DC Appliances and DC Power Distribution

A Bridge to the Future Net Zero Energy Homes

Authors:

Vagelis Vossos, Stephen Pantano[1], Ruby Heard[2], Rich Brown

[1]CLASP

[2]ARUP

Lawrence Berkeley National Laboratory

September 2017

This work was supported by the California Energy Commission, Electric Program Investment Charge, under Agreement No. EPC-14-015 under Lawrence Berkeley National Laboratory Contract No. DE-AC02-05CH11231.

Disclaimer

Abstract

An increasing fraction of residential end-use loads operates on direct current (DC), allowing the direct use of DC from onsite DC sources (Photovoltaics, battery storage), thus avoiding the energy losses from converting DC power to alternating current (AC) and back to DC. Earlier research has shown that essentially all residential electricity end uses can be DC-compatible and are more efficient than their AC counterparts. Direct-DC power systems can provide energy and cost savings in the residential built environment (including net zero energy homes), in which electricity is generated, distributed, and consumed in DC. However, one of the main barriers to the adoption of DC distribution in buildings is the immaturity of the DC-ready appliance market.

We conduct a comprehensive market and cost assessment of the current DC-ready appliance market for the dominant residential end-use applications. We then examine the growing market for DC appliances in off-grid applications to extract relevant product and market trends that may influence grid-connected environments. We also analyze the energy efficiency potential of DC-ready appliances taking into account power supply losses and their coincidence of usage with DC generation from PV or battery storage. Based on these analyses, we offer recommendations on the next steps towards the development of a DC-ready appliance market.

Introduction

Electrical end uses and generation have dramatically changed since the days when the benefits of AC and DC were debated during the war of the currents. Although AC is the dominant power distribution technology, today's appliances and distributed electricity sources actually favor DC, with the proliferation of photovoltaics (PV), light emitting diode (LED) lighting, and consumer electronics, which all natively produce and consume DC in their internal components. Increasing demand for efficiency and energy storage, through the use of brushless permanent magnet DC motors (BLDC) and batteries, has tipped the scales further towards an end-use environment dominated by DC.

According to a 2011 study [1], converting all appliances to high efficiency, DC-internal[1] technologies, is not only technically feasible, but could save about 30% of residential electricity use. In addition, several studies have found that a "direct-DC" building distribution system with onsite PV and DC appliances could save energy by avoiding power conversion losses from DC to AC and back to DC, from as little as 2-3 percent savings to as much as 14 percent of the building's total electricity consumption. [2], [3]

Despite the potential energy benefits of direct-DC distribution systems in buildings, there are several important barriers to their development, one of which is the lack of a mature market for appliances that have a DC input and can readily operate on DC. A recent study, which solicited the input of DC power experts and stakeholders across various backgrounds through surveys and interviews, found that, among respondents, the lack of DC-ready appliances was ranked as the most important barrier inhibiting development of DC systems in buildings. [4]

This study analyzes the state of the market for DC-ready appliances in residential grid-connected and off-grid applications. We conduct a market, efficiency, and cost assessment of the current DC-ready appliance market for the main residential end-use applications, identify product and market trends, and outline a strategy to promote its development.

End Uses and DC Appliances

Electricity use in the United States (U.S.) residential sector accounts for about 45% of total residential energy use. [5] As shown in Table 1, the dominant residential electricity end-uses are space cooling and heating, lighting, refrigeration, water heating, and electronics, accounting for 60 percent of total residential electricity consumption.

---

[1] For the purposes of this document, we refer to 'DC-internal' appliances as appliances that operate internally on DC, or within the appliance's internal power distribution chain (e.g., an appliance driven by a BLDC motor with a variable speed drive), and to 'DC-ready' appliances as those that are DC-internal, but also include a DC power input.

Table 1. Estimated U.S. Residential Sector Electricity Consumption by End Use in 2016

End Use	Share of Total
Space cooling and heating	25%
Lighting	9%
Water heating	9%
Refrigeration (incl. freezers)	9%
Electronics (incl. computers)	8%
Others	40%
Total:	100%

Source: [6]

In this section, and for each of these end-uses, we first examine the current DC-ready appliance market. We then conduct an efficiency assessment of DC-ready appliances by (1) comparing their efficiencies to AC products of similar capacity and utility, and (2) considering the additional potential electricity savings when DC-ready appliances are powered by a direct-DC distribution system, taking into account (AC-to-DC) power supply losses and load coincidence with DC generation from PV or battery storage. We also conduct a cost assessment in which we review cost data where those are available, and discuss cost trends for DC-ready products in the foreseeable future.

Market Assessment

DC-ready appliances have served niche markets for decades, including telecommunications, off-grid residential, recreational vehicles (RV), marine applications, emergency shelters, and rail transport. In the past decade, DC products and DC distribution have also surfaced in grid-connected applications, such as data centers, lighting, and more recently with power over Ethernet (PoE) and universal serial bus (USB). Table 2 shows a selection of available DC-ready appliances for the main residential end-uses.

Table 2. DC-Ready Product Information by End-Use Application

End-Use	Manufacturer/ Distributor	DC Voltage	URL
Cooling & Heating: Ceiling Fans	Nextek	24	https://www.nextekpower.com/fanworks-catalog
	Phaesun	12	http://order.phaesun.com/index.php/loads-40891.html?cat=328
Cooling & Heating: Radiant Heating	Warmfloor	24	http://www.warmfloor.com
Cooling & Heating: Air Conditioners	Hotspot Energy	48	http://www.hotspotenergy.com
	GE Innovations	48	http://www.geinnovations.net
Lighting & Lighting Systems	Phocos	10.5-30	http://www.phocos.com
	Lumencache	12/24V PoE	http://lumencache.lighting/
	NuLEDs	12-36V PoE	http://www.nuleds.com/
	Colorbeam	48V PoE	http://www.colorbeamnorthamerica.com/
Refrigeration	Phocos	12/24	http://www.phocos.com
	GE Innovations	12/24	http://www.geinnovations.net
	Norcold	12	http://www.norcold.com
	Sundanzer	12/24	http://www.sundanzer.com
	Dometic	12/24	https://www.dometic.com
Electronics	Alphatronics	12	http://www.alphatronics.de
	TRU-Vu	12/24	http://www.tru-vumonitors.com/
	Niwa	12	http://www.niwasolar.com/Solar-TV/

Note: The information presented in Table 2 reflects a snapshot of the DC-ready products available in the current market; it is not intended to be an exhaustive catalog of DC product manufacturers.

In cooling and heating applications, we find that only a small number of DC ceiling fans and air conditioners are available[2]. These are equipped with highly efficient BLDC motors, and are typically marketed for off-grid applications. Warmfloor provides a radiant resistance heating system operating typically at 24V DC but also compatible with AC power. In lighting applications, there are a number of DC LED bulb manufacturers who target primarily the off-grid market, but in the past few years, with the emergence of PoE, an increasing number of companies are offering PoE lighting solutions for commercial and residential buildings. Table 2 lists a few of these companies. Regarding refrigeration, all listed manufacturers are drawn from the RV and off-grid market. DC-ready refrigerators and freezers in the market are therefore highly efficient but of relatively small capacity compared to refrigerators used in the grid-connected market. For the electronics market, although all existing products are DC-internal, the majority of larger electronic products includes an internal power supply that rectifies AC voltage to DC. Exceptions include small electronics with external AC-DC power adapters, such as cell phones (typically powered by USB), laptop computers (with a typical input voltage of 19V DC), a small number of computer monitors, and other small electronics. Table 2 shows product manufacturers for TVs (Alphatonics, Niwa) and display monitors (TRU-Vu). We note that there is currently no market for DC-ready water heaters, although such a technology is feasible with the use of air source heat pump water heaters driven by BLDC motors.

Efficiency Assessment

Efficiency Comparison

As discussed earlier, DC-internal (and DC-ready) appliances are generally more efficient than their AC counterparts. In this section, we compare efficiencies of DC-ready appliances to those with an AC-input (AC appliances). For DC-ready appliances, we use data from manufacturer literature found in our market surveys, as well as appliance test data collected for the Global Lighting and Energy Access Partnership (Global LEAP) awards program[3]. [7] For AC appliances, data sources include the California Energy Commission's Appliance Efficiency Database (CEC Database) [8], as well as data compiled from web sites of online retailers in the United States. Figures 1 through 5 show performance data for air conditioners, ceiling fans, LED lighting, refrigerators, and televisions.

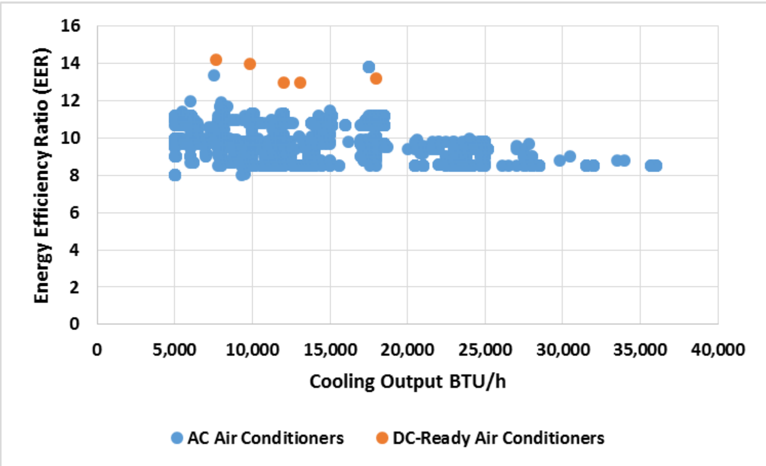

Figure 1. Efficiency Comparison of AC and DC-Ready Air Conditioners.

Note: Higher EER is more efficient. Sources: AC air conditioners: CEC Database; DC-ready air conditioners: Manufacturer literature

[2] Although there are essentially no DC-ready air conditioners marketed for the grid-connected market, several mini splits and heat pumps are now DC-internal.

[3] The Global LEAP program is the Clean Energy Ministerial's energy access initiative. Its programs and initiatives support the growth of sustainable commercial clean energy access markets throughout the developing world.

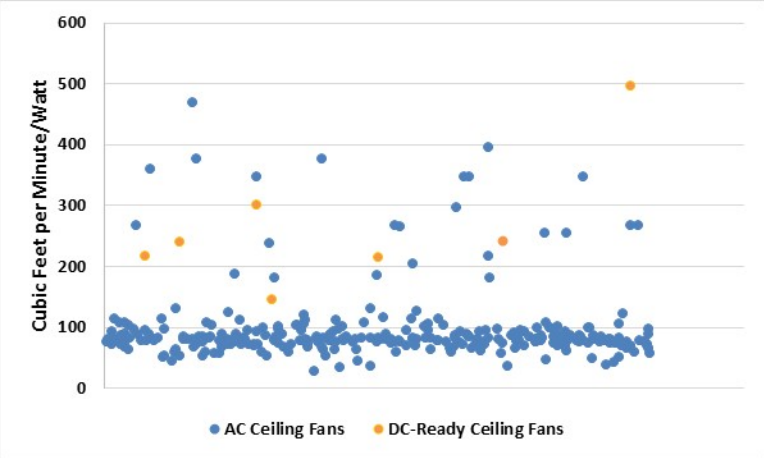

Figure 2. Efficiency Comparison of AC Ceiling Fans, AC Ceiling Fans with DC Motors (DC-Internal), and DC-Ready Ceiling Fans.

Sources: AC ceiling fans: EnergyStar data (2017); DC-ready ceiling fans: Manufacturer literature and Global LEAP data.

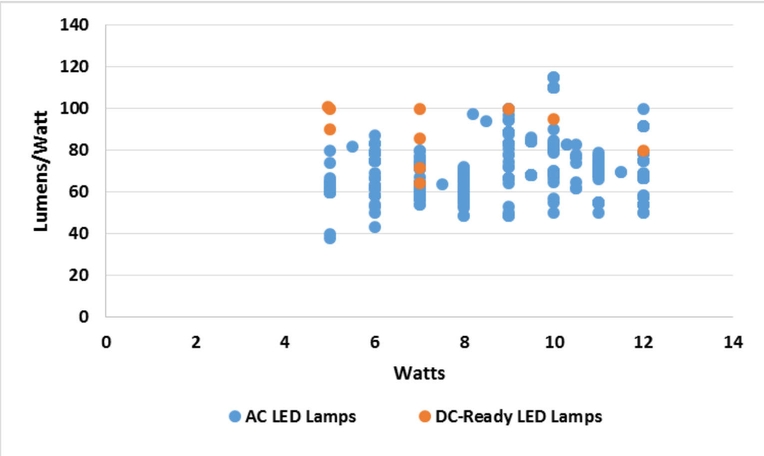

Figure 3. Efficacy Comparison for AC and DC-Ready LED Lamps

Sources: AC LEDs: CEC Database; DC-ready LEDs: Manufacturer literature and online retailers

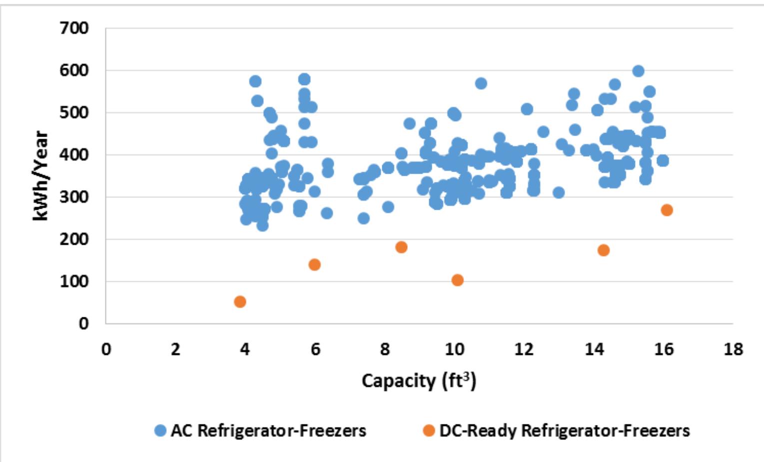

Figure 4. Energy Use Comparison for AC and DC-Ready Refrigerator-Freezers

Sources: AC refrigerator-freezers: CEC Database; DC-ready refrigerator freezers: Manufacturer literature

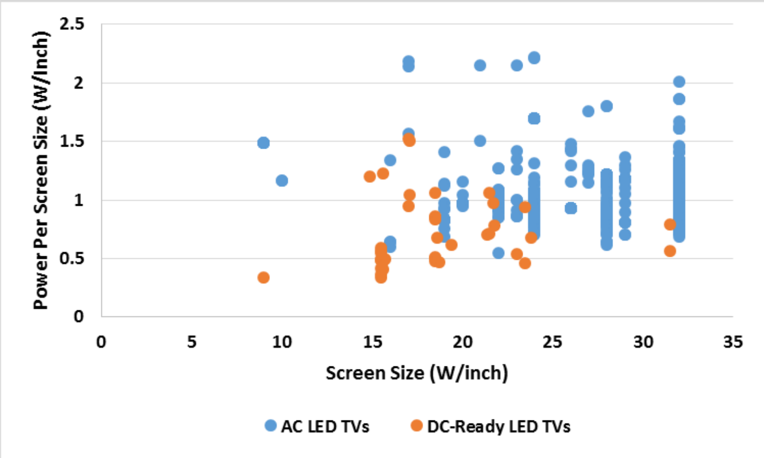

Figure 5. Performance Comparison for AC and DC-Ready LED TVs

Sources: AC TVs: CEC Database; DC-ready TVs: Global LEAP data

The efficiency comparisons shown in Figures 1 through 5 highlight that DC products are clearly more efficient than their AC counterparts. We also note that, where shown (ceiling fans, LED lamps, TVs), efficiencies of DC-internal appliances and DC-ready appliances are generally similar.[4] This means that DC-ready products in the market, other than, e.g., motor technology, share other efficiency design options with equivalent products marketed for grid-connected applications. This is evident in the comparison of ceiling fan performance, in which blade design is an important efficiency characteristic.

Potential for Energy Savings in Direct-DC Building Distribution Systems

As discussed earlier, DC-ready products offer potential for energy savings in a direct-DC building distribution system, where the end-use loads are powered directly from a DC source. Figure 6 shows a simplified schematic of a typical residential grid-connected AC distribution system with net metering, PV, and battery storage (AC building), and the equivalent direct-DC distribution system (DC building). In this schematic, loads for the AC building are assumed to be DC-internal, while loads for the DC building are assumed to be DC-ready (hence, the absence of AC/DC power supplies at the load level). Note that DC distribution is denoted in blue, while AC distribution is denoted in red.

[4] Although data from the Global LEAP are based on third party test data, performance data from manufacturer literature may not be as reliable, since DC-ready products for off-grid applications are generally not regulated or tested under the same test procedures as their grid-connected counterparts. For example, the energy efficiency ratios reported in solar air conditioner manufacturer websites vary between 13 and 21 EER. Such a variance (considering that the listed EERs correspond to the same motor technology) may be due to the test conditions or calculated EER assumptions. Also, the refrigerator-freezer energy use data shown in Figure 4 for DC-ready products may not be based on the same test procedure and reporting requirements as equivalent regulated products.

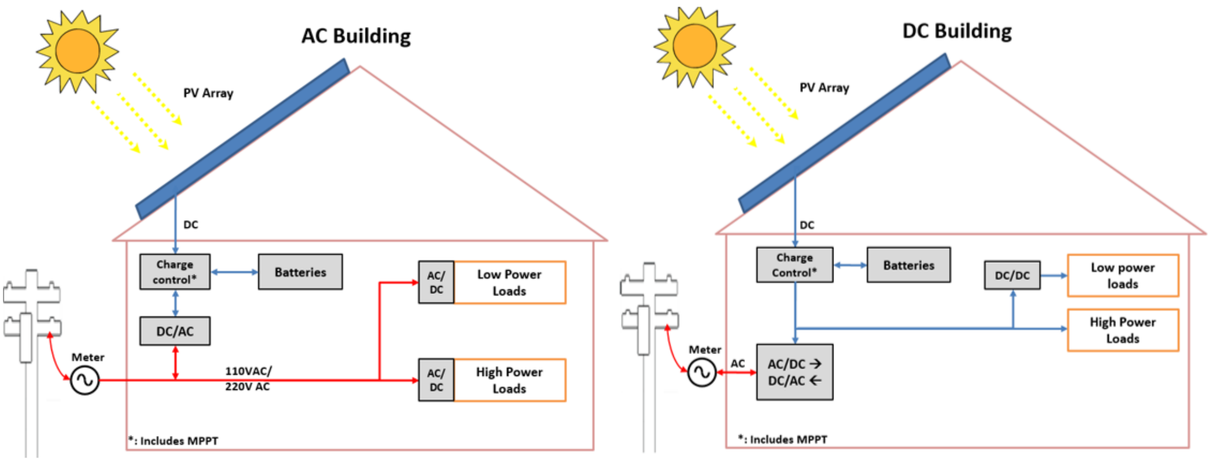

Figure 6. AC Residential Distribution System with PV, Net-Metering, and Battery Storage (AC Building) and Equivalent Direct-DC System (DC Building).

As illustrated in Figure 6, the potential for direct-DC electricity savings is increased when power is fed to the loads directly from the PV array or the batteries. To maximize savings, the timing of electricity consumption must be coincident with DC generation. Savings are also dependent on the relative efficiencies of the AC/DC power supplies for each load type, thus buildings with less efficient AC/DC power supplies will yield greater savings from switching to direct-DC distribution.

Figure 7 shows hourly load shapes for an average day in a simulated residential building in New York City for various end-uses, compared to PV generation.[5] Although actual daily load shapes have greater variability than smooth average load shapes, Figure 7 indicates that some end-uses, such as HVAC and electronics (included in interior equipment), have greater potential for coincidence with PV generation than others (e.g., lighting). Load shifting with smart appliances can also improve the relationship of PV output and load demand for certain end-uses, such as water heating.

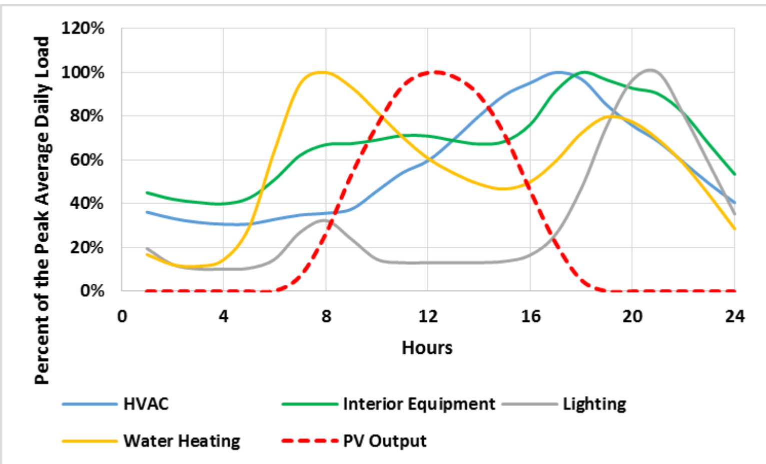

Figure 7. Average Residential Hourly Load Shapes Compared to PV Generation for a Simulated Residential Building New York City

Sources: Load shapes: EnergyPlus data retrieved from http://en.openei.org; PV output: Solar Advisor Model data retrieved from https://sam.nrel.gov

[5] The load shapes are shown for HVAC, water heating, lighting (interior and exterior), and interior equipment. The latter includes all other loads other than the first three (refrigeration, electronics, washing and drying, etc.). The load shapes for each end-use are presented as a percentage of the average end-use peak daily load.

We also review AC-DC power supply efficiencies for various input power ranges and voltages. Figure 8 includes external power supply efficiency curves for computers and servers with an 80PLUS certification.[6] As shown in Figure 8, input voltage and rated power affect power supply efficiency. Low power loads typically have lower power supply efficiencies compared to those rated at higher power.

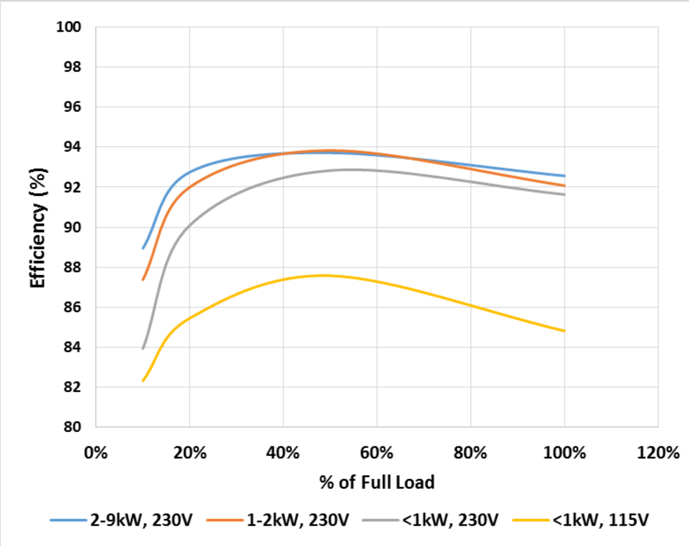

Figure 8. External Power Supply Efficiency Curves for Computers and Servers

Note: Curves in the chart are distinguished by power supply capacity, in kW, and voltage rating. Source: 80PLUS Database https://www.plugloadsolutions.com/80PlusPowerSupplies.aspx

Cost Assessment

As discussed earlier, the current market for DC appliances is limited. DC-ready appliances are most prevalent in off-grid residential, RV, marine, and industrial applications, which are small markets. The low demand for products results in a limited number of manufacturers and products, and higher costs.

In some cases, DC appliances are manufactured by relatively small organizations. These companies have less buying power than large mass-market AC appliance manufacturers and likely also have lower profit margins and smaller R&D budgets. Large mass-market AC appliance manufacturers on the other hand have well established manufacturing processes, can use common components across multiple product lines, and can build long term partnerships with suppliers of components. Larger manufacturers can also take advantage of economies of scale, reducing the costs of each component for large manufacturers, and therefore reducing product prices for consumers. In addition to low demand driving up DC appliance costs, some DC appliances (for example monitors from Tru-Vu) are designed for special applications such as harsh off-grid environments, defense or industrial facilities. This can mean that the components are especially robust (e.g., with enhanced sealing and protection against dust and water ingress or enhanced electromagnetic shielding, and associated higher certification costs) and higher quality than standard AC versions of the equipment, which also results in higher costs. This also skews comparisons of DC and AC equipment as the standard AC product may not be of comparable build quality.

These points are illustrated in Figure 9, which presents a price comparison between DC and AC LED lamps.[7] We notice that AC LED bulbs have a relatively constant price per lumen output ($/lm), while DC LED lamps have higher, but varying $/lm values, which perhaps reflect different pricing schemes, quality of components, and economies of scale. For LEDs specifically, economies of scale have a

[6] The 80 PLUS certification requires power supplies in computers and servers to have higher than 80% efficiency at 10%, 20%, 50%, and 100% of rated load with a true power factor of 0.9 or greater.

[7] The LED bulb data shown correspond to A-shape, medium screw base lamps between 400 and 1000 lumens.

greater impact on pricing, since LED lighting is a relatively new technology and LED prices have undergone dramatic price declines in recent years.

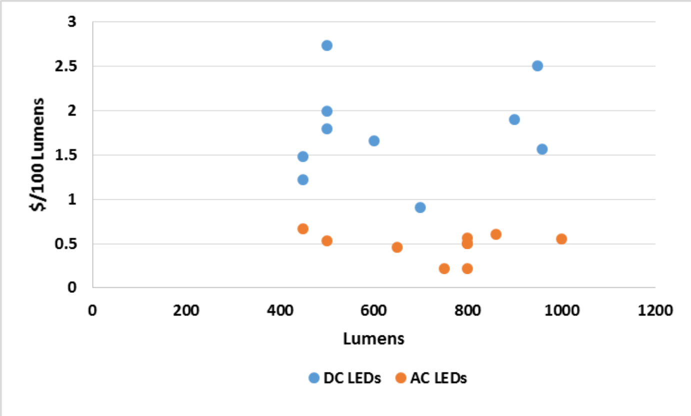

Figure 9. Price Comparison between DC LEDs and AC LEDs

Source: Online retailers

An additional factor that can affect prices (for LEDs, and other DC products), is the presence of DC-DC converters in some DC products. Because the cost of DC/DC converters is typically higher than the cost of bulk manufactured AC/DC converters used in DC-internal products, DC product manufacturers often have to choose between a DC-DC converter that sacrifices quality (and efficiency) to reduce costs, and a DC-DC converter of higher quality (and efficiency), at an increased price premium.

Can DC appliances become cost competitive?

While DC appliances are struggling to become cost competitive in today's market there are two reasons why this may change in the future.

Firstly, we know that demand is the biggest barrier to reducing manufacturing costs. We have seen this barrier overcome in many other hardware markets including small electronics and solar PV modules. With the increasing move towards zero net energy buildings there is space for buildings with substantial DC distribution buildings to become more attractive. There is the potential for the demand of DC equipment and appliances to increase with this trend.

The second driving factor is the expansion of distributed energy systems. The addition of solar PV and battery storage provides the opportunity to utilize the DC side of the system. Since the DC supply infrastructure must be included for the distributed energy system we could look at the AC system as the additional infrastructure cost, flipping the traditional system on its head in the future.

DC Appliances in the Developing World

Demand for DC appliances has historically been driven by the limited number of off-grid applications noted previously, where consumers seek to bring the comforts of home into remote environments where a DC battery and small PV array is the only available source of power. This market is served by an equally small number of appliance manufacturers that specialize in producing DC products for boats and RVs. In recent years this niche market for DC appliances has been eclipsed by rapidly growing demand in the developing world, where billions of consumers[8] are now gaining access to modern energy services. These services come not from the traditional power grid, but from dedicated off-grid energy systems such as "solar home system" (SHS) kits comprising typically a small solar panel, battery, charge controller, and a selection of lights and appliances.

[8] An estimated 1.2 billion people throughout the developing world live entirely without access to electricity; another billion have only unreliable access.

SHS are provided in countries like Bangladesh and Kenya through specialized firms that bundle together the solar and battery components with a selection of lights and appliances, and either sell or finance the complete system to the end user. In these nascent and often unregulated markets, there are a number of factors that play into the demand for appliances. These factors include:

1. Consumer price sensitivity: Both purchase costs and operating costs are important to consumers in developing countries. It has been found that "energy efficiency enables faster achievement of energy access goals by maximizing the energy service that can be achieved by any given energy access investment." [10] In the case of SHS, this means that energy efficient appliances deliver to consumers the same or greater energy service from a given size solar panel and battery. Since the panel and battery are the bulk (approximately 60%[9]) of the total system cost, efficient DC appliances can have a dramatic impact on the total cost of a SHS kit. Figure 10, below, illustrates this point.

2. Evolving consumer preference: As consumers gain access to reliable electric service while the cost of service decreases and technology improves, and as their economic conditions allow, they move into higher tiers of energy access (Figure 11) and naturally seek out new and more complex energy services. For example, a homeowner in a remote village may progress from a simple lighting system, to a larger system that can power lights plus a television and fan, to still larger systems that might power lights, televisions, fans, and also refrigeration. As more consumers move into these higher tiers, their expectations for product functionality and quality also evolve.

3. Product availability: Whereas tens of millions of the latest televisions and refrigerators are shipped to consumers in the developed world each year, very few global manufacturers have shown interest in developing DC appliances for off-grid markets to date. This means that many SHS providers are forced to work with OEMs to develop their own branded appliances for off-grid markets, often without the benefit of prior product development experience. For some sought-after appliances such as refrigerators, there are simply no suitable DC-powered products to be sourced.

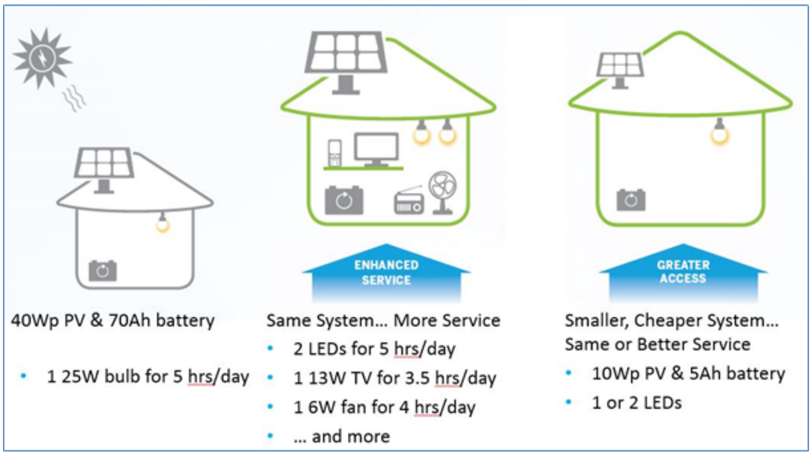

Figure 10. Illustration of the Means by Which Energy Efficient Appliances Can Deliver Enhanced Service and/or Greater Energy Access versus a Baseline Scenario

Source: Globalleap.org

[9] A study in Bangladesh determined that SHS batteries and solar panels account for at least 58% of the total cost that SHS consumers will absorb. [11]

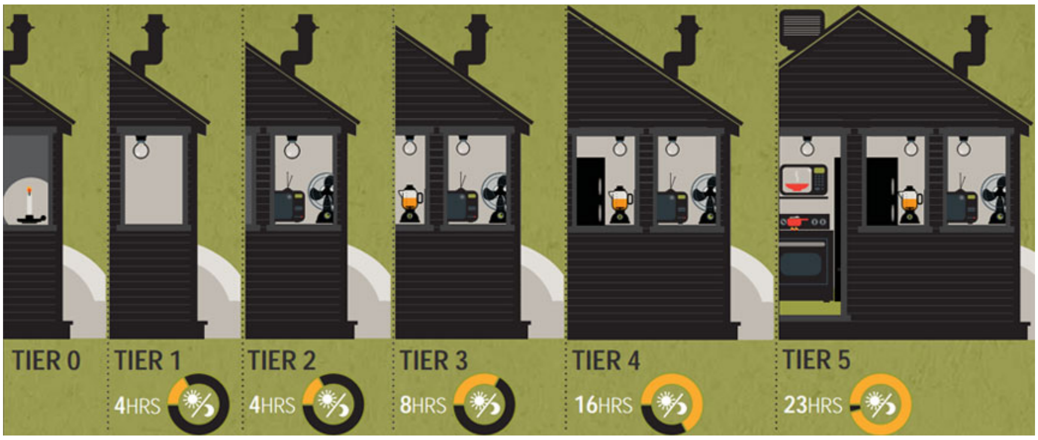

Figure 11. World Bank Tiers of Energy Access

Source: World Bank Group / Sustainable Energy for All via: http://www.se4all.org/content/webinar-multi-tier-framework-tracking-energy-access

Impact investors, aid agencies, and even some large appliance manufacturers are starting to take note of the tremendous potential that efficient, high quality DC appliances have to transform global energy access markets. Major international initiatives including the Global LEAP awards, the World Bank's Lighting Global program [12], and EnDev's Results Based Financing program [13] have realized the demand for efficient, high-quality, affordable DC appliances around the globe and have established awards programs, incentive schemes, and quality assurance frameworks meant to further the market in these directions. Given the scale of the overall off-grid market and the growing sophistication of manufacturers and consumers, we can expect further technological innovation in DC appliances that may soon find its way back to markets in the developed world.

Barriers and Recommendations

One factor hindering the availability of DC-ready products is the "chicken and egg" problem: manufacturers will not offer products if there is no consumer demand, but consumers cannot purchase products if they are not offered for sale. One option to break this impasse and promote greater availability of DC-ready appliances is bulk procurement programs that match large purchasers of appliances with potential vendors. These procurement programs allow purchasers to clearly spell out the performance and quality specifications for the products they would like to purchase, while reducing the risk to manufacturers by assuring a reasonable initial market for new DC-ready products they bring to market. A second option to manufacturers to develop dual-input (DC and AC) products that can operate off either power source. This would allow consumers to purchase long-lived appliances today to ensure DC compatibility in the future, even if the distribution infrastructure will not be in place for months or years.

Information about DC-ready appliances is widely scattered, and often requires calling manufacturers for detailed product specifications, or even purchasing sample units to test a product before determining if it is appropriate for a given application. This lack of easily accessible information increases the "soft cost" of purchasing DC products, because of the extra time involved for a purchaser to gather the available information and make purchase decisions with incomplete and inconsistent information. To reduce these soft costs, it would be helpful to develop a DC resource center with DC product databases, design guidelines for DC homes, and other information such as case studies of actual consumer experiences with DC appliances used in homes. In addition, the lack of awareness of alternative DC products is another factor that limits the size of the DC-ready product market. A marketing campaign to educate consumers about the potential benefits of DC-ready products would help overcome this barrier.

Another factor holding back the availability of DC-ready appliances is the lack of standard voltages and "plug" connectors (other than those for PoE and USB) for DC plug-in devices. This is analogous to the situation with cell phone chargers before USB became widely adopted as a standard. To address this situation, we need to develop key interoperability standards for voltages, connectors, and communication protocols for power control, in order to make DC a plug-n-play option in buildings. This is particularly needed for larger appliances and equipment that require voltages greater than 48 Volts DC. Standards should be international standards where possible, to allow broadening of the market for products to include the rapid penetration of off-grid DC solar systems in the developing world.

Finally, DC-ready products face another problem, which is the lack of DC power infrastructure in homes to provide suitable input power. Other than low-power USB hubs and battery chargers, most homes have no DC infrastructure. In the developing world, the solution to this problem has been the sale of complete solar kits that include the power source, a distribution and storage "hub," and the DC-ready end-use products. A possible solution to the lack of infrastructure in the developed world might be the development of an enhanced DC "power hub" for distribution and storage of power at the scale of a single room. The hub could take power from small-scale solar systems or the AC grid, and directly distribute it to DC loads such as consumer electronics, using standard connections like USB and PoE. This solution would work especially well in spaces such as home offices, entertainment centers, garages, and apartments.

Conclusions

Based on our review of markets for DC-ready products, our conclusion is that these products are mainly still only available in niche markets where DC power is generally available, such mobile and off-grid applications. There are technological and market developments, however, that indicate some opportunities for DC products:

- The accelerating adoption of rooftop PV systems, providing "native" DC supply in over 1 million U.S. homes (based on data from the Solar Energy Industries Association),
- Increasing interest in power reliability, especially after natural disasters like Superstorm Sandy;
- The widespread adoption of USB and PoE as power distribution standards; and
- The growth of the off-grid solar market in the developing world.

From an efficiency standpoint, we find that the available DC-ready products are generally more efficient than their AC counterparts. In some cases, such as air conditioners and ceiling fans, these efficiency improvements can be on the order of 20-30%. Savings are highest when DC appliances can be directly supplied from the on-site PV system, during daylight hours. Our analysis of residential load shapes suggests that HVAC and plug loads are probably the best candidate end-uses for maximizing energy savings from direct-DC power. With increasing penetration of energy storage systems in homes, we expect the reduced energy losses with DC power to be a major driver of the use of DC with on-site solar and storage systems.

Finally, we find that current prices for DC-ready products are noticeably higher than their equivalent AC counterparts. This is primarily a result of the niche status of DC products and their small production volume. We expect this price premium to decline in the future as production volumes increase and market distribution channels become more familiar with DC products. Eventually, the price for DC products could actually be less than AC, due to their decreased parts count and simpler design.

Acknowledgments

This work was supported by the California Energy Commission, Electric Program Investment Charge, under Agreement No. EPC-14-015.

References

[1] Garbesi, K., Vossos, V., and Shen, H., "Catalog of DC Appliances and Power Systems," Lawrence Berkeley National Laboratory, Berkeley, CA, LBNL-5364E, 2011.

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

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

[4] Vossos, V., K. Johnson, M. Kloss, M. Khattar, and R. Brown, “A Market Assessment for DC Distribution Systems in Buildings,” Lawrence Berkeley National Laboratory, Berkeley, CA, Mar. 2017.

[5] U.S. Energy Information Administration, “Annual Energy Outlook 2017. Table: Residential Sector Key Indicators and Consumption,” 2017. [Online]. Available: https://www.eia.gov/outlooks/aeo/data/browser/#/?id=4-AEO2017&cases=ref2017&sourcekey=0

[6] https://www.eia.gov/tools/faqs/faq.cfm?id=96&t=3

[7] http://globalleap.org.

[8] http://appliances.energy.ca.gov/quicksearch.aspx.

[9] Nordman, B., and K. Christensen, “The need for communications to enable DC power to be successful,” in *2015 IEEE First International Conference on DC Microgrids (ICDCM)*, 2015, pp. 108–112.

[10] World Bank, “EA+EE: Enhancing the World Bank’s Energy Access Investments through Energy Efficiency,” World Bank Group, Washington, D.C., Jan. 2015.

[11] Hoque, S. N., and B. K. Das, “Analysis of Cost, Energy and Emission of Solar Home Systems in Bangladesh,” *International Journal of Renewable Energy Research. IJRER*, vol. 3, no. 2, pp. 347–352, 2013.

[12] https://www.lightingglobal.org/

[13] http://endev.info/content/Technologies_Used [Accessed: 15-Mar-2017].