# Demand DC: Adoption Paths for DC Power Distribution in Homes

*Stephen Pantano, CLASP*
*Peter May-Ostendorp, PhD, Xergy Consulting*
*Katherine Dayem, PhD, Xergy Consulting*

**ABSTRACT**

Over the next two decades, electric loads that require direct current (DC) power, such as solid-state lighting, electronics, and electric vehicles will continue to proliferate in the residential sector, along with DC distributed energy resources like rooftop PV and eventually battery storage technology. Homes today distribute electricity as alternating current (AC) despite the fact that their energy needs are shifting to DC, resulting in redundant power conversion steps and waste. Previous studies have estimated that DC power distribution could save upwards of 10% of a home's electricity by reducing the number of power conversion steps, ensuring that a greater proportion of electricity generated and stored on site provides useful energy services. But even relatively high energy savings potential will not overcome the significant market transformation hurdles that this technology faces. We examine several compelling and realistic residential technology adoption paths, ranging from full-home battery backup solutions to the more modest "DC garage", articulating potential energy and non-energy benefits. These scenarios provide a tangible foundation upon which our recommendations for future research and broader market transformation activities are built.

## Introduction

For nearly 100 years, alternating current (AC) power has been the preferred means of transmitting and distributing electricity. 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 direct current (DC) as an alternative generation and distribution choice, at least within buildings.

Today, DC is becoming more and more prevalent in homes. A wide range of devices from lighting products to electronics fundamentally require DC power to drive semiconductors, charge batteries, and provide other useful services to end users. We estimate that about one third of household electric load today is natively DC.[1] This number will continue to grow with the continued proliferation of consumer electronic devices, phase-out of legacy light sources, introduction of advanced DC-motor-driven appliances, and uptake of electric vehicles. This fraction is also expected to be greater in low-energy homes, in which plug and miscellaneous loads comprise a larger share of total electricity use (Norton et al. 2008). Native DC products today require AC-DC power supplies and chargers to rectify and down-convert higher voltage AC power to the lower voltage DC power required by the device — in other words, to adapt loads to our legacy AC grid. Despite our best policy and engineering efforts, these power supplies still turn 10% to 30% of AC power into waste heat in the conversion process. DC is also making significant inroads through distributed generation (DG). In light of ongoing price

[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 (2015).

reductions for DG equipment, electricity rate increases, and favorable tax incentives, residential-scale DG systems with storage may reach grid parity in many regions of the U.S. in the coming decade (RMI 2015a). PV panels and other DG resources, like batteries and fuel cells, produce and store DC electricity and therefore suffer AC-DC power conversion losses of their own, mainly through inverters when power is exported to the AC grid.

Direct use of DC power would eliminate many of these power conversion losses by maximizing self-consumption of the energy produced (and stored) on site and reducing imports of electricity from the grid. As residences evolve to contain an electrical system with mostly DC endpoints, a complementary building-level DC generation, storage, and distribution system will eliminate redundant power conversion steps and yield gains in efficiency, convenience, dematerialization, and other benefits.[2] What might this system look like and what are the most likely constellations of electrical equipment that would benefit from building-level DC distribution? Previous studies have estimated and bounded the technically achievable energy savings potential of DC distribution technologies and characterized market and technological barriers preventing broader adoption (PG&E 2012; Vossos, Garbesi, and Shen 2014; DOE 2014; LANL 2015). Prior studies have also demonstrated that DC distribution technologies could be particularly synergistic when paired with zero net energy (ZNE) buildings, leading to higher relative energy savings (Vossos, Garbesi, and Shen 2014; PG&E 2012).

This paper builds on earlier studies and examines a series of “adoption scenarios” for DC power distribution in homes that would present multiple sources of value to homeowners. Informed by discussions between the authors and a diverse group of DC stakeholders, these scenarios provide a tangible foundation upon which our recommendations for future research and broader market transformation activities are built.

## DC Distribution 101

To understand exactly why DC distribution may be desirable in the future, we first examine how electricity is commonly delivered today, particularly in homes incorporating DG. Most homes import all of their electricity as AC from the grid. Even grid-connected homes with PV convert their generated DC power to AC through an inverter, place it on the grid, then consume or export it as AC. About 5% of the energy is lost in this DC-AC conversion process. Battery storage systems can be added to reduce dependency on the grid, but stored energy must still be converted back to AC to be used in the home. Between round-trip coulombic losses in the battery and conversion losses in the inverter, over 10% of site-produced energy could be lost before reaching the home’s AC wiring. Finally, any DC loads in the home convert the AC they receive using power supplies or battery chargers, losing another 10 to 30% of the remaining electricity. As a result, locally generated and stored electricity undergoes at least two AC-DC conversion steps before being put to productive use, losing about one third of the energy along the way. Taking into account prevailing PV efficiencies, less than 15% of the solar energy striking a panel might ever provide power to native DC loads.

In the future, power supplies and chargers could largely be eliminated as “middlemen”, and DC loads could be directly powered by on-site generation and/or storage, requiring only more simple and efficient DC-DC power conversion to operate. Homes would still be grid-tied and would retain some legacy AC loads. (In the future, homes and the local grid itself could shift

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[2] Although the focus of this paper is residential, many commercial facilities could benefit from similar technologies and strategies.

entirely to DC power, but for the purposes of this paper, we acknowledge that intermediate, hybrid topologies will be required to maintain compatibility with existing infrastructure and certain loads that fundamentally do not benefit from DC power. This hybrid DC home reduces the number of redundant power conversions. Even so, a two-way inverter would still be necessary to provide an interface to the grid and the AC side of the home, converting site-generated DC to AC to feed out to the grid if the home produces surplus energy, or importing AC from the grid if on-site generation or storage is insufficient to meet demand. Figure 1 illustrates this new topology for delivering electricity in homes.

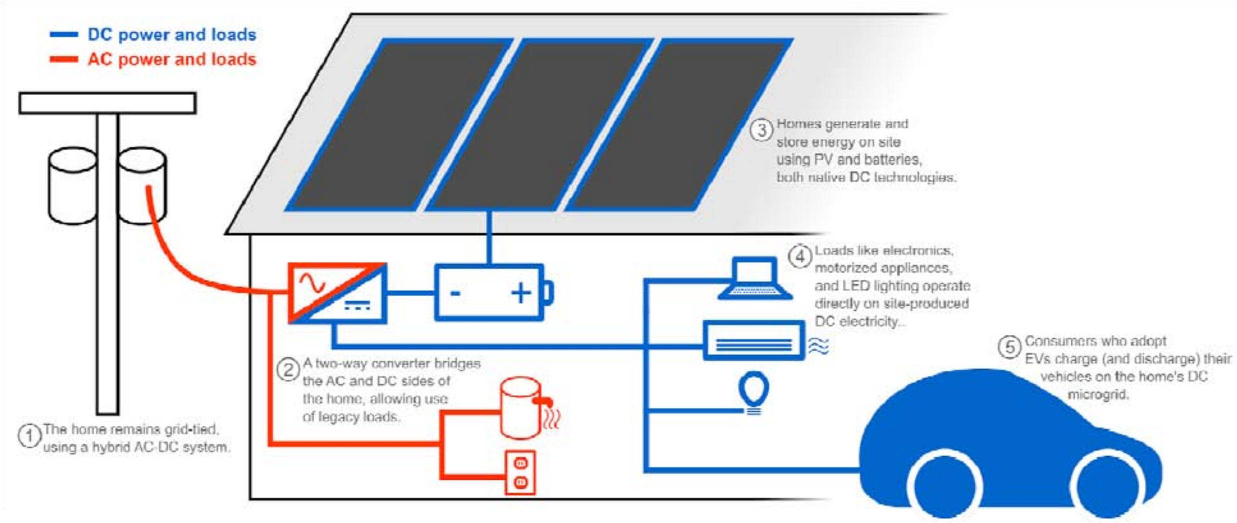


Figure 1: Example of a hybrid DC home.

## Home Energy Trends: an Increasingly DC Future

The benefits of DC distribution in homes begin to accumulate when both a large number of loads and DG are natively DC. A significant portion of loads in today's homes are already DC, and market trends point to growing sales over the next decade.

All residential loads *can* run on DC power, but only some of them absolutely *must* use DC electricity today. These native DC loads include effectively all electronic devices, embedded electronics in large devices such as appliances, and LED and CFL lighting. Additionally, motor loads can be DC, especially when energy efficiency is a design criterion. For example, appliances and HVAC systems designed to qualify for ENERGY STAR typically use brushless DC motors to drive compressors and fans, but the exact market penetration of DC motors in large appliances is unknown. Together, DC-native loads account for about a third of U.S. residential electricity use (Figure 2); however, in homes with an electric vehicle (EV) and efficient appliances and HVAC equipment, this number could be as high as two thirds. Resistive loads, such as incandescent lighting and electric heating elements, are agnostic and can run on either AC or DC power. These loads comprise over a third of U.S. residential electricity use.

Between native DC and agnostic loads, more than 70% of today's residential loads either require or could easily be converted to operate on DC power. The remaining motor-driven loads could be redesigned to operate on DC using existing motor technology. With the anticipated market growth of EVs (IEA 2013), over half of a home's electric load would be natively DC, and more than 80% of the total load could run on DC between agnostic loads and the use of DC motors. Several market trends in DC-native loads, generation, and storage hint at a future in which homes will increasingly rely on DC power for energy services (Table 1).

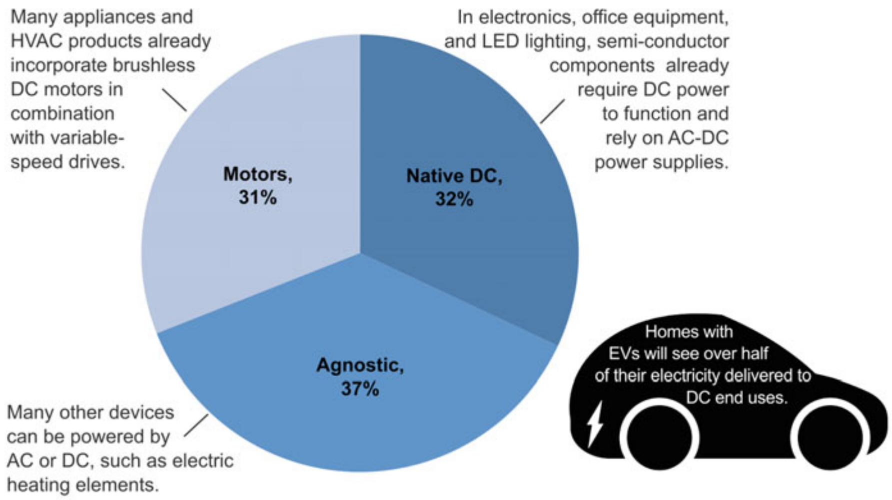


Figure 2: Share of residential electricity used by native DC, motor, and agnostic loads.

Table 1: Market trends toward native DC technologies.

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|---|---|
| **Solid-state lighting** | • 2011-2014: U.S. sales increased by a factor of 10; price for "A" lamps decreased by more than 50% (Vossos, Garbesi, and Shen 2014).<br>• Will comprise >70% of residential installed base by 2030 (DOE 2014). |
| **Electronics** | • Greater than 14% of electrical load in typical U.S. home and growing.<br>• IoT and mobile devices driving expansion.<br>• Emergence of USB Type C allows up to 100W DC power delivery. |
| **DC motor applications** | • 85% of residential motor load used by 5 large applications: central A/C, heat pumps, furnace fans, refrigerators, freezers (DOE 2013).<br>• Growing penetration of DC motors with variable speed drives used in efficient appliances and HVAC systems. |
| **Electric vehicles** | • EV sales expected to increase as battery prices decline and infrastructure expands (IEA 2013). |
| **Solar PV** | • Significant increase in sales due to rapid decline in PV module price: 62% growth in sales between 2010 and 2012, and 1 to 4 million homes in the U.S. with rooftop PV installed by 2020 (DOE 2014). |
| **Battery storage** | • Cost decreased nearly threefold between 2009 and 2013.<br>• PV + battery systems at grid parity in Hawaii, expected in metro areas of California, New York within 10 years (RMI 2015a).<br>• Likely to be included in at least a modest percentage of PV installations (DOE 2014). |

Amidst these trends, efforts are underway to research savings opportunities, develop standards, and establish business cases. Some of the most active organizations include: the EMerge Alliance, an industry consortium developing DC power standards which include standardized voltage; IEEE, whose "DC in the Home" group is examining the data gaps, business case, and need for DC standards; the International Electrotechnical Commission (IEC), whose strategic evaluation group 4 is currently examining the need for IEC-led DC standards; the Alliance to Save Energy (ASE), whose working group is creating a roadmap for DC systems; the Continental Automated Building Association (CABA), who has begun jointly developing a white paper with EMerge on the value of DC systems; and the CEC's Electric Program Investment Charge (EPIC), that has funded two DC research projects, one an investigation of residential and commercial design options led by LBNL and another a demonstration of DC power technology in a warehouse led by Bosch.

## Benefits of DC Distribution

The energy efficiency community has primarily been interested in DC technology for its energy and cost savings potential (e.g., Garbesi et al. 2011; Glasgo et al. 2014; PG&E 2012; Vossos, Garbesi, and Shen 2014). Some, such as Nordman and Christensen (2015), have argued, as we do here, that non-energy benefits will be essential to spur broader adoption. Most studies compare a baseline house with AC distribution to a savings case using DC distribution and 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, which are summarized in Figure 3:

- PV (or other on-site electricity generation) is a vital component to obtain substantial savings. Glasgo et al. (2014) calculate no savings for DC distribution over AC distribution with no PV present, while PG&E (2012) estimate modest savings of 6%.
- PV without storage yields a modest increase in savings to the 2-7% range (Garbesi et al. 2011; Glasgo et al. 2014; PG&E 2012; Vossos, Garbesi, and Shen 2014). 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.
- Savings of 10% or more can be achieved with storage (Garbesi et al. 2011; Glasgo et al. 2014; Vossos, Garbesi, and Shen 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.

To fully leverage the energy savings benefits of DC, therefore, we maintain that DG and storage are necessary components, an assumption that underlies our adoption scenarios later in this paper. In that case, there is potential to reduce home electricity usage by 10% or more compared to an AC home with DG and storage. If applied to every residence in the U.S. 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 of all federal appliance, equipment, and lighting standards in 2010 (ASAP 2012).

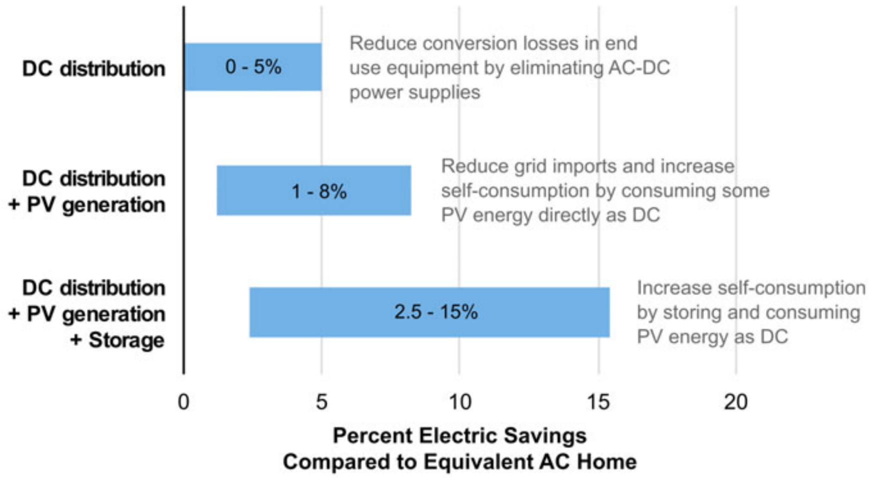


Figure 3: Range of published DC electric savings estimates.

Energy and cost savings alone, however, may not be sufficient to drive adoption of DC technology. A variety of secondary benefits may provide significant additional value to consumers, manufacturers, and the environment (Table 2). Of particular interest may be the reduced conversion losses of DC distribution that would allow new homes to more easily reach ZNE targets. Another tangible secondary benefit is increased resiliency, or the ability to maintain power during natural disasters such as hurricanes and winter storms with a DC microgrid powered by PV and storage. In many cases, DC amplifies the benefits of DG technologies.

Table 2: Benefits beyond electricity savings of DC distribution.

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|---|---|
| **Secondary energy and environmental benefits** | • More feasible ZNE through reduced conversion losses.<br>• Increased use of self-generated electricity if using storage.<br>• Dematerialization of electronics and reductions in e-waste. |
| **Safety benefits** | • Resiliency during grid outages when coupled to storage.<br>• Class 2 “touch safe” wiring can be used for low-voltage loads. |
| **Convenience** | • Option to deliver power and data on one cable (e.g. USB).<br>• Low-voltage wiring can be quickly installed and easily reconfigured |
| **Grid benefits** | • Peak demand reduction.<br>• Improved power quality (i.e., better synchronization of the voltage phase and frequency) compared to commodity power supplies. |

## Adoption Paths

A systematic transition to DC 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 DC-ready loads, but also infrastructure such as power converters and wiring, resulting in higher system costs and the need for a relatively savvy consumer taking an active role in initiating and carrying out the transition. In specific cases of new construction or retrofits, DC may be used in the whole home, but in existing homes, more limited applications could meet particular consumer goals. These goals may range from total energy independence to resiliency during grid outages to the convenience of eliminating external power supplies (or “wall warts”), in addition to saving money on electricity bills. Below, we examine four adoption paths in depth.

In the following scenarios we assume that the house contains specific DC end uses and one or more DC busses of a specified voltage, self-generates and stores electricity, remains grid-connected (except in the off-grid scenario), and thus requires a bi-directional inverter both to convert excess generation to AC for export to the grid and to convert grid power to DC in times of generation/storage deficit (except in the off-grid adoption path). In all but one adoption path, we assume that some loads will remain AC, resulting in a hybrid home like the one depicted in Figure 1.

### Clusters, Hubs, and Nanogrids

In retrofit scenarios, starting with a small DC nanogrid (or even a single DC circuit) within the home may be an attractive adoption path because of lower first costs. The consumer may install a new circuit or repurpose an existing AC circuit to distribute DC power to an electronics-heavy “cluster” within the house. This may be the home entertainment area, with a TV, set-top box, game console, and audio system; a home office with 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.

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 an uncertain payback period given that electricity savings may be small compared to installation costs. On the other side of the equation, manufacturers will see little demand for DC-compatible devices until there is significant installation of DC infrastructure, which is presently hindered by, among other things, a lack of codes and standards.

### Emergency Backup Microgrids

Similar market barriers exist for the “emergency backup microgrid” adoption path. Here 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 amenities like refrigeration, lighting, and heating/cooling. The customer will choose what end-uses and services are essential to connect to the DC microgrid. These devices may include electronics, a portion of the home’s lighting, refrigerators, freezers, cooking appliances, well and sump pumps, and essential medical equipment. Given the diverse range of loads and power requirements, a single DC circuit operating at one voltage will likely not suffice. Larger loads would likely require a high-voltage bus, whereas lighting and electronics may require low-voltage busses. Consequently, more wiring infrastructure may be required, and the need for DC end-uses expands beyond electronics and lighting to include kitchen appliances and other equipment that may not be as easily converted to run off DC. In new construction, one way to mitigate the lack of DC-ready refrigerators and well pumps would be to install a microgrid that is sized to handle all desired end uses in the long term. Ensuring that the home has a DC-ready backup microgrid may add value for prospective owners, who could then add DC devices as they become available.

### DC Garage

The "DC garage" adoption path creates a DC microgrid centered on the largest new DC-native load in the home: electric vehicles. With DC power 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 inverter, high- and low-voltage busses, and an EV charging station. Of these devices, only the PV array and EV are market-ready. Home batteries are just emerging. DC-ready versions of the remaining products are still needed.

### Whole Home

Whole-home adoption paths, whether off-grid or grid-connected, 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. While it may be possible to repurpose existing AC wiring to carry DC, new receptacles and circuit breakers will be required for a DC home retrofit. Due to the cost and complexity of rewiring existing homes for DC, whole-home adoption paths are likely only appropriate in new construction and whole-home electrical retrofits, and only once all common home end uses 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.

The most likely development path for DC end uses is the development of 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 AC-DC rectifier stage of 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. Eventually, market demand for DC products may warrant DC-only devices, but such a transition is still many years away.

## Mitigating Barriers and Strategies for Market Transformation

DC distribution faces a host of market barriers prior to even early adoption, and because it requires simultaneous transformation of multiple building systems and multiple end uses to achieve its full value, it presents a challenging first-mover problem to those organizations that would lead the way. Without standardized DC distribution infrastructure, including standard DC voltages, 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 unlikely to be outfitted with the required distribution infrastructure. How do we take the first steps toward market transformation? Below we suggest several strategies for overcoming DC power's "chicken-and-egg" market transformation barriers. To be successful, it is imperative to both create a push through DC infrastructure (the power distribution components in buildings) and create a pull through DC-ready end uses.

### Avoiding a Format War through Standards

There are two opposing strategies for developing new product ecosystems: the "lock-in" and "open" models. Examples of lock-in abound, including Apple's vertically integrated hardware/software/content model and Tesla Motors' EV/rapid charger network approach. Entities with a significant market footprint, particularly those with the breadth to manufacture several key DC home components — GE, Bosch, Samsung, Panasonic, or LG — could pursue closed ecosystems for residential DC microgrids. This makes it possible to create exclusive or proprietary ecosystems of DC products that would function seamlessly, but might limit consumers' choices in both electrical devices and DG equipment. This could spur "format wars" between competing DC standards, ultimately hindering adoption.

The energy efficiency community can help avoid this scenario by continuing to support and engage with industry alliances (e.g. the EMerge Alliance, the USB Implementers Forum, and others), standards bodies (IEEE and IEC), and individual manufacturers on the development of open standards for DC power distribution. Global standards could pave the way for significantly simplified and globally standardized power connectors for a wide array of products.

### New Alliances and 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, direct reach into homes, could serve as a powerful channel through which DC products are provided. These companies already provide turnkey solar installation and financing services to millions of homes, and some tout battery backup solutions as value-add services as well. As PV + battery systems become increasingly economical, solar vendors and their partners might offer to sell or finance DC appliance bundles (as suggested in the "clusters and microgrids" adoption path) made to operate on a home's DC microgrid. Home improvement stores that sell appliances, home electrical equipment, and PV systems could also be an important channel for packaged solutions. Thus, the energy efficiency and market transformation community may find new market channels emerging through which highly efficient DC products could enter homes. The industry should continue to stay abreast of these market channels in the design of policies and programs to promote DC products.

### Promoting End Use Products

Techniques such as enhanced product labeling and placement, tax incentives, up- and downstream rebates, and mandatory energy performance standards (MEPS) have been strategically applied to almost every energy-using load in the home. The same strategies could also be applied to DC products to remove cost barriers and build capacity in the marketplace. For example, market transformation organizations could develop a brand for appliances that are both "DC-ready" and highly efficient for promotion in retail campaigns and utility incentive programs. Similarly, voluntary labeling programs like ENERGY STAR could adapt labeling programs to recognize the benefits of efficient DC-ready products.

### Promoting Infrastructure

The energy efficiency community has traditionally focused on improving the energy performance of individual, stand-alone products. This narrow focus has resulted in only rare attempts to address the underlying systems and infrastructure necessary to support disruptive new end-use technologies. Only recently has the community begun calling for broader, systems-oriented initiatives to reduce energy consumption (Elliott 2012). Research from the world of EVs suggests that investments in enabling infrastructure can have dramatic market transformation impacts. A recent study showed that investment in EV fast charging stations could achieve 5 times greater impact compared to standard EV tax incentives (NSF 2015). In other words, when an emerging technology like an EV is highly dependent on an enabling technology like fast chargers, it can be more cost effective to invest in the enabling technology itself.

These findings suggest that market transformation efforts should not solely focus on promoting DC-ready end products. They should also promote the infrastructure in homes and businesses to power those products. Market transformation groups could help increase the penetration of DC distribution infrastructure in new homes by: (1) educating homebuilders and DG providers on the benefits of building DC-ready homes, (2) helping to establish and disseminate new training requirements for electricians as new DC standards and components become available, and (3) incentivizing the deployment of DC infrastructure through building codes and standards, potentially by providing favorable compliance paths for designs that incorporate DC features. More detailed costing will be required to identify scenarios in which DC is appropriate as a retrofit in existing homes.

## Unanswered Questions, Next Steps, and Conclusions

This paper posits a series of adoption paths for DC to provide a tangible vision for the evolution of this technology in the home. As noted, the potential benefits of DC are manifold, but their achievement will require substantial coordination between end-use product manufacturers, DG companies, consumers, policymakers, and many other stakeholders. The adoption scenarios are intended to form the basis for a broader discussion of barriers to market transformation and highlight gaps in the existing knowledge base. Following is a list of topics for further study that must be addressed to facilitate market transformation under any adoption scenario:

- **DC standards.** Protocols like USB and Ethernet already provide DC power and data to certain devices. Groups like the EMerge Alliance, IEEE, and IEC are in various stages of researching and developing broader DC power distribution standards at the building level. Standard voltage busses and connectors are a critical early requirement to ensure device compatibility and provide product manufacturers with reference points around which to base their designs. In time, building energy codes must also be updated with DC-specific information and requirements.[3]

[3] Certain new building components, such as batteries, may need to be addressed in building codes for fire and safety, permitting, and inspection issues as well. Codes for in-home battery storage systems are already under review in

- **Proof of concept**. Most studies of DC in homes have calculated potential energy savings. A few demonstration projects have been carried out, but better modeling and more field data, including side-by-side comparison of energy savings and user experience in equivalent AC vs. DC homes is critical to better assess the potential benefits.
- **Cost estimates**. How much does DC infrastructure (including power conversion equipment and wiring) cost? Under what circumstances is a given adoption path cost effective, and which are suitable in retrofits?
- **Quantification of non-energy benefits**. To build a complete picture of the value proposition for consumers, product manufacturers, and others throughout the value chain, it is necessary to quantify the many non-energy benefits such as resiliency, dematerialization, and improved product reliability.
- **Motors**. Although we estimate that DC motors have low penetration rates in residential appliances, little information is currently available on their actual market penetration. Furthermore, what is the end-to-end efficiency gain of a DC motor with DC distribution over its AC counterpart? What motor loads could cost-effectively be converted to DC?
- **Design and implementation best practices**. At this early stage, best practices for design and implementation do not yet exist. In addition to standards development, organizations like EMerge and IEEE can provide guidance and confidence through the DC transition by developing application-specific design guidelines that help put new standards, systems, and products into practice.
- **Economics and rate structures**. The economics of DC distribution in many adoption scenarios depend greatly upon a home's utility rate structure. Time-of-use considerations, utility solar feed-in tariff policies, and potential carbon pricing (through taxes or rate increases) are sensitivities that generally have not been explored in depth in DC distribution 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).

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