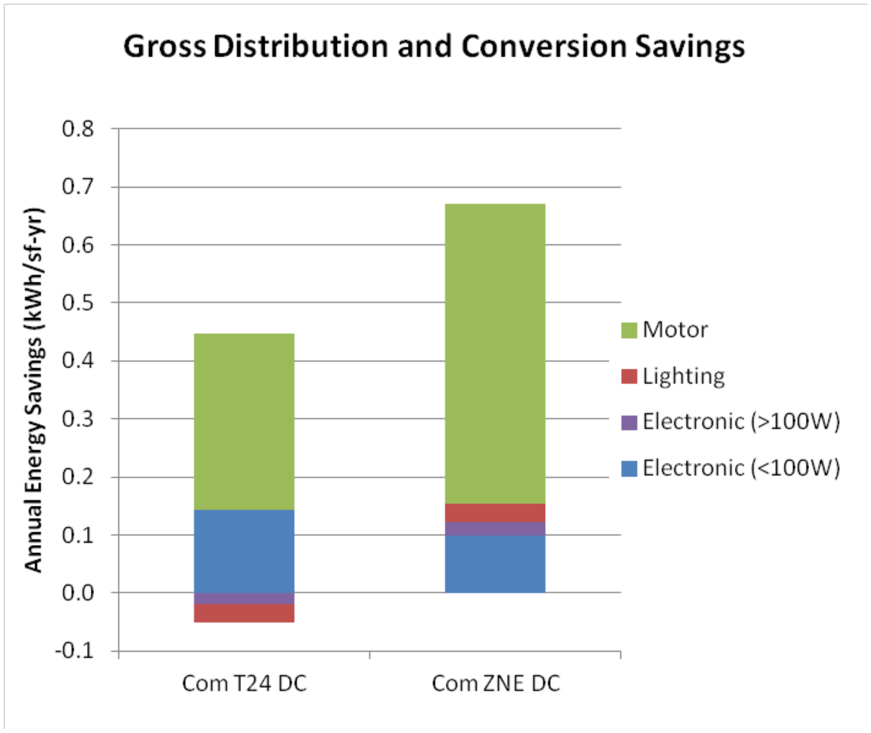

Figure 18. Gross DC energy savings by end-use

Cost Effectiveness Analysis

We examined the cost effectiveness of switching to DC by end-use to highlight the most promising opportunities for near-term and cost-effective savings. In standard commercial buildings built to code, there are more limited cost-effective savings opportunities than in ZNE construction. In the world of energy efficiency, we are accustomed to situations in which a technological advancement decreases energy use but also increases capital costs. Cost-effectiveness can then be easily measured in terms of dollars per kilowatt-hour saved. However, in this project, we see several instances where switching to DC technology not only provides some energy savings but also *reduces* the lifecycle capital costs of the system. One example is in electronic products, which generally become cheaper because they no longer require the AC-DC front end of their power supply. Even though the first cost of highly mass-produced power supplies is quite low, they are replaced frequently, so the lifecycle capital cost of a more permanent building-level converter can be lower. This results in *negative* cost per kilowatt-hour, representing a choice that is so cost-effective that the payback is immediate (Table 5). Detailed cost effectiveness results can be found in the Appendix.

Table 6. Cost Effectiveness of DC Distribution in Commercial Buildings

End-use	T24 Case Cost of Saved Energy ($/kWh)		ZNE Case Cost of Saved Energy ($/kWh)	
Electronics	-$0.40		-$0.30	
Lighting	N/A		-$0.08	
Motors	$0.05		-$0.01	
Resistive	N/A		N/A	
Building level	$0.07		-$0.03	

Highly cost-effective. Reduces capital costs and saves energy.

Cost-effective. Provides energy savings at costs below retail electric rates.

Not cost-effective. Increases costs, energy use, or both.

Other end-uses were not as promising, sometimes resulting in large increases in lifecycle capital costs, increases in lifecycle energy use, or both. This scenario is exhibited by resistive and lighting end-uses in the T24 analysis. In lighting, the current ballasts used are fairly large, so they are both low-cost and high efficiency. Therefore, the building-level conversion required for DC distribution turned out to be more expensive and slightly lower in efficiency.

Table 6 also shows the cost effectiveness for ZNE commercial office buildings. We see improved cost effectiveness in every category except resistive loads because we can generally improve system efficiency and reduce cost. The main reason that cost effectiveness improves in ZNE buildings is because the typical AC system already contains a building-level power conversion stage--the PV inverter—so we do not experience as much of an incremental cost when adding the required DC power conversion infrastructure. In the ZNE case, we are also able to realize greater savings by using more DC energy immediately on site. This means that now lighting and motors are highly cost-effective. Furthermore, the overall case is highly cost-effective, with an immediate payback compared to our ZNE baseline.

DETACHED, SINGLE-FAMILY HOMES

Energy Savings Potential

DC distribution also offers sizeable energy savings in detached, single-family homes, though somewhat smaller than in commercial office buildings. Replacing a home's AC distribution system with a DC distribution system reduces losses in the home's distribution system by 6% in T24 construction and 5% in the best-practice ZNE construction case. This compares to 11% and 24% savings in the respective T24 and ZNE commercial cases (Figure 19).

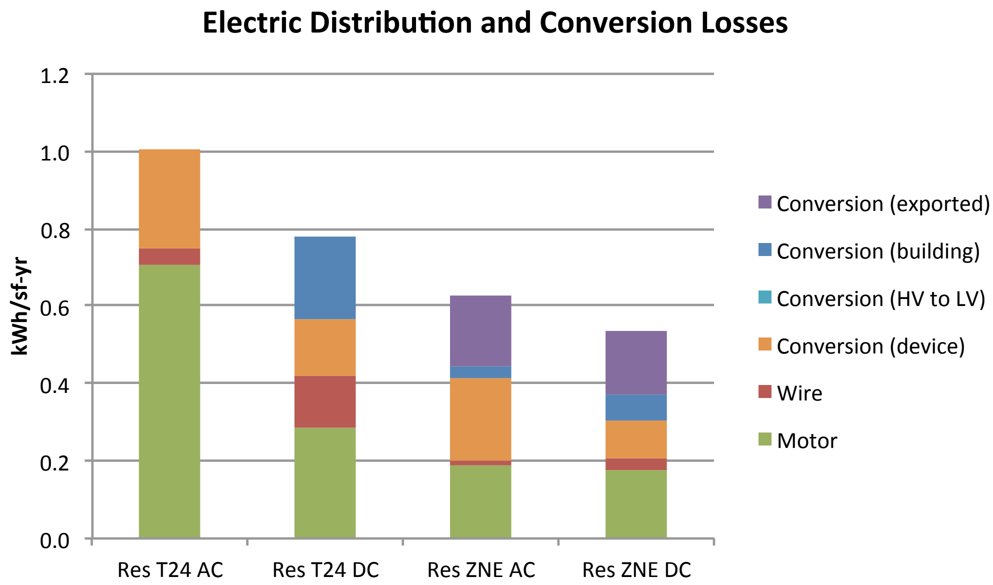

Figure 19. Electric distribution and conversion losses in single-family homes

The main reason we see less significant energy savings potential in homes is because, unlike larger commercial buildings, homes have significantly lower lighting and motor loads. The larger motors that are present in a single-family home (e.g. HVAC compressors) are typically single-speed, so the sizeable VSD-enabled savings seen in the commercial setting are not possible in homes.

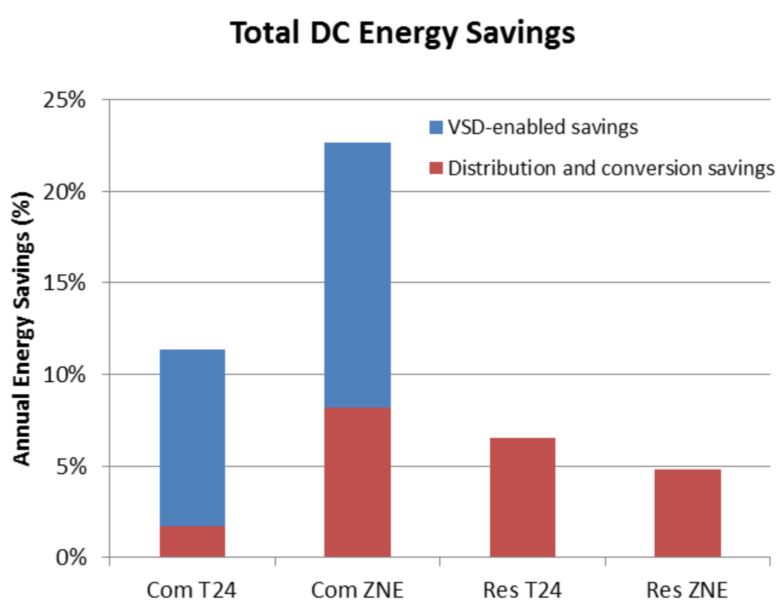

Figure 20. Source of DC energy savings, residential and commercial cases

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Another key distinction in the residential ZNE case is that residential loads are not very coincident with PV generation (we estimated about 30% coincidence). As a result, loads can only run using on-site DC power about a third of the time. This results in a greater proportion of locally-produced energy being exported to the AC grid, thus incurring more conversion loss at the building level.

The 5% to 6% savings opportunity we identified for homes compares favorably with the 2011 investigations of *Garbesi et al.*, who found an almost identical savings opportunity in ZNE residences that do not have on-site energy storage. When storage was factored in, overall savings of 14% were achievable, because it has the effect of increasing the home's load coincidence and ensuring that more load can be met directly by DC without the need for additional conversions or importing grid electricity. Even without storage, our analysis shows that if all U.S. homes could take advantage of DC distribution, the U.S. could save about 70 billion kWh of electricity annually, or about the same amount of electricity consumed by the entire state of Wisconsin.

Cost Effectiveness Analysis

The cost effectiveness of the T24 case for residential is similar to the T24 commercial case in that a couple of end-uses, namely electronics and motors, provide clear, cost-effective savings (Table 7). The remaining loads, lighting and resistive, result in slightly higher energy use and are, thus, not cost-effective at all. Our analysis suggests that DC distribution would only make sense for limited end uses in non-ZNE residential construction.

Table 7. Cost Effectiveness of DC Distribution in Residential Buildings

End-use	T24 Case Cost of Saved Energy ($/kWh)		ZNE Case Cost of Saved Energy ($/kWh)	
Electronics	-$0.98		-$0.55	
Lighting	N/A		-$0.30	
Motors	$0.07		-$0.16	
Resistive	N/A		N/A	
Building level	$0.14		-$0.35	

Highly cost-effective. Reduces capital costs and saves energy.

Cost-effective. Provides energy savings at costs below retail electric rates.

Not cost-effective. Increases costs, energy use, or both.

As in the commercial ZNE case, cost effectiveness dramatically improves in the residential ZNE case because we are able to realize lifecycle cost savings across many end uses in addition to significant

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energy savings. A DC ZNE home would be more energy efficient, cheaper to build, and thus, highly cost-effective.[8]

NON-ENERGY BENEFITS

DC distribution systems can provide a more cost-effective means of distributing electricity, particularly in facilities with on-site DC generation sources like PV. However, they also provide substantial non-energy benefits, many of which may serve as the primary driver for system installations. These include:

- **Reduction in electronic waste**: nearly any consumer electronic product purchased today is sold with an AC-DC power supply, but if buildings eventually transition to DC electric distribution systems, several key stages of today's power supplies would not be necessary, including AC-DC rectification and power factor correction.[9] In a DC building, these functions would be replaced by upstream AC-DC converters that would provide DC power to an entire floor or building. These larger converters would be replaced on a much less frequent cycle than most consumer and office electronics, thus reducing at least a portion of the stream of electronic waste generated each year.
- **Convenience and greater portability for mobile products**: mobile products, including cell phones, laptops, tablets, and portable music players, are typically sold with external power supplies—often referred to as "wall warts." In addition to energy, these devices consume an increasing amount of the plug real estate under desks and behind entertainment centers. Since most power adapters are proprietary, consumers who travel with a large number of electronic products typically need to carry several power adapters as well. In a world with universal DC power distribution, this would not be necessary. A user might only need to bring a cable that can connect their DC-powered electronic device to a standard DC outlet. This might resemble the USB connector cables provided to dock mobile devices with computers (Figure 21).

[8] The meaning of the magnitude of a negative cost of energy saved is not straightforward. However, if there were some capital cost reduction and an infinitesimal energy reduction, the cost of energy saved would be nearly negative infinity. Therefore, generally smaller magnitudes of negative cost of energy saved indicate a better situation. Therefore, since the commercial ZNE case has smaller negative magnitudes than the residential ZNE case, the commercial ZNE case is a better situation. But this distinction is not important because both cases are highly cost-effective.

[9] Power factor correction is required on many AC-DC power supplies to prevent noisy "harmonic currents" or large amounts of reactive power on AC circuits.

Figure 21: Example of DC power cable

- **Easily reconfigurable overhead lighting**: our review of existing DC ceiling grid systems in commercial office spaces shows that one of the primary benefits of this piece of distribution infrastructure is the ease and flexibility with which overhead lighting can be reconfigured. This is a task that normally requires an electrician, but when DC power is provided to overhead luminaires at low voltages (i.e. as Class 2 wiring), lighting systems can be reconfigured by one maintenance staffer with a ladder.
- **Improved power quality**: DC distribution systems have the potential to improve a facility's overall power quality, particularly if large numbers of plug loads can be run off of large, building-level AC-DC converters. Most larger power conversion devices in buildings today (e.g. motor drives, server power supplies, etc.) are required to have power factor correction (PFC) to ensure that they draw current in a smooth sinusoidal pattern rather than in abrupt spikes. The power supplies used in smaller electronic devices—cell phones, laptops, and monitors—often lack PFC circuitry and tax the grid more heavily by requiring intense pulses of current. If those smaller plug loads ran off of larger building-level AC-DC converters with PFC, it would generally improve the power quality of the entire grid. An overall improvement in power factor can have some small, ancillary energy efficiency benefits as well.[10]

[10] In effect, by drawing current through the system in gentle sinusoidal patterns rather than large spikes, the average current draw is reduced, and the resistive losses in the building and grid drop as well.

NEAR-TERM DC OPPORTUNITIES

Despite the many benefits of DC distribution systems, a number of structural barriers in the marketplace as well as design practice currently prevent their widespread adoption. However, there are still near-term opportunities for energy efficiency advocates, policy makers, building designers, and electric utilities to begin piloting this technology and demonstrating the most practical and cost-effective usage cases.

MOST PROMISING END-USE APPLICATIONS

As our analysis showed, DC distribution shines in certain applications. Commercial buildings with on-site PV generation appear to be an ideal application area for the technology due to several factors:

- Large amounts of PV-coincident load that can be powered with on-site DC energy
- A high concentration of lighting, electronic, and motor loads
- Growing industry support for standardization in the form of the EMerge Alliance

Below we provide a summary of some of the most promising end-use applications today in commercial ZNE buildings,[11] along with their estimated energy savings and ancillary benefits. All of these applications would provide *immediate* payback because they would reduce the overall electrical system costs.

Table 8: Near-Term Cost-Effective Applications of DC in ZNE Buildings

	End-Use	Best Available DC-Compatible Technology	Annual Energy Savings (kWh/sf)	Non-Energy Benefits
GOOD	Overhead Lighting	LED or fluorescent lighting coupled with DC drop ceiling	0.64	• Easily reconfigurable • Easy to integrate controls (occupancy sensors, daylighting, etc.)
BETTER	HV Motors (HVAC)	DC motor coupled to VSD	33.55	• Simplified VSD design
BEST	Electronics[1]	DC-powered solutions do not exist, but variety of groups working toward standards	2.45	• Simplified power supply designs • Reduced electronic waste • Smaller devices • Travel chargers not needed

[1] Data centers are a proven and highly cost-effective DC distribution application, but they are a niche opportunity that should be evaluated separate from the general office and consumer electronics opportunity we present here.

[11] Non-ZNE commercial buildings with smaller PV arrays could still benefit, but annual energy savings could be lower.

Our cost-benefit analysis shows that DC can have dramatic energy savings impacts when applied to the right usage cases. Interestingly enough, the preferred applications from a cost effectiveness standpoint do not always align with the realities of the marketplace. For example, our results showed significantly less opportunity for cost-effective savings from DC lighting, and yet DC lighting products are the only major end-use currently available among EMerge-registered products. Standards have not yet been written to thoroughly address motor and electronic loads, and DC-compatible products in these categories are elusive. DC motors are widely available in a range of voltages and capacities, but variable speed drives that accept DC voltages as an input are not. Consumer electronics and office products were consistently one of the most cost-effective DC end-uses, but they too only exist in AC form.

Despite the lack of commercially available DC-ready VSD-motor systems and plug loads, there are still opportunities for utilities, research organizations, and equipment manufacturers to pilot this technology. The plug load opportunity is particularly compelling for several reasons. First, a large number of groups in the building design and energy efficiency communities are examining ways to address plug load energy use. Secondly, organizations outside of EMerge Alliance are pursuing standards to enable "universal" AC-DC power adapters for electronics that effectively would harmonize the way in which many plug loads receive DC power.[12] A consortium of groups with common interests in improving and simplifying electricity distribution to plug loads could be a powerful vehicle to fund more rigorous pilots of the concept and might help jumpstart market transformation processes.

RETROFIT OPPORTUNITIES

Our analysis examined a host of DC solutions all applied to a newly constructed building, but DC systems may be possible in retrofit scenarios as well. For example, if a commercial property owner or tenant were upgrading or repurposing a floor of a building, it would be feasible to replace the suspended ceiling grid with a DC ceiling system. This could be particularly cost-effective if done in conjunction with a major lighting upgrade, such as moving from T12 or T8 fixtures to next-generation solid-state light sources and daylighting controls. If EMerge members make significant progress on DC power standards for modular furniture, standard cubicles could be replaced with DC-enabled versions (this of course would entail an upgrade to compatible DC-powered office equipment as well).

FILLING THE DATA VOID

Our market research and stakeholder outreach revealed that very limited energy monitoring data is currently available for DC distribution projects, particularly in non-data center commercial applications.

[12] The Institute of Electrical and Electronics Engineers (IEEE) is currently pursuing a Universal Power Adapter for Mobile Devices (UPAMD) standard that aims to standardize the DC connector and communication interface for mobile devices.

The few existing monitoring experiments that we identified did not appropriately isolate the DC system benefits from other efficiency upgrades, so it is difficult to interpret the results. If the energy efficiency and building design communities are to fully validate DC energy savings opportunities, more rigorous monitoring projects need to be done. Even better, neutral third parties with an interest in DC power could develop in-depth case studies of existing DC facilities that would capture both the quantified energy benefits as well as user experiences with the technology. Such case studies could provide the context for future design charrettes in which stakeholders could more fully map out a vision for the DC building of the future.

Our analysis also identified several sensitivities that could impact both the energy savings and cost of DC systems. For example, when investigating the cost-effectiveness of DC distribution for plug loads, we assumed that today's AC-powered products used power supplies with typical efficiencies. Best-in-class AC-DC power supply designs today are pushing efficiencies into the 90% range and could reduce some of the savings opportunity in this end use category. Other studies by Garbesi *et al.* (2011) saw suggest that best-in-class AC-powered products could capture about half of the savings opportunity associated with DC distribution. Future studies might conduct a more detailed cost-benefit comparison that compares a best-in-class AC approach with the DC approach.

Our study also identified the cost of building- or room-level power conversion gear as a key driver of overall DC system cost-effectiveness. These products are in the early phases of deployment and have not reached the economies of scale seen in inexpensive, commodity AC-DC power supplies. Advocates of DC power should remain sensitive to the cost of this key component and look for opportunities to mitigate incremental cost through market transformation programs.

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APPENDIX

A. ELECTRICAL DESIGN TRADEOFFS WITH LV DC SYSTEMS

Even once DC voltages have been standardized, other key design decisions must be made that present tradeoffs between system cost, safety, and energy efficiency. In any electrical distribution system, HV transmission allows smaller, cheaper wire to be used for longer distances without excessive energy waste due to resistive losses (Figure 22). This is because HV circuits allow larger amounts of power to travel at in a smaller current. Since resistive losses vary with the square of the current traveling through a resistive element, such as a wire, it is extremely important to maintain low currents in order to reduce heat buildup and power losses. LV circuits like those that run to wall outlets are relatively short to limit resistive losses. In the world of DC distribution, LV applications are gravitating toward a $24V_{DC}$ standard via the EMerge Alliance's Occupied Space Standard. While this is beneficial from a safety and convenience standpoint, it presents efficiency challenges to designers. As Figure 22 illustrates, dropping the voltage of an existing 120 V_{AC} design to 24 V_{DC} (step 1), while providing the same amount of power and maintaining the same circuit length increases wiring costs by an order of magnitude due to the larger conductors required to limit wire losses. A designer can reduce cost while delivering the same power by shortening the branch circuit (step 2). Since moving to DC distribution will generally improve system efficiency, it is likely that there will be a reduction in load as well as a shortening of the circuit (step 3). The end result is that LV DC will generally require a larger number of shorter branch circuits for a given building design compared to traditional LV AC distribution.

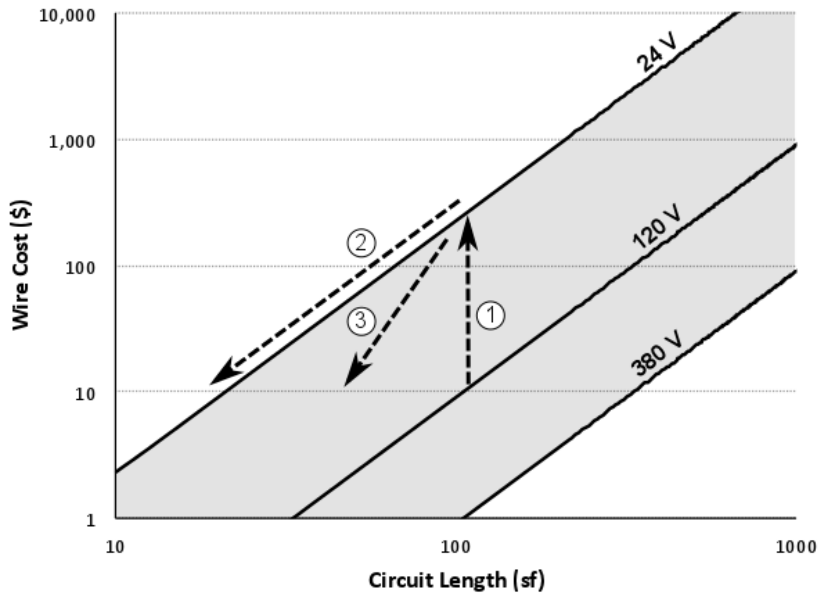

Figure 22: Wiring costs associated with DC circuits at various lengths and voltages[13]

B. STAKEHOLDER LIST

Table 9: List of Stakeholders Contacted

Organization	Contact	Title	Subject Matter Expertise
ABB	Jeff Johnson	VP, DC Applications	Comprehensive DC solutions from grid to end-use levels
Armstrong Inc. and EMerge Alliance	Brian Patterson	General Manager, New Business Development	DC distribution (special focus on DC ceiling grids and emerging commercial applications), EMerge Alliance activities and case studies
Electric Power Research Institute (EPRI)	Brian Fortenbery Dennis Symanski	Program Manager Senior Project Manager	DC distribution (particularly data center applications), EMerge Alliance activities
Herman Miller	Matt Banach	Directory of Engineering, Research, Design & Development	Integration of DC power into modular furniture for plug loads
Lawrence Berkeley National Laboratory (LBNL)	Karina Garbesi	Visiting Researcher	Residential DC distribution
PG&E Pacific Energy Center	Robert Marcial Milena Simeonova	Director Lighting Programs Coordinator	DC ceiling grids and lighting systems

[13] Based on the assumption of delivering 1,500 W of power with wiring losses limited to 4%.

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SteelCase, Inc.	Mark DeWys	Product Manager	Integration of DC power into modular furniture for plug loads
Universal Electric Corporation	David Geary, Tim Martinson		DC system design and implementation, particularly in data centers
University of Pittsburg	Dr. Greg Reed		Grid and local DC distribution modeling and research

C. DETAILED ENERGY AND COST MODELING ASSUMPTIONS

Load Assumptions

The electric load composition and operation of commercial and residential buildings are different, so we developed separate load assumptions for each scenario. For the commercial cases we assumed a 50,000 sf office building, and for the residential cases we assumed a 2,000 sf single-family home. We then leveraged data from two energy use surveys, both relevant to the State of California to acquire a breakdown of annual electricity use by end-use for the commercial and residential base cases (CEUS, 2006 and RASS, 2009). We grouped the end-use data into six comprehensive categories that capture the building's entire electricity use and specifically selected categories to lump products with similar power conversion requirements and performance together. The end-use categories are summarized in Table 9 with example end-use products.

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Table 10. Categorization of End-Uses

Voltage level	End-use category	End-use subcategory	End-use examples
Low Voltage (LV)	Electronics	Small (<10W)	Cell phone charger
		Medium (10 to 100W)	Laptop computer
		Large (100W+)	Plasma television
	Lighting	Fluorescent/HID lighting	Task lighting
		LED lighting	
		Incandescent lighting	
	Motor	AC motors	Small motorized appliances (e.g. refrigerators)
		DC motors	
	Resistive	–	Space heaters, electric water heaters, electric ranges
High Voltage (HV)	Lighting	Fluorescent/HID lighting	Overhead lighting
		LED lighting	
	Motor	AC motors	HVAC equipment
		DC motors	

The electronics category captures plug loads containing power supplies such as computers and other consumer electronics. We further broke the electronics category into power bins to be able to distinguish between the efficiencies and costs of this very diverse end-use category. Although this study did not specifically address the unique power system requirements of datacenters, we included information technology energy use into the “electronics” end-use category for the commercial case. Lighting includes sub-categories for fluorescent, LED, and incandescent lighting technologies. The motor category includes loads like air conditioners and refrigerators. The “resistive” category was used as a catch-all to account for devices such as space heaters and electric water heaters that operate without the need for any major power conversion components.

The energy intensities used in our model are depicted in Figure 23. Note that the electric load density in commercial office buildings is over four times as high as that of residential households. Furthermore, commercial load composition is comprised much more heavily of high voltage motors and lighting.

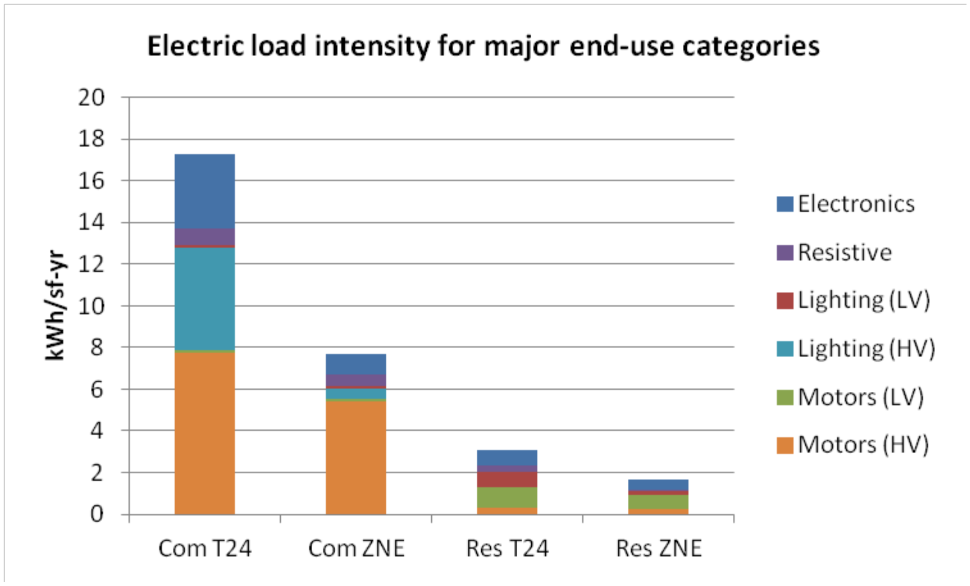

Figure 23. Energy intensity for model base cases, separated by end-use category

To develop load assumptions for ZNE construction, we examined existing ZNE monitoring data (NREL, 2011) as well as the Tier II voluntary efficiency target established in the CalGreen green building standard (30% reduction in energy from Title 24 2008) to advise the ZNE load compositions and energy intensity. Because we have adopted a zero net *source* energy definition for ZNE, we sized photovoltaic (PV) systems in our ZNE cases to be large enough to offset both source electric and gas consumption.

Motors comprise a large amount of commercial building electricity use, and DC alternatives exist for most traditional AC motor loads (e.g. air conditioners, ventilation, refrigeration). Therefore when switching to DC distribution, we altered our load assumptions by replacing all AC motor loads with DC motors in both the T24 and ZNE commercial cases. All other loads remained the same. In the residential cases, our load assumption remained unchanged between the AC and DC cases.

Model Electric Distribution Assumptions

The commercial AC distribution case assumes that power is delivered at two voltages throughout the building: 277V 3-phase, which we have defined as “high voltage” (HV), and 120V single-phase, which we have defined as “low-voltage” (LV). Similarly, the residential AC distribution case assumes power to be delivered at 240V (HV) and 120V (LV) respectively. Based on a survey of literature and examination of proposed industry standards, we assume that DC power will be distributed at two voltages in the building: 380Vdc and 24Vdc. Distribution voltages used in the model are summarized in Table 11.

Table 11: Voltage levels defined for residential and commercial cases.

	AC distribution		DC distribution	
	High voltage (HV)	Low voltage (LV)	High voltage (HV)	Low voltage (LV)
Commercial	277V 3-phase	120V	$380V_{DC}$	$24V_{DC}$
Residential	240V	120V	$380V_{DC}$	$24V_{DC}$

Energy loss occurs at many points in a building's electric distribution system prior to reaching the load. Our model accounts for three significant types of loss:

- **Wire loss**. Resistive wire loss occurs on any circuit through which an electric current flows. Wire loss is related to wire gauge (cross-sectional area), length, resistivity, and the overall amount of energy that passes through the wire.[14] Our model accounts for wire loss in both HV lines and LV lines.
- **Conversion loss**. Where utility distribution lines enter a building, the utility-level voltage must be reduced, often through a series of converters, before it can be utilized by end-uses. Each conversion stage incurs an energy loss. We modeled converter loss at three levels, as shown in Figure 15 above. These include a building-level converter (or inverter, in the ZNE AC case), a room-level converter (step-down transformer in the AC cases) to reduce voltage from HV to LV, and device-level converters.
- **Motor loss**. Lastly, we included a variety of losses associated with motors. In most end-uses, we save energy by simply eliminating redundant power conversion steps. However, when motors are switched from AC to DC, they save energy in several ways. First, the AC to DC front end of a variable frequency drive (VFD) can be eliminated. Second, brushless DC motors are inherently more efficient than single-speed AC induction motors at converting electrical energy into mechanical. Finally, moving from single-speed AC motors to DC motors with variable frequency drives (VFDs) causes a reduction in shaft power required in many applications, including fans and compressors. We assume that the typical energy savings is 50% when this is implemented. We only assume this is implemented in the commercial cases, not the residential ones.

[14] Resistive power losses are the product of the wire resistance (in ohms) times the current (in amperes) squared, so small changes in current can have dramatic effects on losses.

D. DETAILED COST EFFECTIVENESS ANALYSIS TABLES

Table 12. Cost Effectiveness of DC Distribution in T24 Commercial Buildings

End-Use Category	Lifecycle Incremental Cost ($/sf)	Lifecycle Savings (kWh/sf)	Cost of Saved Energy ($/kWh)	Assessment
Electronics	-$0.97	2.43	-$0.40	Highly cost-effective. Capital cost decrease and significant energy savings.
Lighting	$1.24	-0.65	N/A	Not cost-effective. Capital cost and energy use increase.
Motors	$2.00	39.50	$0.05	Cost-effective.
Resistive	$0.46	-2.06	N/A	Not cost-effective. Capital cost and energy use increase.
Building Level	$2.72	39.23	$0.07	Cost-effective.

Table 13. Cost Effectiveness of DC Distribution in ZNE Commercial Buildings

End-Use Category	Lifecycle Incremental Cost ($/sf)	Lifecycle Savings (kWh/sf)	Cost of Saved Energy ($/kWh)	Assessment
Electronics	-$0.73	2.45	-$0.30	Highly cost-effective. Capital cost decrease and significant energy savings.
Lighting	-$0.05	0.64	-$0.08	Highly cost-effective because capital cost decrease and significant energy savings
Motors	-$0.40	33.55	-$0.01	Highly cost-effective because capital cost decrease and significant energy savings
Resistive	$0.08	-0.27	N/A	Not cost-effective. Capital cost and energy use increase
Total	-$1.10	36.37	-$0.03	Highly cost-effective because capital cost decrease and significant energy savings

Table 14. Cost Effectiveness of DC Distribution in T24 Residential Buildings

End-Use Category	Lifecycle Incremental Cost ($/sf)	Lifecycle Savings (kWh/sf)	Cost of Saved Energy ($/kWh)	Assessment
Electronics	-$0.39	0.40	-$0.98	Highly cost-effective. Capital cost decrease and significant energy savings.
Lighting	$0.40	-1.20	N/A	Not cost-effective. Capital cost and energy use increase.
Motors	$0.43	5.90	$0.07	Cost-effective.
Resistive	$0.22	-0.55	N/A	Not cost-effective. Capital cost and energy use increase.
Building Level	$0.66	4.55	$0.14	Cost-effective.

Table 15. Cost Effectiveness of DC Distribution in ZNE Residential Buildings

End-Use Category	Lifecycle Incremental Cost ($/sf)	Lifecycle Savings (kWh/sf)	Cost of Saved Energy ($/kWh)	Assessment
Electronics	-$0.48	0.89	-$0.55	Highly cost-effective. Capital cost decrease and significant energy savings.
Lighting	-$0.03	0.11	-$0.30	Highly cost-effective. Capital cost decrease and significant energy savings.
Motors	-$0.12	0.77	-$0.16	Highly cost-effective. Capital cost decrease and significant energy savings.
Resistive	$0.04	-0.06	N/A	Not cost-effective. Capital cost and energy use increase.
Building Level	-$0.60	1.71	-$0.35	Highly cost-effective. Capital cost decrease and significant energy savings.