Demand DC

Accelerating the Introduction of DC Power in the Home

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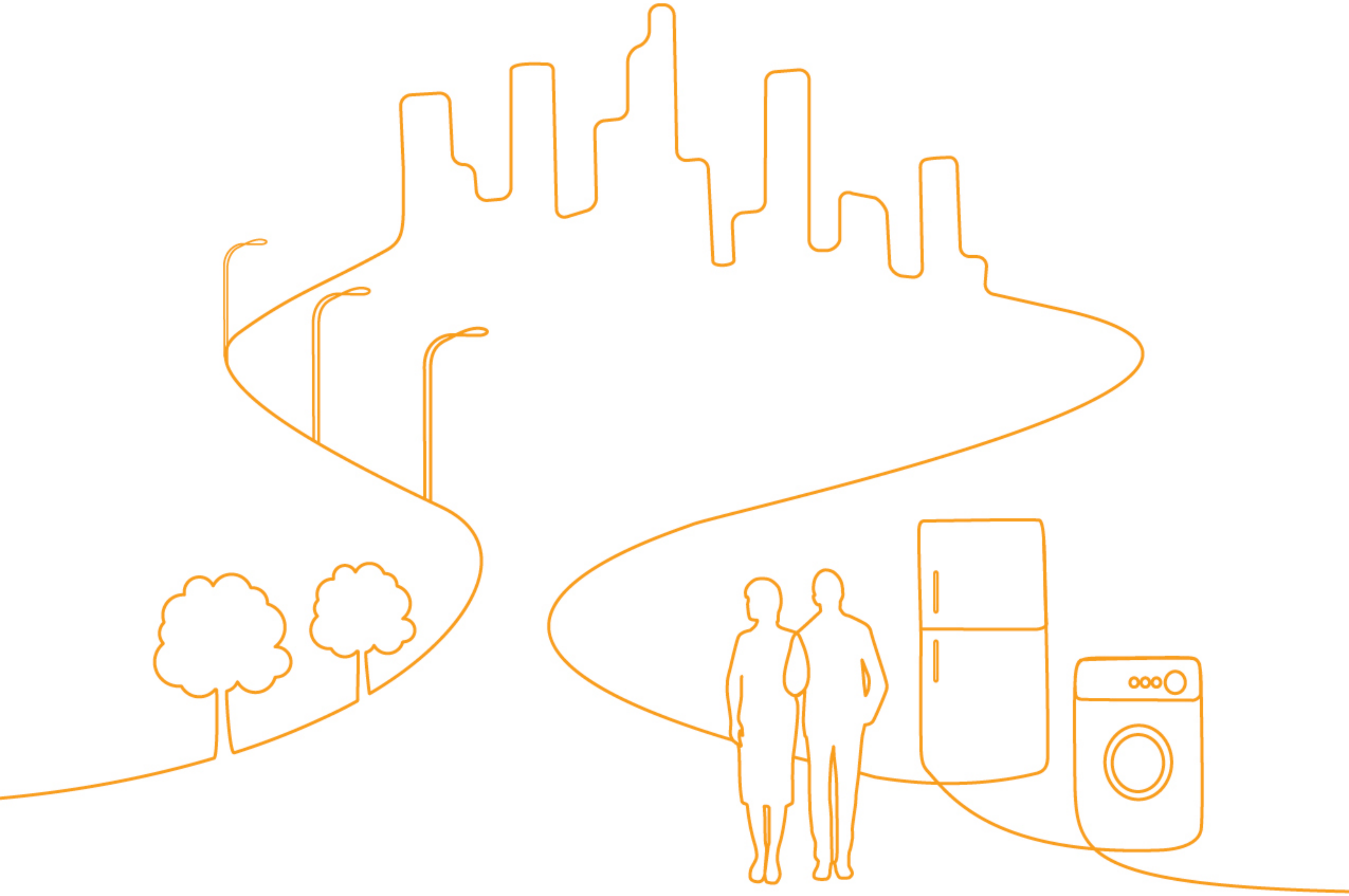

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Executive Summary

The last major technological leap forward in electricity distribution occurred more than 100 years ago. Inefficient, inflexible, and increasingly fragile, our system of alternating current (AC) power distribution is now showing its age. Last century's AC infrastructure was designed at a time when today's diverse energy demands could not have been imagined. In an era before distributed energy generation, the ability to transmit AC over hundreds of miles from central plants to individual outlets made it king. Today, however, the homogeneous centralized generation model is giving way to distributed generation, and an alternative method of delivering electricity within homes and buildings is emerging.

Direct current (DC) is the power of our sustainable energy future – it is produced by solar panels, stored in batteries, and consumed by the lights and appliances that we have in our homes and offices today. More than five thousand solar energy systems are installed on US rooftops every week, challenging traditional electric utility service models. Soon many buildings will also be outfitted with batteries for on-site energy storage. Our electronics, modern LED and fluorescent lighting, and many of today's appliances – which account for more than a third of household electricity consumption – require DC to function. The portion of native DC loads will only continue to grow with the proliferation of efficient lights, consumer electronics, advanced motor-driven appliances, and eventually electric vehicles.

As technology propels us toward a DC-powered future, legacy AC infrastructure anchors us to the past, hindering our ability to realize the full potential of ultra-efficient appliances and distributed energy. Modern distributed energy systems produce DC that must be converted to AC to supply the existing electric grid. This wasteful process is compounded when millions of lights, electronics, and appliances must each convert AC back to DC in order to operate. Up to 30 percent of site-produced DC power may be lost during these redundant conversions as it is transferred from PV panels and batteries through multiple layers of power conversion (see the Appendix "Following the Losses").

> We lack a coordinated effort to promote the demand for DC through manufacture of DC-ready lighting and appliances, and to build public awareness of the benefits achievable through direct use of DC in buildings.

We envision a future where AC and DC power distribution co-exist within buildings, each serving the needs to which they are best suited. In this scenario more DC power is put to use where it is produced and stored, rather than converted, exported to the grid, and converted again. With DC power we can unlock remarkable benefits for consumers, product manufacturers, and the environment. For example:

- **Consumers** could lower their energy bills and improve the resiliency of their homes during grid outages;
- **Appliance and lighting manufacturers** could produce more efficient, more reliable, and higher-performance products, while simultaneously reducing material and shipping costs;
- **Solar and energy storage companies** could offer greater value to their customers and explore new business models through an ecosystem of DC-ready systems and products;
- **Electric utilities** could experience better load control and minimize exposure to intermittent distributed generation sources behind the meter; and

- **The environment** would be subject to reduced emissions from central generation plants due to lower total demand and reduced transmission and distribution losses**.**

Achieving this vision requires cooperation, open dialogue, and a shared commitment among those who have a stake in generating, storing, distributing, and consuming DC power.

There are three parts to the DC equation: supply (generation), distribution, and demand (consumption). The first two elements are already progressing. On the supply side, renewable energy companies and battery storage and electric vehicle manufacturers continue to grow their markets and increase the presence of DC power in homes. In terms of infrastructure, coalitions of businesses, nonprofits, and government organizations are busy developing standards and components necessary for reliable DC power distribution in buildings.

> Achieving this vision will require cooperation, open dialogue, and a shared commitment among those who have a stake in generating, storing, distributing, and consuming DC power.

But there is still one critical missing piece of the equation: **we lack a coordinated effort to promote the demand for DC through manufacture of DC-ready lighting and appliances, and to build public awareness of the benefits achievable through direct use of DC in buildings**. Appliances and lighting are the most important interface between people and energy in the home, and their manufacturers and users are an untapped and powerful force to propel market transformation.

In this paper we provide a glimpse into a more energy efficient, reliable, and secure energy future, one in which generation, storage, distribution, and consumption of electricity in the home is increasingly – though by no means entirely – based in DC. We illustrate how in the years to come consumers will radically change the way they access energy services, and examine how market and technological forces are already driving the transition. We explore adoption paths to demonstrate how DC distribution can be introduced into existing buildings in a meaningful way. Lastly, we demonstrate why action is needed in the next one to three years to spur market transformation through DC-ready appliances and lighting, and identify opportunities where greater coordination can maximize the benefits that can be realized in the transition.

Why Direct Current & Why Now?

AC power has long been the preferred means of transmitting and distributing electricity from large, centralized generating stations down to individual sockets and end-use products in homes and businesses. Recently, however, diverse groups of product manufacturers, researchers, efficiency advocates, and even some electric utilities have questioned AC's primacy and have begun to explore DC as a more logical electricity generation and distribution choice, at least within buildings.

Today, a wide range of devices from lighting products to electronics require DC power to drive semiconductors and charge batteries as a means of delivering useful service to end users. We estimate that about one third[1] of household electric load today is natively DC. This fraction will grow with the continued proliferation of consumer electronic devices and LED lighting, the introduction of advanced motor-driven appliances, and the uptake of electric vehicles. To date we have required AC-DC power supplies and chargers to rectify and down-convert higher voltage AC power to the lower voltage DC power required by high-tech devices — in other words, these products must be adapted to our legacy AC grid. Despite our best policy and engineering efforts, these AC-DC power supplies can still turn anywhere from 10% to 25% of the electricity passing through them into waste heat through conversion losses.

What About Microgrids?

DC power distribution is often conflated with the concepts of microgrids (and even nanogrids), but there are a variety of services that grids provide beyond power distribution. Grids must maintain balanced operation, dynamically coordinating generation and storage resources to meet demand. As a result, modern smart grids also provide bi-directional communication of power and information to facilitate operation. These additional grid services can be provided by both AC and DC power; however, many have argued that DC technologies may be better suited than AC to provide grid functions within buildings (Nordman and Christensen, 2015). For purposes of this paper, we primarily investigate the opportunities presented by DC power distribution. DC micro- and nano-grids will be essential in realizing several important adoption paths discussed later in this paper, although a detailed treatment of their features is beyond the scope of this work.

DC is also making significant inroads in distributed generation. A recent and sustained decline in solar photovoltaic (PV) prices has led to continued double-digit growth of rooftop PV installations in residences. PV cells and other distributed energy resources like wind turbines and fuel cells produce DC electricity. This must be converted to AC before being distributed through the home or exported to the grid. These conversion steps result in additional energy losses that effectively reduce the useful energy service that can be provided by a system. These losses could be reduced by distributing and consuming the power in its native DC form.

On-site energy storage technologies, particularly battery storage, continue to enter the market and drop in price. This trend that will further tip the scales toward DC in the coming years. As with PV,

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1 Estimates based on the fractions of electricity consumed by electronics, solid-state lighting, and fluorescent lighting in U.S. homes today, according to EIA (2013): Lighting, electronics, computers, and other miscellaneous and assumed to be native-DC electric load use 14%, 11%, 3%, and 4% of total household electricity, respectively, In sum, these native DC loads use 32% of residential electricity.

batteries are natively DC, making them naturally compatible with our increasingly DC-based loads. Batteries also play a critical role in allowing PV owners to consume more of the energy they generate rather than exporting it to the electric grid. These trends in on-site generation and storage may make residential-scale distributed generation systems commercially viable in many regions of the US in the coming decade (RMI 2015a).

As the energy load and generation mix in buildings continues to shift towards DC, a complementary building-level DC distribution system together with DC-ready products will eliminate redundant power conversion steps and yield gains in efficiency, convenience, dematerialization, and other benefits. **CLASP is opening a dialogue with stakeholders across the DC power delivery spectrum on this emerging energy savings opportunity.** Our goal is to leverage the scale of electronics and appliance ecosystems and harness consumer demand to motivate a shift to DC distribution technology, thereby improving overall system efficiencies and capturing other critical, non-energy sources of value along the way. In this white paper — a first step in the process — we examine the potential benefits and market barriers associated with a series of “adoption paths” for DC power distribution in buildings. We also offer recommendations on market transformation strategies that could help accelerate adoption.

For simplicity, we examine use cases that primarily apply to residential buildings. However, many small commercial building types (e.g., offices, hotels) could benefit from the same technologies and strategies, and may offer equivalent or better routes for early adoption of DC power distribution.

The Promise of DC Distribution

DC Distribution 101

To understand exactly why DC distribution may be desirable in the future, we first need to examine how electricity is commonly delivered today. In today’s AC home, all electricity is imported from the grid as AC and then distributed to a combination of AC and DC loads. Power supplies or battery chargers are required to convert AC to DC for each DC load in the system. When a PV system is added to the home, so is some amount of DC distribution(Figure 1A), if only from the PV system to the inverter where DC is converted to AC and fed onto the grid. In this typical case, all of the site-generated electricity must then be converted back to DC before being put to use by DC end-use products.

But what if the DC loads could instead be powered directly from the on-site generation and/or storage which is already DC (Figure 1B)? In the hybrid case shown, some AC loads remain in the house and the addition of DC power distribution reduces the total number of power conversions.[2] A bi-directional AC-DC converter provides an interface to the AC side of the home, converting site-generated DC to AC to feed onto the grid when the home produces surplus energy, or importing AC electricity from the grid when on-site generation or storage is insufficient to meet demand. This hybrid AC-DC power distribution architecture forms the basis for the remaining discussion in this paper.

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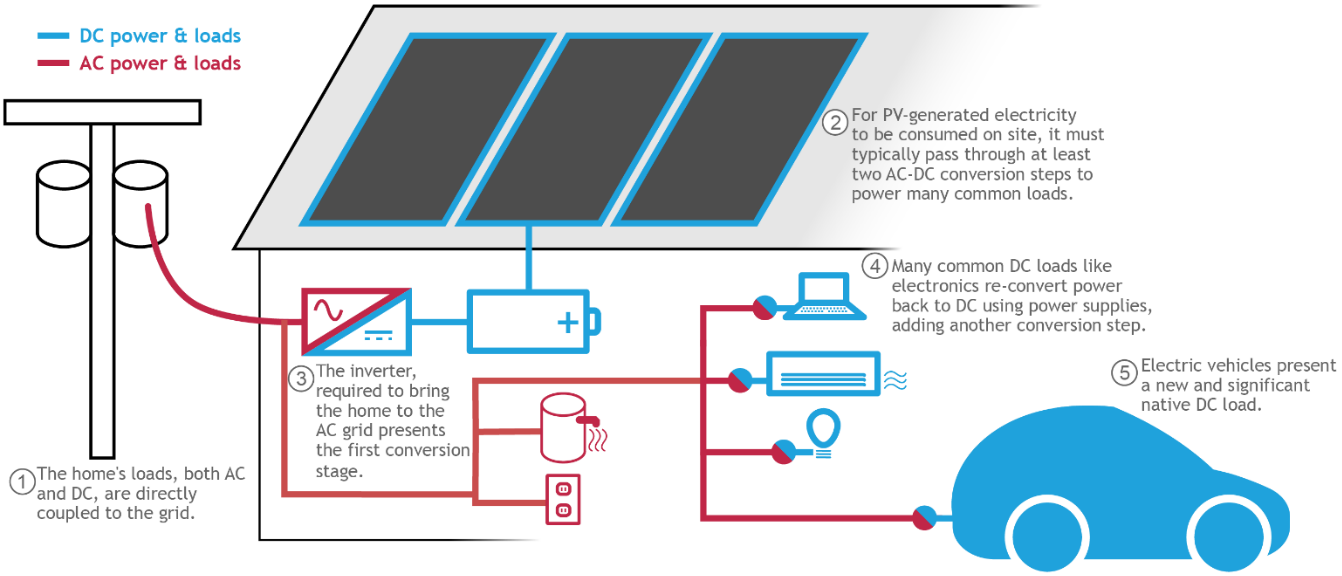
[2] In fact, the addition of DC power distribution will impart new electrical losses in the system that will offset some of the benefits obtained by eliminating AC-DC power conversions. These losses are dependent upon the DC distribution voltage, conductor run lengths, and other factors. The net benefits obtained from DC power distribution will vary based on the unique configuration and design of components, end-use products, etc. As an area for future research resulting from this paper we propose conducting a thorough investigation and quantification of these costs and benefits through a side-by-side demonstration of a DC (or hybrid DC) home against an equivalent AC home.



① The home's loads, both AC and DC, are directly coupled to the grid.

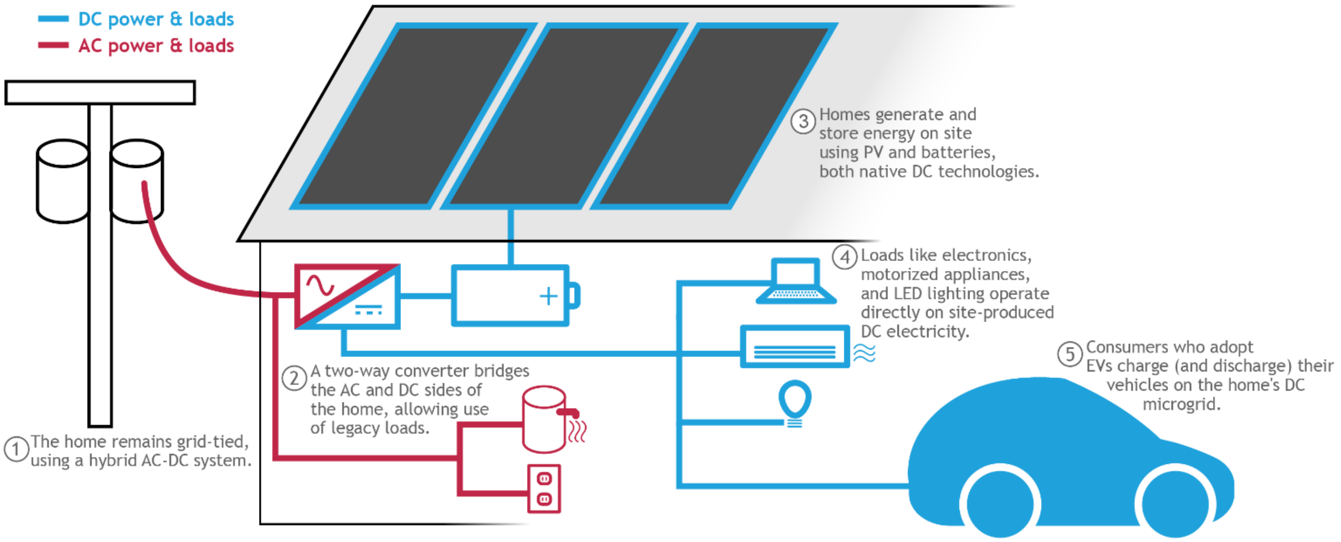
② For PV-generated electricity to be consumed on site, it must typically pass through at least two AC-DC conversion steps to power many common loads.

③ The inverter, required to bring the home to the AC grid presents the first conversion stage.

④ Many common DC loads like electronics re-convert power back to DC using power supplies, adding another conversion step.

⑤ Electric vehicles present a new and significant native DC load.

Figure 1(A): Simplified schematic of power distribution in a traditional AC house with installed PV. Red and blue lines indicate AC and DC distribution, respectively; red and blue shapes indicate AC and DC loads, respectively.



① The home remains grid-tied, using a hybrid AC-DC system.

② A two-way converter bridges the AC and DC sides of the home, allowing use of legacy loads.

③ Homes generate and store energy on site using PV and batteries, both native DC technologies.

④ Loads like electronics, motorized appliances, and LED lighting operate directly on site-produced DC electricity.

⑤ Consumers who adopt EVs charge (and discharge) their vehicles on the home's DC microgrid.

Figure 1(B): Simplified schematic of power distribution in a Hybrid-DC house. Red and blue lines indicate AC and DC distribution, respectively; red and blue shapes indicate AC and DC loads, respectively.

Trends Toward DC Power Distribution

The DC power distribution model outlined in this paper only begins to make sense as a design strategy when a large number of loads and other energy resources are natively DC. A significant portion of loads in today's homes are already DC, and market trends point to significant growth in many of these categories over the next decade.

All residential electrical loads *can* run on DC power, but only some of them absolutely *must* use DC today. Native DC loads — loads that must use DC power — include stationary electronics such as computers, monitors, and TVs, mobile electronics such as tablets and mobile phones, and embedded electronics such as a digital control pad on an appliance. LED and CFL lighting are also native DC loads. Many efficient motor-driven appliances that qualify for ENERGY STAR use brushless DC motors to power compressors and fans, though the market penetration of DC motors in large appliances is still unclear.

Together, these native DC loads account for about 32% of US residential electricity use. In homes with electric vehicles and efficient appliances and HVAC equipment that use DC motors, native DC loads could be as much as 63 to 74% of the total (Figure 2). Resistive loads such as incandescent lighting and electric heating elements are agnostic – they can run on either AC or DC. We estimate that these agnostic loads comprise 37% of US residential electricity use.

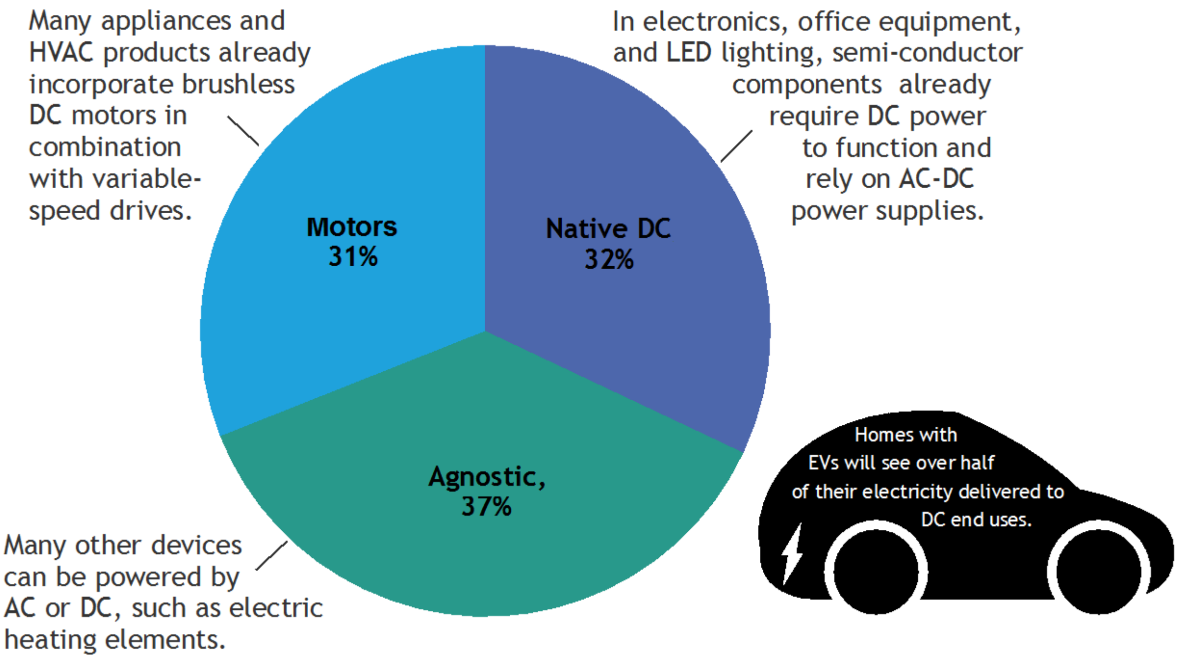


Figure 2: Percentage of US residential electricity consumption that is native DC, AC-DC agnostic, and motorized. Estimates based on the fractions of electricity consumed by electronics, solid-state lighting, and fluorescent lighting in U.S. homes today, according to Navigant (2013). Lighting, electronics, computers, and other miscellaneous and assumed to be native-DC electric load use 14%, 11%, 3%, and 4% of total household electricity, respectively, In sum, these native DC loads use 32% of residential electricity. Motor loads use 4.7 quads primary electricity (DOE 2013) of the residential total of 15.3 quads (EIA 2013), or 31%. We assume that agnostic loads consume the remaining 37%. (B) Share of loads with addition of an electric vehicle. The average U.S. home uses 10,900 kWh/yr of electricity (EIA 2015), and we estimate an average EV uses 4,500 kWh/yr (15,000 mi/yr at 0.3 mi/kWh), assuming that all charging is done at home.

All told, upwards of 70% of residential electric load either requires DC power today or could be easily converted to operate on DC power. The remaining 30% of load from AC motors could be made to operate on DC if products were redesigned, but this might not make economic sense in all cases. We therefore assume that while homes could be made fully DC, a more realistic near-term market adoption scenario would involve hybrid DC solutions such as the one illustrated in Figure 1B.

All told, upwards of 70% of residential electric load either requires DC power today or could be easily converted to operate on DC.

Across the many points of electricity generation, distribution, and consumption in the home, market trends continue to favor native DC technologies and point to a future in which homes will increasingly rely upon DC to provide energy services.

LED Lighting

From 2011 to 2015, sales of general service “A” LED lamps in the US increased thirty-fold as prices fell by an average of 32% per annum (LBNL 2015). US DOE expects prices to decline threefold by 2030, when LED lamps are expected to comprise over 70% of the installed base in homes (DOE 2014). We note that electronically-ballasted fluorescent lighting technologies are also DC-compatible and currently comprise a larger socket share than LED lighting, although LED is rapidly catching up.

Electronics

Electronics are some of the fastest growing loads in homes, and they continue to proliferate as wireless networking and mobile devices have brought electronics to new applications. Electronics and computer equipment alone comprise over 14% of typical electrical loads in US homes, and their fraction of total household load is expected to increase. This will be especially true as homes are retrofitted and designed more efficiently and heating and cooling loads diminish (Parker et al. 2008; Malinowski et al. 2014).

Electronics are perhaps the most likely end-uses to be adapted to run directly off DC power. Many devices — such as notebook and some desktop computers, tablets, mobile phones, computer monitors, video game consoles, and smaller televisions — already receive DC power through external power adapters, so adapting to DC power might only be a matter of selecting a standardized connector. Many small electronics like tablets and phones already rely on the USB standard for power delivery. With the advent of the emerging USB Type C power connector, which can support up to 100W of DC power delivery, the number of USB-powered products may greatly expand (see section “Standardizing DC”).

DC Motor Applications

About 25% of total primary energy in the US residential sector flows through electric motors. 85% of this motor load is consumed in five principle applications: central air conditioning, heat pumps, furnace fans, refrigerators, and freezers. Pool pumps, room air conditioners, laundry equipment, dishwashers, and dehumidifiers make up most of the remaining 15% (DOE 2013). Highly efficient DC motors have seen widespread use in a range of low-power applications such as hard disk and CD/DVD drives. These are used less frequently in traditional motor-driven products (e.g. small kitchen appliances, legacy HVAC equipment and appliances) due to their higher cost. A growing number of motor-driven devices, such as ENERGY STAR-labeled appliances and HVAC systems, do incorporate DC motors alongside variable frequency drives. These reduce power during periods of low load by allowing for more efficient control of motor speeds. In 2013 US DOE estimated that about 2% of household electric load could be eliminated by implementing best-practice motor technologies in the five principle product categories listed above. This represents a large energy efficiency opportunity even in the absence of DC power distribution technologies (DOE 2013). Adding DC distribution increases the savings.

Electric Vehicles

Electric vehicle sales are still a small fraction of total vehicle sales, typically totaling less than 1% even in most advanced economies (IEA 2015). However, as battery prices decline and charging infrastructure expands, the EV market is expected to increase to over 20 million globally by 2020, with the US and China comprising about half of the sales. The presence of an electric vehicle could drive up the fraction of native DC load in a home from about 30% to over 50%.

Solar PV

Since the rapid decline in PV module prices starting around 2009, rooftop PV sales have skyrocketed, enjoying a 62% increase from 2010 to 2012 alone. Rooftop solar is already at cost parity with the grid in many portions of the US, even without government subsidies, and could reach grid parity in 80% of countries worldwide by the end of 2017 (Deutsche Bank 2015).

Battery Storage

Battery storage systems for use within buildings (behind-the-meter) are rapidly reducing in price. This is thanks in large part to the experience and economies of scale achieved through the production of larger, cheaper, more energy-dense batteries for electric vehicles. Between 2009 and 2013, the cost per kWh of capacity of batteries has dropped nearly threefold. One of the leading home energy storage products, the Tesla Powerwall, is priced at $350 to $425/kWh, a 5- to 6-fold decrease from typical prices in 2010. Analysts at Rocky Mountain Institute forecast that residential PV + battery systems are already cost-competitive with grid power in high-rate markets like Hawaii and will reach grid parity in California and New York metro areas in the coming decade (RMI 2015a).

The Benefits of a DC Home

Electricity & Cost Savings

The energy efficiency community has primarily been interested in DC technology for its energy and cost savings potential. The best data available comes from several studies that estimated electricity and cost savings in homes using simplified energy flow calculations. Necessary for these calculations are assumptions of end-use efficiencies, power conversion, and battery equipment. The investigators usually assume the entire house uses DC power, supplied by two voltages: 24 V for low voltage end uses such as lighting and electronics, and 380 V for large appliances and HVAC.

Scenarios and savings estimates are summarized in the Appendix. The studies compare a baseline house with AC power distribution to a savings case using DC power distribution. All scenarios except PG&E’s (2012) Title 24 scenario include on-site PV generation in both the baseline and the savings case. Assumed power conversion efficiencies are similar across studies.

The studies to date agree on several important findings:

- **PV (or other on-site electricity generation) is a vital component to obtain any savings**. Glasgo (2014) calculates no savings for DC versus AC distribution with no PV present, while PG&E (2012) estimates savings of 6%. When a building imports AC electricity from the grid, some AC-DC conversion must happen regardless to deliver power down to end loads. There may be some efficiency advantage to be gained by centralizing this power conversion in one highly efficient converter rather than several smaller, less-efficient converters.
- **PV without storage yields a modest increase in savings to the 2-7% range** (Glasgo 2014; LBNL 2011, 2014; PG&E 2012). The elimination of dual AC-DC conversion between the PV and the DC loads amplifies the benefits, at least when DC loads are coincident with PV production. The savings result from reduced grid-imported energy through increased self-consumption of PV electricity in its native DC form.
- **Greater savings may be achieved with storage** (Glasgo 2014; LBNL 2011, 2014). Storing self-generated electricity eliminates conversion losses associated with exporting and then importing electricity for loads that are not coincident with on-site generation, though it must be noted that significant electrical losses can also result from the repeated flow of energy through the battery itself (LANL 2015). As with the "PV without storage" case above, the scope of savings are at the billing meter level and do not include potential system benefits that may accrue at the distribution level from having storage located in homes.

There is potential to reduce electricity usage by 10% or more. If applied to every residence in the US today, this would equate to about 290 TWh per year in savings, nearly the amount of electricity consumed by all homes in Texas.

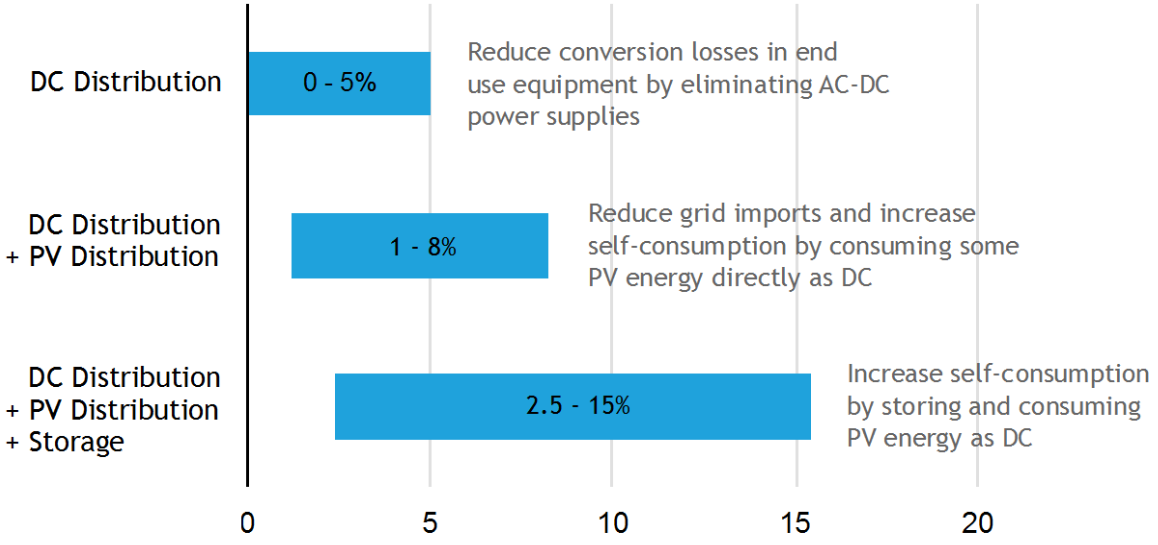


Figure 3: Range of savings estimated in the literature for DC vs. AC residential distribution. Primary benefits of DC distribution are listed to the right of each savings bar.

In summary, savings estimates range from about 2 to 7% for PV-only scenarios, and are about 13% for PV with storage scenarios. To make a case for DC distribution from an energy savings standpoint, distributed generation and storage are both key components. In that case, there is potential to reduce electricity usage by 10% or more. If applied to every residence in the US today, this would equate to about 290 terawatt-hours per year in savings, nearly the amount of electricity consumed by all homes in Texas (EIA 2015). To put this opportunity in a policy perspective, this is equal to the annual electricity savings from all federal appliance, equipment, and lighting standards in 2010 (ASAP 2012).

DC power distribution alone, without on-site generation or storage, is not expected to produce significant savings (Figure 3). Appreciable savings accrue when PV is included on the house, and double-digit savings may be possible when storage is part of the system. US DOE projects that there will be between 1 and 4 million homes in the US with rooftop PV installed by 2020. As noted previously, energy storage is likely to be coupled with PV in some of these installations (DOE 2014).

Given the wide range of savings estimates in the literature, and the fact that only a few demonstration projects have been carried out to date, a more comprehensive and thorough assessment of the relative costs and benefits of DC versus AC distribution is called for. The promise and potential of DC can best be proven by conducting a series of side-by-side comparisons of DC power distribution applications (see Adoption Paths in Table 1) versus their traditional AC equivalents. These comparisons must include a full accounting of material and installation costs, energy savings, reliability improvements, user experience, and other costs and benefits as noted below. In the following scenarios we consider PV (or other on-site generation) and usually storage to be required elements in DC power distribution systems.

Other Benefits

Energy and cost savings alone may not be enough to drive mass-market adoption of DC power distribution. However, there are a number of secondary benefits for consumers, manufacturers, and the environment that will enhance the overall value proposition of DC. These other benefits include:

- **Resiliency during grid outages**. Recent large storms, wildfires, and other natural disasters have exposed vulnerabilities in the AC grid system, causing widespread and lengthy outages. PV and battery backup systems are an attractive (though much more expensive) alternative to backup diesel generators. PV and battery backup tied to a DC distribution system would minimize losses, increasing the operation time or power for a backup system.
- **Increased use of self-generated electricity**. When storage is added to the mix, reduced power conversion losses increase the portion of electrical loads that can be powered from self-generated electricity and reduce the need for imported grid energy. This effectively acts as a discount on the cost of electricity provided by the home’s distributed generation resources.
- **Dematerialization of electronics and reductions in e-waste**. Electronics that draw their power from an AC grid must have internal or external power supplies to convert AC to DC. A DC power distribution system would eliminate the need for these power supplies,[3] reducing materials, size, and weight of the electronics. Consumers would need fewer “wall wart” power converters. Manufacturers and distributors would benefit from reduced materials and shipping costs. Over 120,000 metric tons of external power supplies are shipped every year (ITU and GeSI 2012), so this shift could obviate tens of thousands of metric tons of e-waste.

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3 Some DC-DC conversions will still be required internally for many products, much as they are today.

- **Touch-safe wiring for low-voltage loads**. Low-power, low-voltage (less than 100 watts and 60 Vdc) loads can be powered by Class 2 wiring, a category of conductor established by the US National Electric Code that is safe to touch even when energized. While it is likely that larger motor-driven and resistance-heating loads in the home will require high-voltage (e.g., 380 Vdc) Class 1 circuits, the ability to power smaller loads (e.g., light fixtures, charging sockets) with Class 2 wiring will increase occupant safety, reduce installation complexity, and enable innovation in the delivery of energy services in the home.
- **Combined power and data**. Protocols such as USB, Thunderbolt, Ethernet, and HDBaseT can be used to deliver both data and power in a single cable. These "managed DC" protocols provide the ability to send information among end-use devices and on-site generation and storage systems to negotiate voltages and power delivery (e.g., from the on-site generation, from on-site storage, or from the AC grid) in the local context in response to generation rates, grid pricing, and storage capacity, as described by Nordman and Christensen (2015).[4] If new wiring is installed for DC distribution, it may make sense to use technologies that bundle communications and power capability in the same cable to increase overall value.
- **A path to ZNE**. With fewer conversion losses from on-site generation to the end loads, DC distribution will help buildings achieve zero-net-energy (ZNE) targets, which are mandated for new homes in California by 2020. PG&E (2012) estimates that DC distribution in a ZNE home uses about 5% less electricity than does AC distribution.
- **Grid backup**. Distributed energy storage systems (e.g., in-home batteries and electric vehicles) may become a resource for the grid during periods of peak demand. An example of using a home battery as grid backup is demonstrated in the Honda Home (discussed below).

Standardizing DC

Much work has already been done to make DC power distribution technology ready for market adoption. A growing number of institutions have been advancing the concept of DC distribution in homes, office buildings, and data centers since the late 2000s. The EMerge Alliance - a consortium that includes appliance, component, and power electronics manufacturers such as Armstrong, Cisco, Emerson, Lutron, GE, Philips, Bosch, and Osram Sylvania – is developing standards for DC power distribution in data centers, homes, and commercial interiors. EMerge has already developed a standard for 24V DC power delivery in occupied spaces as well as a 380V standard for power delivery in data centers and telecommunications facilities (EMerge 2016). The Institute of Electrical and Electronics Engineers (IEEE) Power and Energy Society is convening a "DC in the Home" committee to research the organization's role in researching and promoting DC power for residences. The organization signed a memorandum of understanding with the EMerge Alliance in December of 2015 to further collaboration on hybrid AC and DC standards for residential power delivery (IEEE 2015). The American National Standards Institute has addressed system and installation safety for energy storage in its Standardization Roadmap for Energy Efficiency in the Built Environment (ANSI 2016). Similarly, the International Electrotechnical Commission (IEC) has established a Systems Evaluation Group[5] to evaluate international standardization efforts and recommend strategic directions for the IEC in the area of DC power for low-voltage applications.

Outside of this group of proponents, several other industry groups have focused on developing and standardizing low-voltage interfaces that can deliver both data and power. For example, the USB

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[4] These are in contrast with "standard DC" power distribution solutions that only provide power on a standardized bus.

[5] IEC Systems Evaluation Group 4 – Low Voltage Direct Current Applications, Distribution and Safety for Use in Developed and Developing Economies. http://www.iec.ch/dyn/www/f?p=103:186:0::::FSP_ORG_ID:11901

Implementers Forum now maintains standards that enable up to 100W of power delivery over USB connectors, with specific voltages negotiated between devices. Power delivery can be bi-directional, meaning that a laptop could charge accessories and receive power itself through the same port and connector (albeit not simultaneously). The new USB Type C connector supports this power delivery mechanism. A new version of the Thunderbolt interface (3.0) will also be able to implement USB Power Delivery. IEEE provides similar functionality through the Ethernet standard (informally known as Power Over Ethernet - PoE), which enables power delivery of up to 20W over Ethernet cables.

Demonstration Projects

A few DC power demonstration projects have been carried out to date. The earliest home demonstration project we know of was built in Korea by Samsung C&T.[6] The Green Tomorrow house includes DC distribution, 25 kW on-site generation, and 22 kWh of storage (Cho 2011). It is claimed to be 1.5% to 3% more efficient than an equivalent AC house and is ZNE. Japanese architecture and engineering firm NTT Facilities has also purportedly launched several residential DC power distribution demonstration projects in Japan, although results are not yet publicly available.

The Honda Smart Home in Davis, California is a net-metered, ZNE house with a very small DC power distribution system that ties together a PV generation system, an electric vehicle, and a home battery pack.[7] An energy management system is used to monitor generation and consumption of electricity, control battery resources and EV charging, and send electricity to the grid during high demand periods.

The NextHome demonstration project is a partnership between NextEnergy, the EMerge Alliance, and product and equipment manufacturers.[8] The first demonstration home was built in Detroit, Michigan and includes a 3.2 kW PV system, a 13.1 kWh storage system, and EV with vehicle to home (V2H) capability (the entire house can be powered off of the EV for backup purposes). The NextHome project takes a hybrid approach to power distribution, using DC from on-site generation to power lighting, electronics, and some appliances, and AC from the grid to power the rest (EMerge 2015).

Additional Work

In addition to developing standards and carrying out demonstration projects, several groups are actively working to further research savings opportunities and establish business cases. The Alliance to Save Energy (ASE) Systems Efficiency Initiative[9] includes a working group focused on DC power distribution, and the Continental Automated Building Association (CABA) has begun jointly developing a white paper with EMerge on the value of DC systems. In addition, the CEC's Electric Program Investment Charge (EPIC), has funded two DC research projects, one an investigation of residential and commercial design options led by Lawrence Berkeley National Laboratory and another a demonstration of DC power technology in a warehouse led by Bosch.

DC Adoption Paths

A systematic transition to DC power distribution in homes presents a much steeper technology adoption curve than market transitions for stand-alone products. Installing or converting to DC requires not only

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[6] Samsung blog post: http://www.samsungvillage.com/blog/2011/11/10/samsungblog-living-a-life-the-sustainable-and-smart-way/

[7] Honda Smart Home website: http://www.hondasmarthome.com

[8] Webinar describing NextHome project: https://www.youtube.com/watch?v=T2cyWZcwgxQ&feature=youtu.be

[9] ASE Systems Efficiency Initiative: http://www.ase.org/systemsefficiency

DC end-use products, but also infrastructure such as power converters and wiring. This means first costs are greater and the consumer must take a relatively active role in facilitating the transition to DC. Consequently, the introduction of DC makes sense in specific cases of new construction or retrofits for whole-home applications, or in more limited applications depending on consumer motivations. Table 1 outlines several of the “adoption paths” that we see as likely entry points for residential DC power distribution. In many instances, a given home might be ripe for a combination of adoption paths.

A key component of all adoption paths, whether the consumer’s goal is energy savings, resilience against power outages, or something else, is on-site electricity generation. Distributed generation technologies such as PV, wind, and fuel cells are natively DC. Distributing this power through a local DC distribution system to reduce conversion losses (rather than converting it to AC and sending it out to the grid) is a primary motivation in all adoption paths. Energy storage amplifies these self-consumption benefits. Instead of sending excess electricity to the grid, it can be stored for later use when production drops or during grid outages. In the following scenarios we assume that houses remain grid-connected, and thus require a bi-directional power converter to export excess generation to the grid, or to convert grid power to DC in times of generation/storage deficit (except in the off-grid adoption path). The final element is the DC end-use devices. In all but one adoption path, we assume that some AC power will still be needed, resulting in a hybrid home like the one depicted in Figure 1C.

Consumer motivations range from total energy independence to resiliency during grid outages to the convenience of eliminating external power supplies, in addition to saving money on electricity bills. The adoption paths proposed in Table 1 are crafted around these motivations. In most cases, a whole-home DC solution is not warranted. The DC garage, for example, addresses the motivation to reduce the cost of electricity to charge an EV. The emergency grid backup solution allows a consumer to power essential devices in the event of a grid outage. Below, we examine three of the adoption paths in depth.

Table 1: Potential Residential Adoption Paths

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

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

Adoption Paths in Detail

AP1: Clusters & Hubs

In retrofit scenarios, a small DC power distribution system (such as a single DC circuit) within the home may be an attractive adoption path because of lower first costs. In the "clusters and hubs" adoption path, the consumer may install a new circuit or potentially repurpose an existing AC circuit to distribute DC power to an electronics-heavy area of the house. This may be the home entertainment area, with electronics like a TV, set-top box, game console, and audio system; a home office with electronics such as a computer, monitor, router, and printer; or a bank of LED luminaires. Providing DC power to these clusters would eliminate the need for individual AC-DC power supplies and enable the direct use of site-generated power (especially when the home has storage), thus reducing conversion losses and energy use.

Although end-use products envisioned in this adoption path are all native DC, designing these devices to be DC-ready may not be as simple as removing the AC-DC power supply because electronics are not generally standardized around one DC voltage level. For example, most computers convert incoming power to multiple DC voltages (e.g., 12V, 5V, and 3.3V) for use by various subsystems. To be powered by DC, the computer must be designed to accept an incoming standard DC voltage, say 24V, which it will then step-down to 12V, 5V, and 3.3V.

In addition to the need for PV and storage, barriers to adoption from the consumer's point of view include lack of DC-compatible devices available on the market, and the value proposition given that energy savings may not be large enough to offset the first costs of installing the DC circuit. On the other side of the equation, manufacturers will see little demand for these devices until there is significant uptake of DC infrastructure, which is presently hindered by a lack of trained installers, low demand from consumers, and building codes and standards that do not clearly address DC power distribution.

AP2: Emergency Backup Power

In the "emergency backup power" adoption path the consumer is motivated by a desire to maintain some level of electrical service during grid outages and therefore must have on-site generation and storage sized to provide sufficient runtime for critical amenities such as refrigeration, lighting, heating/cooling, sump/well pumps, and medical devices. Given the range of possible loads and power requirements, a single DC circuit operating on one voltage will likely not suffice. Refrigerators, cooking appliances, and pumps, for example, would likely require high-voltage distribution, whereas lighting and electronics would require low-voltage distribution. Consequently, more wiring infrastructure is required for this path than for the simple cluster path, and the need for DC end-use devices expands beyond electronics and lighting to include kitchen appliances and other equipment that may not be as easily converted to run off DC.

AP3: DC Garage

The "DC garage" adoption path creates a DC power distribution system targeting the largest new native DC load in the home: electric vehicles. With DC infrastructure installed in a garage, other products stored there can be DC-powered as well, depending on the size of the space, PV and battery capacity, and consumer preferences. Likely candidates include the garage door opener (with the added bonus of being able to operate the device during a grid outage), chargers for battery-powered tools (hand tools, lawn mower), and appliances (chest freezer, water heater, HVAC equipment, washer/dryer). Required infrastructure components include a bi-directional power converter (we envision most homes would want to maintain grid connectivity), high- and low-voltage power distribution, and an EV charging station. Of these devices, only the PV array and EV are market-ready. Home batteries are on their way. DC versions of the remaining products would need to be produced at scale and be readily available in the market at competitive prices.

AP4/5: Whole Home Adoption Paths

Whole-home adoption paths, whether in the off-grid or grid-connected case, present similar market barriers as those discussed above, with the additional complexity of requiring all wiring, power conversion, and end-uses to be DC-ready. Due to the cost and complexity of completely rewiring existing homes for DC, whole-home adoption paths are likely only appropriate in new construction, and only once a sufficient number of end uses in the house are DC-ready. In the near-term, a hybrid solution in which homes would provide parallel AC and DC wiring may be the only feasible approach to accommodate legacy AC devices. Existing homes may be able to transition to hybrid wiring over time, replacing AC circuits and devices as DC-ready products become available, but the economics are likely far less favorable. Another possible development path for DC end uses is via hybrid devices that may be connected to either AC or DC in the home. For a device with an internal power supply, this can be accomplished by including a DC connector that bypasses the power supply. For a device with an external power supply, products could be packaged with two cords, one with the familiar power supply and AC connector, the other with a DC connector.

In new construction, one way to mitigate the lack of DC-ready refrigerators and well pumps would be to install DC power distribution systems sized to handle all desired end uses in the long term. Ensuring that a home has DC-ready backup power may add value for prospective buyers, who could then add DC devices as they become available.

Motivations for Manufacturers & Other Stakeholders

In order for a consumer to decide to use DC power in the home, DC (or AC-DC hybrid) end use and infrastructure products must be available for purchase at a competitive price, and consequently motivations must exist for manufacturers to produce such products before a clear market demand exists. Manufacturer motivations may include the following:

- **Reduced cost of manufacturing and shipping products**. Every native DC device (e.g., electronics, DC motors, LEDs) requires a power supply, either internal or external, to convert AC to DC at the device. Eliminating this power conversion step eliminates the need for AC-DC power supplies, reducing the cost of materials used in manufacturing and the weight and volume of the finished product.
- **Improved product safety**. With AC power delivery, devices must not only convert from AC to DC, but also must step-down voltage from 120 Vac to DC voltages required for operation. DC distribution eliminates high voltage AC within a product enclosure, improving product safety, and delivers standard DC voltages (e.g., low voltage at 12, 24, or 48V, high voltage at 380V) that products are designed to use.
- **Standardized power connectors**. With today’s AC infrastructure, supply voltage and frequency varies across geographies, necessitating different power connector and conversion designs for different markets. Standard voltages and sockets/plugs for DC devices would mean the same product could be shipped to every market in the world.
- **Increased sales leveraged by growth in residential PV**. DC may allow appliance manufacturers to better differentiate their products on the basis of high-efficiency, high-tech features, for example by associating DC-ready appliances with the growing movement to PV and other distributed energy products.

- **A vertical strategy for big players**. Global manufacturers such as Bosch, Panasonic, and Sharp build a range of potential DC products, from the end uses, to power conversion and infrastructure, to batteries. Creating a full product line may enable innovation enhancements to the entire customer experience.

Other entities may also be motivated to encourage adoption of DC distribution. Small/innovative product manufacturers, for example, may see DC as an opportunity to gain market share from larger, more traditional market actors. Solar companies may see opportunities to up-sell products and services at the time of PV installation by installing DC power converters, infrastructure, and load management systems. Utility companies might see opportunities for more effective demand response programs if DC power delivery facilitates access to usage data or if DC systems can power unpredictable loads like electronics and appliances, keeping more predictable and dispatchable loads like HVAC on the grid.

The motivations and benefits of DC distribution are spread across several entities. The challenges of market transformation, therefore, are to coordinate efforts across these entities to avoid “chicken-and-egg” problems (such as consumers waiting to install DC distribution because no desirable DC end-use devices exist, or manufacturers waiting to develop them because no DC infrastructure exists), and to take steps now to develop standards that ensure that DC products that do gain a foothold in the market are designed to meet consumer expectations for quality and performance.

Barriers & Opportunities for Market Transformation

DC distribution faces a host of market barriers prior to even early adoption (Table 2). This is mostly because it implicates so many building systems and end uses. Thus it requires the involvement of a diverse group of stakeholders to fully realize the opportunity’s value and lead product and standards development. In this way, the emergence of DC falls into a category of highly disruptive building energy efficiency solutions that face unique barriers to market adoption, requiring simultaneous buy-in from consumers and manufacturers (of both end-use devices and the power distribution infrastructure components and systems) in order to even begin to cross the chasm. Without standardized DC distribution infrastructure, consumers will not purchase and manufacturers will not produce DC-ready products; yet without the availability of products that run on DC, new and existing homes are highly unlikely to build out the required distribution infrastructure. How do we take the first steps?

> DC power falls into a category of highly disruptive building energy efficiency solutions that face unique barriers to adoption in the marketplace, requiring simultaneous buy-in from consumers and manufacturers in order to even begin to cross the chasm into early market adoption.

Fortunately, we can look to other technology transitions for guidance about mitigating such seemingly intractable barriers. The growth of electric vehicles, for example, involves the transition to an entirely new motive technology that is highly dependent on both supply of infrastructure — in this case charging stations — as well as demand for EVs themselves. Below we suggest several strategies for overcoming DC power’s “chicken-and-egg” market transformation barriers. Note that these strategies are not mutually exclusive; they may complement each other if pursued in tandem.

Table 2: DC Market Adoption Uncertainties and Barriers

Safety	- What solutions are readily available to eliminate DC arcing for higher voltage loads?
Product quality & reliability	- Will DC products function as reliably and be produced with as high quality as their AC counterparts?
Cost	- How much cost will hybrid DC wiring and receptacles add for new construction? For existing homes? - How costly will balance-of-system components such as bi-directional power converters be, and will market transformation programs be needed to bring those components to scale? - Will manufacturers charge a price premium for DC-ready products or otherwise introduce DC-ready features at the top tier of their product lines as has been done with smart appliances?
Availability & compatibility	- When will leading brands offer DC-ready products to compete with lesser-known brands that currently serve off-grid and RV markets? - Will DC products purchased today work with DC homes in the future?

Avoiding a “Format War” Through Standards

There are two opposing strategies for building out new and potentially disruptive systems: the “lock-in” model and the “open” model. Examples of lock-in abound, perhaps the most familiar being Apple’s vertically integrated hardware/software/content model. Similar trends have emerged in the smart home market, in which there are currently several small ecosystems of products — “islands” of interoperability — centered on key smart home OEMs, as with Nest Labs and its “Works with Nest” program. In the world of electric vehicles, Tesla Motors has pursued a vertically integrated, lock-in strategy to grow its market footprint. In 2012, Tesla announced that, in addition to selling its top-of-the-line Model S and Roadster EVs, it would also construct a nationwide “Supercharger” network across the US to provide customers with rapid charging services for free. In effect, Tesla used its large market capitalization to secure the infrastructure needed for nationwide adoption of its products. Today, drivers can find Superchargers in most major metro areas in the US. While this is a boon for Tesla owners, the Supercharger network currently cannot be used with other brands of EVs.

Entities with a significant market footprint, particularly those that manufacture a number of key DC home components, could pursue a similar path toward residential DC power distribution. However, this may not be an optimal outcome for consumers. Larger entities such as GE, Bosch, Samsung, Panasonic, or LG have the capacity to manufacture critical DC infrastructure components within their own organizations. This makes it possible to create exclusive or proprietary ecosystems of DC products. Such ecosystems might function very well together, but would lock consumers into one brand of kitchen appliances, PV panels, or lighting. This would ultimately limit consumer choice and set up “format wars” in which different proprietary DC standards battle for dominance, much like Thomas Edison and Nikola Tesla’s original DC vs. AC battle.

The energy efficiency community can help avoid a lock-in scenario by continuing to support and engage with industry alliances (e.g. the EMerge Alliance, the USB Implementers Form, and others), standards bodies (IEEE and IEC), and individual manufacturers on the development of consensus, open standards for DC power distribution. Aside from avoiding potential lock-in, global standards for DC voltages and connectors will continue to pave the way for significantly simplified and globally standardized power connectors for a wide array of products, as USB and Ethernet have done over the past two decades. This would benefit consumers and manufacturers alike.

New Alliances & Market Channels

As the rooftop solar industry continues to change the relationship between homeowners and their power, so too could it change the way in which energy-related services and appliances are sold into homes. In a DC power world, large residential solar providers such as Solar City, Vivint, and Sunrun, who already have tremendous and direct reach into homes, could serve as a powerful new sales and distribution channel for DC products. These companies already provide turn-key solar installation and financing services to millions of homes. Some, such as Solar City[10] and Helios, are beginning to tout battery backup solutions as value-add services. This means that major PV system providers are already in the business of providing two key elements of the DC power distribution vision.

As PV + battery systems become increasingly economical, vendors and their partners could become a key vehicle for introducing both DC power infrastructure and appliances to homes.[11] They might offer to sell or finance appliance bundles (as suggested in the “clusters” adoption path) made to operate on DC. The associated PV + battery system could be designed to achieve ZNE targets or to simply provide grid resilience and backup for critical loads. Big box home improvement stores like Home Depot that sell appliances, home electrical equipment, and PV systems could also be an important channel for packaged solutions. The energy efficiency and market transformation community should consider these new market channels through which highly efficient, DC products could be introduced to homes.

Promoting DC End-use Devices

Market transformation programs most commonly utilize knowledge of supply chains, market channels, and marketing techniques to permanently overcome barriers to the adoption of efficient products. Techniques such as enhanced product labeling and placement, tax incentives, rebates, and mandatory efficiency standards have been strategically applied to almost every imaginable energy-using load in the home, including lighting, appliances, electronics, HVAC equipment, and even EVs. The same strategies could eventually be applied to DC products to remove cost barriers and to help build capacity in the marketplace. For example:

- **Creating a DC brand**: Appliances that are both “DC-ready” and highly efficient could be labeled and promoted through retail campaigns and utility incentive programs.
- **Developing awards and labeling programs**: Voluntary labeling programs like ENERGY STAR may be willing to develop Emerging Technology Awards and eventually labeling programs to recognize efficient DC-ready products.
- **Establishing financial incentives**: Electric utilities and efficiency program sponsors could offer financial incentives, possibly coupled with ENERGY STAR criteria, to reduce the cost of DC-ready products and encourage more rapid market adoption.
- **Establishing tax incentives**: Governments could spur adoption of efficient DC-ready appliances through special tax incentives. This approach might be most appropriate for

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[10] Solar City is leveraging Tesla’s Powerwall as part of its energy storage solution. Elon Musk, Tesla Motors’ CEO, is also the chairman of Solar City, so Tesla Motors may also influence the course of DC distribution systems in a meaningful way by using its battery expertise to penetrate the distributed energy resources market through its Powerwall battery storage system.

[11] The practice of “bundling” lighting and small appliances alongside solar PV systems is standard practice for installers in developing countries, where energy access is limited and centralized AC electric grids are unreliable or non-existent.

larger motorized end-uses, such as refrigerators or air conditioning units, where DC motors might offer substantial energy savings on a per-product basis.

Promoting DC Infrastructure

Despite the great success of market transformation strategies in transitioning certain discrete products like lighting and appliances toward higher efficiency, the energy efficiency community has not often attempted to address the infrastructure surrounding end-uses nor to take on larger, system-oriented initiatives to reduce energy consumption.

Recent research from the world of EVs suggests that a limited product-based approach may be shortsighted. An NSF-funded project has recently used behavioral economic models to explore the effects of current federal tax incentives — a traditional market transformation policy measure — on the sale of EVs (NSF 2015). Researchers compared the sales-generating effects of current EV tax incentives versus simply investing in the construction of fast charger stations (in other words, the benefits of incentivizing end products versus infrastructure). EV sales are highly dependent on the presence of charging infrastructure, and the group estimated that direct infrastructure investments in fast chargers could have spurred *five times* as many EV sales as those achieved through EV tax incentives. In short, market transformation objectives could have been more effectively achieved by focusing on infrastructure and not end-use products.

> Market transformation organizations should not solely focus their efforts on promoting DC-capable end-use products. They should also focus on building out the infrastructure in homes and businesses to power those products.

At a minimum, these findings suggest that market transformation organizations should not solely focus their efforts on promoting DC-capable end products. They should also build the infrastructure in homes and businesses to power those products. More detailed cost estimates will be required to identify scenarios in which DC is appropriate as a retrofit in existing homes. In new construction, DC wiring and outlets may already be cost-competitive to implement at scale. Market transformation groups could help accelerate the introduction of DC distribution infrastructure in new homes by:

- **Engaging partners**: Engagement with the homebuilder and PV + battery communities on the value of DC distribution and appliances can help ensure that future homes can be designed to be “DC-ready”.
- **Educating and training stakeholders**: With the transition to DC, electricians will need to adapt to a new system of codes, conductors, receptacles, and other system-level components. As was the case with renewable energy technologies, new training requirements will need to be established and disseminated to the trades.
- **Promoting codes and standards**: building codes and standards for energy efficiency, such as California’s Title 24, can be used as a vehicle to incentivize the adoption of DC infrastructure at the building level, potentially by providing favorable compliance paths for designs that incorporate DC technology. Consideration of DC strategies may provide additional flexibility in meeting zero net energy targets as jurisdictions like California begin transitioning building codes in this direction.[12]

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[12] California has the stated goal that all new residential construction will be zero net energy starting in 2020 and is aligning development of Title 24 building standards accordingly.

Conclusions

In this paper we have provided a view into a more energy efficient, reliable, and secure energy future; one in which generation, storage, distribution, and consumption of electricity in the home is increasingly — though by no means entirely — based in DC. The path to realizing these future scenarios requires cooperation, open dialogue, and a shared vision among those who have a stake in generating, storing, distributing, and consuming DC power. We have suggested a series of plausible market adoption scenarios to provide a vision for the evolution of DC power distribution technology in the home. These scenarios are intended to form the basis for a broader discussion of barriers to market transformation and to highlight gaps in the existing knowledge base.

Following is a list of areas for further study that must be addressed to facilitate market transformation under any adoption scenario:

- **Conduct proof of concept testing**. To date, researchers have calculated the energy savings potential of DC power distribution on paper, and a few demonstration projects have shown the technical feasibility of the concept. However, more field data about energy savings, installation and operating costs, multiple benefits, and user experience would further substantiate the concepts articulated in this paper. In particular, fair assessments of end-to-end power losses and costs, including losses and costs in distribution wiring, need to be conducted to compare DC and AC distribution on equal footing.
- **Evaluate economics and rate structures**. The economics of DC power distribution depend greatly upon utility rate structures. Time-of-use considerations, solar feed-in tariffs, and carbon pricing (through taxes or rate increases) are sensitivities that have not been explored in depth in previous studies. Related studies on load flexibility and PV + battery economics suggest that DC systems would fare well and that these factors may only hasten the pace at which the technology becomes economically favorable (RMI 2014, 2015a, 2015b).
- **Understand market dynamics and supply chains.** A transition to DC power distribution requires dozens of energy-using products to be made DC-ready. Deeper understanding of market structures, market channels, and physical implementation of a variety of potentially disparate products could reveal potential synergies across dissimilar end uses.
- **Promote codes and standards.** Groups like EMerge, IEEE, and IEC are in various stages of researching and developing DC power distribution standards. These are a critical early requirements to ensure device compatibility and provide manufacturers with reference points around which to base their product designs. Residential building codes may also be updated to facilitate the installation of DC in retrofit or new-build applications.
- **Document design and implementation best practices**. Since only a few DC installations have been demonstrated at the scale envisioned in this paper, best practices for design and implementation do not yet exist. In addition to standards development, organizations like EMerge and IEEE provide guidance and confidence through the DC transition by developing application-specific design guidelines that help put new standards, systems, and products into practice.

With this paper, CLASP is opening a dialogue with stakeholders across the DC power delivery spectrum on this emerging energy savings opportunity. Our goal is to leverage the scale of electronics and appliance ecosystems and harness consumer demand to motivate a shift to DC distribution technology, thereby improving overall system efficiencies and capturing other critical, non-energy sources of value along the way.

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Appendix: Summary of Electricity Savings by Previous Studies

Study	Baseline	Scenario	Description	Est. Savings
Glasgo 2014	AC distribution with PV and net-metering	Central AC rectification for DC distribution within the house (no on-site generation)	Data set is 24 homes, Pecan Street Project	0
		DC distribution with PV and net metering		0.2-2.2%
		DC distribution with net metering, and storage PV		0.5-4.3%
LBNL 2011, LBNL 2014	AC distribution with PV and net-metering	Average residential load with PV	PV sized for ZNE	7%
		Average residential load with PV and storage	81% round trip efficiency	13%
		Shifted average residential load with PV	load shifted two hours earlier in day during cooling season	8%
		Shifted average residential load with PV and storage		13%
		Average residential load with PV and EV	DC load (not V2G), charged for 8 hours at night	5%
		Average residential load with PV, EV and storage		8%
LBNL 2014	AC distribution with PV and net-metering	Improved power system conversion efficiencies, Average residential load with PV	House rectifier efficiency improved from 93% to 95% DC-DC converter efficiency improved from 95% to 97%	9%
		Improved power system conversion efficiencies, Average residential load with PV and storage		14%
		Improved appliance AC-DC conversion efficiencies, Average residential load with PV	Cooling load efficiencies improved from 90% to 95% Non-cooling load efficiencies improved from 87% to 90%	4%
		Improved appliance conversion efficiencies, Average residential load with PV and storage		9%
PG&E 2012	AC distribution	CA Title 24 code	Home built for 2008 T24 compliance, no PV	6%
	AC distribution with PV and net-metering	ZNE	On-site PV generation offsets load for ZNE	5%

Appendix: Following the Losses

In a contemporary grid-tied PV system, power produced on site could encounter several conversions before reaching an end-use load and providing useful service. What follows is a simplified and conservative estimate of how these conversions could compound to yield significant power losses.

Power emerging from a PV system may first be used to charge a battery backup system, passing through a charge controller and then being chemically stored in the battery itself. Here we use an assumption of 92% round-trip efficiency, as reported by Tesla for its Powerwall battery system. This includes power losses through the charge controller as well as coulombic losses in the battery.

For integration into the home's AC wiring and the grid, DC power from the PV system and/or battery will pass through an inverter for conversion to AC. Today's inverter efficiencies are reported in the greater than 95% range (here we use a manufacturer-reported efficiency from Sunny Boy/SMA of 97.5%). Manufacturers typically report peak efficiencies for such equipment, though, and actual efficiency could be below 90% at partial loads.

Once power is on the home's AC wires, it will pass through AC-DC power supplies before supplying the various native DC loads discussed in this paper. This last step also incurs the greatest losses. Peak power supply efficiencies today can top 90% in some end uses. However, when using power supplies with lower power ratings and when operated at part load, these efficiencies can be well below 80% (based on an analysis of external power supply data available through Canada's EnerGuide program, available at http://www.nrcan.gc.ca/energy/products/12509). For the purposes of this analysis, we have used a typical operating efficiency of 75%, which could be far lower in many applications.

Compounding these efficiencies/losses together, we find that between 27% and 33% of power provided by PV panels might be lost before it can be used on site, depending on the presence of battery backup systems or not. Based on the available data, we assume that most of this loss occurs at the final power conversion stage at the load.