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FINAL PROJECT REPORT

Energy Research and Development Division

Efficient and Zero Net Energy-Ready Plug Loads

California Energy Commission

Gavin Newsom, Governor

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ACKNOWLEDGEMENTS

PREFACE

The California Energy Commission's Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solution, foster regional innovation and bring ideas from the lab to the marketplace. The California Energy Commission and the state's three largest investor-owned utilities – Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company – were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The Energy Commission is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- · Providing societal benefits.

- · Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.

- · Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.

- · Supporting low-emission vehicles and transportation.

- · Providing economic development.

- · Using ratepayer funds efficiently.

Efficient and Zero Net Energy-Ready Plug Loads is the final report for the Efficient and ZNE-Ready Plug Loads project (Contract Number EPC-15-024), conducted by Lawrence Berkeley National Laboratory. The information from this project contributes to Energy Research and Development Division's EPIC Program.

All figures and tables are the work of the author(s) for this project unless otherwise cited or credited.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

Plug loads are the devices plugged into common electrical outlets. Modern buildings contain hundreds of these devices which, together, are responsible for at least 25 percent of the energy use in California buildings. Energy consumed by plug loads is increasing because the "Internet of Things" is, to a great extent, the "Internet of Plug Loads." This project developed technologies that will reduce the energy use of plug loads. Two crosscutting strategies were investigated in detail: (1) technologies to reduce standby power use to near zero, and (2) methods to increase the use of direct current (DC) as a power source. Two new approaches to reduce standby to near zero were developed and have potential applicability to a wide range of devices. Prototype DC appliances were developed to demonstrate energy savings by bypassing power supplies and avoiding other losses. Networks of DC-powered devices can save even more energy and provide other benefits, such as resiliency during power outages. A unique category of energy-using devices was identified that provide life safety, health, and security to building occupants. Their installation or use is dictated by building codes, health providers, insurance companies, and other entities—none of whom would ordinarily prioritize energy efficiency. In the case of ground fault circuit interrupts (GFCIs), savings of 80 percent appear possible, simply by adopting the most efficient designs. Home medical equipment, particularly oxygen concentrators, are a rising category of energy use where significant savings are possible. This report also reviews the codes, standards, and other policies that affect energy use of plug loads.

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Introduction

Plug loads are generally defined as the devices that are connected to an alternating current (AC) power outlet using a cord and plug but excluding major end uses such as furnaces, clothes washers, and dryers. Modern buildings contain hundreds of plug loads, ranging from all sorts of electronic devices to coffeemakers to under-sink water heaters, and aquariums. The term "plug load" is unusual because it defines products by the way in which they are powered, rather than the device's function.

Regardless of the definition, plug loads consume a lot of energy; they are responsible for at least 25 percent of the energy use in California buildings. Figure ES-1 depicts the profiles for hourly electricity use of plug loads and the total electricity use observed in a California office building. In California, electricity demand attributed to plug loads is about 50,000 gigawatt-hours (GWh)/year, although estimates differ because definitions of plug loads vary. Unlike other end uses of energy, the energy consumed by plug loads appears to be increasing. The Internet of Things is, to a great extent, the "Internet of Plug Loads" in both residential and commercial buildings.

Figure ES-1: Hourly Electricity Use Profiles for Plug Loads and Total Electricity in a California Office Building
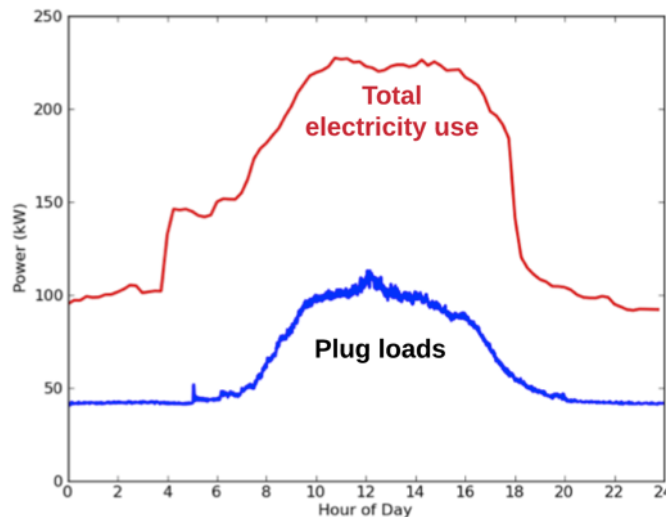
Source: LBNL

Project Purpose

This project aimed to advance technologies that will reduce plug load energy use in existing and ZNE buildings, including making the energy used by plug loads easier to supply from a zero net energy (ZNE) building's on-site renewable energy sources. Lower energy use by this category will reduce electricity use, carbon emissions, and consumer costs. When these products achieve very-low-energy use, consumers will be able to more economically tap renewable energy sources and achieve greater energy security.

Project Process

The methods employed in this project included paper studies, field measurements, laboratory tests, and technical innovation. Activity was undertaken in all areas. However, the diversity of plug loads means that, for some devices, only the first step was accomplished. In others, however, commercialization is already underway. Limited resources prevented a comprehensive approach; instead the project focused on devices where the research team felt significant innovations were possible or it had unique expertise. Deploying new technologies is as important as developing them in the first place. For that reason, this report also considers the codes, standards, and other policies that affect energy use of plug loads.

Project Results

The project was divided into major tasks, and the results for each task are summarized below.

Zero Standby Technologies

Standby power consumption is the electricity consumed by a device when switched off or not performing its principal function. It is responsible for about 3 to 16 percent of residential electricity use. The earlier reductions in the standby energy usage by single devices achieved through government regulations and voluntary initiatives have been offset by the growth in the number of devices having standby power use—the Internet of Things. This research sought methods to reduce standby power use to zero or nearly zero. For reference, saving 1 watt of continuous power corresponds to 8.8 kilowatt-hours (kWh)/year, or about $1.50 per device at typical California residential electricity rates.

The past works discussed in this report have proposed numerous standby solutions for many plug load devices, but burst mode, sleep transistors, optical wake-up, and wake-up radio appeared to be the most attractive. As shown in Figure ES-2, these solutions contribute to the growing portfolio of standby reduction technologies. Figure ES-2 also summarizes this project's key components related to reducing standby power.

Figure ES-2: A Portfolio of Standby Reduction Techniques and Solutions. The Labeled Solutions Are Discussed in This Report.

Source: LBNL

2
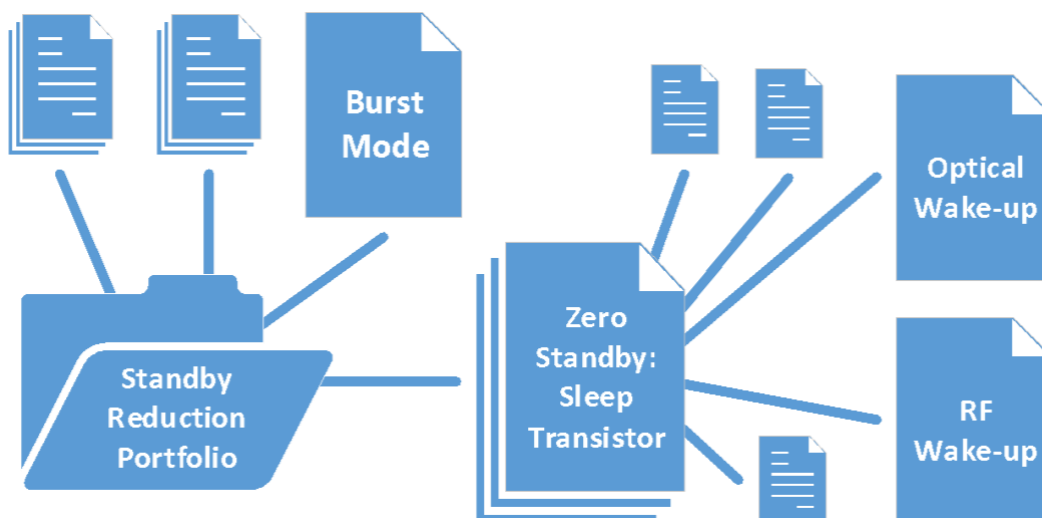
Each solution in this particular report makes use of a sleep transistor, which is a solid-state standby killer switch that can connect or disconnect the main device from its power supply. The first solution demonstrates the value of "burst mode" for lightly loaded power converters. Burst mode allows a lightly loaded power converter to operate at a higher efficiency point. A stand-alone controller was developed that could enhance any power converter with burst mode.

The second and third solutions employ optical energy harvesting to turn on line-of-sight remote-controlled devices such as TVs, set-top boxes, lights, and fans. One uses infrared light (IR) energy harvesting to wake the device. However, the prototype could not deliver sufficient activation energy because the IR beam was too diffuse. In the other solution, the receiver instead harvests visible light energy from a laser pointer and was able to activate a device at a range of 25 meters. However, its drawback is in the spatial accuracy required to hit a small target with the laser pointer.

The fourth solution uses an ultra-low-power "wake-up radio" to activate the device. The prototype's range is limited to 3 meters due to its use of low-frequency magnetically coupled wireless communication. Nonetheless, it demonstrates the principle of using a wake-up radio in conjunction with burst mode and a sleep transistor.

This work demonstrates zero or near-zero standby power as being technically feasible in several families of products. These solutions have both advantages and drawbacks and will require further technical improvements and reductions in cost before they can be commercialized and introduced into new devices. In addition, the portfolio of solutions will need to be broadened before standby power use can be confidently—and economically—eliminated. There is reason to be optimistic, however, since many of the technologies investigated here barely existed a decade ago.

Direct Current Power

This work categorized the types of loads whose efficiency directly benefits from a direct current (DC) input. DC-connected loads can be designed to connect directly to DC distribution, thus providing higher efficiency at lower cost. DC input can allow for a great reduction in the size of the DC capacitors, and will also improve power quality. Several types of loads were modified or prototyped as direct-DC, including an external power supply, bath fan, refrigerator, and task lamp. The intent of each design was to leverage DC input to improve the efficiency of the conversion.

In electronics, DC input can allow for the downsizing or elimination of wall adapters. The efficiency benefits generally favor DC, though the comparisons must be made with careful attention to the distribution voltage and conversion process. In motor loads, the most efficient type of brushless DC (BLDC) motor is designed such that its internal DC capacitor bus naturally operates at the DC input voltage. Although there is very little loss across a diode bridge rectifier, a power factor correction (PFC) boost rectifier is notably less efficient. In lighting, task lamps that connect to a universal serial bus (USB) power adapter with programmable power supply capability can use the adapter as the light-emitting diode (LED) driver. Zone lighting can benefit greatly from series remote drivers, but further research must validate their feasibility.

DC power distribution networks are becoming increasingly attractive because they provide energy savings and security during power outages, especially when attached to a battery and a dedicated photovoltaic (PV) panel. A prototype was constructed and tests were conducted to demonstrate proof of concept.

Safety, Security, and Health Devices (SSHDs)

This investigation identified a unique category of energy-using devices that provide life safety, health and security to buildings. Their installation or use is dictated by building codes, health providers, insurance companies, and other entities. None of these entities would ordinarily consider energy efficiency as a priority feature. While SSHDs are currently responsible for about 2 percent of total residential electricity use, they are a rapidly growing category and represent about 10 percent of a new home's electricity use.

Many SSHDs are "builder-installed loads"; loads installed by builders in new homes to comply with codes or meet customer expectations. Examples include ground fault circuit interrupters (GFCIs), arc fault circuit interrupters (AFCIs), hard-wired smoke alarms, continuous mechanical ventilation, and illuminated street numbers. Figure ES-3 depicts the rise in code-required safety devices in homes. Measurements of 13 new homes showed that builder-installed loads were responsible for an average 1,200 kWh/year—17 percent of an average California household's electricity use—before anybody had moved in. In-home medical equipment, such as oxygen concentrators—about 3,000 kWh/year per unit—have become major energy consumers in those homes using them. While SSHD energy use as a whole can be significant, most individual SSHDs consume little energy and therefore offer correspondingly small energy savings, even when reductions of 80 percent are technically feasible. The efficiency improvements may still pay for themselves in reduced operating costs, but even though the improvements will pay for themselves, consumers, contractors and others will not spend time or money implementing the changes because the payoff is so small.

Diverse strategies are needed to reduce future SSHD energy consumption. For GFCIs and mechanical ventilation systems, the best-on-market models consume less than half as much power as typical models. Efficiencies of medical equipment could be greatly improved through better compressors and controls. Battery-charging systems for a host of devices can also be made more efficient.

A strong case exists for improved efficiency of GFCIs, since efficiency does not appear to cost more. The average power use of a sample of U.S. GFCIs was 1.67 watts, while models available in Japan drew less than 0.20 watts, with one model drawing only 0.09 watts (or 5 percent of the average U.S. model).

Figure ES-3: Growth in Residential Life-Safety Devices Required by Building Codes
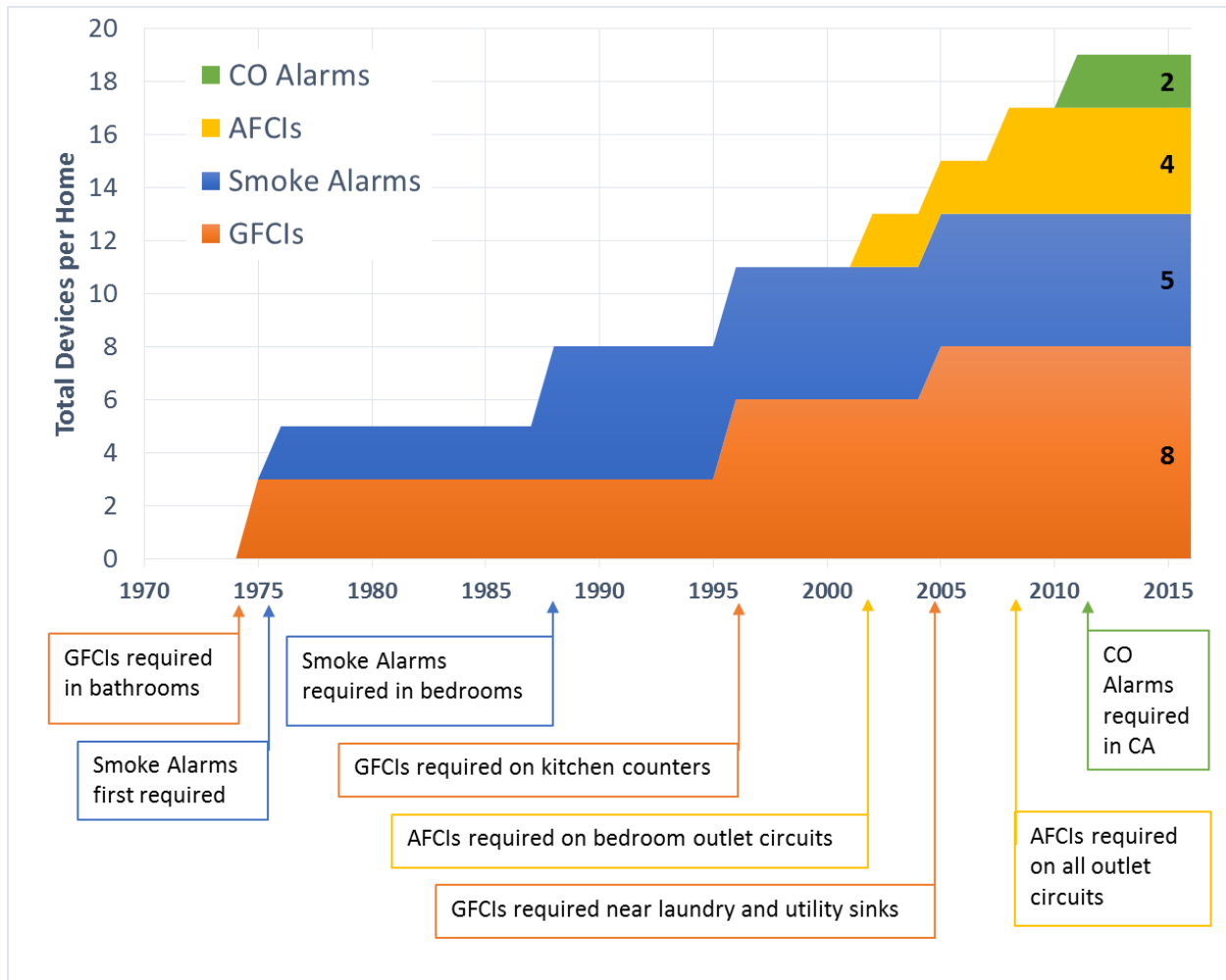
Current number of individual devices are shown on the right.

Source: LBNL

Wildfires in California caused power outages and several deaths when people were unable to drive out of their garages. For this reason, California recently enacted legislation requiring new garage doors to be equipped with backup batteries. The battery chargers add a few watts—continuously—to a home's electricity use, and they must be replaced periodically. This SSHD's energy use could be mostly offset if it is incorporated into a DC network, described above.

Test Methods

Test methods, codes, and standards do not yet capture the unique features of plug loads with zero or very-low standby power. Those unique features span energy consumption, behavior, materials, and health and safety. Establishing test methods and standards is especially challenging because most products have a small environmental footprint—drawing less than a few watts of power and consisting of only a few grams of materials—but the cumulative impact of billions of these small plug loads is enormous. This is the product space occupied by the Internet of Things.

For nearly all energy test methods, the boundaries of measurement need to be re-considered to reflect new behaviors of the technologies. The boundaries include upstream energy use, environment, and duration of measurement. In new, very-low-energy commercial buildings, the traditional hot water end use is disappearing and is being replaced by small, under-sink water heaters—new plug loads. Simulations for code compliance need to be revised to capture this trend.

All test methods and standards need to consider that more and more products will operate for long periods unconnected to the grid. This phenomenon extends beyond today's portable electronics to electric vehicles and vacuum cleaners. The testing dilemma is how to define (and measure) standby modes when "disconnected" may be a common configuration.

Higher-power DC products are appearing in the market, but energy test procedures have not been updated to reflect this market shift. The ultimate goal should be comparable treatment of AC and DC products.

Future zero-standby solutions may require manufacturers to comply with new health and safety requirements. For example, lasers might be used to enable energy harvesting. Similarly, life cycle assessments of materials associated with low-standby technologies need further investigation. Most studies of energy storage, for example, focus on much larger products.

Fortunately, none of these requirements appear insurmountable.

Health and life safety devices are presently exempt from most energy standards and codes. Our research suggests that energy consumption for these products is growing.

Recommended Future Work

This project covered several, distinct research areas so the recommended future work is necessarily diverse. No single technology will eliminate standby power use but several technologies appear promising for specific applications, including the wake-up radio, burst mode, and energy harvesting and storage combinations. In the long run, coordinated improvements in efficiency, energy harvesting, and energy storage will be the best strategy to achieving zero standby power use. Rather than focusing on the products themselves, DC power research should focus on robust integration of products, such as improving DC network power management and developing DC networks of high-priority communications and safety devices, possibly supported by storage and dedicated PV.

For devices providing safety, security, and health, future work should focus on moving the market to the most efficient products already available on the market. In some cases, such as for GFCIs, this alone can achieve almost 80 percent savings. For smoke and carbon monoxide alarms, research should be undertaken to obviate the need for a power supply. This might be accomplished through a "10-year" battery, possibly combined with energy harvesting. This solution will require changing building codes, but might reduce overall costs if wiring costs can be eliminated. Some safety devices, notably garage door openers, may benefit from connection to a new DC network. These networks offer important other benefits, such as resiliency to power outages and reduced environmental burdens caused by battery replacements.

A sustained research effort will be needed to improve the energy efficiency of devices where health or safety considerations prevent innovations. This research needs to be carefully linked to the health and safety communities to understand the service needs, identify technical solutions, and field-test prototypes. The first two targets should be oxygen concentrators and mechanical ventilation systems.

Benefits to California

When the technologies outlined in this project are adopted, it is estimated that California will reduce its electricity use by about 6,000 GWh/year, and will save ratepayers about $1.2 billion/year. In addition, electrical demand will be reduced by 690 megawatts (MW), and greenhouse gas emissions will be reduced by 1,900 million tons of carbon dioxide equivalent each year.

This report also outlines future research and actions that could lead to even further energy savings, increased energy security, and life safety.

CHAPTER 1:
Background and Introduction

1. Background: What Are Plug Loads and Why Are They Important?

Plug loads are generally defined as the devices plugged into 120 volt alternating current (AC) power outlets. These products are mostly electronics and miscellaneous devices. There are hundreds of plug loads in modern buildings. Some plug loads in homes are TVs, printers, cordless phones, coffeemakers, vacuum cleaners, and aquariums. In commercial buildings, some plug loads are computers, copiers, Ethernet switches, and under-sink water heaters. The term "plug load" is unusual because it defines products by the way in which they are powered, rather than by the device's function. Researchers and policymakers apply other names to this group of electricity-using products. The most common term is "miscellaneous electrical loads" or "MELs," but it also is referred to simply as "other uses." Statisticians have sometimes even called it "residual" energy use, reflecting consumption remaining after accounting for space heating, cooling, water heating, and other recognized end uses.

Regardless of the name applied to them, plug loads represent a significant category of energy consumption. They are responsible for at least 25 percent of energy use in U.S. buildings (U.S. Department of Energy 2015) and an even larger fraction in California buildings. In California, electricity demand attributed to plug loads is about 50,000 gigawatt-hours (GWh)/year (EPIC 2015), although estimates differ because definitions of plug loads vary. Unlike other end uses of energy, the energy consumed by plug loads appears to be increasing. The Internet of Things (IoT) is, to a great extent, the "Internet of Plug Loads" in both residential and commercial buildings.

The enormous contribution of plug loads to California's building energy use was highlighted in two recent studies. In a detailed analysis of an existing office building (Lanzisera et al. 2013), plug loads were responsible for 40 percent of the building's electricity use (Figure ES-1).

A second study (Borgeson 2013) of hourly electricity consumption of 25,000 Northern California homes showed that the continuous electricity use—caused mostly by plug loads— was responsible for more than 40 percent of total electricity use in about half of the homes (Figure 1).

Plug loads are also changing in response to demographic and environmental trends. Two examples explored in this report highlight these linkages. The aging population (along with health-care policies) have pushed numerous medical services—and equipment—into homes. As a result, home oxygen concentrators have become a significant plug load. The tragic wildfires in California caused power outages and, in a few cases, caused deaths because people in affected areas were unable to open their garage doors. As a result, recent California legislation requires new garage doors to be equipped with batteries to supply back-up power. These back-up systems are a new plug load.

Figure 1: Fraction of Annual Energy Use Occurring as Constant Load
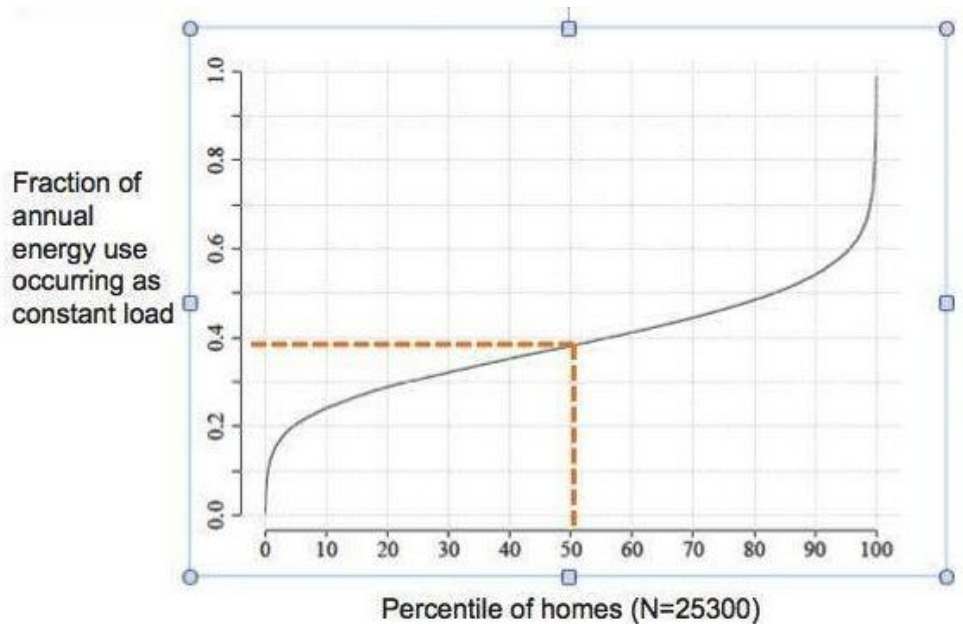
Source: Borgeson 2013

A characteristic of many plug loads is their continuous use of electricity, even while not providing their principal service or function. This is called "standby power use." Many electronic devices have standby power use, if only because they have power supplies that convert AC into direct current (DC). Standby power use in most modern electronic devices is generally small—less than 2 watts (W)—but is nevertheless significant because this consumption occurs 8,760 hours per year and because there are so many old, high-standby electronic devices in buildings today. For that reason reducing standby power continues to be a goal of energy efficiency strategies.

Meanwhile, California has mandated ambitious reductions in energy use and climate-related emissions, including requirements for future buildings to consume almost zero net energy (California Air Resources Board 2014). Meeting these climate and energy targets will require large reductions in all end uses of energy, but especially in plug loads. California cannot achieve these twin goals without a dramatic reduction in plug load energy use.

A host of diverse factors will influence the extent and speed at which the market adopts energy-saving plug loads. The financial payback for reducing plug loads is challenging because of the small dollar savings resulting from an individual device's saved energy. Saving 1 W continuously over one year corresponds to less than 10 kilowatt-hours (kWh), or about $1.50. Many consumers will reject these opportunities because they are unaware of them, or they are not worth the effort. Manufacturers will be reluctant to make improvements because of uncertainty that consumers will pay any premium for higher efficiency. But when a household has more than 100 plug loads (and a commercial building has thousands), the collective savings become important to the occupant and to society. Therefore, an important goal is to find compelling reasons for consumers to choose devices that offer new features that just happen to include greatly reduced energy consumption.

2. Project Objective: A Multi-Pronged Strategy to Reduce

Energy Used by Plug Loads

The aim of this project was to develop technologies that will reduce the energy use of new plug loads. Lower energy use by this category will reduce electricity use, carbon emissions, and consumer costs. When these products achieve very-low-energy use, consumers will be able to more economically tap renewable energy sources and achieve greater energy security from energy interruptions.

No single technology will reduce energy use in new plug loads because they are so diverse. Nevertheless, some technical solutions can be applied to families of products. One theme of this research project was "powering" plug loads differently so as to reduce energy use. Powering differently refers to shifting away from total reliance on electricity from the 120 V outlets through combinations of DC power, energy harvesting, enhanced device control and, of course increased efficiency. But many plug loads have unique requirements—such as medical and life safety devices—and so must be examined individually.

The approach adopted in this project was therefore multi-pronged and consisted of three steps:

1. Identify plug loads and evaluate current technologies
2. Develop low-energy technologies
3. Commercialize solutions

Activity was undertaken in all steps. However, the diversity of plug loads means that, for some devices, only the first step was accomplished. In others, however, commercialization is already underway. Limited resources prevented a comprehensive approach; instead the project focused on areas where the research team felt significant innovations were possible or it had unique expertise.

Deploying new technologies is as important as developing them in the first place. For that reason, this report also considers the codes, standards, and other policies that affect energy use of plug loads.

3. Organization of this Report

This report describes research and findings on technologies to reduce energy use of plug loads. Chapter 2 focuses on methods to reduce standby power use of new devices. Solutions to this problem will apply to hundreds of different products in residential and commercial buildings. Chapter 3 explores methods of powering plug loads with DC (rather than AC) and applies those methods to actual devices. Chapter 4 addresses plug loads that provide safety, health, and security services in buildings. Here, too, the products are diverse, but they share many performance and institutional characteristics. Chapter 5 reviews codes and standards applicable to plug loads. Several smaller investigations and updates are summarized in Chapter 6. The project's overall benefits are described in Chapter 7, and the ways in which the findings have been transferred to Californians are covered in Chapter 8. Finally, Chapter 9 offers some conclusions and, importantly, recommendations for future research and activities related to energy use of plug loads.

CHAPTER 2:
Zero Standby Technology Power Supplies and Devices

1. Introduction

Background and Motivation

Standby power consumption by appliances, electrical devices, and other products continues to represent 3 to 16 percent of residential energy use, although that varies by country (IEA 2001; Urban, Tiefenbeck, and Roth 2011; Delforge, Schmidt, and Schmidt 2015; T. K. Lu, Yeh, and Chang 2011; De Almeida et al. 2011; Clement, Pardon, and Driesen 2007). Considerable progress in reducing standby consumption in specific products has been achieved through a variety of policies and technologies. For example, technical advances in mobile phone chargers, the "poster child" of standby consumption, have enabled reductions in standby power from more than 2 W in the year 2000 to below 0.3 W today. Most new low-voltage power supplies have standby power consumptions below 0.5 W, reflecting minimum energy efficiency standards in Europe, California, and elsewhere (IEA 2014).

However, the last 20 years has seen an explosion in the number of devices that rely on power supplies and continuous power consumption. The growth can be attributed to the proliferation of devices that operate entirely on DC power, traditional AC-powered devices that now have electronics, and mobile devices with batteries. Many of these devices fall into the miscellaneous electrical loads (MELs) category, which continues to grow rapidly in terms of both population and energy use (Comstock and Jarzomski 2012). At the same time, many more devices require higher functionality in order to sustain communications. These devices fall into the broad category of the "Internet of Things."

With the increasing number and diversity of electronic products with standby modes, the need to reduce standby power therefore continues to be an important policy and technical challenge. However, as technologies mature, there is a declining potential savings per device, coupled with an increasing number and diversity of electronic products with standby modes. This means that the costs of "saving the last watt" must be extraordinarily low to be cost-justified. For reference, saving 1 W of continuous power corresponds to only 8.8 kWh/year, or about $1.50 at typical California residential electricity rates.

This work describes several approaches to further reductions in standby power consumption of new plug loads, some of which completely eliminate standby. The tremendous diversity of products with standby consumption means that no single solution is likely to emerge. Instead, a portfolio of widely applicable solutions presents the best path forward, and this work contributes to the portfolio.

General Approach

The energy consumption behavior of a device can be represented as a histogram of the time it spends in each power mode. As shown in Figure 2, most modern devices have a continuous low-power standby consumption, with brief intermittent periods of high-power operation. They may utilize other intermediate power modes that, if relatively low, may be lumped into the

standby category. The area under the curve corresponds to the device's annual energy consumption. The solutions described in this report target the long periods of very-low-power use and, ultimately, the other low-power modes. The goal is to reduce the power and duration of those modes, in a savings strategy referred to as "shrinking the staircase," which is also illustrated in Figure 2.

Figure 2: Shrinking the Staircase
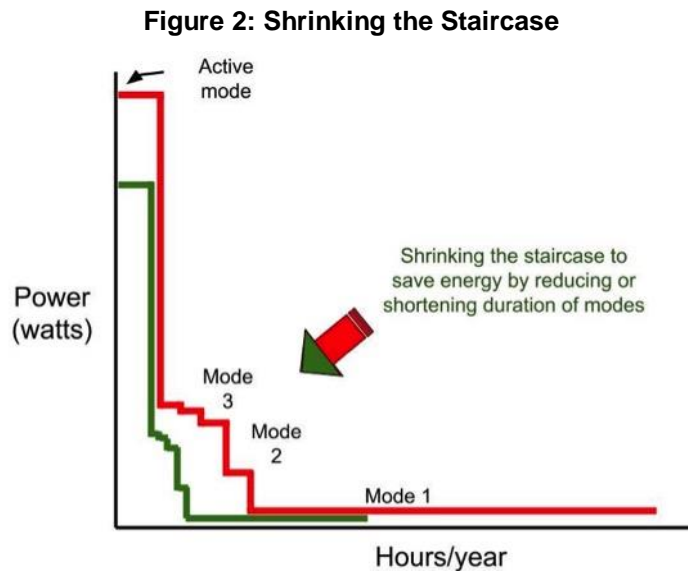
An example of the distribution of an electrical device's power modes with respect to time. The red "staircase" represents the initial modes, and the green staircase represents the impact of numerous energy-saving modifications.

Credit: Alan Meier

There are several technical strategies for "shrinking the staircase," that is, reducing standby energy consumption. First is increasing the device's efficiency at various modes, which lowers overall power consumption. Another technique involves augmenting the device to harvest and store ambient energy, which can be utilized during low-power operation. Finally, modifications in operational design and internal circuitry can remove consumption at various low-power modes altogether, depending on the application. This paper focuses on the latter technique, and describes several methods for removing standby consumption.

The strategies applied to a power supply are generalized and illustrated in Figure 3. In certain applications of these strategies, the device will be able to operate for periods of time without any grid-supplied power (Ellis, Siderius, and Lane 2015). The no-grid power time has been termed the "standzero" time (Meier and Siderius 2017). Many mobile devices already have long standzero times, and the solutions described in this paper illustrate standzero strategies in various other types of devices.

Figure 3: Generalized Power Supply
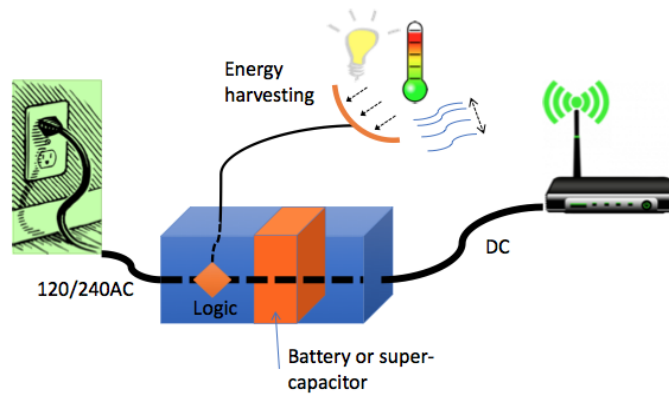
A generalized power supply that leverages energy harvesting, storage, and/or other mechanisms to reduce standby power consumption

Credit: Alan Meier

Portfolio of Standby Solutions

The wide diversity of electronics featuring standby mode mandates development of a portfolio of solutions. Past works have proposed numerous standby solutions for many applications. Of these solutions, the most relevant to this paper are burst mode (Lo, Yen, and Lin 2008; Lee et al. 2013; B.-C. Kim, Park, and Moon 2011; Huh et al. 2004), sleep transistors (Jiang, Marek-Sadowska, and Nassif 2005; Shi and Howard 2006; Long and He 2004; Fallah and Pedram 2005; Fukuoka et al. 2013, 2012; Chao and Harrison 2008), optical wake-up (Kang et al. 2011; Yamawaki and Serikawa 2015a, 2015b), and wake-up radio (Demirkol, Ersoy, and Onur 2009; Magno et al. 2014; Umeda and Otaka 2007; Gamm et al. 2010; Oller et al. 2013). As shown in Figure 4, these solutions contribute to the growing standby reduction portfolio.

Figure 4: Standby Reduction Portfolio
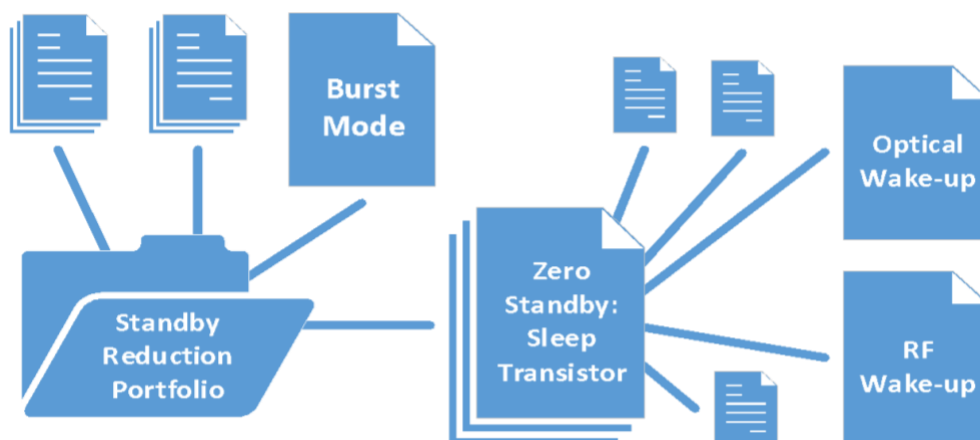
A portfolio of standby reduction techniques and solutions. The labeled solutions are discussed in this report.

Credit: Daniel Gerber

Organization

This work focuses on describing the evaluation of several different standby reduction technologies through analysis and prototypes. Section 2 of this chapter describes burst mode for power converters and experimentally demonstrates the savings potential. Section 3 explains the operation of sleep transistors such as the footer, header, and cascoded (stacked transistor) header switch. Finally, in Sections 4 and 5 these techniques are used to prototype zero-standby solutions with optical-and radio-frequency (RF)-based wake up signals, respectively.

2. Burst Mode

Description

Burst mode is a control method for switching power converters that was developed in the early 2000s to address standby consumption (Lo, Yen, and Lin 2008; Lee et al. 2013; B.-C. Kim, Park, and Moon 2011; Huh, Kim, and others 2004). Lightly loaded power converters are generally inefficient because of losses in switching and control that are constant regardless of the output power. Burst mode allows a converter to temporarily shut down and power the load from its output supply capacitor. However, the converter must periodically turn on to recharge the capacitor.

As shown in Figure 5, burst mode can be implemented with a supply capacitor and special burst mode logic. Ideally, the power converter has an enable pin that allows the burst controller to shut down the converter.

Figure 5: External Burst Mode Controller
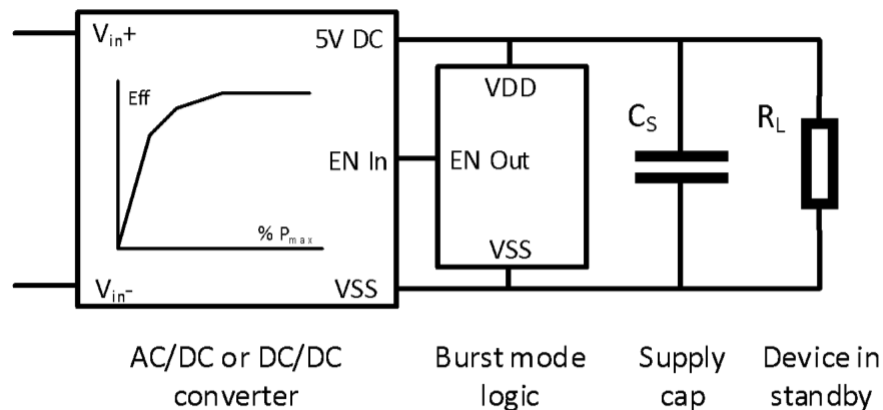
Burst mode requires a supply capacitor and its necessary recharge logic. Converters that do not already have burst mode can still be used in burst mode if they have an enable (EN In) pin.

Credit: Daniel Gerber

As shown in Figure 6, a simple burst controller can be implemented with two resistors, two voltage references (band gap or low-dropout), two comparators, and a set-reset (SR) latch. These components all can be easily integrated into the power converter's controller. The resistor divider scales the voltage on the supply capacitor, which is then compared to a high and low reference. If the scaled voltage falls below the low reference, the latch is set, and the converter

is enabled. Once the scaled voltage rises above the high reference, the latch is reset, and the converter is disabled.

Figure 6: Simple Burst Mode Logic
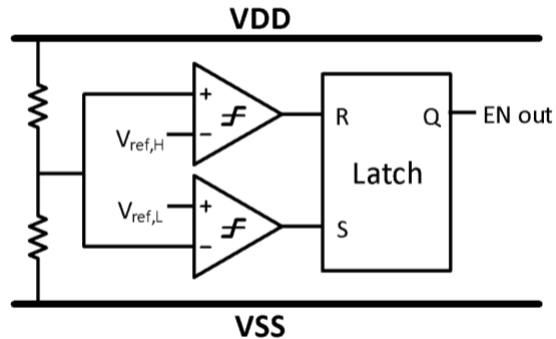
One of the simplest types of burst mode logic. The resistor divider scales the supply capacitor voltage, which is compared to high and low references. The reference voltages can be generated by nano-watt band gap references or low dropout regulators. The comparators drive an SR latch, which determines if the converter is enabled.

Credit: Daniel Gerber

Converters generally perform poorly at low power, as indicated by the efficiency curve embedded in Figure 5. Instead of constantly operating at a low point on the curve, burst mode allows the converter to operate at a high point for a short period of time. Burst mode completely shuts down the converter, allowing for savings on the switching and controller losses within the converter.

Burst mode's most notable drawback is that the output voltage will ripple between the two voltage thresholds, depending on the burst logic and the size of the output capacitor. Nonetheless, many electronics can tolerate a small voltage ripple, particularly in standby mode. In some cases, the ripple introduces audio-frequency noise, which can be problematic in certain analog applications. Another minor drawback is in the resistive losses from charging and discharging the supply capacitor, which is usually minor compared to the potential savings.

Experiment and Results

Burst mode prototypes were created following the schematics in Figure 5 and Figure 6 and verified by the oscilloscope traces in Figure 7. The burst period in these experiments ranged from 0.25 to 2.25 seconds depending on the load. Nonetheless, 0.25 seconds is considerably longer than most products with burst mode, many of which have smaller output supply capacitors. These prototypes experimented with adding burst mode functionality for two DC/DC converters: the 2 W Delta PG02S2405A and the 25 W Murata OKX-T/5-D12N-C. These converters do not inherently have burst mode, but they each have an enable (EN) pin and a 5 V output. The burst mode controller is comprised of a TPS78001DDCR LDO reference, MCP6542 comparator, CD4043BE latch (output requires inversion), and two 10 millifarad (mF) 10 V electrolytic supply capacitors. These components all have an ultra-low quiescent current of 500 nanoamperes (nA), 600 nA, and 100 nA, respectively. Finally, the LDO outputs and resistor divider were stabilized with 33 nanofarad (nF) and 3.3 nF capacitors, respectively.

The experiment compared burst mode and normal operation for each converter. It simulated standby consumption by loading the converter with 470 ohms (Ω), 4.7 kilo-ohms (kΩ), and 47 kΩ resistors (R_L). The output power was measured in normal operation, and estimated in burst mode. The burst mode estimate solved for the average power based on the burst period T, and the high and low voltages V_1 and V_2, respectively:

$$P_{avg} = \frac{1}{R_L T} \int_0^T \left(V_1 e^{-t/\tau}\right)^2 dt$$
$$\tau = \frac{T}{\ln(V_1) - \ln(V_2)} \, .$$

As shown by the results in tables 1–4, burst mode can save a considerable amount of energy for light loads. The unloaded average power consumption of the PG02S2405A and OKX-T/5-D12N-C is 89 milliwatts (mW) and 471 mW, respectively. The burst mode's savings are primarily a result of eliminating the unloaded input power. These savings become less significant with heavier loads (smaller load resistance).

This work makes several recommendations for industry to consider. First, more converters should be designed with a burst mode capability. In particular, application-specific wall adapters should always consider burst mode, depending on the tolerable voltage ripple for the application in standby mode. Second, packaged converters without burst mode should contain an enable pin so that burst mode can be added as the application allows. Finally, a separate burst mode logic chip should be designed for such converters.

Figure 7: Burst Mode Waveforms
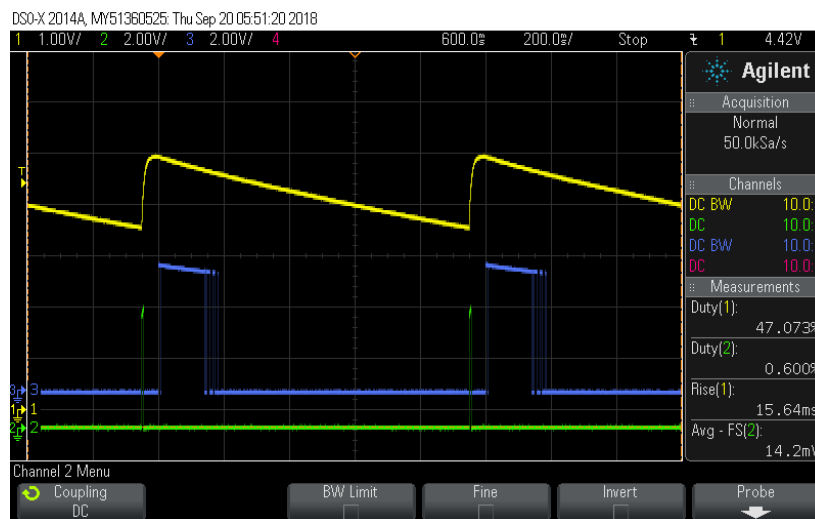
(a)
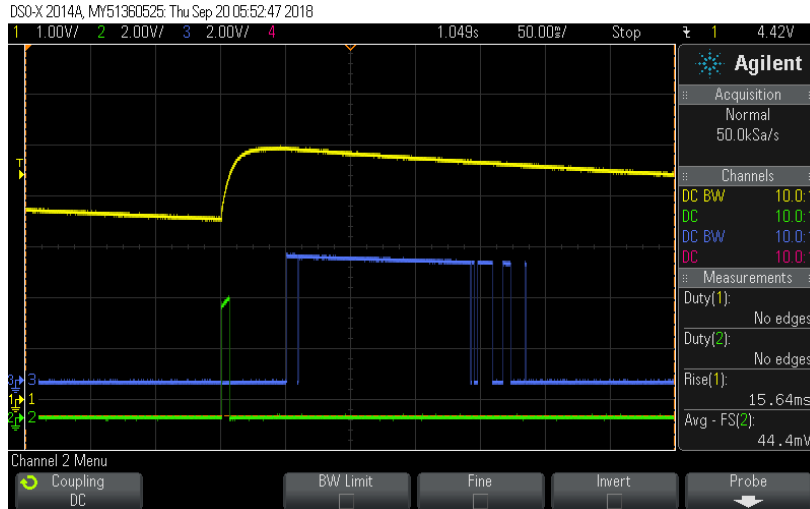
(b)

Oscilloscope waveforms with the supply capacitor voltage (yellow), low threshold comparator output (green), and high threshold comparator output (blue). These waveforms are from the PG02S2405A, loaded with a 4.7 kΩ resistor.

Credit: Daniel Gerber

Table 1: PG02S2405A Normal Operation

Load Resistance (Ω)	Average Input Power (mW)	Average Output Power (mW)	Efficiency (%)
470	153.5	52.1	34.0
4,700	95.4	5.2	5.5
47,000	90.7	0.5	0.6

Table 2: PG02S2405A Burst Mode

Load Resistance (Ω)	Average Input Power (mW)	Output Power Estimate (mW)	Efficiency (%)
470	80.3	36.4	45.3
4,700	14.9	3.9	26.0
47,000	8.5	0.4	4.6

18

Table 3: OKX-T/5-D12N-C Normal Operation

Load Resistance (Ω)	Average Input Power (mW)	Average Output Power (mW)	Efficiency (%)
470	528.0	52.7	10.0
4,700	476.1	5.3	1.1
47,000	473.6	0.5	0.1

Table 4: OKX-T/5-D12N-C Burst Mode

Load Resistance (Ω)	Average Input Power (mW)	Output Power Estimate (mW)	Efficiency (%)
470	177.5	36.8	20.7
4,700	44.2	3.8	8.6
47,000	29.5	0.4	1.3

3. Sleep Transistors

General Background

A sleep transistor is a type of solid-state power switch that can electrically disconnect the main device or module from its power rails. Solid-state switches are preferable over mechanical relays in low-power electronics since they do not corrode and have a considerably faster switching speed. Sleep transistors have traditionally been used for selectively deactivating modules in digital integrated circuits (ICs) (Jiang, Marek-Sadowska, and Nassif 2005; Shi and Howard 2006; Long and He 2004; Fallah and Pedram 2005). In particular, low-voltage digital ICs greatly benefit from sleep transistors due to the excessive sub-threshold leakage present in low-voltage transistors. Sleep transistors with high gate thresholds have been applied in these modules to block that leakage current.

There are two main sleep transistor configurations: the footer switch and the header switch. It is important to note that the footer and header switches only work with a DC supply. Future work may extend these solid-state solutions to AC through the use of triacs.

Either configuration also can be cascoded (stacked transistors) to allow for a greater blocking voltage. Sleep transistors can have drawbacks such as on-state resistance and leakage current, but these drawbacks can usually be mitigated by proper MOSFET (metal-oxide semiconductor field-effect transistor) selection.

Footer Switch

The footer switch, shown in Figure 8 and Figure 9, is an N-type MOSFET that connects the ground of the main device to the ground of the power supply. Due in part to their simplicity and reliability, footer switches have become a recent favorite in standby reduction techniques (Fukuoka et al. 2013, 2012).

Figure 8: The Footer Switch
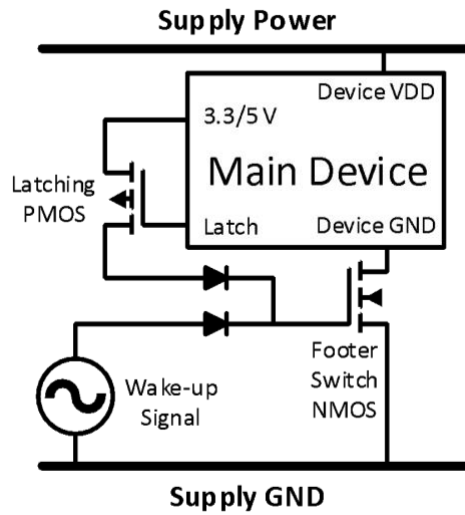
A footer switch connects the device ground to the supply ground. A wake-up signal is required to drive the gate of the footer switch.

Credit: Daniel Gerber

Figure 9: Operation of a Footer Switch

(a)   (b)   (c)
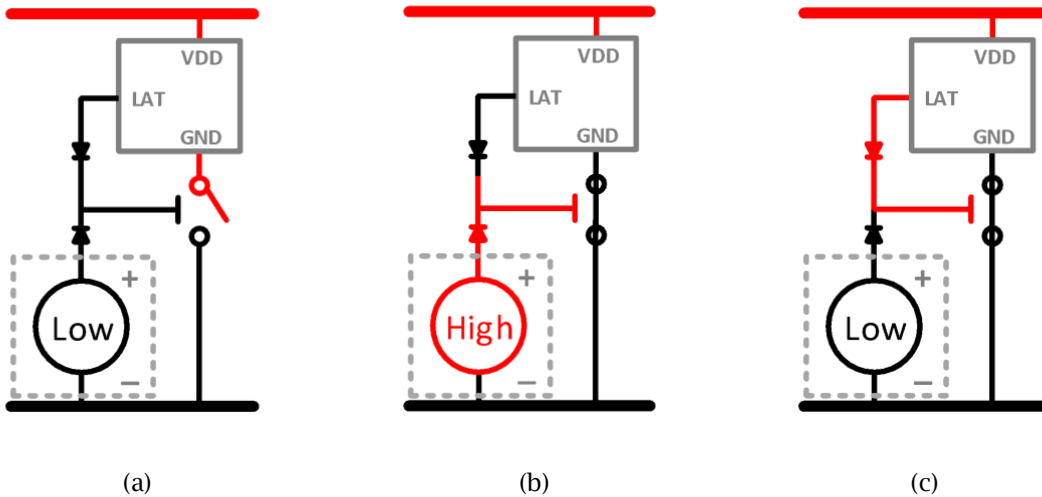
Operation of a footer switch. (a) The device ground is disconnected from supply ground in standby mode. (b) When the wake-up signal goes high, the device ground is connected to supply ground, and the device receives power. (c) The device must latch the gate of the footer switch to remain powered, even if the wake-up signal goes low. To deactivate, the latch goes low.

Credit: Daniel Gerber

The footer switch allows the main device to completely shut down, resulting in zero standby power consumption. However, the device can only turn on if a sufficient wake-up drive signal is applied at the gate of the footer switch. Once awake, the device must also latch the gate high so as to maintain its connection to the supply ground. After completing its operation, the device can return to a zero standby mode by unlatching the footer switch gate. Sections 4 and 5 detail various methods for providing this wake-up signal.

Header Switch

The header switch is a high-side PMOS sleep transistor alternative, as shown in Figure 10. This configuration is useful in applications that require a fixed ground reference between the device and wake-up signal. In this topology, the wake-up signal activates a low-power NMOS, which then activates the gate of the header switch PMOS through a pull-up resistor (Chao and Harrison 2008).

Figure 10: The Header Switch
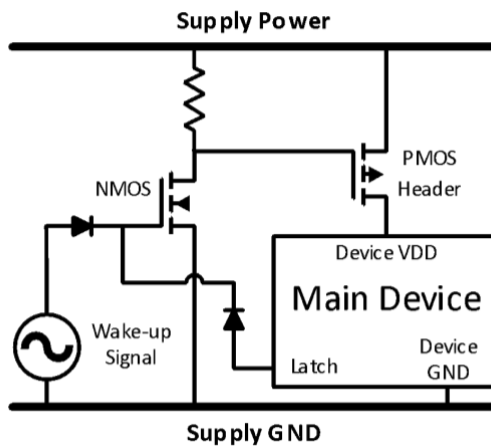
A header switch topology. The wake-up signal activates an NMOS, which activates the PMOS header switch through a pull-up resistor.

Credit: Daniel Gerber

Cascoded Header Switch

The cascoded header is a variant of the header switch that is ideal for a high supply voltage, such as the ~170 V output of a bridge rectifier on 120 V AC power. It was developed in this work explicitly for the laser-based zero standby solution described in Chapter 4. As shown in Figure 11, the cascoded header uses two NMOS transistors to activate the header switch gate. The top NMOS (M2) is a high-voltage device, and the bottom NMOS (M1) is a low-voltage device with a low gate-threshold voltage. This combination of devices allows for a low gate threshold, while simultaneously being able to withstand a high supply voltage.

Figure 11: The Cascoded Header Switch
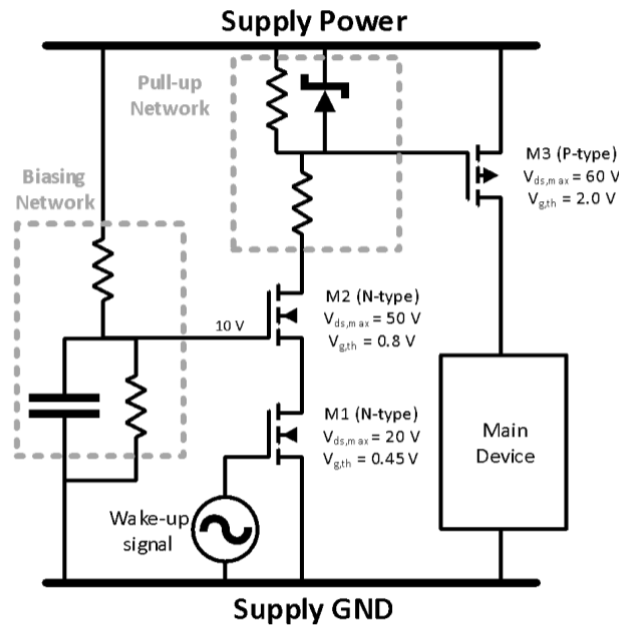
A cascoded header switch topology with example transistor values for a 48 V DC supply. The biasing network functions to bias the gate of M2 at 10 V. The pull-up network contains a Zener diode to protect the gate of the header switch M3. The latch signal is not shown.

Credit: Daniel Gerber

4. Optical Wake Up

Infrared Wake-up Signal

Several papers propose infrared (IR) energy harvesting from a remote as a wake-up drive signal. As shown in Figure 12 this method involves a high-power transmission to wake the device, and low-power signaling for all other functions. Yamawaki and Serikawa describe a method for driving the footer switch using IR energy harvested from a photodiode (Yamawaki and Serikawa 2015b, 2015a). Although the intended application was for set-top boxes, their work can extend to any device that requires line of sight activation, such as lights, ceiling fans, and window coverings. The main drawback of this method is in the wide-beam nature of the IR light-emitting diodes (LEDs), which disperses much of the transmission power. As a result, the transmission range for consistent successful wake-up was limited to 3 meters (m), which poses a practical constraint. Kang et al. proposed a similar method that involved using a 15 mW IR laser to drive a relay, but that work yielded an even smaller range of 2 m (Kang et al. 2011). In all cases, the wake-up duration is on the order of milliseconds.

Figure 12: Proposed IR Energy Harvesting Method

(a)

(b)
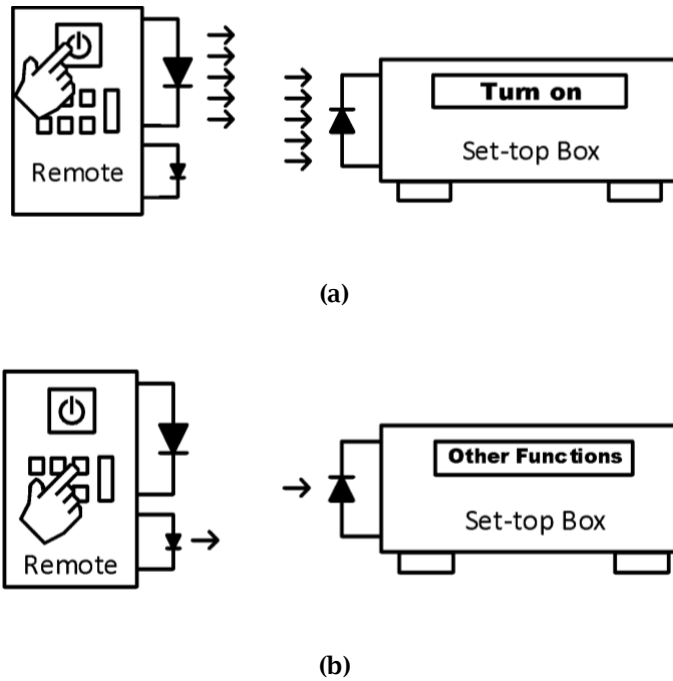
Proposed IR energy harvesting method for set-top boxes. (a) When the power button is pressed, a high power IR signal is transmitted to wake the device. (b) Once the device is awake, ordinary low-power IR signals can be used for all other functions (e.g., changing the channel).

Credit: Daniel Gerber

The IR-based prototype discussed in this report is based on the architecture developed by Yamawaki and Serikawa (2015b, 2015a). As shown in Figure 13, the method uses a photodiode array at the receiver to harvest energy from a high-power IR transmission at 38 kilohertz (kHz). The photodiode array generates an output voltage relative to the transmission strength and the number of photodiodes illuminated by the beam. To activate a typical mid-power 50 V footer switch, the photodiode array usually needs to generate about 0.5–0.8 V. In this application, the output of the photodiode array is passed through a 38 kHz band-pass filter and rectified to provide an appropriate wake-up signal at the gate of a footer switch. As discussed in Chapter 3, the footer switch connects the device to ground, thus eliminating power consumption during standby.

Figure 13: The Receiver for an IR-based Zero Standby Supply
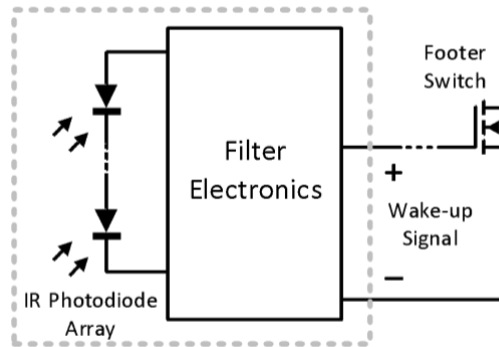
The receiver for a zero standby supply with an IR-based wakeup signal. The photodiode harvests IR energy from the IR signal, which drives the gate of the footer switch.

Credit: Daniel Gerber

A prototype, shown in Figure 14, was developed to test the practicality of the IR-based zero standby method. The transmitter provides 14 W pulses to four IR LEDs, and the receiver contains an array of 12 photodiodes. Although the prototype can successfully attain zero standby power consumption, it has several practical shortcomings. First, the wide beam angle of the bulb-shaped IR LEDs limited the prototype's reliable transmission range to 1 m. Second, the IR LEDs must be well aligned with the photodiode array, despite their wide beam. Since IR emissions are not visible to the naked eye, it is difficult to manually make this alignment. Finally, the required transmission power approaches a level that becomes questionable for eye safety.

Figure 14: Prototype of the IR-Based Zero Standby Supply
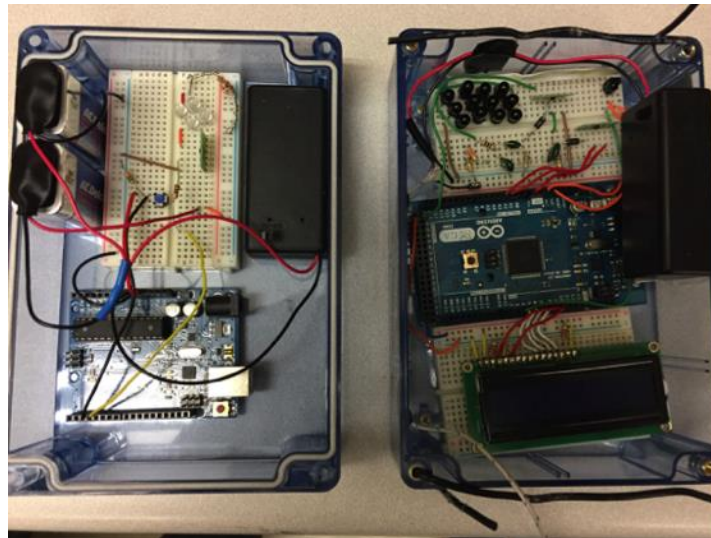
A prototype of the IR-based zero standby supply. The remote control with four clear IR LEDs is shown on the left, the receiver with 12 dark photodiodes and the device (LCD screen) are shown on the right.

Credit: Daniel Gerber

Laser Wake-up Signal

A laser-based zero-standby supply was developed to address the IR method's shortcomings. The main advantages of a visible-light laser are that it is easy to aim and its narrow beam significantly increases the activation range. Similar to the IR method, the laser's receiver harvests light energy to drive the gate of a footer switch. The main differences are in the front-end wake-up circuit. First, the laser's receiver only needs a single photodiode to operate. However, it can be difficult to dexterously aim the laser pointer at a single photodiode, and an array of photodiodes can still be helpful. Second, the laser's receiver requires a special front-end circuit to drive the gate of the sleep transistor.

The need for a front-end circuit is related to the safety concerns relevant to high-power lasers. Any laser with an instantaneous power greater than 5 mW (laser class IIIa) is subject to strict regulations. As such, the transmitter is limited to operate below 5 mW, which is similar to a common laser pointer. This presents a challenge since most affordable photodiodes cannot generate the requisite gate-drive voltage from 5 mW. For example, a SFH206K photodiode can only generate up to 0.5 V, whereas a typical 50 V NMOS has a gate threshold voltage of 0.8 V. Two front-end circuit topologies were developed to address this challenge.

The first topology is the cascoded header switch in Figure 11, which allows the bottom NMOS to have an extremely low gate threshold voltage. The gate threshold of the Si3460DV NMOS is 0.45 V, which can be activated by the 0.5 V photodiode wake signal. Nonetheless, this topology leaves little margin for error, and an angled or diffracted illumination may fail to activate the device.

The second topology utilizes a charge pump circuit to step-up the output voltage of the photodiode. The Dickson charge pump, shown in Figure 15, is particularly convenient in harvesting applications since it can be completely self-powered. In addition, the input voltage can be multiplied by several stages, allowing the voltage at the footer switch gate to be well above its gate threshold. Since the charge pump requires an AC input, the laser is pulsed at 1 kHz. The main drawback is in the Schottky diode drop of 0.2 V, which causes each stage to be less efficient, ultimately increasing the overall hardware cost.

Figure 15: Four-stage Dickson Charge Pump
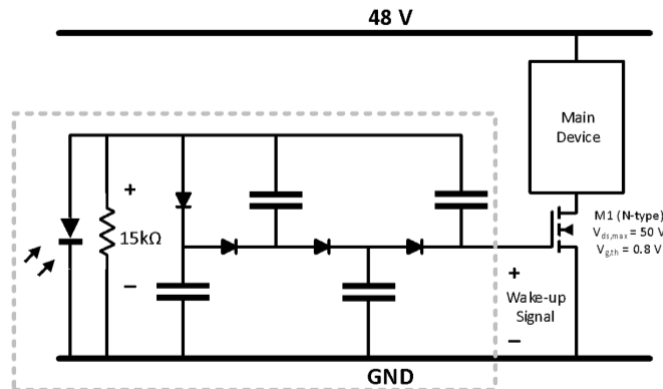
Laser standby solution with a four-stage Dickson charge pump attached to an NMOS footer switch M1.

Credit: Daniel Gerber

The prototypes, shown in Figure 16, were built from inexpensive off-the-shelf components. Both of the laser-based prototypes can successfully activate a sleep transistor. The charge

pump battery-powered lamp in Figure 16a was demonstrated at a transmission range of 25 m. Overall, the laser-based method is potentially useful in reducing standby power consumption in set-top boxes and other similar devices.

Figure 16: Prototypes of the Laser-Based Zero Standby Supply

(a)   (b)
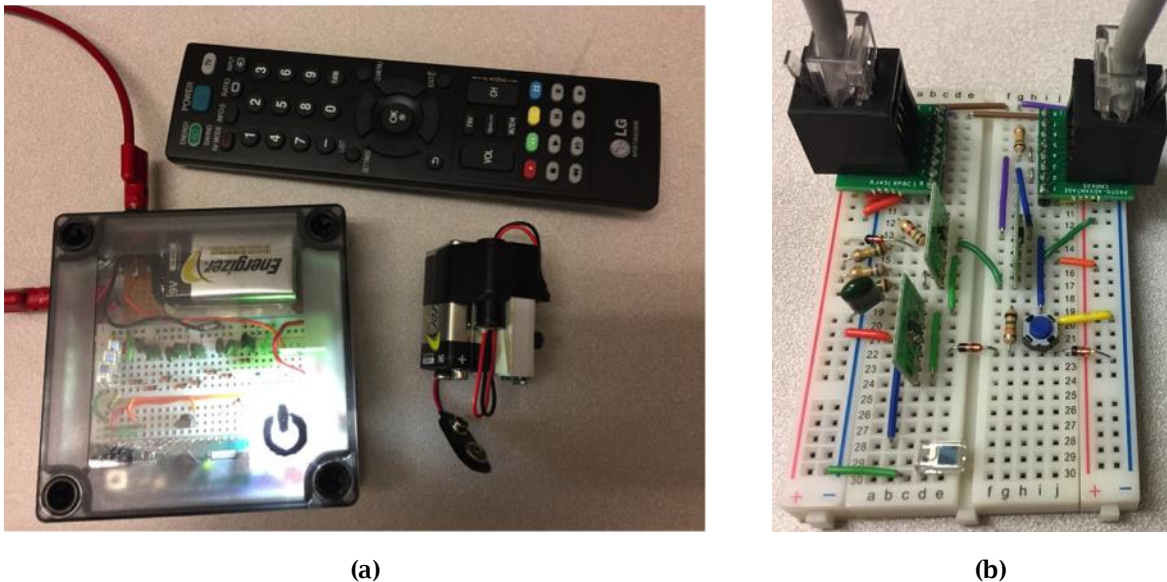
The prototypes of the laser-based zero standby supply. (a) The charge pump prototype in a battery-powered lamp. The receiver is shown on the left, the laser on the right, and the low-power IR remote on the top, which would contain the laser in practice. (b) The cascoded header prototype in a 48 V power over Ethernet (PoE) application.

Credit: Daniel Gerber

The laser-based zero-standby topologies may also prove useful in fiber and optical-link applications. Fiber communication transmits at a similar power level, and benefits from a wave-guide to focus the light. Further research is required to verify the applications of any fiber-based zero-standby solution.

5. Wake Up Radio

A radio frequency (RF)-based wake-up signal is appealing due to the proliferation of wirelessly connected technologies that contain a built-in transceiver and antenna. Various ideas have been proposed for ambient or broadcasted RF harvesting (Kim et al. 2014; X. Lu et al. 2015). However, in most cases, the amount of transmission power required for pure RF harvesting makes it difficult to justify its use in plug-load applications.

For plug loads, the wake-up radio (WuR) is a more appealing method. WuRs are a family of ultra-low-power receivers that are designed solely to wake the main device from sleep mode (Demirkol, Ersoy, and Onur 2009; Magno et al. 2014). At present, most research in WuRs is applied to prolonging battery life in remote IoT applications. Some studies, such as Umeda and Otaka, propose the application of WuRs in plug loads (Umeda and Otaka 2007). As shown in Figure 17, WuRs are electrically separate from the device's primary high-power transceiver but share the same antenna. They can be programmed to be individually addressable, thus allowing the wake-up broadcast to wake only individual devices.

Figure 17: Wake-up Radio System
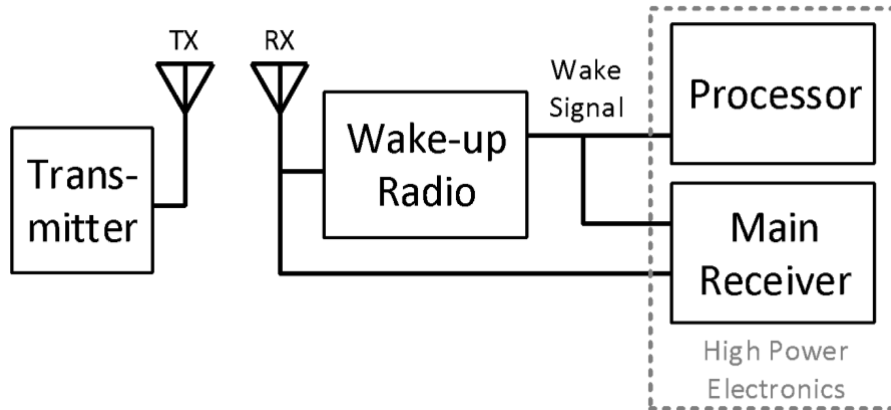
The microwatt wake-up radio can share an antenna with the high-power transceiver.

Credit: Daniel Gerber

Modern and future trends in electronics suggest that many devices and appliances will be wirelessly IoT connected. Even set-top boxes and remotes have begun to transition from IR to WiFi-based communication. Although the WuR does not strictly allow for zero standby consumption, its microwatt consumption is practically negligible. At present, WuRs are most commonly used in battery-powered wireless applications. This research aims to demonstrate that WuRs can also be employed for standby power reduction in plug loads.

As shown in Figure 18, plug load WuRs can toggle a footer switch similar to the IR- and laser-based methods. Unlike these methods, the WuR requires a constant current of several microamps. While the wall adapter can provide this current, many converters do not operate efficiently at low power. In addition, the wakeup radio might operate at a lower voltage compared to the rest of the device electronics. As such, this work recommends powering the WuR using the burst mode techniques discussed in Chapter 2. With these modifications, the WuR is an effective way to reduce standby power in wirelessly connected plug loads.

A prototype for the method in Figure 18 was developed using the AS3932 WuR chip. This prototype, shown in Figure 19, uses near-field magnetic coupling at 125 kHz to turn the device on from across the room. However, its range is relatively limited at 3 m, and is heavily affected by metal shielding. Nonetheless, various RF techniques have demonstrated that the AS3932 can operate with an 868 MHz (or even higher) input at a range of 50 m (Gamm et al. 2010; Oller et al. 2013). With proper design of the antenna, board, and RF down converter, the prototype in this work can be upgraded for a similar frequency and range.

Figure 18: Wake-up Radio Operational Block Diagram
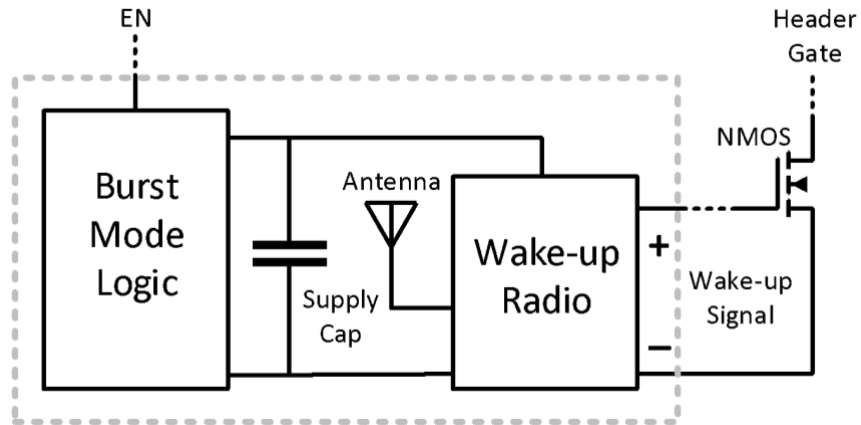
Block diagram for how the WuR can be used to reduce standby power consumption in plug loads. The supply capacitor and burst mode logic provide a constant supply of micro amp current to the wake-up radio. If the WuR needs to communicate with the main device, the circuit will require a header switch to maintain a common ground for the communication signals.

Credit: Daniel Gerber

Figure 19: Wake-up Radio Prototype
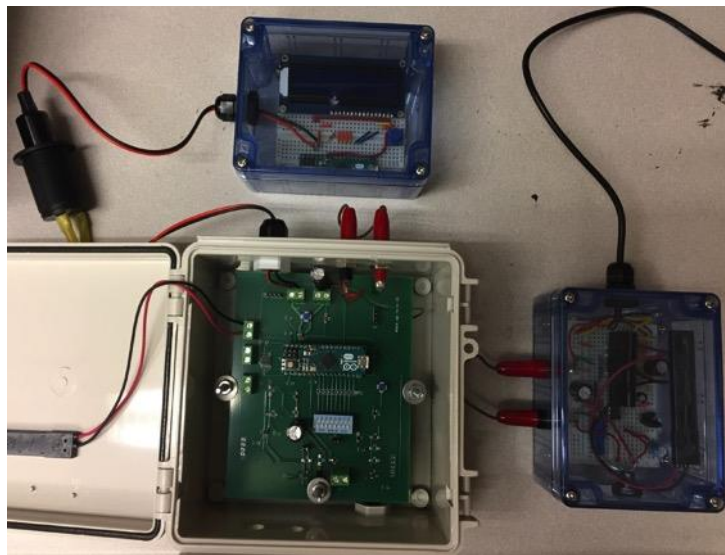
Prototype of the WuR method for standby power reduction. Includes the transmitter (right), receiver (bottom left), and display load (top). All of the receiver board components can be integrated into the WuR except for the electrolytic supply capacitor.

Credit: Daniel Gerber

This study recommends the WuR for all wirelessly connected products, both battery-powered and plug loads. Nonetheless, addressing protocols must be standardized before WuRs can become prevalent. One possibility is for the Wi-Fi access point to become a centralized broadcasting unit. Remotes could request the router to broadcast a wake signal addressed to

the remote's specific target. Alternatively, IoT devices with occasional periodic functions could request the router to schedule a periodic wake-up.

This work also recommends integrating burst-mode logic into commercial WuR products. Burst mode would provide a convenient and efficient means of powering the WuR, and help expand its application in many types of products.

6. Conclusion

Improvements to power supplies have drastically reduced standby consumption over the last 20 years. However, the need for standby power reduction persists due to the increasing population of power-connected devices with standby modes. Since modern electronics are very diverse in application and requirements, this work suggests a portfolio of solutions to tackle standby consumption. Several such solutions were presented and prototyped. The first demonstrates the value of burst mode for lightly loaded converters. The second uses IR energy harvesting to activate a footer switch and wake the device. The third, instead, harvests visible light energy from a laser pointer. The fourth solution uses a wake-up radio to activate a header switch. As IoT technology transitions loads to become small and numerous, intensive standby reduction will be crucial for energy-efficient products.

This work demonstrates zero or near-zero standby power as being technically feasible in several families of products. These solutions have both advantages and drawbacks and will require technical improvements and reductions in cost before they can be commercialized. In addition, the portfolio of solutions will need to be broadened before standby power use can be confidently—and economically—eliminated.

CHAPTER 3:
Efficient, Direct DC Devices

1. Background and Motivation

Motivation for DC Distribution in Buildings

Direct current power distribution systems have become a recent topic in building energy research as a means of reducing consumption. In the past, AC was well suited to power the nineteenth and twentieth century loads such as the incandescent lamp, resistive heating, and fixed speed induction motors. However, with the proliferation of electronics, LED lighting, and variable frequency drives (VFDs) for motor-driven loads, an increasing fraction of today's electric loads operate internally on DC (Garbesi, Vossos, and Shen 2011). In addition, the recent growth in on-site photovoltaic (PV) generation (Perea et al. 2017) and battery storage (GTM Research 2016) adds even more DC components to the building network. DC power distribution between the on-site generation, storage, and loads can reduce losses in converting between AC and DC, leading to electricity savings across the board (George 2006).

The potential electricity savings from DC distribution systems in buildings have been addressed in numerous studies (AlLee and Tschudi 2012; Backhaus et al. 2015; Savage, Nordhaus, and Jamieson 2010; Denkenberger et al. 2012; Sannino, Postiglione, and Bollen 2003; Thomas, Azevedo, and Morgan 2012; Garbesi, Vossos, and Shen 2011; Engelen et al. 2006; Glasgo 2017; Hammerstrom 2007; Liu and Li 2014; Noritake et al. 2015, 2014; Paajanen, Kaipia, and Partanen 2009; Starke, Tolbert, and Ozpineci 2008; Willems and Aerts 2014; Gerber et al. 2018; Gerber et al. 2017; Frank and Rebennack 2015; Weiss, Ott, and Boeke 2015; Boeke and Wendt 2015; Fregosi et al. 2015). For the commercial building sector, the reported savings vary widely from 2 percent (Backhaus et al. 2015) to as much as 19 percent (Savage, Nordhaus, and Jamieson 2010). Gerber et al. (2018) performed a series of highly detailed parametric simulations that varied solar and storage capacity in several equivalent AC and DC buildings. The results suggested that the highest savings occur in buildings with large PV and storage capacities, such as zero net energy buildings. An additional loss analysis revealed that low-power load rectifiers contributed the most loss in the AC buildings. In general, the reported savings are highly dependent on the system converter efficiencies, the system topology and voltage levels, and the coincidence of generation and load.

Systems with 380 V DC distribution have been proposed and successfully implemented in data centers, where estimated savings range between 7 and 28 percent. These high savings are a result of the load being predominantly electronics (AlLee and Tschudi 2012). Commercial buildings have seen several instances of early adoption for DC distribution systems, primarily in lighting applications (Fregosi et al. 2015; Nextek Power Systems n.d.; Wright 2016). Several other experiments developed DC loads and test beds to evaluate the savings and power quality with DC (Weiss, Ott, and Boeke 2015; Boeke and Wendt 2015; Fregosi et al. 2015; Kakigano, Miura, and Ise 2010; Ito, Zhongqing, and Akagi 2004). Weiss et al. (Weiss, Ott, and Boeke 2015) modeled a 380 V DC system with measured efficiency data in a variety of loads to estimate the DC savings at 5 percent. Fregosi et al. (2015) performed a similar analysis on lighting test beds with the Bosch DC microgrid, resulting in savings of 6 to 8 percent. Finally, Boeke and Wendt (2015) reported 2 percent measured and 5 percent potential electricity savings from an office LED lighting test bed at the Philips High Tech Campus, in Eindhoven, Netherlands. Many of

these experimental DC loads and test beds exhibit significantly lower savings than those predicted by past analyses and simulations.

This work assists in addressing the pressing need for the development of efficient DC loads. It aims to demonstrate savings with DC loads, and suggest ways in which experimental loads in DC test beds can be improved.

Previous Works in DC Modification

Currently, there is a small market for DC plug loads for recreational vehicle (RV) and boating applications (Vossos et al. 2017). These loads are often compact and designed for 12 V or 24 V DC from the vehicle's battery. In the next few decades, low-voltage DC solar home systems will penetrate the markets in developing countries that currently lack universal electrification.

Several previous works have prototyped DC plug loads for newly constructed DC buildings in the residential and commercial sector. Many of these efforts create prototypes for a variety of DC appliances as a means of performing system or microgrid tests (Mishra, Rajeev, and Garg 2018; Ryu et al. 2015; Makarabbi et al. 2014; Noritake et al. 2015; Stippich et al. 2017). Recent research has produced DC prototypes in many end-use categories such as lighting (Weiss, Ott, and Boeke 2015; Boeke and Wendt 2015; Ryu et al. 2015; Makarabbi et al. 2014; Noritake et al. 2015; Stippich et al. 2017; Jhunjhunwala et al. 2016), motor loads (Ryu et al. 2015; Noritake et al. 2015; Stippich et al. 2017; Jahromi et al. 2014; Das et al. 2016; Chauhan et al. 2017; Yukita et al. 2017), electronics (Ryu et al. 2015; Makarabbi et al. 2014; Noritake et al. 2015; Stippich et al. 2017; Rani et al. 2016), and induction cooking (Makarabbi et al. 2014; Lucia et al. 2013).

Despite the wealth of research on developing DC loads, there are still several important gaps. First, many of the previous works compare AC and DC loads of different technologies. It has been common, for example, to compare a DC variable frequency drive motor appliance to an outdated AC induction motor equivalent. Second, many of the previous prototypes are not designed to operate at the DC distribution voltages, and require DC/DC converters at the input. Such practice neglects the many design optimizations allowed by DC power that can result in higher device efficiency and lower cost. Finally, most of the previous studies use prototype DC plug loads, but do so as a means of showcasing another research topic such as a DC microgrid demonstration or a new control strategy.

This work aims to improve on previous works by focusing on the optimal development of DC loads. Although it demonstrates savings in various prototypes, the main goal is to suggest ideas and practices that can and should be implemented in future products. In addition, this work gives detailed explanations of the benefits of DC from the load perspective.

2. DC Load Modifications

Existing DC Voltage Standards

There are several considerations selecting the voltage for DC power distribution. Safety is a primary concern, and OSHA standard 1910.303(g)(2)(i) (OSHA 2015) considers voltages below 50 V AC or DC to be touch-safe (the UK IET BS 7671:2008 (BS 7671:2008) specifies it at 50 V AC and 120 V DC). Second, higher voltages require more insulation to protect against dielectric breakdown. Finally, low-voltage systems experience higher wire loss and voltage drop for any given power level and wire gauge. For a device with constant power requirements P_L, the current can be expressed as $I = P_L/V$. Since the wire loss decreases quadratically with the wire's voltage ($P_w = I^2 R_w$), it is recommended that high-power devices be powered from high-voltage lines.

This work investigates several existing or emerging standards for DC plug voltages:

- USB Type C: 5-20 V, 100 W
- PoE: 48-57 V, 91 W
- EMerge Alliance Data/Telecom Center Standard: 380 V

USB-C is emerging as the single standard technology to power any low voltage device. Its point-to-point power delivery architecture allows for simultaneous power and communications. Power over USB-C strictly adheres to the USB power delivery (USB-PD) protocol ("Universal Serial Bus Power Delivery Specification, Version 1.2, Revision 3.0" 2018). USB-PD controllers are required in the sending and receiving devices in order to transfer power at voltage greater than 5 V. Past USB-PD standards set the programmable voltage to 5 V, 9 V, 15 V, or 20 V. However, as of USB-PD 3.0 (2018), the port can now function as a programmable power supply (PPS) and outputs voltages between 3 V and 21 V with 20 mV increments. USB-C connectors contain 24 pins, of which 8 are for power, 2 are for dedicated USB-PD communications, and the rest are for data. USB is best suited for short-range power distribution such as a cubicle because of the voltage drop and wire loss inherent with low-voltage distribution.

Another competing USB protocol is Qualcomm Quick Charge (QC), which has voltage and power specs similar to USB-PD (Qualcomm, n.d.). QC works with traditional USB-A or B ports, but requires use of the data lines for power signaling communications. It also has a PPS capability with 200 mV increments (QC 3.0), allowing it to charge batteries much more quickly and efficiently. Although this fast charging capability made QC very popular, USB-PD 3.0 now has much of the same functionality. Recent versions of QC also support USB-PD, and it is possible that the two standards will soon merge.

Power over Ethernet (PoE) nominally operates at 48 V, although the standard allows up to 57 V at the source to compensate for wire drop (Osorio et al. 2015; Petroski 2016; Johnston et al. 2012). The 802.3bt Type 4 standard allows PoE to transfer 91 W of power over Category 5 Ethernet cable using a four-pair power transfer mode. Currently, PoE is used in applications that require both power and communications, such as phones, cameras, and routers. Since many buildings are already wired with Ethernet cables, PoE offers one of the easiest ways for DC power distribution to enter the market. In addition, PoE operates near the Occupational Safety and Health Administration (OSHA) touch-safe limit (50 V), thus optimally minimizing wire loss while ensuring safety. While USB is best suited to power a workspace, PoE can extend to multiple rooms or even an entire residence.

The EMerge Alliance has established a high-voltage DC standard, with specifications for powering datacenters at 380 V DC (EMerge Alliance 2013; Geary et al. 2013; Becker and Sonnenberg 2011). This standard allows for easy retrofitting since 380 V DC cabling has similar insulation requirements with 277 V AC. Besides datacenters, 380 V DC holds much promise for powering other types of high-capacity loads (such as large motors), and allows for efficient coupling with solar and storage power electronics (Gerber et al. 2018). Nonetheless, 380 V DC distribution presents new arcing issues in protection and breaker technology, which must be addressed before 380 V DC buildings can become common.

Devices that Benefit from DC

Internally, DC loads are classified as being direct-DC or native-DC, depending on whether the building distribution is DC or AC, respectively (Backhaus et al. 2015). Direct-DC loads connect to the DC building distribution either directly or through a DC-DC converter. Native-DC loads always require a rectifier to interface with the AC building network.

This work further classifies loads based on how they can benefit from an interface to a DC distribution network (Figure 20). Common plug loads are classified as follows:

- DC-connected: The internal DC stage of these loads can be connected or hardwired directly to the DC distribution if properly designed. A direct-DC input would bypass the input voltage conversion (and/or rectification) stage, thus allowing for savings in efficiency and cost. As such, these loads stand to receive the greatest benefit from DC distribution.

- DC-converted: The internal DC stage of these loads requires a DC-DC converter in order to connect to the DC distribution at the proper voltage level. However for most loads, the direct-DC version greatly outperforms its native-DC counterpart in efficiency, cost, and size. As such, these loads stand to receive some benefit from DC distribution.

- DC-indifferent: The load can be hardwired to an AC or DC distribution with equivalent cost and efficiency. These loads are equivalently efficient with AC or DC.

Figure 20: Categorization of Loads by Benefit from DC Input
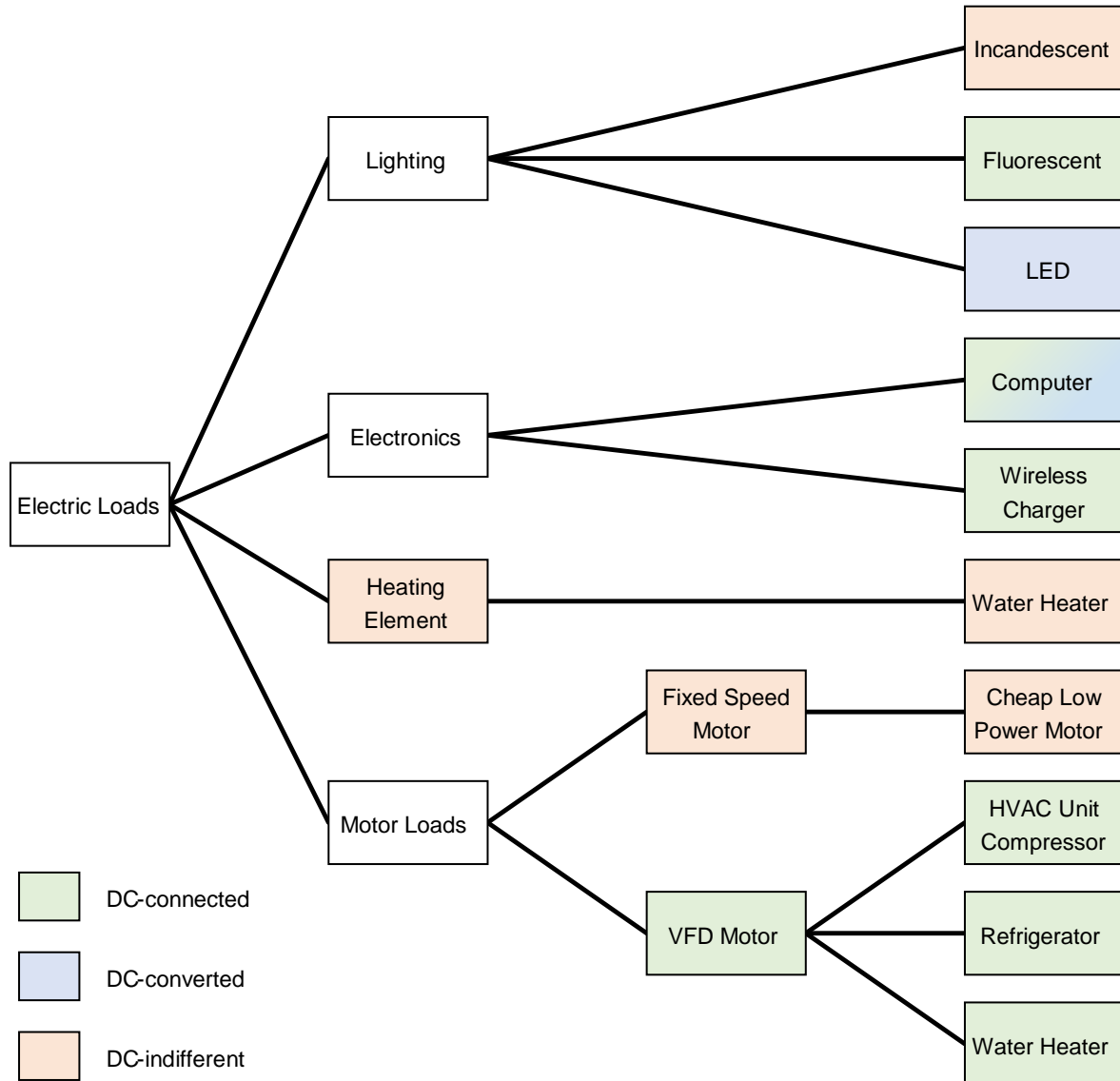
DC-connected loads have an internal DC stage that can be connected or hardwired to DC distribution. DC-converted loads require an input DC/DC converter, but still benefit from a DC input. DC-indifferent loads do not benefit from a DC input.

Credit: Daniel Gerber

DC-connected

DC-connected includes loads with a fixed internal DC bus, many of which require AC power at a frequency different from the 60 hertz (Hz) mains. These loads include variable frequency drive (VFD) motors and wireless power transfer (e.g., wireless charging).

VFD motor loads contain a brushless DC motor, which is essentially an inverter-driven induction motor. They are frequently used in control-heavy applications, and have become commonplace in compressors for cooling and heating. Due to their efficiency benefits, VFDs will eventually replace fixed speed motors in air conditioners, refrigerators, heat-pump air and water heaters, ventilation fans, and pumps (Saidur et al. 2012; Rooks and Wallace 2004; Didden et al. 2005). For this reason, fixed-speed motors are not considered in this study. As shown in

Figure 21a, native-DC VFD motors require a rectification stage for the 60 Hz AC input. The output of the rectifier is stored on a DC capacitor bus, which powers a set of inverters that supply the stator coils with variable frequency AC. In well-designed direct-DC VFDs, the DC capacitor bus could be connected directly to the DC distribution, as shown in Figure 21b. A direct connection bypasses the rectification stage, thus allowing for savings in efficiency and cost. In addition, the DC capacitors no longer have to filter the 120 Hz AC power ripple, and can be reduced depending on the inverter switching noise.

Figure 21: Block Diagram of a VFD Motor

(a)

(b)
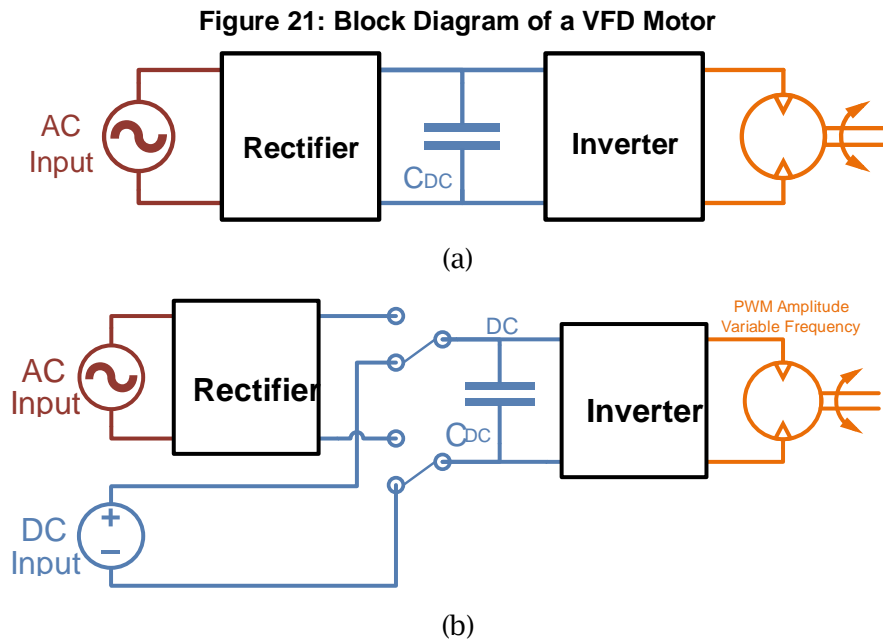
Block schematic of a VFD motor, as present in the refrigerator and bathroom fan. The inverter is powered from an internal DC stage (blue), and outputs AC at a variable frequency (orange). (a) A rectifier is required to convert 60 Hz AC (red) to DC. (b) A proposed modification, with multiplexed AC and DC inputs.

Credit: Daniel Gerber

Wireless power (e.g., charging a phone) requires the production of AC at a frequency much higher than 60 Hz. In this way, wireless power transmitters are structurally similar to VFDs: they contain a rectifier, a DC stage, and a power amplifier (similar to an inverter). The power amplifier outputs AC power at the resonant frequency of the antenna. Transmitters are present in any wirelessly connected plug-loads, including routers, computers, and IoT devices. In addition, wireless chargers and induction stoves employ near-field wireless power transfer. Like VFD motors, wirelessly powered devices can all benefit from a DC input.

Inverter-based topologies can also be found in other applications, such as electronically ballasted fluorescent lamps. The fluorescent lamp driver uses a resonant AC output to start the lamp, and then uses variable frequency AC as a means of current control.

DC-converted

DC-converted includes current-controlled loads and loads with multiple internal busses. LEDs are a current-controlled load, since their luminosity is nearly proportional to their current. As such, the LED driver is necessary, even with DC distribution. However, the efficiencies of DC LED drivers can often be found in the 95–98 percent range, whereas AC LED drivers often exhibit 86–93 percent efficiency (Gerber et al. 2018; Fregosi et al. 2015). DC LED drivers may be less expensive because they do not have to rectify the AC input, apply power factor correction (PFC), or cancel the 120 Hz AC power ripple. They are also more reliable since their capacitor requirements are lower than AC drivers.

Computers are an example of a DC-converted device with multiple internal busses that power different parts of the computer. Even when powered from DC distribution, computers require multiple DC-DC converters to power the various internal DC power rails. However, it also can be argued that many computers could be designed with a direct DC connection to the computer's internal DC bus. For example, laptops use a wall adapter to convert 120 V_{RMS} AC to a single DC output voltage, usually in the range of 14–20 V DC (varies by model). A low-voltage DC input would obviate the need for a wall adapter, thus allowing for benefits similar to other DC-connected devices.

DC-indifferent

DC-indifferent includes heating elements and fixed speed motors. Resistive heating elements are often found in water heaters, ovens, and incandescent bulbs. These devices can be hardwired to an AC or DC distribution without any benefit to either. Fixed speed motors are often found in inexpensive and inefficient motor loads such as fans. In an AC system, these loads are often implemented as brushed, universal, induction or synchronous motors. In a DC system, simple motor loads would likely use a brushed DC motor. Brushed DC motors are inefficient and require more maintenance due to the commutating brushes. While AC induction motors are more efficient, they have low power quality.

Experimental Method

This work examined several types of electric loads, which were selected to represent a wide range of end uses and internal component types. The loads were a wall adapter, bathroom fan, refrigerator, LED task lamp, and LED zone lighting rig. The wall adapter represents electronics, in which localized conversion between 120 V AC and low-voltage DC is a common necessity. The refrigerator represents plug loads with a compressor. High efficiency refrigerators contain VFD motors, whose DC capacitor stage can be directly connected to the DC distribution. The bathroom fan represents ventilation units. Modern high efficiency ventilation fans use VFD motors with multi-speed control. The task lamp and zone lighting rig together represent the lighting end-use category.

The prototypes and modifications were intended to demonstrate savings with a direct-DC input. As such, the prototypes were all designed so as to leverage DC input to reduce the number of conversion stages. The means of demonstrating savings varied by load, and included measuring the input power consumption, nominal operating efficiency, and efficiency curves. Efficiency measurements used $\eta = P_{out}/P_{in}$, where P_{out} is the power measured at the device's internal DC stage, and P_{in} is measured at the AC or DC input.

3. Wall Adapters

Modifications for DC Input

Wall adapters provide low-voltage DC to many household plug load electronics. With the emergence of the Internet of Things, electronics are trending toward widely distributed low-power units. DC distribution is attractive because it eliminates the wall adapter, improving overall cost and efficiency. The wall adapter must first rectify the 120 V AC input to 170 V DC, and then step the 170 V DC rectifier output down to the relatively low 5–20 V DC appropriate for electronics. Low-power wall adapters with a high DC/DC conversion ratio are often very inefficient. As of February 2016, the United States Department of Energy (DOE) requires wall adapters to adhere to the Level VI efficiency standard (CUI Inc, n.d.; SL Power Electronics, n.d.). For Level VI, the highest specified efficiency requirement is 88 percent (varies with power), which leaves plenty of room for improvement.

This work presents efficiency measurements for several wall adapters, most of which have a USB-C output at 5-20 V DC. The measured efficiency represents the losses for native-DC electronics. As shown in Figure 22, this work considers direct-DC electronics as being DC-connected and assumes that the DC distribution can provide the correct voltage to the device's internal DC bus. In this sense, the energy saving with DC is equivalent to the wall adapter's measured loss. Other more realistic scenarios may require a DC wall adapter, which is further discussed in following sections.

Figure 22: Direct-DC Wall Adapter Modification

(a)

(b)
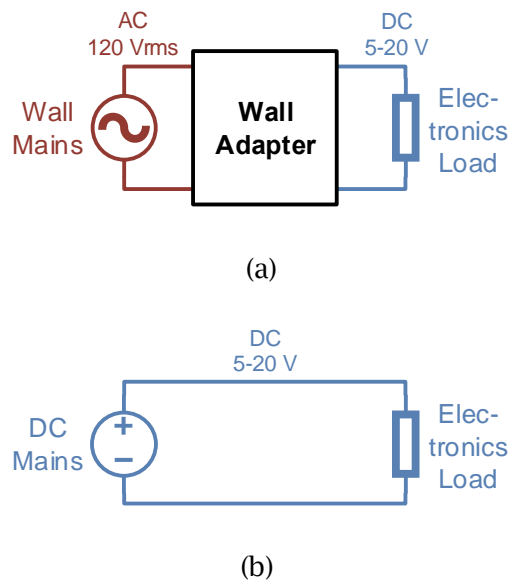
Two different means of powering the internal DC bus in electronics. (a) Native-DC electronics require a wall adapter.

Present and future wall adapters will have a USB-C output at 5–20 V. (b) This study considers direct-DC electronics to be DC-connected.

Credit: Daniel Gerber

Experimental Prototype and Results

The five USB-C wall adapters, shown in Table 5, vary in power capacity and quality. These adapters are loaded with a 5 V Anker Powerpack battery and a MacBook that attempts to request up to 20 V. The efficiency is calculated from ten-minute measurements of the input and output energy.

Table 5: Wall Adapter Efficiency

Adapter	Output Voltage (V)	Efficiency (%)	Average Measurement Output Power (W)
Choetech 15 W	5	84.73	15.7
Pixel 18 W	5	87.18	11.0
	9	88.24	17.6
Anker 30 W	5	90.82	10.7
	20	91.22	29.2
Choetech 39 W	5	87.15	10.4
	15	91.96	37.7
Macbook 87 W	5	89.92	10.6
	20	94.91	59.8

Discussion

The results show that wall adapters contribute significantly to the AC system loss. Realistically, electronics in a DC building also require a DC/DC conversion stage, since the distribution voltage is usually higher than 5–20 V suitable for electronics. For example, a 380 V DC building would require a USB charging station to have an internal 380/5 V DC/DC converter. Nonetheless, there are several practices that would allow considerable savings with direct-DC electronics.

In general, high-power converters are more efficient than their low-power equivalents. AC wall adapters exhibit the use of many distributed low-power converters. However, DC distribution allows for centralizing the conversion in a high-power charging station, as shown in Figure 23a. Such charging stations could be mounted in a cubicle to power all the electronics in the workspace. They could utilize high-power DC technology such as the Vicor BCM6123xD1E1368yzz, an 800 W chip with 8–13 V output that peaks at 97 percent efficiency. Of course, an additional conversion stage may be necessary to ensure that each USB-C output adheres to the USB-PD specifications.

Figure 23: Direct-DC Wall Adapter Discussion

(a)

(b)
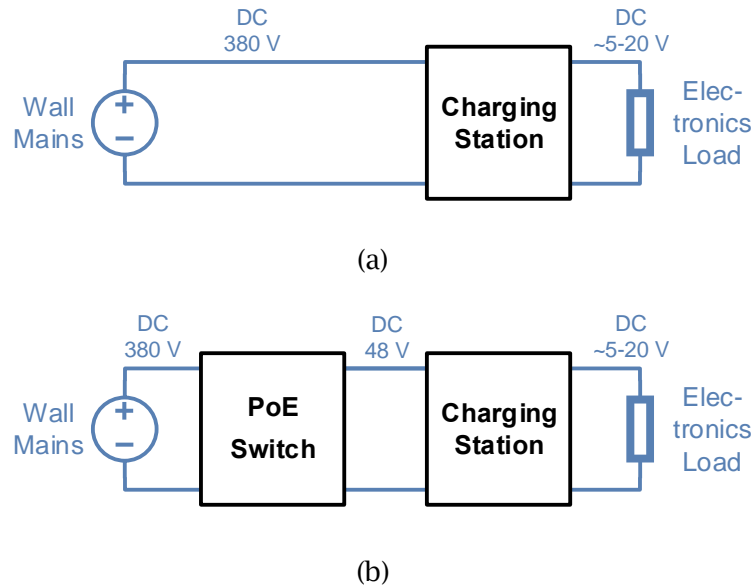
Two ways to power direct-DC electronics in a 380 V DC building. (a) The charging station performs a conversion from 380 V DC, and also outputs at the requested voltage of each USB-C port. This may be most efficient in two separate DC/DC conversion stages. (b) A PoE switch performs a 380/48 V DC conversion, and the charging station steps-down from 48 V DC to each desired port voltage.

Credit: Daniel Gerber

Alternatively, the charging station could be designed for a 48 V DC input, as shown in Figure 23b. 48 V charging stations may be advantageous in both safety and applicability to residential 48 V DC networks. In Figure 23b, the PoE switch can contain a fixed-conversion 380/48 V DC unit such as the Vicor BCM6123xD1E5135yzz, a 1,750 W chip with a staggering 98 percent efficiency. The charging station would contain an efficient step-down converter for each USB-C output (Rani et al. 2016). The design of such a charging station is left for future work.

4. Bath Fan

Modifications for DC Input

VFD loads have an internal DC capacitor stage that buffers the inverter. The proposed modification, shown in Figure 24b, would add a DC-connected input directly to the DC capacitor stage. Such a modification is easiest when the device's nominal DC capacitor voltage is equal to one of the DC standard voltages. Electronic components can be damaged when the input voltage is greater than the device's nominal DC capacitor voltage, and the stator coils may be overheated when the input voltage is too low.

Figure 24: Direct-DC Bath Fan Modification
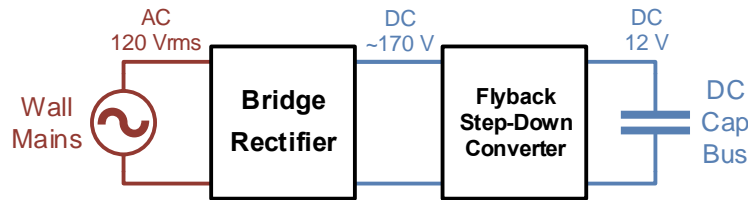
(a)
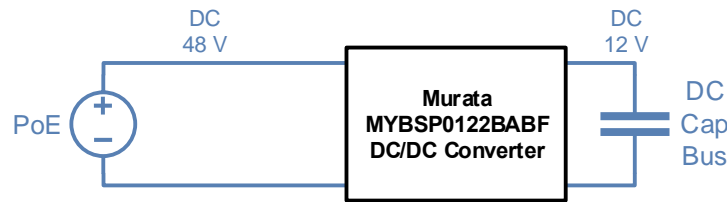
(b)
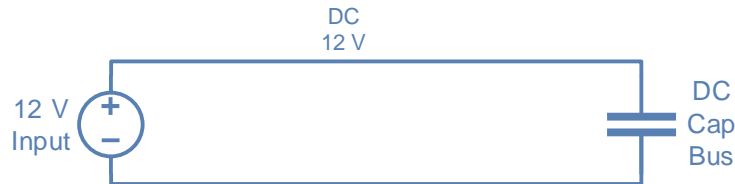
(c)

Methods of providing power to the bath fan's DC capacitor bus and inverter stages. (a) The fan's original AC/DC rectifier board. (b) The DC-converted modification for 48 V PoE input, using a DC/DC converter. (c) A DC-connected modification for a hypothetical 12 V DC input. This configuration represents how DC input would be beneficial if the motor and inverter was designed for 48 V DC.

Credit: Daniel Gerber

The nominal DC capacitor voltage of a Delta GBR80 bath fan (Figure 25) is 12 V. Although it could connect to USB-C, homeowners would seldom want to power their bath fan from a short-range USB-C connection. PoE is the practical alternative, but at 48 V, it is far outside the 12 V operating range of the fan's inverter. As such, the fan must interface with PoE through a 48/12 V DC/DC converter. The modification has no effect on the fan motor's speed or torque since the DC capacitor bus and inverter remain the same.

Figure 25: Direct-DC Fan Prototype
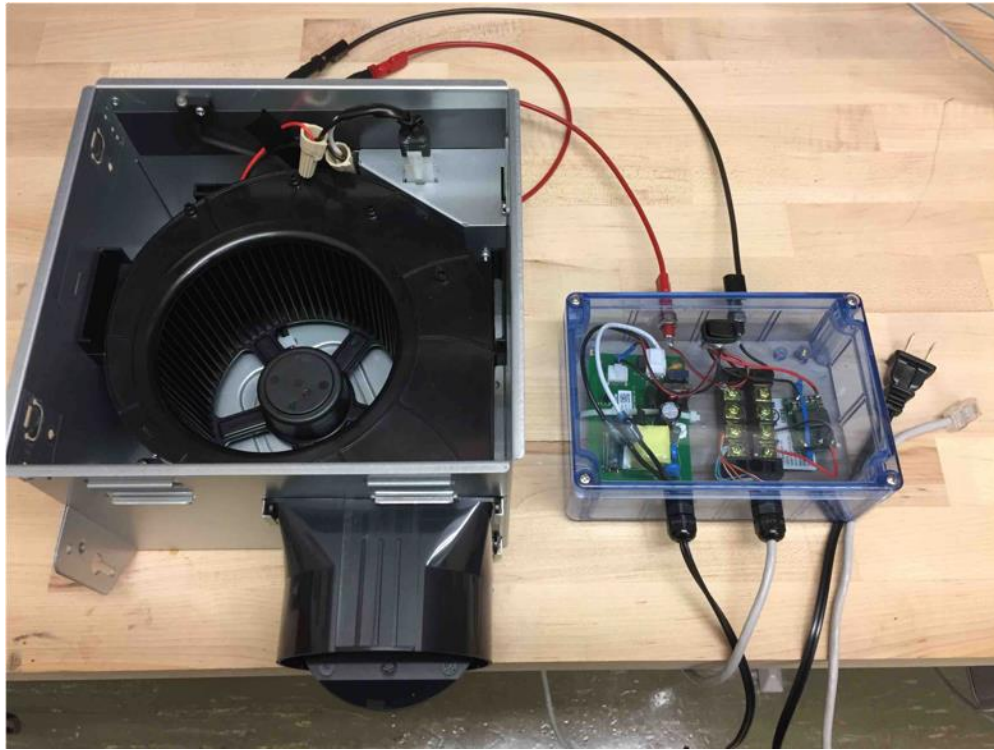
Prototype of the Delta GBR80 bath fan, modified to accept a PoE input. The blue box contains the AC and DC boards, with a switch to toggle between AC or DC input.

Credit: Daniel Gerber

Experimental Prototype and Results

The bath fan prototype, shown in Figure 25, was designed to have a multiplexed AC or DC input, as previously depicted in Figure 21b. The blue electrical box contains both the original AC rectifier board, and the 48/12 V DC/DC converter. The original AC board, shown in Figure 26a, used an isolated flyback topology to step down the input voltage to 12 V. The modified DC input used a 25 W Murata MYBSP0122BABF 48/12 V isolated DC/DC converter (~$12), shown in Figure 26b.

The results suggest that DC input can improve the fan's power consumption. The efficiency curves in Figure 27 show that the DC/DC converter is up to 6 percent more efficient than the original rectifier board. Table 6 shows a decrease in the fan's input power with DC input. In addition, the fan draws even less power with a 12 V input, which represents the potential savings when the input voltage is matched with the nominal DC capacitor voltage. In this experiment, the exhaust valve was held open or shut to simulate a lightly or heavily loaded fan, respectively.

Figure 26: Fan Boards

(a)   (b)
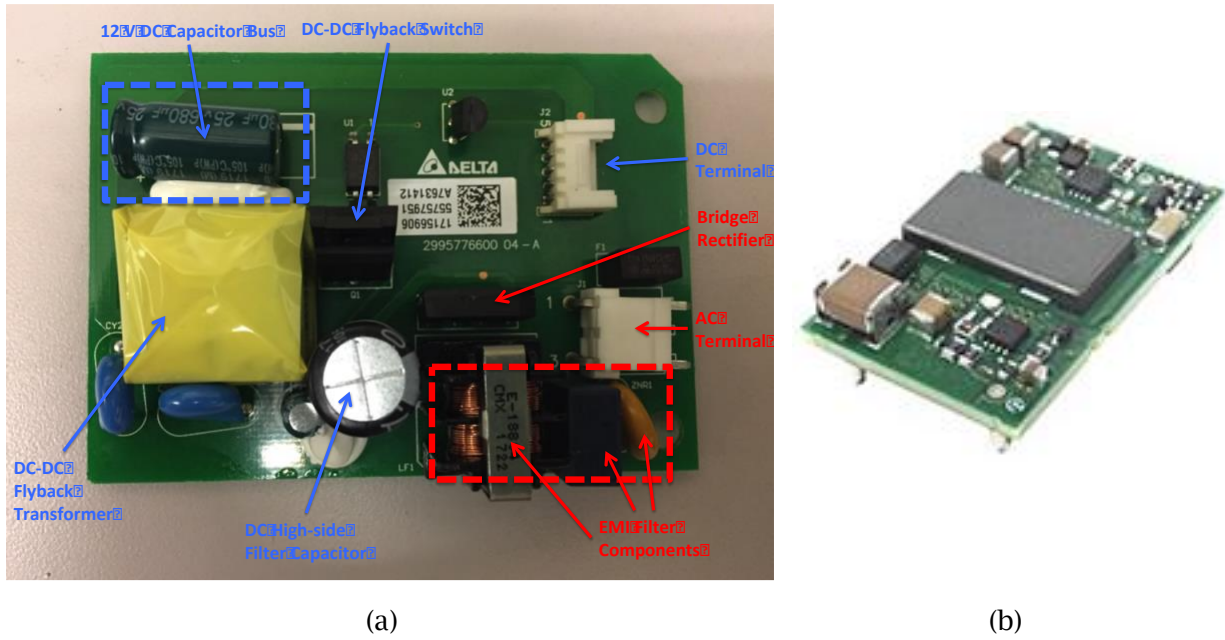
Input power conversion boards for the Delta bath fan. (a) The original rectifier board that converts 120 V$_{RMS}$ AC to 12 V DC. The board dimensions are 8 x 6 centimeters (cm). (b) A Murata MYBSP0122BABF 48/12 V DC/DC converter for interfacing the DC capacitor stage with PoE. The board dimensions are 3.5 x 2 cm.

Credit: Daniel Gerber

Figure 27: Efficiency Curves for the Bath Fan Boards

Credit: Daniel Gerber

42
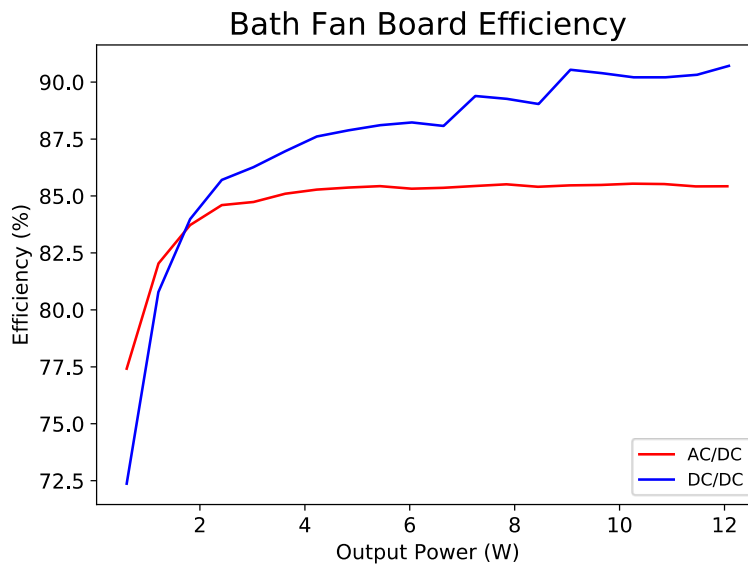
Table 6: Fan Prototype Power Consumption

Input Type	Conversion	Input Power Light Load (W)	Input Power Heavy Load (W)	AC Power Factor
Original 120 V$_{RMS}$ AC	AC/DC	7.75	9.01	0.64
DC-converted 48 V DC	DC/DC	7.43	8.65	N/A
DC-connected 12 V DC	None	6.6	7.72	N/A

Discussion

There are two general reasons why the 48 V DC modification is more efficient than the original 120 V$_{RMS}$ AC converter board. First, the 48 V DC modification in Figure 24b only has a single 48/12 V conversion stage. In contrast, the 120 V$_{RMS}$ AC converter board in Figure 24a must both rectify 120 V$_{RMS}$ AC to DC, and then step-down to 12 V DC. Second, switching converters are generally more efficient with a smaller conversion ratio V_{out}/V_{in}, such as the 48/12 V conversion. Smaller conversion ratios allow switching converters to frequently conduct power from input to output. In contrast, large conversion ratios often require the switches to frequently block power, although parasitic losses still occur even while blocking. The 120 V$_{RMS}$ AC converter board uses a flyback topology to mitigate some of this loss by instead converting through the flyback transformer's turns ratio. However, inclusion of a flyback transformer adds cost, size, and a small amount of parasitic loss in the transformer and output rectification.

The 12 V DC input in Figure 24c is the most efficient of the three because it does not require any conversions. However, running 12 V power to the fan is impractical due to low-voltage wire loss. Nonetheless, the 12 V measurement shows that the highest savings occurs when the internal DC voltage of the BLDC motor is matched to the distribution voltage. If this motor were designed with a 48 V DC inverter, then the 48 V DC PoE modification could also be much more efficient. The next section shows how a BLDC motor can be redesigned to operate with a different internal DC voltage.

DC Capacitor Voltage in BLDC Motors

Brushless DC motors are designed with an intended AC input voltage to the stator windings. The AC winding voltage is important because it dictates the inverter's DC input voltage from the DC capacitor bus. Direct-DC loads can be DC-connected if the nominal DC capacitor bus voltage is the same as the DC distribution voltage. This section shows how a motor's input voltage can be designed independently of its power rating, and can ultimately be designed such that the DC capacitor bus can seamlessly connect to the DC distribution. Figure 28 shows the winding area for two motors with equal input power and magnetic flux.

Figure 28: Motor Winding Area
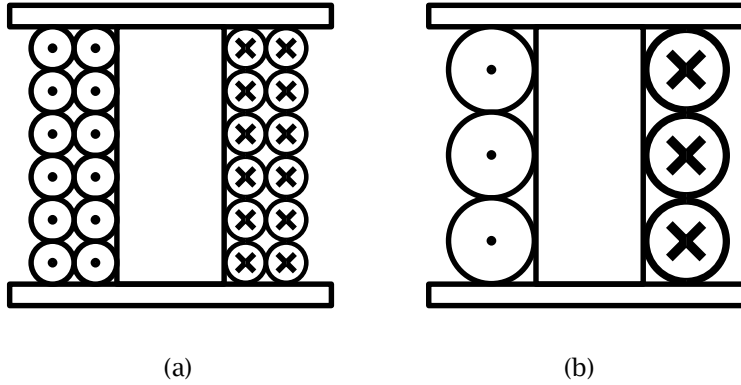
(a)   (b)

Winding area diagram for two motors with equal input power and magnetic flux. The winding area in both motors is roughly equal. (a) A high-voltage motor that requires 12 windings, but they can be relatively thin. (b) An equivalent low-voltage motor only requires 3 windings, but they must be thick enough for the relatively high winding current.

Credit: Daniel Gerber

For a given application, assume that the motor's electrical input power P_{const} is specified and constant. Also assume that the motor's magnetic flux φ_{const} is constant and is directly related to the mechanical output power. The relations between the electrical stator windings and the magnetic core are shown in equations 1–3:

$$P_{const} = VI \tag{Eq. 1}$$
$$\phi_{const} = \frac{NI}{\mathcal{R}_{tot}} \tag{Eq. 2}$$
$$E = N\frac{d\phi_{const}}{dt}, \tag{Eq. 3}$$

where V and I respectively are the winding's input voltage and current, N is the number of windings, $\mathcal{R}_{tot}$ is the total reluctance of the magnetic core, and E is the back electromagnetic force (EMF) generated in the windings.

Consider a comparison between motors 1 and 2, which both have the same input power $P_1 = P_2$, and magnetic flux $\phi_1 = \phi_2$. However, the main difference is that the winding voltage of motor 1 is designed to be K times greater than that of motor 2. Since $V_1 = KV_2$, $I_1 = \frac{1}{K}I_2$. If the two motors are specified with the same magnetic flux and core parameters, then $N_1 = KN_2$. In other words, the motor 1 requires K times as many windings, but the windings only pass $\frac{1}{K}$ times as much current. Finally, it follows that $E_1 = KE_2$ but since $V_1 = KV_2$, then each motor has proportionally as much voltage headroom, and each motor can attain the same maximum speed.

The overall result is that high-voltage motors use less current and have more stator windings than low-voltage motors of the same input power and flux. Since the low-voltage motor requires thicker windings capable of passing a higher current than the high-voltage motor. Nonetheless, the low-voltage motor requires fewer windings, and so the overall winding packing window is comparable between the two motors, as shown in Figure 28.

5. Refrigerator

Modifications for DC Input

Like the bath fan, the DC input modification of the 11 ft³ LG LTNC11121V inverter-based refrigerator follows the procedure shown in Figure 21b and 29. The main difference is that the rectification stage in the refrigerator uses a Delon doubler (i.e., full-wave doubler), whose unloaded DC output is 340 V DC. As such, the refrigerator is modified to accept a 340 V DC input. Although not a standard DC voltage, this input represents what the efficiency and power draw would be at 380 V DC.

Figure 29: Direct-DC Refrigerator Modification

(a)

(b)
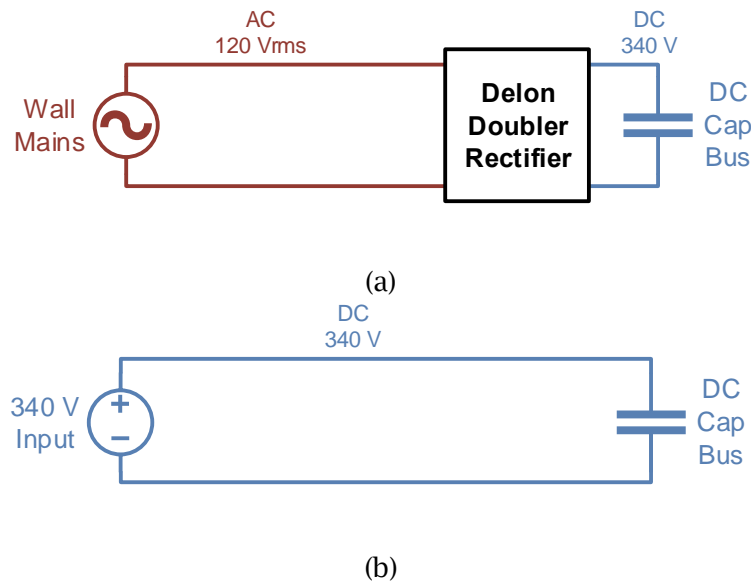
Methods of providing power to the refrigerator's DC capacitor bus and inverter stages. (a) The refrigerator's original AC/DC Delon doubler rectifier circuit. (b) The DC-connected modification for 340 V input, which approximately represents connection to a 380 V DC bus.

Credit: Daniel Gerber

Experimental Prototype and Results

The refrigerator prototype, shown in Figure 30, added a 380 V DC-connected input to the DC capacitor stage. The inverter board shown in Figure 31 contains an input electromagnetic interference (EMI) filter and protection components on the AC input. Although the prototype's DC input did not include these protective elements, it did contain a thermistor that protected the DC capacitors from over-current at startup. In this experiment, the refrigerator's defrost coils were deactivated, and the power was drawn solely by the compressor and electronics.

The efficiency of the rectification stage in Figure 29a was determined as $\eta = P_{out,DC}/P_{in,AC}$, where $P_{in,AC}$ and $P_{out,DC}$ are the power in and out of the rectifier, respectively. The average efficiency was 99 percent over 50 measurements with power ranging from 50 W to 80 W. There was little to no correlation between power and efficiency in this range. The extremely poor AC power factor was 0.65, and was caused entirely by harmonics.

Discussion

The refrigerator barely benefited from a high-voltage DC input, since bypassing the rectification stage only saved 1 percent of the input power. LG designed the motor to operate natively off the 340 V output of the Delon doubler rectifier. As previously discussed, this means that the compressor windings use low current and a large number of turns. While the high 340 V operation is extremely efficient, its main drawbacks are in hardware size and cost, as can be inferred from the power components in Figure 31. In contrast, many low-voltage DC refrigerators such as the Danfoss 101N0212, shown in Figure 32, can make do with smaller electronics. This inverter board operates on 24 V DC, implying that its compressor has fewer but thicker windings.

Figure 30: Direct-DC Refrigerator Prototype
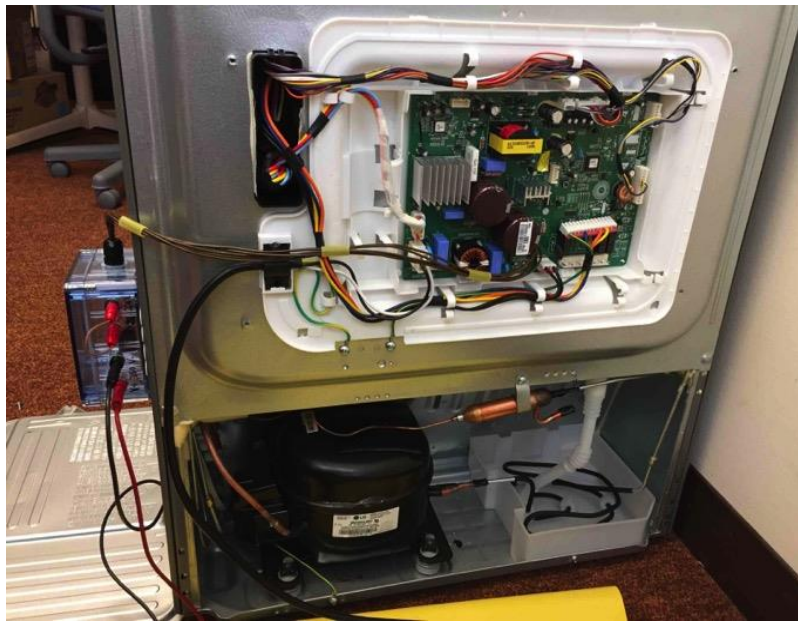
Prototype for the DC input modification of a refrigerator. The blue box on the left side allows for a 340 V DC input to the inverter board's DC capacitor bus. The compressor is the BMA069LAMV model.

Credit: Daniel Gerber

It is important to note that this refrigerator does not use power factor correction (PFC), and thus has a poor power factor of 0.65. Although inverter-based refrigerators are generally subject to the stringent IEC 61000-3-2 Class D harmonic specifications, these requirements only apply for devices that draw more than 75 W of power (Harmonic Current Emissions 2010; IEC 2014). While the LG refrigerator sometimes draws up to 80 W to operate its compressor, it usually operates below 75 W. The defrost coils draw up to 175 W, but they are a resistive load with unity power factor. As such, this refrigerator barely slips under the threshold of PFC requirements. Slightly larger refrigerators would require PFC, which lowers the AC efficiency and increases hardware costs.

Figure 31: LG Refrigerator Inverter Board
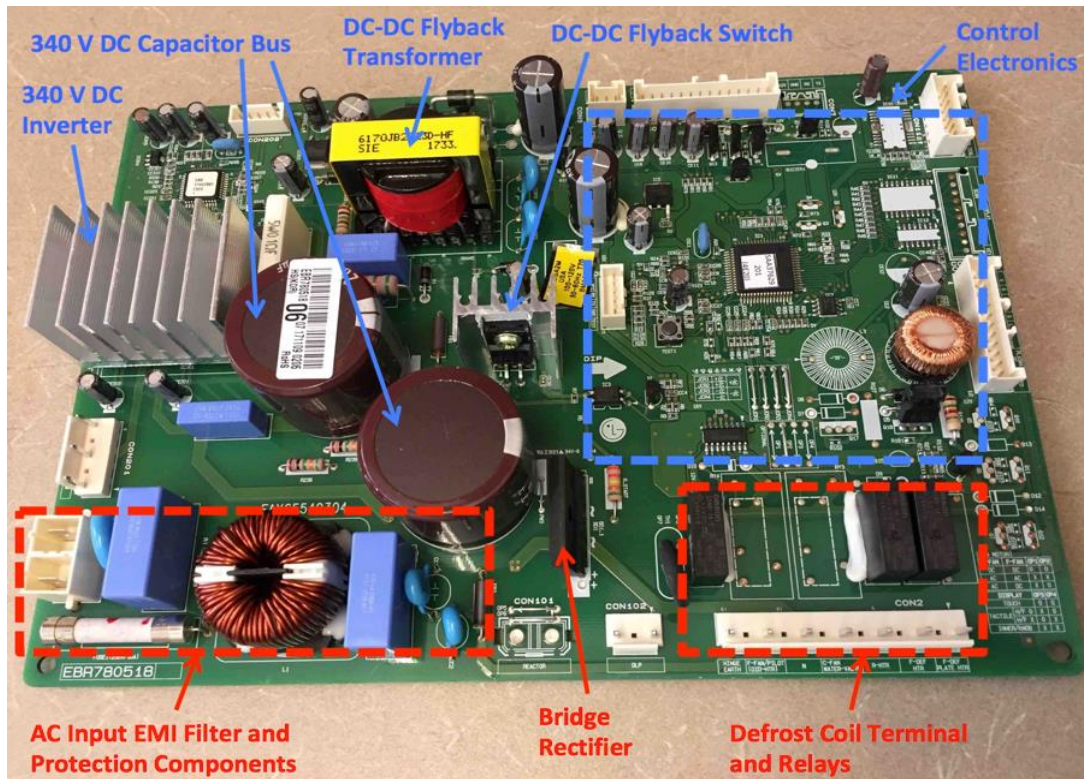
Inverter board for the LG LTNC11121V refrigerator. The inverter is a high-voltage three-phase SIM6822M chip. The board dimensions are 23 x 16 cm.

Credit: Daniel Gerber

Finally, DC input allows for a reduction in the size of the DC capacitor bus. Not only are high-voltage high-capacitance electrolytics bulky and expensive, as shown in Figure 31, they are prone to failure and may limit the lifespan of the entire unit (Gu et al. 2009; Chen and Hui 2012). The DC capacitor bus is sized to filter 120 Hz AC power ripple, provide an energy buffer for rapid changes in motor torque, and filter the high-frequency inverter pulse-width modulation (PWM) current injected back onto the line (Salcone and Bond 2009). In general, the line-injected EMI filtering requirements are satisfied by accounting for the other two. The energy buffer requirements are also considerably lower in variable speed compressors that can ramp-up their input power. Overall, the large DC capacitor bus in Figure 31 is required for filtering the 120 Hz AC power ripple, and can be greatly reduced with DC input.

Figure 32: Danfoss/Secop Inverter Board

Danfoss/Secop 101N0212 inverter board, for a Danfoss 12/24 V DC refrigerator. The board dimensions are 10 x 6.5 cm. This inverter board can provide up to 113 W when connected to a BD50F compressor at 3,500 RPM and 30°C ambient temperature.

Credit: Daniel Gerber

6. Task Light

Modifications for DC Input

LEDs are current controlled, and thus DC systems still require a DC LED driver. Nonetheless, DC LED drivers are more efficient than AC LED drivers, and lighting stands to benefit from DC distribution (Gerber et al. 2018; Fregosi et al. 2015). In addition, the large electrolytic capacitor present in many LED drivers can be significantly downsized. Instead of demonstrating the already well-known advantages of DC LED drivers, this work instead details two unique ideas for efficient DC lighting design.

Task lights are usually localized to a workspace, and low-voltage DC input from a workspace USB charging station can often be convenient and efficient. Many USB task lights in today's market are powered by a constant voltage 5 V USB-A port and use a ballast resistor for current control, as shown in Figure 33a. The ballast resistor is not only inefficient, but it is also very susceptible to bus voltage swing and does not allow for dimming. Upcoming products will likely leverage USB-PD, shown in Figure 33b, which allows for higher voltage, higher power, and lower cable loss. Higher-end products will also incorporate an LED driver, which allows for dimming and can be more efficient than a ballast resistor.

A further improvement is possible, shown in Figure 33c, in which the USB charging station becomes the LED driver. Such a solution requires a charging station that supports USB protocols with a programmable power supply (PPS) capability (USB-PD 3.0 or QC 3.0). With a programmable supply voltage, the lamp needs only to sense the LED current, and program the

48

supply voltage accordingly. This method effectively removes the LED driver conversion stage, while still offering all the benefits of an LED driver, such as dimming.

Figure 33: Direct-DC Task Lamp Modification

(a)

(b)

(c)
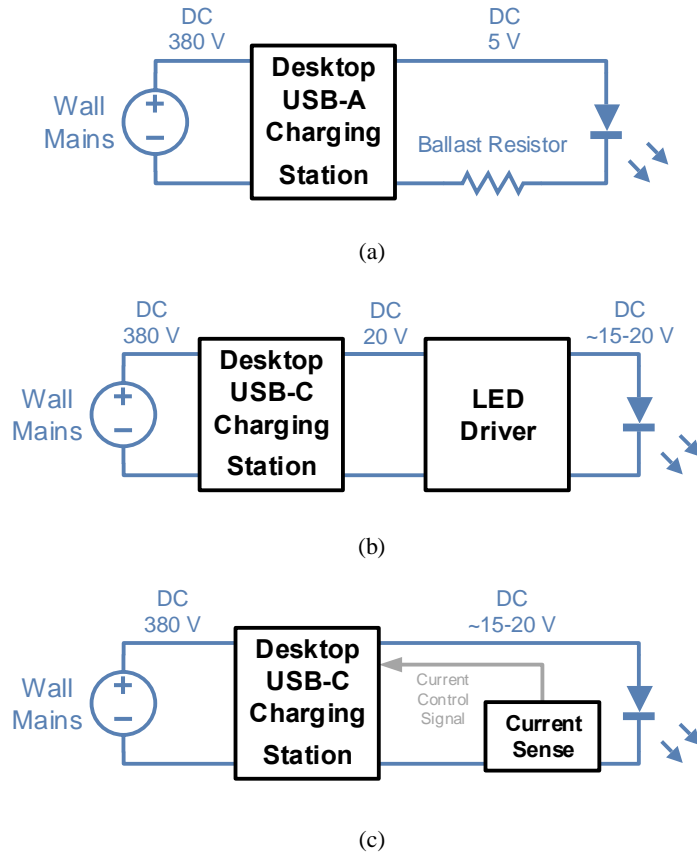
Methods of powering a task lamp with DC input from a desktop charging station. Note that the wall mains could also be 120 V$_{RMS}$ AC or 48 V DC. (a) Use a ballast resistor for current control. (b) Connect the LED driver in the lamp to the charging station's output. (c) If the charging station has PPS capability, the charging station can become the constant current LED driver.

Credit: Daniel Gerber

Experimental Prototype and Results

The task light prototype, shown in Figure 34, demonstrated the driverless topology in Figure 33c. This task light was powered from an Anker PowerPort charger with QC 3.0. Since USB-PD 3.0 was not available at the time, QC 3.0 was the only option that had a programmable power supply (PPS) capability. The Anker PowerPort provided up to 12 V to three 1.5 A LEDs (Cree MTG7-001I-XTE00-NW-0GE3). At its brightest operating point, the LEDs drew 1.5 A at 14.3 W (9.815 V). An Arduino microcontroller produced the control signals for brightness and dimming, and the signals were sent via the USB data lines as per the QC protocol (Deconinck, n.d.). Although this proof-of-concept prototype used voltage control, current control is recommended for future products.

Figure 34: Direct-DC Task Lamp Prototype

Credit: Daniel Gerber

Discussion

As previously shown in Figure 33c, the prototype effectively uses the charging station as an LED driver, thus reducing the number of power conversions. From a hardware perspective, this method is possible in any point-to-point DC topology, since every port is current-controlled. The only software requirement is a charging station that supports a DC protocol with PPS capability.

DC protocols such as PoE may have problems combining the LED driver into the PoE switch, since the protocol's tight 48–56 V range is intended only to mitigate voltage drop over the wire. One possibility, shown in Figure 35, would be to design the LED driver with a solid-state bypass switch that can connect the LEDs directly to the PoE line in their brightest state. Dimmed states would disconnect the bypass, and instead use a conventional LED driver to provide constant current at the appropriate voltage to the dimmed LEDs.

Figure 35: Direct-DC Task Lamp Discussion
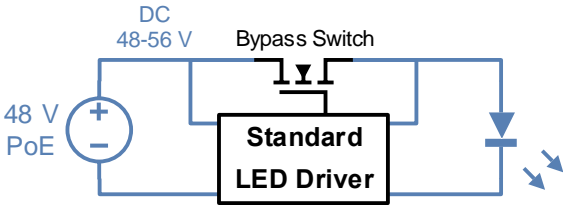
Credit: Daniel Gerber

7. Zone Lighting

Modifications for DC Input

Zone lighting systems simultaneously operate many light fixtures, and are often found in office and retail buildings. LED bulbs in older buildings have internal LED drivers, and are designed to plug into existing incandescent or fluorescent fixtures. In this design, the LED drivers are distributed between the fixtures and may require a separate signaling line for dimming. This system is standard in AC buildings, and many of the experimental 380 V DC test beds also use the distributed LED driver architecture shown in Figure 36a (Boeke and Wendt 2015).

Remote external LED drivers are physically separate from the lamp's LEDs. They have traditionally been popular in commercial or outdoors lighting systems such as streetlights and lit signs (1000bulbs.com 2014). Nonetheless, several companies have started promoting the use of remote LED drivers in lighting systems for newer buildings. First, remote drivers can be very cost-effective since each driver can power multiple fixtures, as shown in Figure 36b. Second, remote drivers can greatly reduce maintenance costs. Since the driver usually limits the lifespan of the entire lamp, a low-cost replaceable driver in an easily accessible location is advantageous. Finally, dimming and control functionality is easier with a remote driver that serves multiple fixtures.

Most commercial remote LED drivers use a parallel design, shown in Figure 36b, which is ideal for applications that require individual fixture control. Another topology, shown in Figure 36c, uses a single line to power the LED fixtures in series. This topology is very uncommon, and the few companies that develop series remote drivers seldom intend for their application in zone lighting for buildings.

This work aims to demonstrate that series remote drivers are an excellent design for zone lighting in 380 V DC buildings due to their low overall cost and high efficiency. The cost benefit is a result of using simple low-power hardware to drive many fixtures, as shown in Figure 36c. In addition, the driver's switch stress does not increase with the number of fixtures N, implying a constant hardware cost.

Series remote drivers also can be significantly more efficient than their parallel counterparts. In general, buck converters are most efficient at a high MOSFET conduction duty cycle, which happens when the output voltage is closely matched to the input. The drivers in Figure 36a and Figure 36b undergo a significant step-down from the mains to the fixture voltage V_{FIX}. In contrast, the series driver in Figure 36c performs a much lighter step-down when several fixtures are attached.

Figure 36: Direct-DC Zone Light Modification
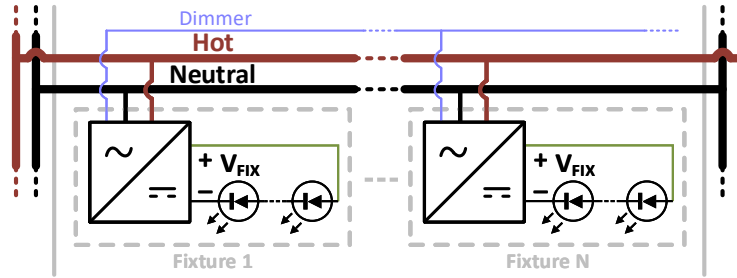
(a)
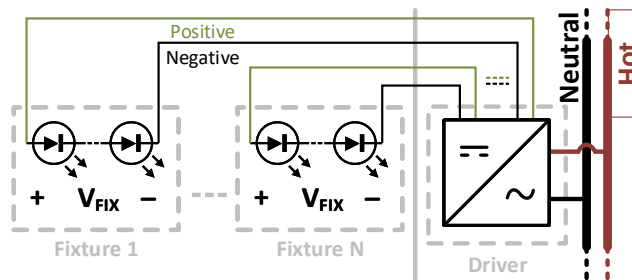
(b)
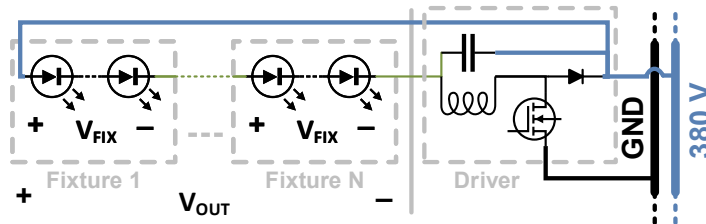
(c)

Methods of wiring lighting fixtures. (a) The conventional design with distributed drivers and a dedicated 0–10 V analog dimming line. (b) Most remote driver topologies use an array of parallel current-controlled lines. (c) Series remote driver topology with a buck-based driver. Although depicted with a DC input, series drivers are currently designed for an AC input. In this topology the number of fixtures N is limited to N*V$_{FIX}$<380 V. Nonetheless, a buck-boost LED driver can allow for more fixtures to be attached.

Credit: Daniel Gerber

Experimental Prototype and Results

A 380 V DC series remote driver was prototyped using the topology in Figure 36c. The prototype, shown in Figure 37, used an MP4000 controller, a 600 V IGBT, and a 10 millihenry (mH) inductor. The experimental fixtures were a set of 75 V 18 W four-foot T8 LED tubes, which come from removing the driver of a PT-T84FP18W. As shown in Figure 38, the driver's efficiency increased with the number of tubes. For reference, the original tube-integrated AC LED driver, shown in Figure 39, operates at 92 percent efficiency and 0.97 power factor.

Figure 37: Direct-DC Zone Light Prototype

Credit: Daniel Gerber

Figure 38: Direct-DC Zone Light Prototype Efficiency
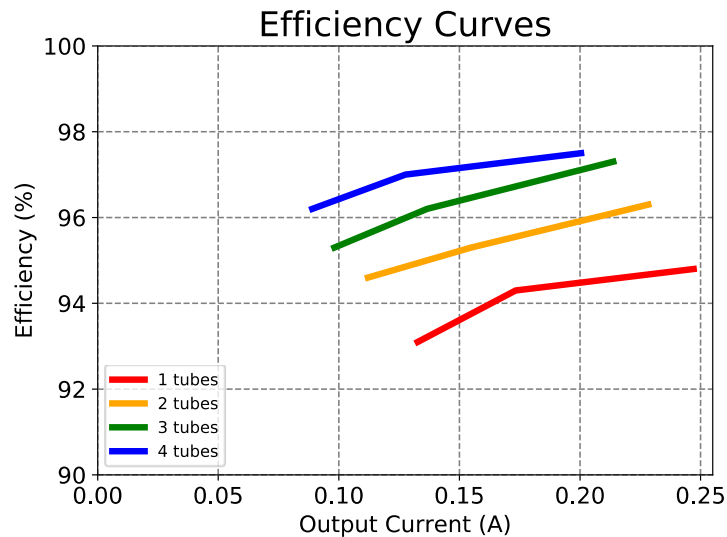
Efficiency curves for the 380 V DC series remote driver with 1–4 LED tubes attached in series. The driver's efficiency increases with the number of attached tubes.

Credit: Daniel Gerber

Figure 39: Original AC LED Driver

Original AC LED driver packaged in a PT-T84FP18W four-foot LED tube. The board dimensions are 3.5 x 2 cm.

Credit: Daniel Gerber

Discussion

Remote drivers have many advantages over conventional internal drivers, such as cost, maintenance, and control functionality. However, the main drawback is a loss of the plug-and-play simplicity of traditional light bulbs. In addition, remote drivers can have problems with transmission voltage drop when the output LEDs are wired over a long distance. Series remote drivers add the potential to further decrease hardware costs and greatly increase efficiency. Nonetheless, their drawbacks include non-trivial wiring and a loss of the ability to dim individual fixtures in a set. As such, series remote driver architectures are best suited for commercial zone lighting. Overall, further study is required to fully determine the value of series remote drivers in industry applications.

One potential concern with series LED fixtures is that a single LED failure would disable the entire multi-fixture string. This drawback can be overcome by equipping each fixture with a bypass circuit. An example bypass circuit, shown in Figure 40, is based on a design for bypassing individual LEDs (Bollmann and Penick 2013). In this case, the SCR and Zener diode would be sized such that their breakdown voltage is greater than the nominal LED fixture voltage.

Figure 40: Fixture Bypass Circuit
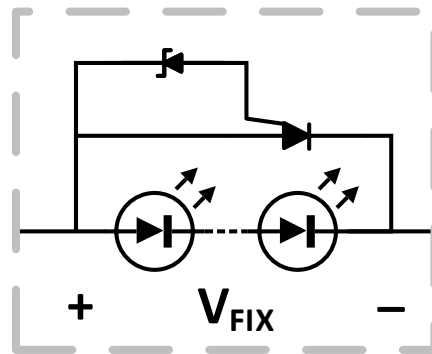
Bypass circuit for the LED fixtures connected to a series remote driver. This circuit will allow other fixtures to remain powered despite a failure in the series string.

Credit: Daniel Gerber

Another important point of discussion is in the number of fixtures that can be powered by a 380 V series driver. In this experiment, the 380 V buck-based driver only allows five 75 V tubes to be stacked in series. It is important to note that newer LEDs provide more power with less voltage drop (Keeping 2012; Solly 2007). For example, an 18 W bulb with three modern 6 V 1 A LEDs would only drop 18 V. Twenty-one such bulbs can stack to 380 V, which is enough to cover a moderately sized room. Another possibility is a buck-boost driver (instead of the buck driver in Figure 36c), which would allow the lighting designer the flexibility to install even more fixtures. However, efficiency and safety begin to decline once the series voltage exceeds 380 V.

8. Conclusions

Buildings with DC power have taken the recent spotlight in research, but the development of highly efficient DC-ready loads has lagged. This work categorizes the types of loads whose efficiency directly benefits from a DC input. Several types of loads were studied, and some of them are modified or prototyped as direct-DC. These loads include a wall adapter, bath fan, refrigerator, task lamp, and zone lighting rig. The main focus of each design is to leverage DC input to eliminate or improve the conversion stages.

This project obtained new insights during the design, development, and measurement phases. These insights are specific to the categories of electronics, motor loads, and lighting. In electronics, DC input can allow for the downsizing or elimination of wall adapters. The efficiency benefits generally favor DC, though the comparisons must be made with careful attention to the distribution voltage and conversion process. In motor loads, the most efficient type of BLDC motor is designed such that its internal DC capacitor bus naturally operates at the DC input voltage. Although there is very little loss across a diode bridge rectifier, a PFC boost rectifier in higher-power products is less efficient than a DC-DC boost converter of the same input and output voltage. In lighting, task lamps that connect to a DC charging station with programmable power supply capability can use the charging station as the LED driver. Zone lighting can benefit greatly from series remote drivers, but further research must validate their feasibility. In all loads, DC input can allow for a great reduction in the size of the DC capacitors, and will also improve power quality. Further study is required to determine the full value of these secondary effects.

CHAPTER 4:
Reducing the Energy Use of Safety, Security, and Health Devices

1. Background and Introduction

An increasing number of energy-using devices are required to provide safety, security, and health functions. These include circuit breakers, AFCI/GFCI outlets and breakers, smoke alarms, carbon monoxide alarms, exit signs, and emergency lighting. This report uses the term Safety, Security, and Health Devices (or SSHDs) to describe them. These devices have been largely overlooked with respect to their energy consumption and opportunities for energy savings. Some SSHDs are specifically exempted from energy efficiency regulations (e.g., medical devices and security systems using external power supplies). Other SSHDs continuously consume electrical energy, even when the device is not providing its primary functionality. The lack of attention by policymakers is reasonable because the individual components typically draw very little power or they were not especially common (or both). Over time, however, the number of devices required by codes, or made commonplace through evolving medical policies, has increased dramatically, and new technologies have appeared that could enable lower energy consumption. These trends suggest that SSHDs deserve renewed attention to determine if significant energy savings are now feasible.

SSHDs represent one category in the collection of end uses called "miscellaneous electrical loads (MELs)" or "plug loads." One approach to understanding, and ultimately reducing, MELs energy use is to identify groups of devices with common characteristics, such as technologies, responsible authorities, or installers. This approach is likely to reduce costs of gathering data, understanding the industry, and developing energy-saving strategies. In the case of SSHDs, the common characteristic is the strong role played by authorities responsible for life safety, long-term health, and security. Their responsibility and power generally trumps the interests of energy conservation.

Chapter Organization

This report is organized as follows. It begins by defining SSHDs and explaining why they deserve to be considered as a unique category of devices. A list of important, or "priority," SSHDs are proposed. The priority devices are explored in terms of their governing regulations, functions, technologies, and energy use. Next, opportunities for reducing SSHD energy use are investigated and estimates of statewide energy savings are made. Finally, the results are summarized and recommendations are made for further actions to reduce SSHD energy use.

2. Safety, Security, and Health Devices in Buildings

SSHDs assure occupant safety and building integrity, both with respect to acute and chronic hazards. Table 7 lists prominent SSHDs and their functions. There are three main administrative categories of SSHDs: (1) those regulated by building codes and standards (hereafter referred to as "regulated SSHDs"), (2) those specifically exempted from energy efficiency standards (hereafter referred to as "exempted SSHDs"), and (3) other. Figure 41 shows how the SSHDs are divided among these administrative categories.

Table 7: Prominent Safety, Security, and Health Devices

Device	Purpose
Ground-Fault Circuit Interrupters (GFCI)	Protects people from electric shock, especially in presence of standing water
Arc-Fault Circuit Interrupters (AFCI)	Protects building from fires started by arcing wires
Smoke alarms	Warns occupants of fire and smoke
Carbon monoxide (CO) alarms	Warns occupants of dangerous CO levels
Security/Alarms	Detects and signals building intrusion ("burglar alarm")
Illuminated address signs	Ensures readability of street address at night
Garage door openers with battery backup	Ensures that people can evacuate during a power outage
Home oxygen concentrators	Concentrates oxygen from ambient air for use by people with low oxygen levels in their blood
Continuous positive airway pressure (CPAP) ventilators	Treats sleep apnea by providing continuous airway pressure during sleep
Exit signs	Illuminated displays to assist occupants in leaving a building during an emergency
Emergency lighting	Illumination to assist occupants in evacuation of a building when grid power has been interrupted

Device	Purpose
Mechanical ventilation fans	Ensures supply of fresh air and removal of moisture, pollutants, and odors
Radon mitigation fans	Controls indoor radon gas levels
Sump pumps	Removes water that has accumulated in a water-collecting sump, commonly found in basements
Sewage (ejector) pumps	Ejects and pumps sewage when plumbing fixtures are below grade of sewer line
Flood/leak alarms	Detects and signals standing water
Local Network Equipment	Provides network connectivity using devices such as modems, switches, routers, and optical network terminals

Figure 41: SSHDs by Administrative Category

Regulated SSHDs
— Smoke and carbon monoxide alarms
— Ground- and arc-fault circuit interrupters
— Exit signs
— Emergency lighting
— Mechanical ventilation
— Radon fans

Exempted SSHDs
— Security systems*
— Intercom devices*
— Medical devices*

* Only exempted if powered by an external power supply

Other SSHDs
— Flood sensors
— Sump pumps
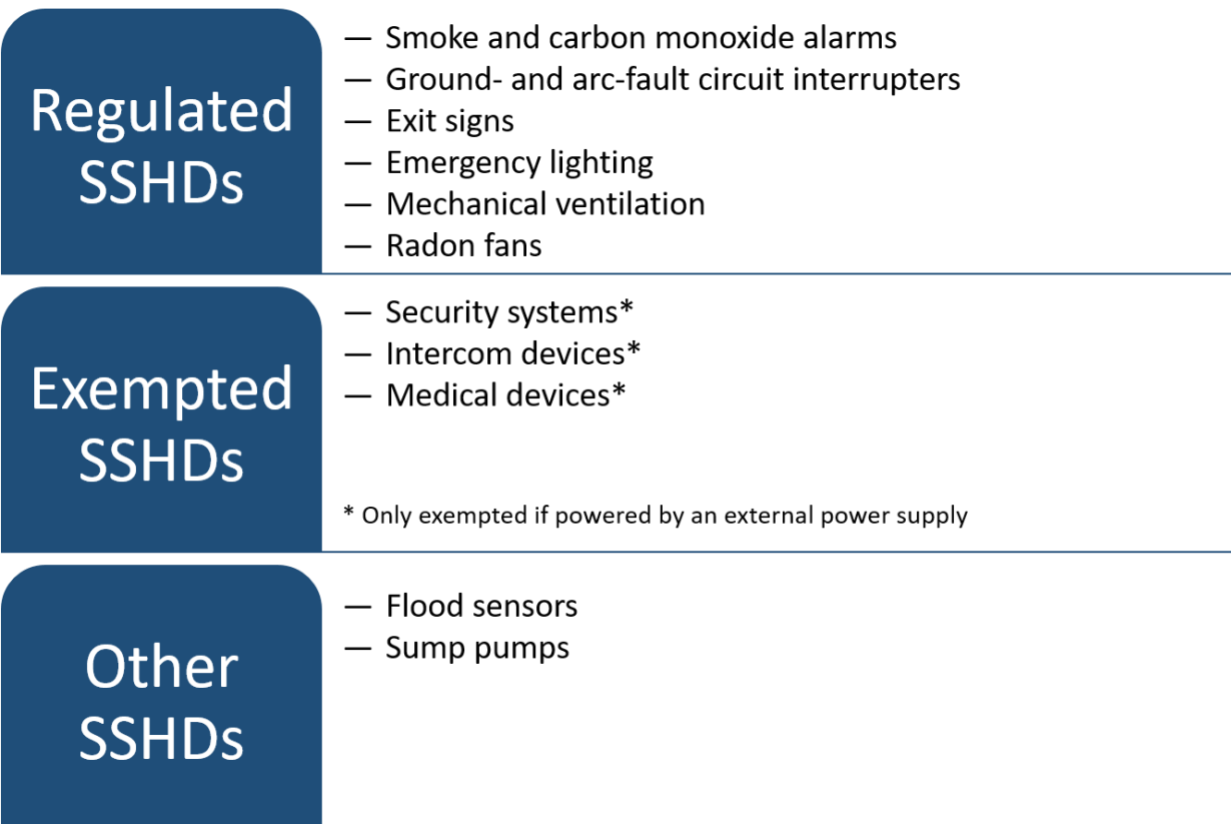
The list of SSHDs will grow. Recent California legislation (September 2018) mandates installation of back-up power with all new automatic garage door openers (Dodd 2018). This will enable garage doors to be opened in the event of a power failure (such as those caused by the Tubbs fire in 2017 and the Camp fire in 2018). However, maintaining the battery charge also adds several watts to the home's electricity use. Surveillance systems—wired and wireless—are emerging as a distinct product separate from other types of security systems. These units can easily draw 10 W (90 kWh/year). Some California communities require homes to have illuminated street address numbers. These lights can draw as much as 8 W (70 kWh/year). Most operate continuously because they lack switches or photo-controls.

Other devices are sure to enter this category. For example, a few advanced buildings have systems to counteract seismic forces or wind loads (Saaed et al. 2015). The seismic technologies are typically divided into passive, active, and hybrid approaches. Active systems—which are still rare—appear to require continuous power. Home medical equipment will become both more extensive and diverse in response to the rising costs of hospitalization and increasingly sophisticated automated health delivery equipment.

SSHDs and Energy Efficiency Regulations

Most of the SSHDs identified in this report are not covered under state or national energy efficiency standards. This can be partially attributed to enacted legislation from section 325(u)(3)(E) of the Energy Policy and Conservation Act, which concerns the "non-application of no-load mode energy efficiency standards to external power supplies for certain security or life safety alarms or surveillance systems." Under the provisions of section 325(u)(3)(E)(i)(I), smoke and carbon monoxide alarms, as well as security systems, fall under the definition of "security or life safety alarm or surveillance system." While smoke and carbon monoxide alarms are rarely powered by an external power supply, security systems typically are. Similarly, the 2016 California Appliance Efficiency Regulations (Baez et al. 2016) do not cover external power supplies that require Federal Food and Drug Administration (FDA) listing and approval as a medical device. Additionally, on January 23, 2017, the Power and Security Systems (PASS) Act— a bill which, in part, extends the currently expired energy conservation standards exemption for external power supplies for security or life safety systems until July 1, 2023—passed the House without amendment (U. S. Congress 2017).

California's Title 20 requires that all self-contained lighting controls—which are included in emergency lighting systems—manufactured on or after February 1, 2013, and having indicator lights that are integral to the system must use indicator lights that consume no more than 1 W per light. Additional regulations applying to the standby power consumption of emergency lighting systems were not found.

However, DOE does regulate the energy consumption of illuminated exit signs manufactured on or after January 1, 2006, which are currently required to have an input power demand of 5 W or less per face (10 CFR 431.206). Exception 2 to Section 140.8 of the 2016 California Building Energy Efficiency Standards for Residential and Nonresidential Buildings mandates that exit signs meet the requirements of the appliance efficiency regulations.

Existing Literature Pertaining to SSHD Energy Use

The existing literature on the power consumption of SSHDs is sparse and highly dispersed. The absence of literature is due partly to most devices drawing very little power (hence unimportant), being difficult to measure, or simply escaping notice. Sometimes manufacturers' specification sheets list power consumption for specific products, but these may be peak or

nameplate values. A few reports and white papers have been published that provide some insight into the power consumption of these devices. Table 8 summarizes the results of the literature search.

Table 8: Reported Power Consumption of Some SSHDs

Source	SSHD	Results
Permanent Electrical Loads in New Homes (Meier and Aillot 2016)	Various, including smoke alarms, AFCIs, and security systems	This paper covers, in some detail, many of the SSHDs discussed here. Of their measurements, most of the SSHDs consumed 4 W or less (Figure 3).
Eaton White Paper AP08324002E (effective July 2010) (Eaton 2010)	Circuit breakers	Results reported for numerous types and ampacities of molded-case circuit breakers (MCCBs). MCCBs rated at 20–40 amps use between 0 and 8 W (Table 27).
Natural Resources Defense Council (NRDC) Issue Paper 15-03-A (May 2015) (Delforge, Schmidt, and Schmidt 2015)	GFCI outlets and security systems	From a 10-home sample, GFCI outlets consumed an average of 1 W while security systems consumed an average of 8.2 W (Table 3).
LG&E Watt Finders Guide (LG&E 2018)	Smoke alarm	2 W
Low-Power Mode Energy Consumption in California Homes (CEC-500-2008-035, September 2008) (California Energy Commission 2008)	GFCI outlets and smoke alarms	GFCI outlets consume an average of 0.7 W and smoke alarms consume an average of 0.6 W.

The findings provided in Table 8 come mainly from outdated sources. There are also discrepancies among the reports. Nevertheless, the findings from these sources indicate that SSHDs have a continuous, non-trivial power draw. The remainder of the report draws upon additional sources for specific aspects and cites them as appropriate.

Priority SSHDs

Based on the literature search and preliminary calculations, 10 "priority" SSHDs were selected for further investigation. This group consists of both high numbers of users and high populations. Most of the devices are mainly in residential buildings, but two ubiquitous devices—exit signs and emergency lighting—are only in commercial buildings. Table 9 lists the priority SSHDs, the principal building sector in which they are installed, and regulations that cover them.

Table 9: Priority Devices Selected for Further Investigation in this Report

SSHD	Sector	Required by Building Code	Regulated by Energy Code	Exempted from Energy Code
		Regulation		
GFCIs	Residential	✓		
AFCIs	Residential	✓		
Smoke alarms	Residential	✓		
CO alarms	Residential	✓		
Security/Alarms	Residential			✓
Oxygen concentrators	Residential			✓
CPAP ventilators	Residential			✓
Mechanical ventilation	Residential	✓		
Exit signs	Commercial	✓	✓	
Emergency lighting	Commercial	✓		

3. Investigations of Priority SSHDs

Introduction

SSHDs provide a wide range of services, so it is not surprising that they rely on diverse and often esoteric technologies to accomplish them. The details of these technologies are poorly documented in the open literature and are sometimes proprietary. Many SSHDs are "hard-wired" into a building's electrical infrastructure and require special equipment to safely meter their electricity consumption and behavior—a simple Kill A Watt® meter available from many public libraries will not suffice. As a result, the only means of truly understanding their energy consumption and the opportunities for energy savings involves detailed physical investigation. These investigations involve direct inspection, measurement, and disassembly. This work also includes careful review of relevant codes, technical standards, and manufacturers' component specifications. For each of the priority devices, the codes, market situation, energy use, and other relevant issues were reviewed. Teardowns of selected SSHDs were performed and opportunities for improvements based on those investigations are discussed.

The technical specifications and performance of many SSHDs are covered by health and safety codes and standards, such those issued by the National Fire Prevention Association (NFPA), Underwriters Labs (UL), and the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE). These are typically referenced in state and local building codes. Table 10 summarizes the key health and safety codes applicable to the life safety devices.

Table 10: Residential Health and Safety Devices Required by Building Standards

Device	Code/Standard
Ground-Fault Circuit Interrupter (GFCI)	NFPA 70 UL 943
Arc-Fault Circuit Interrupter (AFCI)	NFPA 70 UL 1699
Smoke alarm	NFPA 101 UL 217
Carbon monoxide (CO) alarm	NFPA 720 UL 2034
Continuous mechanical ventilation	ASHRAE 62.2
Emergency lighting	UL 924
Exit signs	UL 924

These codes do not explicitly address the devices' energy consumption (although their specifications can affect it). For example, a minimum rate of air exchange can only be achieved by a ventilation system causing air movement that requires a minimum power.

Ground-Fault and Arc-Fault Circuit Interrupters

A GFCI is a device that detects an imbalance between the current in the hot and neutral lines of a circuit and disconnects the circuit before any harm can be done. The National Electric Code (NEC) first required residential outdoor receptacles be protected by GFCIs beginning in 1975 (Berman 2009). Since then numerous other receptacles in the home have been added, including those in bathrooms, kitchens, garages, basements, and crawlspaces. The GFCI can be integrated into both breakers and outlets, but because outlets are cheaper (and more user friendly), builders and contractors tend to use them almost exclusively (Figure 42). The current stock of residential GFCIs were calculated by estimating the number of GFCIs installed in new construction for each year since 1980 using the code requirement at the time and the number of new housing units. It is estimated that there are currently over 23 million GFCIs in California homes and that the average new home has eight (although this can easily be many as 15). A contractor can reduce the number of GFCIs by daisy-chaining nearby outlets or using a breaker. The estimated stock of GFCIs is conservative because it includes only single-family homes and excludes GFCIs installed during renovations. In addition, commercial buildings are

not included. The actual number could be over 50 million. This information was used to estimate statewide energy use in Table 16, in Chapter 4.

Figure 42: Ground-Fault and Arc-Fault Circuit Interrupters

While the purpose of a GFCI is to prevent electrical shock, the primary purpose of an AFCI is to prevent fires. It does this by continually analyzing the circuit waveform for characteristics known to be associated with wire arcing. The NEC first required that bedroom outlet circuits be protected by AFCIs in 2002 and extended the requirement to all outlets in new homes beginning in 2008 (Tuite 2007). Because AFCIs protect the wire, not the device or person, they are almost exclusively used in breakers, although an outlet AFCI will protect appliance cords and extension cords plugged into it. Using the same method as for GFCIs, it is estimated that about 4.7 million AFCIs are in California's homes and that the average new house has four AFCIs.

According to Section 210.8 of the 2016 California Electric Code and the 2014 and 2017 National Electric Codes (NFPA 70), circuits in various locations in dwelling and non-dwelling units (e.g., bathrooms, kitchens, crawl spaces, and garages), as well as boat hoists, kitchen dishwasher branch circuits, and crawl space lighting outlets are required to be protected by GFCIs under certain conditions. Similarly, for AFCIs, Section 210.12 of the 2016 California Electric Code and the 2014 and 2017 National Electric Codes (NFPA 70) requires circuits in various locations in dwelling units (e.g., bathrooms, kitchens, family rooms, dining rooms, and bedrooms), as well as dormitory units, guest rooms and guest suites, and branch-circuit extensions or modifications to dwelling and dormitory units to be protected by AFCIs under certain conditions.

Smoke and Carbon Monoxide Alarms

Residential smoke alarms detect smoke and emit an audible alarm when smoke is detected (Figure 43). They employ two types of sensing technology: ionization, which uses a radioisotope to ionize air molecules, and photoelectric, which operate on a light scattering principle. The first modern ionization smoke alarm became available for use in 1963, but their widespread use in residential homes did not begin until the early 1970s (U. S. Nuclear Regulatory Commission 2017). Smoke alarms were first required in homes starting in 1976 and the requirements were extended to all bedrooms starting in 1988 (Public/Private Fire Safety Council 2006). Using the same method for estimating stock as for GFCIs, it is estimated that 19.5 million hardwired smoke alarms are in California homes and that the average new house has five smoke alarms.

Figure 43: A Smoke and Carbon Monoxide Alarm

According to Section 907.2 of the 2016 California Fire Code and 2015 International Fire Code, smoke alarms in new construction shall receive their primary power from the building wiring, shall have a battery backup, and shall be interconnected with other smoke alarms in locations where more than one smoke alarm is required to be installed. Furthermore, Sections 29.5 and 29.6 of the 2016 National Fire Code (NFPA 72) require alarms and heat alarms to be interconnected and also require household fire alarm systems to have two independent power sources consisting of a primary source (such as mains power) and a secondary source (such as a battery). Finally, Section 9.6 of the 2018 Life Safety Code (NFPA 101) references NFPA 72 for the power requirements of smoke alarms, other than those permitted by other sections of NFPA 101 to be battery-operated.

Carbon monoxide (CO) alarms detect the presence of CO gas, usually due to malfunctioning gas-fired equipment such as furnaces and water heaters. They are a much more recent addition to homes than smoke alarms, being required by AB 183 starting in 2011 (State of California 2010). Gundel et al. (1998) indicates that three types of CO sensor can be used: biomimetic, metal oxide sensor (MOS), and electrochemical cell. Section 4.5 of the 2015 National Standard for the Installation of Carbon Monoxide (CO) Detection and Warning Equipment (NFPA 720) requires that unless the CO alarm is installed with an uninterruptible power supply (central battery backup), it must have at least two independent and reliable power supplies. The primary power supply must be a branch circuit supplying no other loads. Additionally, Sections 915.4 and 915.5 of the 2016 California Fire Code and 2015 International Fire Code require that

carbon monoxide alarms receive their primary power from the building wiring (with a secondary battery backup), and alarms are required to be interconnected in locations where multiple alarms are required. Using the same method as for GFCIs, it is estimated that 0.8 million hardwired CO alarms are in California homes and that the average new house has two alarms.

Both smoke and CO alarms are required to be hard-wired in new construction projects in California, as well as in other states that have adopted these regulations.

Security and Alarms

Home security systems (Figure 44) detect a variety of building conditions and intrusions and then signal an audible or electronic alarm when an intrusion occurs. These systems consist of many components, which are linked either through wires or wirelessly. Components include power supplies, battery chargers, controls, keypads, communication hardware, active and passive sensors, and cameras (and illumination for them). Common sensors include motion detectors, occupancy sensors, and door and window sensors. Alarm controls are typically powered by one or two 24 VAC transformers that keep the backup battery charged. Measured energy use of security systems is mostly anecdotal from single devices or small samples. Partly this is due to the difficulty in measuring a product that has to be itself secure. For this analysis it is assumed that security systems used 8.2 W (Delforge et al. 2015) and that 20 percent of single-family homes, or 1.8 million, had one (Security System News 2009).

Figure 44: A Home Security System

Oxygen Concentrators

About 1.8 million Californians have chronic obstructive pulmonary diseases (COPD) such as bronchitis and emphysema (U. S. Centers for Disease Control and Prevention n.d.). Many of these people will require home oxygen therapy to help them breathe, mitigate the symptoms of their disease, or slow disease progression. The oxygen required is typically delivered by an oxygen concentrator (Figure 45), which removes nitrogen from the air using an air compressor to drive a pressure swing adsorption (PSA) cycle. The PSA cycle is an energy intensive process, but its total cost is lower than other oxygen systems, such as high-pressure cylinders or cryogenic liquid, which they have mostly replaced for home use. Oxygen concentrators are available as both stationary, mains-powered and portable, battery-powered devices. They can

deliver 1 to 10 liters per minute of oxygen and draw 70–450 W, typically continuously, corresponding to 600-4,000 kWh/year. Portable units typically draw less power than stationary units and can further reduce power use by delivering oxygen using a "pulse" when the user inhales. Rated power use of stationary units appears to be well correlated with rated capacity, averaging 70 W/l/minute (Table 11). What is unknown is how reducing oxygen flow affects power use (how proportional the power use is). It appears that, at best, power is weakly proportional, so assuming rated power for all operating hours may be reasonable. The large range in energy use indicates that there may be energy saving opportunities, such as using portable technology in stationary devices and controlling the oxygen delivery rate more intelligently.

Figure 45: A Stationary Oxygen Concentrator

About 18.5 percent of Medicare patients with COPD used sustained oxygen therapy in 2010 (Nishi et al. 2015). Assuming the same rate for the general population and applying it to the 1.8 million California COPD patients results in an estimate of 320,000 oxygen concentrators in California.

Table 11: Power Use of Stationary Oxygen Concentrators

Concentrator	Capacity (l/min)	Power (W)	Normalized Power (W/l/min)
Philips Everflow 1020001	5	350	70
Philips Millennium 605	5	450	90
AirSep NewLife Elite 5	5	350	70
AIRSEP® VISIONAIRE™	3	175	58
AIRSEP® NEWLIFE® INTENSITY	10	590	59

CPAP Ventilators

About 22 million Americans suffer from sleep apnea—a temporary cessation of breathing while sleeping. Continuous positive airway pressure (CPAP) ventilators (Figure 46) are used to treat sleep apnea by providing continuous airway pressure during sleep. In addition to the air pump, CPAP machines have heaters and humidifiers to condition the ambient air when it is cold or dry. Heaters and humidifiers add significantly to CPAP energy use and may be responsible for the majority of it. New CPAPs have data collection and upload features (through Wi-Fi or cellular networks) that enable health providers and patients to monitor their usage. The data features and displays also contribute to continuous energy use.

Figure 46: A CPAP Ventilator

CPAP machines draw 10–100 W (depending on the selected pressure, temperature, and humidity) but are used at most 8 hours per day. Therefore, a CPAP's annual electricity use is 30–300 kWh/year. It is estimated that 80 percent of the cases of moderate and severe obstructive sleep apnea go undiagnosed and 50 percent of the people diagnosed with disordered breathing actually use the recommended CPAP device. By combining these factors, it is estimated that there are approximately 260,000 CPAP ventilators in use in California.

Exit Signs

Although exit signs (Figure 47) have been ubiquitous in non-residential buildings since the 1940s, their characteristics have changed significantly. Modern exit signs are either LED or electroluminescent (which can use as little as 0.25 W) and have integrated battery backup. According to Section 1013.6 of the 2016 California Fire Code and 2015 International Fire Code,

exit signs shall be illuminated at all times (requiring continuous primary power), and they must be connected to an emergency power system in the event of primary power loss. Based on an audit of a 60,000 square foot office building, it is estimated that there are 0.73 exit signs per thousand square feet, which results in an estimate of 6 million exit signs in California. This information is used to estimate statewide energy use in Table 16, in Chapter 4.

Figure 47: Exit Sign

Emergency Lighting

Emergency lighting (Figure 48) is used to illuminate egress pathways in the case of power failure. They typically consist of either stand-alone wall mounted units or battery-backed ballasts in existing fixtures. Requirements for emergency lighting can be found in national building codes as far back as the 1920s (Wilson 2012).

Figure 48: Emergency Lighting

According to Section 1008.3 of the 2016 California Building Code, an emergency electrical system shall automatically illuminate specific areas of buildings, rooms, and spaces for a duration of at least 90 minutes in the event of primary power failure in buildings, rooms, and spaces that require at least two means of egress. Furthermore, this emergency power system shall consist of storage batteries or an on-site generator. Section 7.9 of the 2018 Life Safety Code also specifies various locations for which emergency lighting for means of egress must be provided, along with specific performance requirements (i.e., illumination levels and duration). Based on the same audit as for exit signs it is estimated that there are 0.86 emergency lights per 1,000 square feet, which results in an estimate of 7 million emergency lights in California.

Mechanical Ventilation

Beginning in 2009, the California Building Energy Standards (Title 24, Part 6) adopted requirements for mechanical ventilation based on ASHRAE 62.2 (Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings). The ventilation can be provided in a number of ways, including balanced (heat recovery ventilators and energy recovery ventilators), supply only (integrated into the HVAC system), and exhaust only (a dedicated exhaust fan, typically in the bathroom). Home builders typically select the exhaust-only method because it is the cheapest to purchase and install. Exhaust-only ventilation is intended to operate continuously, thereby increasing electricity consumption. However, field studies have shown that up to 75 percent of systems are disabled by the occupants (Walker et al. 2019), presumably to avoid drafts, thermal discomfort and noise, and to save energy. Mechanical ventilation was first required in the 2009 code, so it is assumed that it would begin to be used in 2011 new homes, resulting in 400,000 systems. This number was reduced to 25 percent to reflect actual usage rates.

Detailed Analysis of Residential Life Safety SSHDs

Four categories of the priority SSHDs were subjected to detailed measurement and analysis: GFCIs, AFCIs, smoke alarms, and CO alarms. All of them are life safety devices that have been required in new homes for many years (often in many locations). In new construction they are nearly always hardwired (that is, installed as a permanent part of the home's electrical infrastructure) and thus difficult to measure. These SSHDs are fully mature, commodity items (though IoT technology may change them in the future).

As a first step, the market was surveyed by reviewing the types of devices available and the features that might influence energy usage, such as basic configuration, manufacturer, and options. Table 12 shows the range of manufacturers and options that are readily available for each category of device. Two to five major manufacturers typically offer products and are readily available, although as many as 10 manufacturers were identified in each category.

Options vary depending on the category of device. Both AFCIs and GFCIs can have various combinations of LEDs to indicate the state of operation, while currently only GFCI outlets are required to have a self-test capability. Both smoke and CO alarms can use different types of sensors. For smoke alarms the primary sensors are ionization and photoelectric or a combination of the two. Only CO alarms with electrochemical sensors were found to be available.

All alarms installed in new homes are required to be networked and most use a simple 9 V hard-wired network, but there are also wireless devices available that use either proprietary RF or Wi-Fi. In addition to these basic options, some CO alarms can have a digital display of CO levels, and some alarms can have voice annunciators instead of or in addition to the traditional alarm.

Table 12: Market Survey of Residential Life Safety Devices

Device Category	Number of Manufacturers	Self Test	Indicator Light
GFCI outlet	4	Yes/No	Yes/No
GFCI breaker	4		Yes/No
AFCI outlet	2	Yes/No	Yes/No
AFCI breaker	4		Yes/No
AFCI/GFCI outlet	3	Yes/No	Yes/No
AFCI/GFCI breaker	4		Yes/No

Device Category	Number of Manufacturers	Sensor Type	Network	Other
Smoke alarm	5	Ionization Photoelectric Dual	Wire, RF, Wi-Fi	Voice
CO alarm	4	Biomimetic Metal oxide semiconductor (MOS) Electrochemical	Wire, RF, Wi-Fi	Display
Smoke/CO alarm	4	Photoelectric/electrochemical Split-spectrum/electrochemical Proprietary	Wire, RF, Wi-Fi	Voice

The goal of the testing was to identify the effect of technology options on energy use and to then infer available efficiency improvements. Given the broad range of devices and options, a sparse test matrix of devices was developed. For each category of device, a base configuration of product was selected and as many manufacturers as possible with this configuration were identified. Then one manufacturer was selected and a number of other configurations were identified to see what effect they might have on energy use. Table 13 shows an example matrix for smoke alarms. Initially 35 products were identified to purchase. However, during the purchase process, 10 were not available and had to be replaced with equivalent devices. Replacements were available for all but one product. Table 14 shows a summary of the final set of 34 products. (A full list, along with the manufacturer, cost, and options, are provided in Appendix A.)

Table 13: Smoke Alarm Test Matrix

Manufacturer	Sensor Type			Interconnection	
	Photoelectric (Base)	Ionization	Dual	Wired (Base)	RF
A1 (Base)	✓	✓	✓	✓	✓
A2	✓			✓	
A3	✓			✓	
A4	✓			✓	

Table 14: Summary of Residential Life Safety SSHDs Tested

Device Category	Number of Devices	Number of Manufacturers	Base Configuration	Additional Options
GFCI outlet	5	5	LED, Self-test	-
GFCI breaker	3	3	-	-
AFCI outlet	2	2	LED	-
AFCI breaker	3	3	LED	-
AFCI/GFCI outlet	2	2	LED, Self-test	-
AFCI/GFCI breaker	2	2	LED	-
Smoke alarm	7	4	Ionization, LED, Wired	Photoelectric, dual, RF
CO alarm	4	3	Electrochemical, LED, Wired	Display, no interconnect
Smoke/CO alarm	6	4	Photoelectric / electrochemical, LED, Wired	Voice, RF, Wi-Fi

Measurement Procedure

Because all of the residential life safety SSHDs were hard-wired it was necessary to construct a measurement fixture for each category of device to safely measure their power consumption. The GFCI and AFCI outlets and the alarms were mounted to a single-gang junction box wired with a short appliance cord with a NEMA 5-15 plug. The breakers were each mounted in one of three small load centers (one for each type of breaker) that were wired similarly to the duplex box. The junction box test fixture and one of the load center test fixtures are shown in Figure 49.
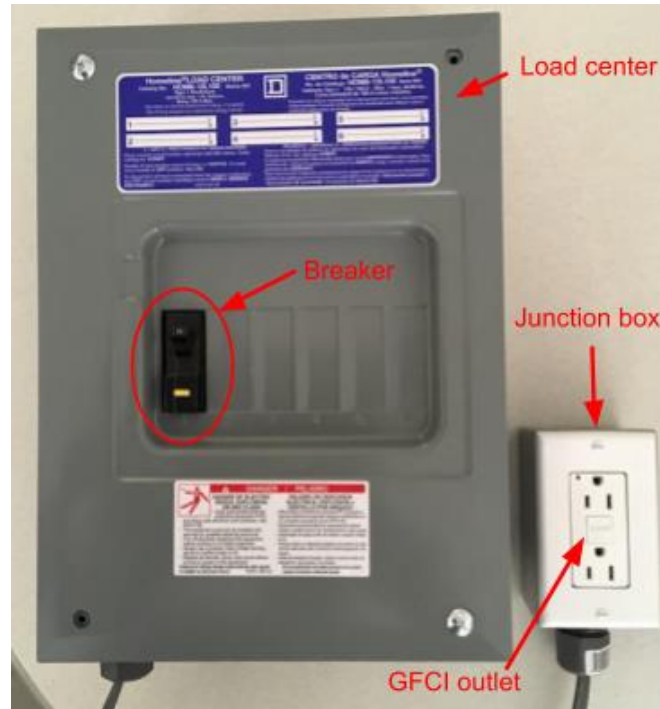
Figure 49: Test Fixtures

Junction box on the right and one of the load centers on the left.

Power was measured using a Chroma 66202 Digital Power Meter which can measure power to 0.1 mW resolution with an accuracy of 0.1 percent of reading ∓0.1 percent of range. The devices under test were connected to the power meter using the Chroma A662003 measurement test fixture, which is used for measuring plug loads (Figure 50). Data were recorded on a one-second basis using the Chroma Soft Panel software running on an attached PC. Data points recorded included voltage, current (amps), average power (watts), apparent power factor, total harmonic distortion of the current (THDi), and total harmonic distortion of the voltage (THDv).

Figure 50: Power Measurement Test Configuration

A smoke alarm is mounted to the junction box test fixture, which is connected to the Chroma 66202 digital power meter using the A662003 measurement test fixture.

To accurately and repeatedly measure the energy use of the residential life safety SSHDs a test method based on IEC 62301 was developed (see Appendix B-2). Each device was measured for 10 minutes continuously and then data gathered during the last 5 minutes of the test period were used to calculate the results (with the first 5 minutes acting as a warm-up period). Since the controls of GFCI and AFCI outlets are on the line side, they were measured in both set and tripped mode (breakers have the controls on the load side and thus have no energy use in tripped mode). The alarms equipped with wireless networking were measured in both connected and non-connected modes. For all devices the status of all lights and displays were noted and a picture of the voltage and current waveforms was recorded (an example is shown in Figure 51).

Figure 51: Example Current and Voltage Waveforms from a Smoke Alarm
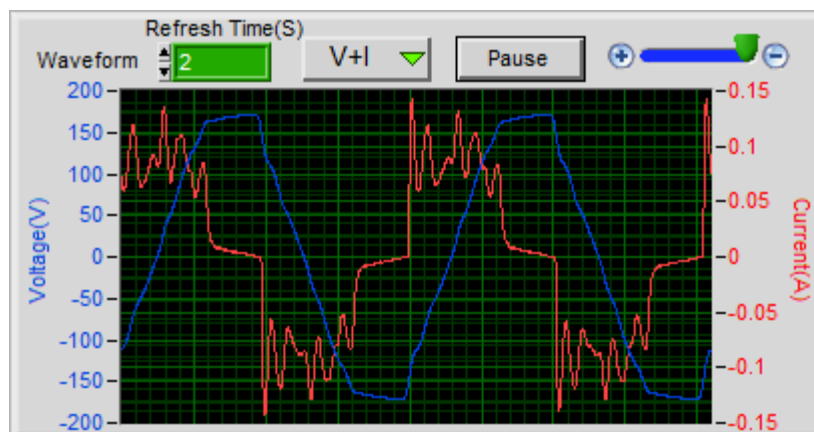
Some additional calculations were performed In addition to the recorded data. To verify that the power mode was stable, a linear regression of the power with respect to time was performed with the slope required to be less than 1 percent. Power use of the device was calculated as the mean of the 5-minute power measurements. The measured power factor is the apparent power factor (pf_{app}), the ratio of the real power to apparent power, which is made up of two components: the distortion power factor (pf_{dist}) and the displacement power factor (pf_{disp}). The distortion power factor was calculated from measured THDi using equation 4 and the displacement power factor was calculated using equation 5.

$$\frac{1}{\left(\left(1+\left(\frac{THDi}{100}\right)^2\right)^{0.5}\right)} \frac{1}{\left(\left(1+\left(\frac{THDi}{100}\right)^2\right)^{0.5}\right)} \frac{1}{\left(\left(1+\left(\frac{THDi}{100}\right)^2\right)^{0.5}\right)} pf_{dist} =$$

$$\frac{1}{\sqrt{1+\left(\frac{THDi}{100}\right)^2}} \qquad\qquad \text{(Eq. 4)}$$

$$pf_{disp} \frac{pf_{app}}{pf_{dist}} \frac{pf_{app}}{pf_{dist}} \frac{pf_{app}}{pf_{dist}} = \frac{pf_{app}}{pf_{dist}} \qquad \text{(Eq. 5)}$$

Findings

Power use for all residential life safety SSHDs was very consistent and stable (for example see Figure 51). Linear regression of the power with respect to time resulted in slopes averaging—2.3 x 10^{-4} W/s (IEC62301 requires a slope of less than 10^{-2}), and no device had a slope greater than -6.6 x 10^{-4} W/s. A summary of the results of the testing are summarized in Table 15 (A full set of results is provided in Appendix B. For each device category Table 15 lists the device power (average, minimum, and maximum within the category) and power factor (average, minimum, and maximum within the category). Note that the average power for each category is quite similar, averaging 0.72 ±0.15 W (20 percent). But the power use of individual devices within each category can differ by as much as a factor of five.

Another observation is that multiple-function devices such as GFCI/AFCI outlets and smoke/CO alarms do not typically use more energy than single-function devices; in fact, they often use less (Figure 52).

Table 15: Summary of Test Results

Device Category	N	Average Power (W)	Minimum Power (W)	Maximum Power (W)	Average Power Factor	Minimum Power Factor	Maximum Power Factor
GFCI breaker	3	0.60	0.56	0.65	0.84	0.53	0.99
AFCI breaker	3	0.73	0.65	0.84	0.65	0.12	0.99
GFCI/AFCI breaker	2	0.79	0.25	1.34	0.27	0.20	0.35
GFCI outlet	5	0.81	0.53	1.01	0.92	0.72	1.00
AFCI outlet	2	0.80	0.79	0.81	0.45	0.12	0.78
GFCI/AFCI outlet	2	0.69	0.36	1.01	0.71	0.61	0.81
Smoke alarm	7	0.89	0.31	1.19	0.25	0.11	0.71
CO alarm	4	0.58	0.40	0.79	0.25	0.08	0.41
Smoke/CO alarm	6	0.62	0.31	1.23	0.29	0.09	0.51

Figure 52: Comparison of GFCI Outlet Power
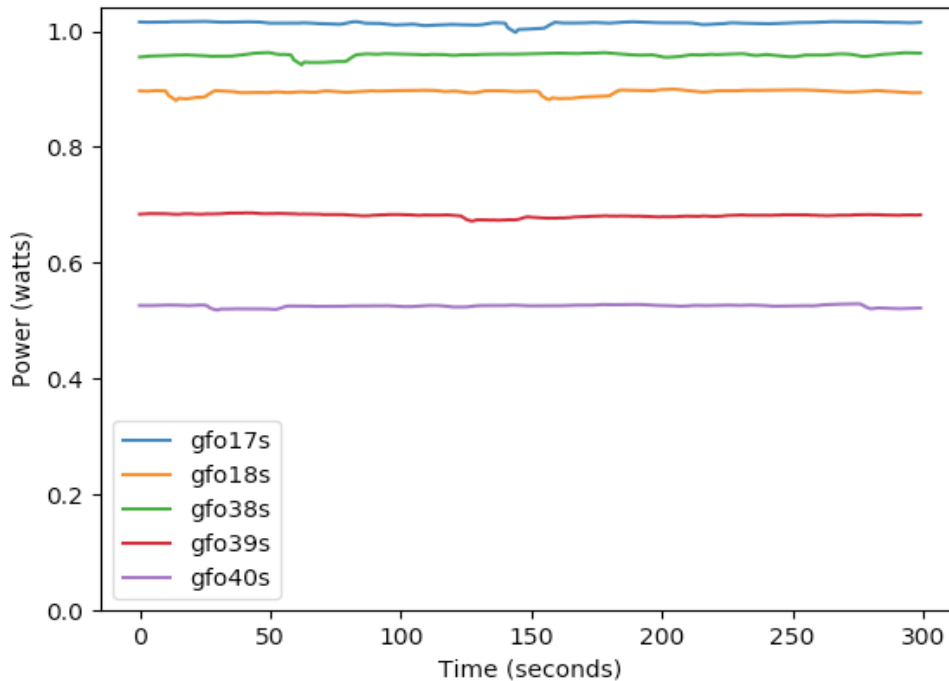
The variation in power factors is also of interest as they vary immensely, ranging from 0.08 to 1.00. It was expected that low power factor might indicate low quality and possibly higher power use; instead, the results showed that power factor was not at all correlated with power use (Figure 53). Even among the lowest power factor devices (<0.25), power ranged from 0.4–1.4 W.

75

Figure 53: Plot of Power Factor with Respect to Power for All Tested SSHDs
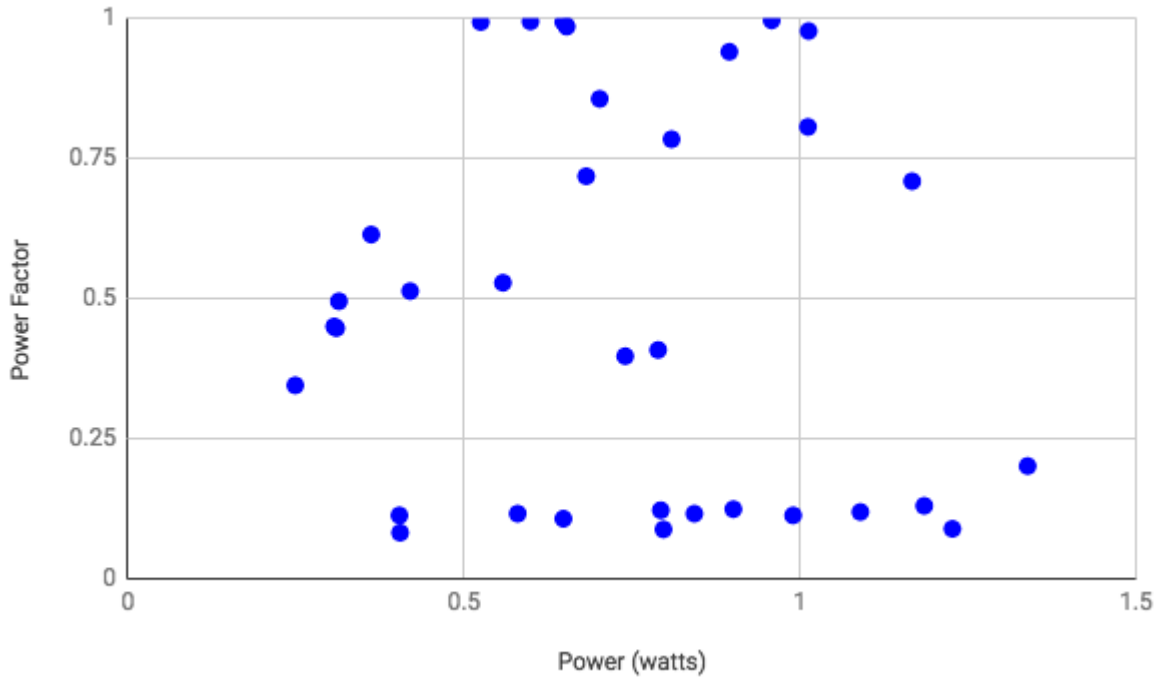
Although low power factors in residential equipment are typically not an issue to the utility, the power factor and waveforms of a device can be used to infer the type of power supply that is used. Five different categories of waveforms produced by the measured devices were identified (Figure 54). Waveform A (resistance) is most likely a resistance voltage divider. Seven outlets and breakers have this waveform and all have almost unity power factor. Waveform B (half-wave) is most likely a half-wave rectifier. Ten devices of all types have this waveform, and power factor can vary from 0.17 to 0.72. Waveform C (Noisy) is most likely an RC voltage divider. Ten alarms and two breakers have this waveform, which has the worst power factor of all, almost entirely displacement due to the capacitor. There are no obvious interpretations for waveform D (square) and waveform E (smooth), but each is used by only one manufacturer.

Figure 54: Selected SSHD Voltage and Current Waveforms

A: Resistance - N = 7, Average PF = 0.98
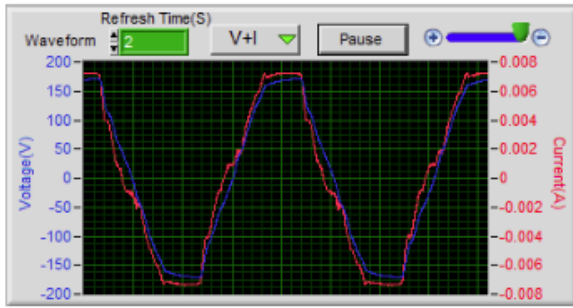
D: Square - N = 3, Average PF = 0.82
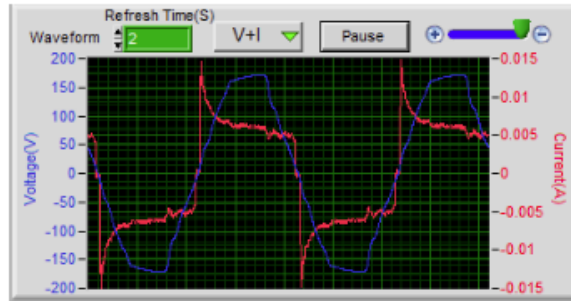
B: Half-wave - N = 10, Average PF = 0.44
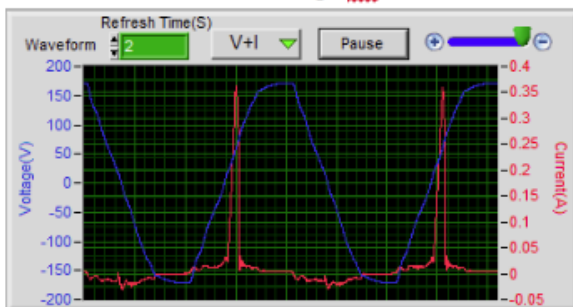
E: Smooth - N = 2, Average PF = 0.40
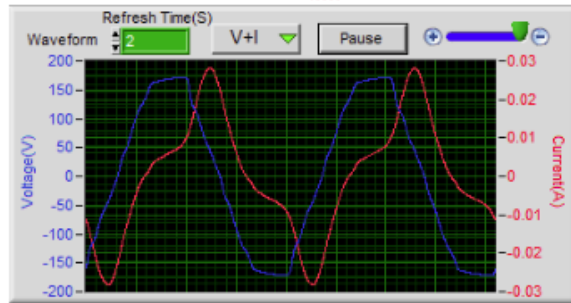
C: Noisy - N = 12, Average PF = 0.16
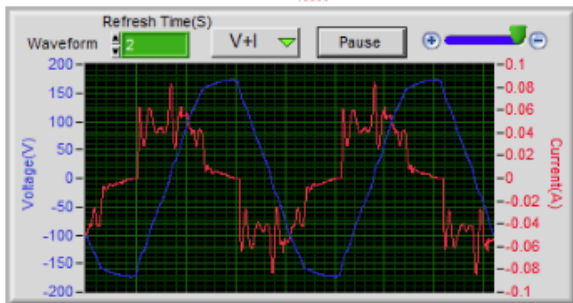
Explanations were sought for the variation in power use (Figure 55), including manufacturer, cost, category, waveform, and power factor. No significant correlations were identified other than a very weak one for cost, as shown in Figure 56. Note that although the relationship is quite weak ($R^2 < 0.2$) and mostly driven by the two higher cost devices, it does show that while at low costs (< \$25) you cannot find low power use (< 0.5 W), and higher costs (> \$25) do not guarantee low power use.

Figure 55: Measured Power Consumption of SSHDs
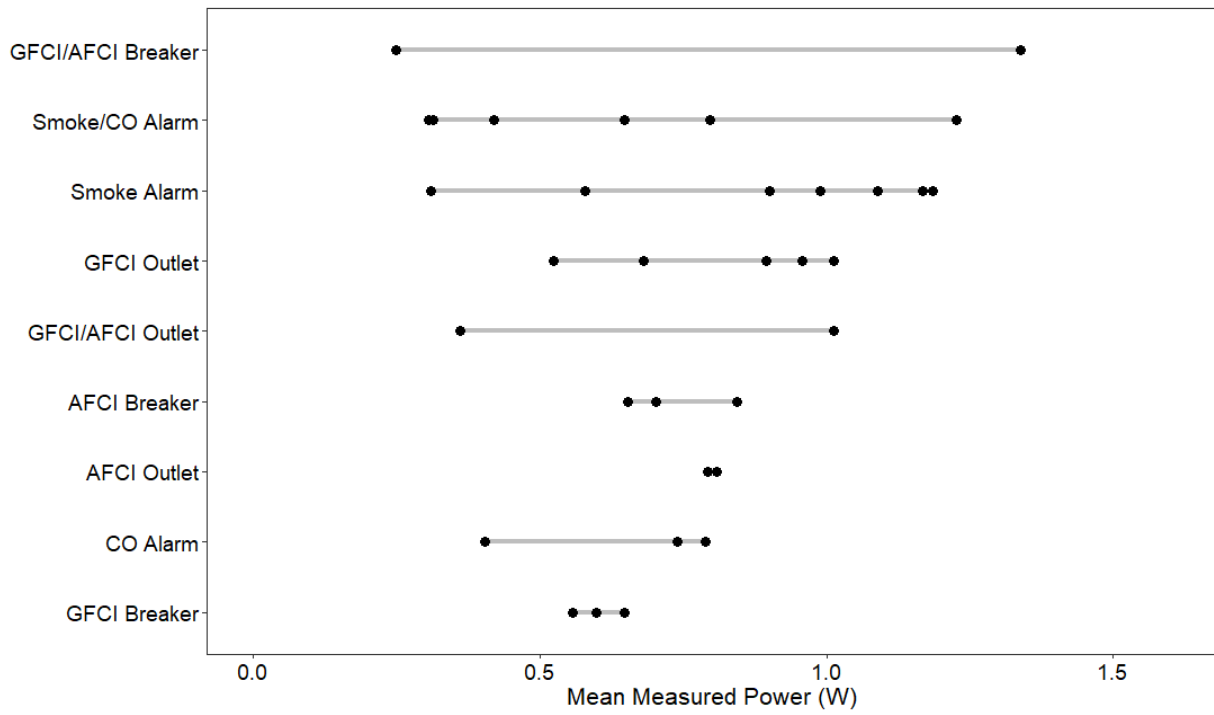
Figure 56: Relationship of SSHD Power Use to Cost

Teardowns

Based on data gathered during testing of the residential life safety SSHDs, five devices were selected for teardowns to try to determine what design factors affected device power use (Table 16). Low-power devices were selected for teardown because they indicated the minimal power use for their application out of the devices on the market. Examining the lower power devices allowed us to determine potential areas of further power saving. On the other hand, high-power devices were selected for teardown to contrast them with the low-power ones. Examination of the high-power devices and comparisons to the low-power devices helped explain why some devices use more power than others.

Table 16: SSHDs Selected for Teardown

Device ID	Category	Power (W)	Power Factor	Cost ($)	Power Supply	Selection Reason
GFO17	GFCI outlet	1.01	0.98	14	Voltage divider	High power
GFO38	GFCI outlet	0.96	0.96	14	Voltage divider	High power
AGO31	AFCI/GFCI outlet	0.36	0.61	30	Half-wave	Low power
SMA36	Smoke alarm	0.99	0.11	20	RC divider	High power
SMA07	Smoke alarm	0.31	0.45	50	Switcher	Low power

Outlet Teardowns

Several outlets were disassembled to better understand how they were designed and which components used energy.

Figure 57 shows the teardown of the GFO38 GFCI outlet. The mechanical circuit turned out to be slightly complex. One of the initial suspicions of static power draw from GFCIs and AFCIs was that the relay is normally open, requiring power to hold them closed. From examining the mechanical circuit, however, that was not found to be the case. The mechanical circuit featured a bistable latching mechanism involving two spring forces.

Figure 57: GFO38 GFCI Outlet Teardown
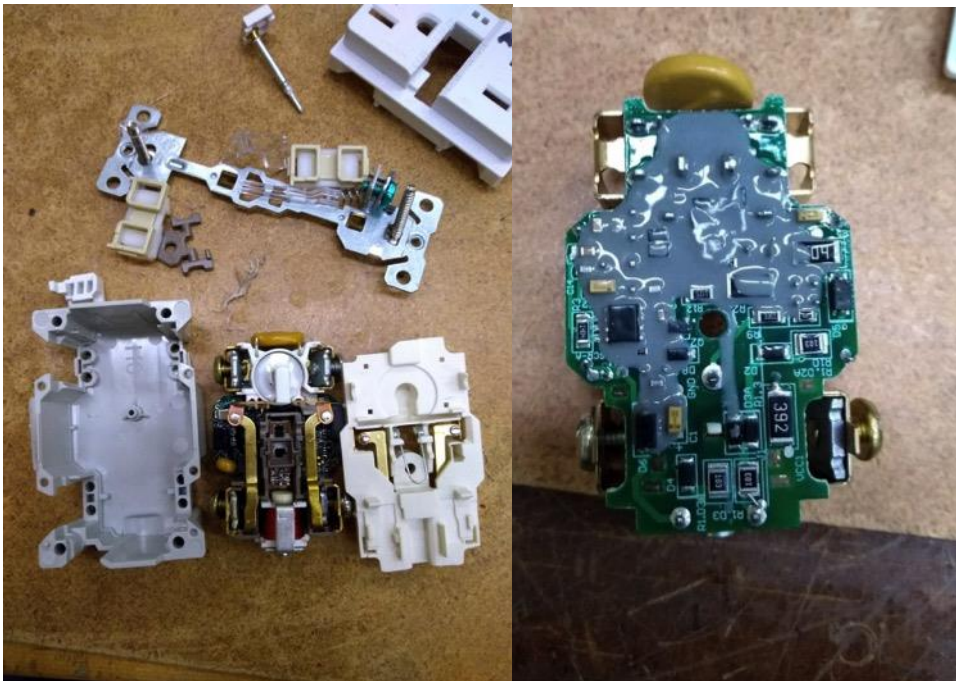
On the left is the mechanical circuit, and on the right is the electrical circuit.

On the electrical side, the GFO38 uses a GFCI IC in the 8-SOP package to implement the ground fault detection logic. GFCI ICs such as the Fairchild RV4141A draw tens of milliwatts of power and do not explain the 300–1,000 mW power draw measured. The power supply to power the circuit is deduced from looking at the device's input current and voltage waveforms and also the circuit components. For this device, the power supply is determined to be a full wave rectifier with a series resistor to convert 120 V into a lower voltage. If the lower voltage is 10 times lower than the line voltage, then the power supply efficiency using such a circuit is at most 10 percent efficient. Additionally, the low voltage is unregulated.

Figure 58 shows the teardown of the AGO31 AFCI/GFCI outlet, which has the dual functionality of ground fault and arc fault detection. Manufactured by the same company as the GFO38, the mechanical circuits for both were found to be the same, so the mechanical circuit is not pictured. The electrical circuit is much more complex than that of the GFO38 because it detects arc faults, which requires signal processing. Signal processing in turn requires a microcontroller, and a microcontroller requires a stable, regulated voltage.

Figure 58: AGO31 AFCI/GFCI Outlet Teardown—Electrical Circuit
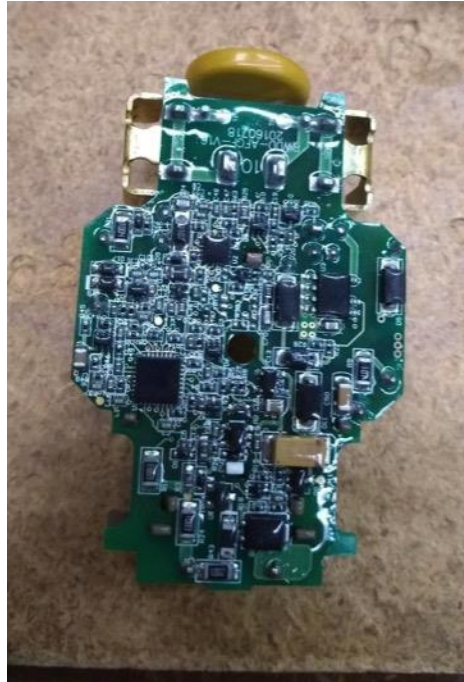
The power supply for the AGO31 is deduced to be a half wave rectifier stage cascaded with a Buck converter from the input voltage and current waveforms and the identification of an inductor on the printed circuit board (PCB). Buck converters are much more efficient than using a resistive voltage divider. Additionally, feedback control can be used to regulate the output voltage.

Figure 59 shows the teardown of the GFO17 GFCI outlet. A different mechanical latching mechanism from the GFO38 and AGO31 was found. A possible IC used is On Semiconductor NCS37010. The circuit uses a silicon controlled rectifier (SCR) to drive a solenoid that triggers the bistable mechanical circuit, the same process as the previous devices. The power supply of this device and the GFO38 were determined to be very similar. A full wave diode bridge IC can be seen near the upper left, and the resistance to convert voltages can be seen to the right of it in the form of surface mounted device (SMD) resistors labeled "E81."

Figure 59: GFO17 GFCI Outlet Teardown—Electrical Circuit

Smoke Alarm Teardowns

Figure 60 shows the teardown of the SMA36, a photoelectric smoke alarm with no wireless networking functionality. It is deduced that the power supply for this device is a resistance-capacitive voltage divider. Cost is most likely the driving factor behind the choice of this circuit.

Figure 60: Teardown of the SMA36 Smoke Alarm—Electric Circuit

Figure 61 shows the teardown of the SMA07, a photoelectric smoke alarm with wireless networking. There were three PCBs: a main board, the power supply board, and the wireless board. The power supply topology is a Buck converter. The power supply board outputs two voltages: 9 V and 3.6 V. The 9 V output is not well regulated, but the 3.6 V output is. The efficiency curves of both outputs were measured and can be seen in Figure 62.

Figure 61: Teardown of the SMA07 Smoke Alarm

From top left clockwise: main PCB, power PCB, and wireless PCB.

Figure 62: SMA07 Smoke Alarm Power Board Efficiency Curves
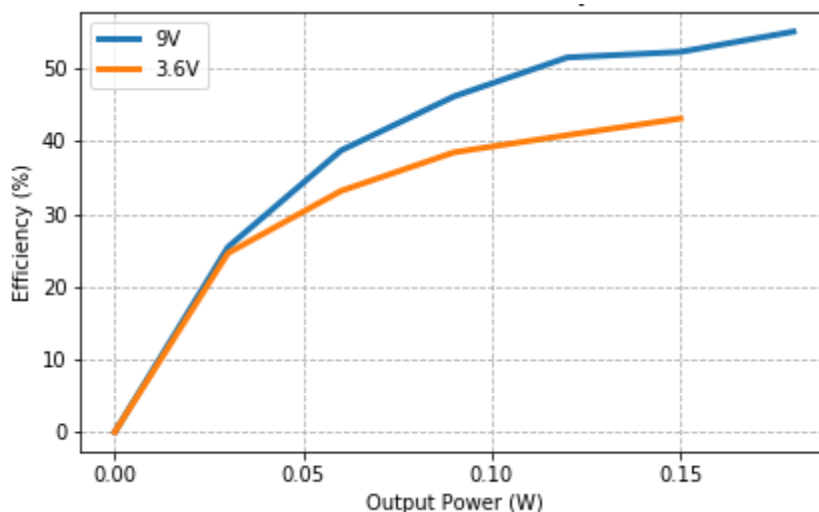
Overall Observations

Surprisingly, the smoke alarms and outlets that had more functionality were found to consume less power. While the SMA07 smoke alarm had wireless networking functionality, it consumed less power than all other smoke alarms. Additionally, the AGO31 arc fault / ground fault outlet consumed less power than other ground fault outlets. It was found that in the more complex devices, Buck converters were being used, probably due to the presence of microcontrollers. The microcontrollers require better quality and regulated power, which cannot be provided by cheaper solutions such as using a resistive divider. Buck converters are able to be much more efficient.

The findings from the teardown suggest that most of the power loss is due to the power supply inefficiencies. Supporting this statement is the existence of battery-powered smoke alarms that last several years on one battery. Those smoke alarms draw milliwatts or even less power. Being powered from a battery results in much simpler circuitry, as the battery voltage is already low voltage. When the device is connected to line power, however, there must be additional power electronics to convert between 120 VAC and low voltage. To remain cheap, manufacturers have chosen simple but inefficient methods of achieving that voltage conversion.

5. SSHD Energy Use

Section 4 summarized the laboratory measurements of nine separate categories of life safety devices, consisting of 34 separate products. These measurements were combined with data on the other selected SSHDs to estimate statewide consumption of the selected SSHDs, which is presented here.

Stock and Statewide Energy Consumption

The stock, sales, and annual energy consumptions of SSHDs were calculated based on estimates of device saturation and building construction by year since 1980. This is summarized in Table 17. There is considerable uncertainty associated with some of the underlying data and assumptions. For example, the actual number of GFCIs could be smaller if installers daisy-chain the outlets together—it is not clear how common this energy-saving (but labor-increasing) measure is undertaken. Behaviors greatly affect the energy use of certain devices, such as ventilation systems and CPAPs.

Table 17: Stock and Energy Consumption of SSHDs in California Buildings

Device	Stock (millions)	Sales (thousands)	Unit Energy Consumption (kWh/year)	Stock Energy Consumption (GWh/year)	Sales Energy Consumption (GWh/year)
Single Family Homes					
GFCIs	23.4	1,990	7	164	13.9
AFCIs	4.7	527	6	29	3.2
Smoke alarms	19.5	2,219	8	154	17.5
CO alarms	0.8	192	5	4	1.0
Security systems	1.8	311	72	129	22.3
Oxygen concentrators	0.3	33	3,066	1,003	100.3
CPAP ventilators	0.3	53	155	41	8.2
Mechanical ventilation fans	0.1	22	438	46	9.7
TOTAL				**1,523**	**166**
Non-Residential Buildings					
Exit signs	6.0	516	21	126	10.8
Emergency lighting	7.1	612	13	94	8.0
TOTAL				**187**	**16**

Based on these calculations, SSHDs in the average existing California single-family home use about 170 kWh/year. SSHDs in newly constructed homes use about 700 kWh/year (~80 W).

The combined electricity consumption of the installed stock of prominent SSHDs is approximately 1.7 terawatt-hours (TWh) per year, representing about 0.6 percent of California's electricity use. The residential portion, at 1.5 TWh/year, represents about 1.6 percent of total residential use in California, and the commercial fraction represents 0.1 percent of commercial

electricity use.[1] For comparison, residential refrigerators consume roughly 12 TWh/year in California.[2]

Oxygen concentrators have the largest use among the devices examined, about 1 TWh/year. This was an unexpected finding, but not entirely surprising after considering the device's high electricity consumption and the large number of devices in use. Considerable uncertainty surrounds all inputs to this estimate—power, usage characteristics, and stock—but the true value is still likely to be larger than any other SSHD investigated.

The other medical device, the CPAPs, are responsible for much less statewide energy, about 40 GWh/year. The uncertainties surrounding this number are relatively larger than for oxygen concentrators because there are more operational variables. CPAPs have individual adjustments for heating and humidification. These variables drive energy consumption more than pumping, so the unit energy consumption (UEC) is sensitive to assumptions regarding how people select heating and humidification. In any event, oxygen concentrators consume much, much more.

The UEC of mechanical ventilation systems is also high. At slightly over 400 kWh/year, this represents about 5 percent of an average California home's total electricity consumption. The high consumption arises from a relatively high-powered fan operating continuously. Mechanical ventilation systems would consume much more statewide energy except that most people switch them off—allowances were made for this—and the small fraction of homes that have them. As new homes replace older ones and remodeling occurs, electricity consumed for mechanical ventilation will become much larger (assuming occupants operate them as intended and don't switch them off), eventually resulting in about 5 percent of total residential electricity use. There is still time to develop technologies and policies that both maintain indoor air quality and avoid this increase in electricity use.

GFCIs are responsible for only about 7 kWh/year in today's average California home. This corresponds to about 160 GWh/year. The combined energy consumption of the code-required life safety equipment is about 350 GWh/year, or about 0.3 percent of current, statewide residential electricity use. This consumption will grow steadily for at least two decades through renovations and new construction. Figure 63 shows the historical rise in number of SSHDs in California homes as a result of code changes.

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[1] The total, residential, and commercial electricity use estimates for California were obtained from http://www.ecdms.energy.ca.gov/elecbycounty.aspx for the year 2016.

[2] This assumption is based on an estimate of 1,000 kWh/year being used by a California household's refrigerator(s), along with an estimated 12 million households in California according to Census data.

Figure 63: Growth in Residential Life-Safety Devices Required by Building Codes
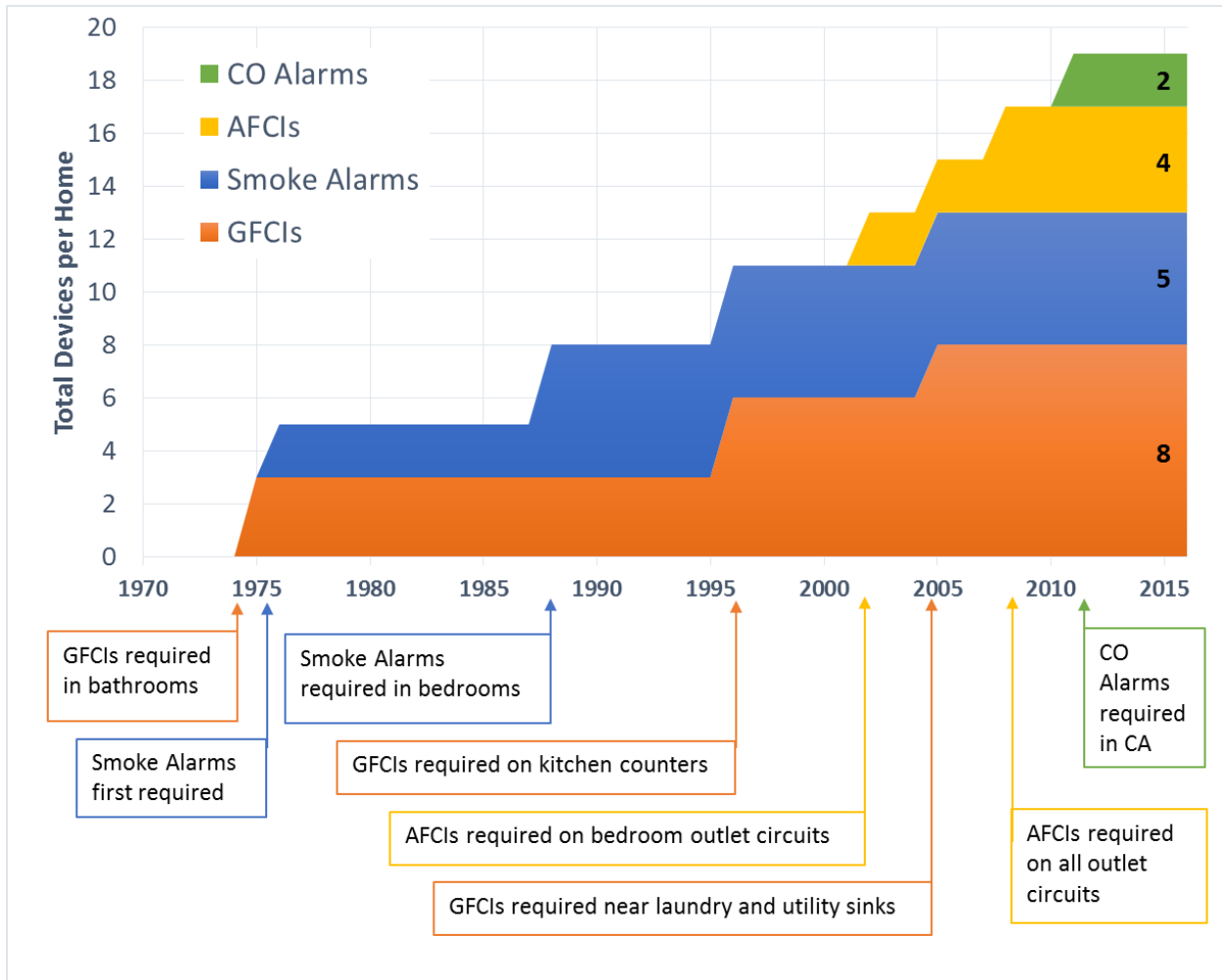
Current number of individual devices are shown on the right.

6. Prospects for Energy Reductions in SSHDs

The stock and energy consumption of SSHDs in California's buildings will surely grow. More SSHDs will be installed as new homes and commercial buildings are built and existing buildings are renovated. But increases beyond this natural upgrade are also likely as new kinds of SSHDs appear. It is easy to imagine increases above 200 kWh/year for each California home. The battery back-up to open garage doors, which just became mandatory by recent legislation, is an example of a response to a safety threat. This device alone will add up to 100 kWh/year for each garage door in California. Surveillance systems, which provide security around homes, will also become commonplace. These systems will consume up to 90 kWh/year per home. Home medical equipment already ranks among the most energy-intensive devices in homes, but its high consumption will probably not be a barrier to further growth. Its energy consumption may be high, but those costs will be far less than they would be for hospitalization, and the value of independent living is immeasurable.

As a result, the primary policy goal will be to minimize growth in SSHD energy use rather than reduce it. The following sections outline strategies to constrain growth in California SSHD energy use.

Laboratory Research

A sustained research effort should be undertaken to improve the energy efficiency of devices where health or safety considerations prevent innovations. This research needs to be carefully linked to the health and safety communities to understand the service needs, identify technical solutions, and field-test prototypes. The first two targets should be oxygen concentrators and mechanical ventilation systems.

For oxygen concentrators, research questions include:

- Can the concentrators be designed to more closely adjust their power requirement to match oxygen delivery rates (e.g., power scale)?

- Are patients receiving more oxygen than they require?

- Can improved sensing and algorithms result in less wasted oxygen delivery?

- Are other concentrating technologies ultimately more efficient?

- Are patients using concentrators correctly? Can the user interface be improved to avoid wasted oxygen?

- Can Internet-connected devices enable more precise treatment regimens and, ultimately, less wasted oxygen?

- Can surplus electricity from on-site PV be used to concentrate and store oxygen?

- What are the most effective points to enter the development cycle to help encourage use of more efficient approaches?

The problem is different for mechanical ventilation systems because occupants appear to be switching off the systems and exposing themselves to poor indoor air quality to avoid thermal discomfort and noise. Here the goal is to increase ventilation, which leads to higher electricity consumption. More precisely, the goal is convincing occupants to take other measures to reduce their exposure to indoor air pollutants. Some of this research crosses into social science and public policy. The research questions include:

- Can ventilation systems be designed to be still quieter and cause less thermal discomfort?

- What technical measures can be implemented to make operation of the systems more desirable (and how can these be achieved with the lowest possible energy penalty)?

- What new sensors, algorithms, and controls can be installed to reduce thermal and audio discomfort and to encourage higher utilization?

- Given the reluctance of occupants to operate the fans continuously, what combination of consumer acceptance, health impacts, and ventilation energy has the lowest overall social cost?

- Can ventilation systems be more closely linked to Internet-connected thermostats to provide better control and feedback to occupants?

- Why do consumers decide to disable the ventilation systems?

The technologies employed in GFCIs and smoke alarms proved to be surprisingly complex and resistant to inspection of individual components. In addition, the devices had unexpectedly high part counts. Further research will still be required to identify energy savings (if they exist). Potentially the savings might be obtained in conjunction with reduced parts count, leading to lower costs.

For smoke and CO alarms, research should be undertaken to obviate the need for a power supply. This could be accomplished through a "10-year" battery, possibly combined with energy harvesting and wireless networking. This solution will require building codes to be changed but could significantly reduce installation costs.

Further research is also needed to understand the usage of CPAPs and the opportunities to save energy; for example, whether local sensing and algorithms can be developed to minimize heating/humidification energy.

Programmatic Activities

Most SSHDs consume little energy, and therefore offer correspondingly small energy savings, even when reductions of 50 percent are technically feasible. The efficiency improvements may still pay for themselves in reduced operating costs, but even though they will pay for themselves, consumers, contractors and others will not spend time or money implementing the changes because the payoff is so small. Government, utilities, and other entities need to design programs that require little or no additional effort on the part of consumers, contractors, and other decision-makers to shift from current products to the most efficient available. Possible actions include the following:

- Support labeling efficiencies of medical equipment

- Establish minimum efficiency requirements for key SSHDs, such as for GFCIs

- Include high-efficiency SSHDs in the specifications for premium home designations

- Offer rebates for high-efficiency garage-door battery systems

- Educate contractors on energy-savings from daisy-chaining GFCIs

- Establish energy test procedures for SSHDs

- Educate healthcare providers on energy impacts of medical equipment and measures that can reduce them

- Determine if ventilation codes can be designed to reflect actual occupancy

These actions illustrate the range of participants that must be involved to save energy.

California (and other entities) face an administrative problem related to SSHDs. Who should be responsible for SSHD energy use? Presently nobody is. For example, efficiencies of exit lights fall in Title 20 (appliance standards) but installation of GFCIs is covered by building codes. No entity has responsibility for energy use of medical equipment. Indeed, the DOE is prevented from addressing these devices. This situation probably cannot be fixed; however, an "SSHD Coordinating Council" might bring disparate groups together and encourage energy savings. One of the council's early goals might be to coordinate battery back-up capacity for SSHDs and other priority devices.

7. Conclusions

This investigation identified a unique category of energy-using devices that provide life safety, health, and security for buildings. The installation or use of these devices is dictated by building codes, health providers, insurance companies, and other entities. None of them would ordinarily consider energy efficiency a feature. These devices are part of the miscellaneous electric loads (MELs) end use.

While not particularly large today, SSHD energy use will steadily climb as existing buildings begin to comply with new codes and new types of SSHDs appear. Also, these estimates understate their total contribution because devices now appearing or shifting from elective products into SSHDs were not covered (such as modems, Wi-Fi access points, optical network terminals, and batteries for garage door openers). This growth helps explain why MELs are projected to grow faster than any other end use.

There are diverse strategies to reduce future SSHD energy consumption (or lessen growth rates). For some devices, such as GFCIs and mechanical ventilation systems, the best available models consume less than half as much power as typical models. It appears that efficiencies of medical equipment could be greatly improved through better compressors and controls. Battery-charging systems for a host of devices can also be made more efficient. Completely new solutions, possibly relying on custom ICs, could also offer energy savings.

At the same time, reducing the energy consumption of SSHDs is challenging. Most SSHDs consume little energy and therefore offer correspondingly small energy savings, even when reductions of 50 percent are technically feasible. The efficiency improvements may still pay for themselves in reduced operating costs, but even though they will pay for themselves, consumers, contractors and others will not spend time or money implementing the changes because the payoff is so small. Few people will devote an hour searching for an SSHD that uses 5 kWh/year—about $1—less electricity.

A second obstacle is that higher priorities determine the performance and characteristics of many SSHDs. These range from safety—electrical and fire—to health. Energy impacts rarely enter into the policymaking decisions for these devices (or, if they do, it is to exempt the devices). A coordinating council might help by raising the profile of energy use in these devices.

An important element of this investigation involved careful measurement, inspection, and teardown of SSHCs. With this information, the goal was to first identify how these devices actually used energy and then to propose lower-energy solutions. Unfortunately, these devices were more resistant to teardowns and detailed measurements than expected. As a result, it was not possible to identify as many savings opportunities as anticipated.

No obvious administrative entity manages SSHDs, owing to their diversity. Because the list of SSHDs will grow, establishing a coordinating council might make sense. The council's goal would be to bring energy and operating cost impacts into the policy discussions regarding future SSHDs.

8. Future Work

A sustained research effort will be needed to improve the energy efficiency of devices where health or safety considerations prevent innovations. This research needs to be carefully linked to the health and safety communities to understand the service needs, identify technical solutions, and field-test prototypes. The first two targets should be oxygen concentrators and mechanical ventilation systems.

For oxygen concentrators, research includes the following:

- Design units to more closely adjust their power requirement to match oxygen delivery rates (e.g., power scale)

- Improve sensing and algorithms to waste less delivered oxygen

- Determine if other concentrating technologies ultimately are more efficient

- Consider out-of-box solutions, such as novel concentrating methods and use of PV to concentrate and then store oxygen for later delivery

The problem is different for mechanical ventilation systems because occupants switch off the systems and expose themselves to poor indoor air quality to avoid thermal discomfort and noise. Here the goal is to increase ventilation, which leads to higher electricity consumption. More precisely, the goal is convincing occupants to take other measures to reduce their exposure to indoor air pollutants. Some of this research crosses into social science and public policy. The research topics include the following:

- Design ventilation systems to be still quieter and cause less thermal discomfort

- Improve new sensors, algorithms, and controls to reduce thermal and audio discomfort, encourage higher utilization, while reducing energy use

- Use Internet-connected thermostats to provide better control and feedback to occupants

The technologies employed in GFCIs and smoke alarms proved to be surprisingly complex and resistant to inspection of individual components. In addition, the devices had unexpectedly high part counts. Further research will still be required to identify energy savings (if they exist). The savings might be obtained in conjunction with reduced parts count, leading to lower costs.

Further research is also needed to understand the usage of CPAPs and the opportunities to save energy. For example, can local sensing and algorithms be developed to minimize the heating/humidification energy consumed by these devices?

Programmatic Activities

Most SSHDs consume little energy and therefore offer correspondingly small energy savings, even when reductions of 50 percent are technically feasible. Government, utilities, and other entities need to design programs that require little or no additional effort on the part of consumers, contractors, and other decision-makers to shift from current products to the most efficient available. Possible actions include the following:

- Label efficiencies of medical equipment

- Establish minimum efficiency requirements for key SSHDs, such as for GFCIs

- Include high-efficiency SSHDs in the specifications for premium home designations

- Offer rebates for high-efficiency garage-door battery systems

- Educate contractors on energy-savings from daisy-chaining GFCIs

- Establish energy test procedures for SSHDs

- Educate health-care providers on energy impacts of medical equipment and measures that can reduce them

These actions illustrate the range of participants that must be involved to save energy.

CHAPTER 5:
Very-Low-Power Standby Products: Implications for Codes, Standards, and Test Methods

1. Scope

Electrical devices that draw no—or very little—power in their standby modes are relatively new phenomena whose behaviors are not fully captured in current codes and standards. These devices (which are a subset of plug loads) typically draw very little power but, because billions are in use, it still represents a significant aggregate energy consumption in buildings. This chapter reviews current applicable codes and standards for zero-standby and very-low-power devices. The scope is broader than only energy characteristics because some zero-standby solutions have characteristics with impacts on electromagnetic radiation, health, and materials.

How do these new technologies interact with the ecosystem of test methods and applicable efficiency and health standards? A general overview of the interaction between codes and standards, test methods, and products is provided in Figure 64. Test methods are designed to measure certain product characteristics that are regulated and/or required by codes and standards. This chapter first discusses relevant test methods and then the codes and standards (although these are sometimes difficult to separate). Finally, the implications of characterizing and regulating products with zero- or very-low-power standby features are discussed.

Figure 64: The Relationship Between Codes and Standards, Test Methods, and Products
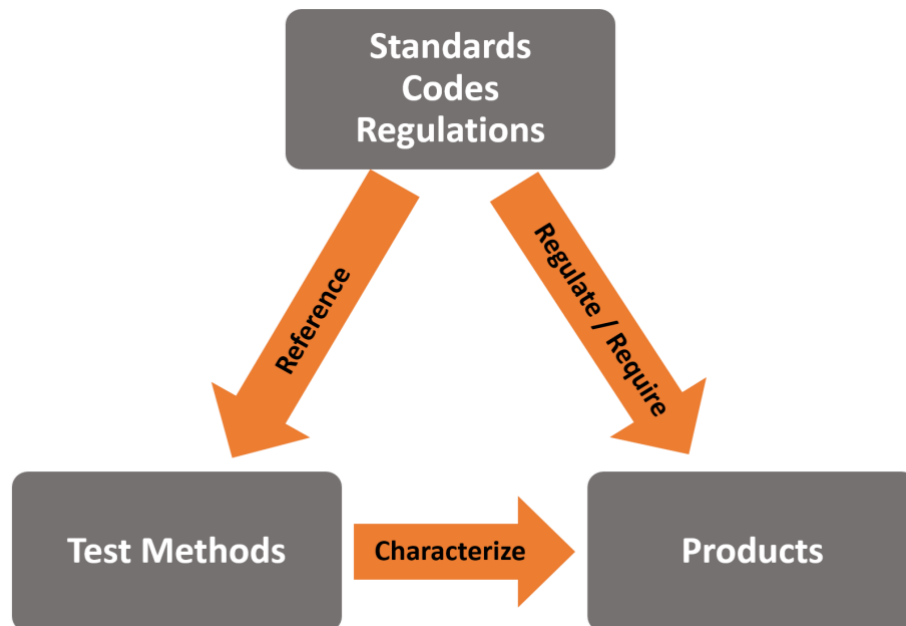
This investigation is part of a larger project to understand and develop very-low-energy plug loads—what this report calls "ZNE plug loads"—that will ultimately provide essential services in sustainable buildings of the future (Meier 2015). Other parts of the project involved developing technologies to enable zero, or near-zero, standby power use and identify future applications of these solutions.

Test methods

Test methods provide a consistent (and agreed-upon) procedure to assess the behavior of a device, material, and (recently) service. New test methods are needed whenever new devices, materials, and services appear or have a new application. This is the case for zero-standby technologies. They have different behaviors with respect to energy, materials, health, and safety. The current test procedures are reviewed as they apply to the energy, health, and safety of zero-standby and direct DC-powered products and identify areas where gaps may exist.

Energy

A consistent procedure for measurement of standby power—actually for all low-power modes—is essential for any policy or program seeking to affect it. This project has already identified or developed several new solutions that transform standby power from a fairly constant load into a load with much more beneficially diverse behavior. This transformation is reflected in the standzero concept and technologies like the zero-standby power supply, the wake-up RF system, and direct DC-powered appliances. The California Energy Commission (Energy Commission) is currently gathering comments on ways to collect data to characterize low-power modes for a wide variety of products using a common test procedure.[3] Issues discussed in the document include wired and wireless network connections, sensors, rechargeable peripherals, DC power, and systems of devices.

Standby and Low-Power Modes

Low-power modes are typically measured with procedures established by the International Electrotechnical Commission (IEC) 62301 test method (International Electrotechnical Commission 2011). The test methods described in 62301 fall into three categories: sampling, average reading, and direct meter reading. All take place in carefully specified conditions to ensure consistency of results. The sampling method is required where power is not stable or the mode is of limited duration. Sampling is the only method permitted for cyclic loads and short duration modes. The original IEC 62301 test method was designed to address AC-powered products with relatively stable consumption. Furthermore, the product boundary was clear and environmental conditions were not especially important. IEC 62301 has been incorporated into many energy consumption test methods, examples of which are listed in Table 18.

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[3] Request for Public Comment on Low Power Mode Test Procedure Discussion Document. https://efiling.energy.ca.gov/GetDocument.aspx?tn=223875

Table 18: Examples of Standby Energy Use in Other Test Methods

Method by Which Standby is Measured	Applicable products (not comprehensive)	Description
IEC 62301	Dishwashers, battery chargers, clothes washers, furnaces, microwaves ovens, etc.	IEC 62301 is referenced by the relevant test method for the product.
Captured in active-mode test cycle	Refrigerators, water heaters	Energy use of controls is included in the aggregate energy metric.
IEC 62087	Audio/video equipment	
IEC 62623	Desktop and notebook computers	Off mode is measured and added to the total electric consumption.
(CFR) part 430, subpart B, appendix M	Air conditioner condensing units	Off-mode seasonal power and energy consumption is measured and reported separately from seasonal energy efficiency ratio (SEER).

Direct DC

Low-voltage direct DC-powered consumer products have traditionally been used in four areas: (1) off-grid, (2) marine, (3) RV (recreational vehicle), and (4) the public switched telephone network (PSTN). DC-powered products are now appearing in grid-powered buildings with the advent of managed DC networks such as power over Ethernet (PoE) and USB. However, energy test methods for most DC-powered products in buildings are relatively new and still evolving.

DC-powered products have a growing potential in developing countries, where grid power is unavailable, intermittent, or expensive. Some of the standards activities have taken place outside of the IEC and other technical standards entities. For example, the Clean Energy Ministerial energy access initiative has developed the Global LEAP program, which supports energy access in the developing world. For this purpose, Global LEAP has developed test methods for off-grid TVs, fans (pedestal, table, and ceiling), and refrigerators,[4] which typically operate with a DC power input. These methods are mostly based on existing IEC methods for AC-powered products (IEC 62087 for TVs, IEC 60879 for fans, IEC 62552 for refrigerators, and IEC 62301 for standby power). These methods allow testing with a DC cable and DC power supply, or an AC power supply and an AC/DC converter, depending on whether the product is intended for direct-DC or AC power input, and using the power cable provided with the product.

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[4] For existing and under development test methods developed by the Global LEAP program, see Global LEAP Off-Grid Appliance Test Methods at http://globalleap.org/resources/.

For solid-state lighting (SSL) products, the Illuminating Engineering Society (IES) LM-79-08 specifies a test method for both AC- and DC-powered products. For the latter, LM-79 requires measurement of input DC voltage and input DC current using a DC voltmeter and DC ammeter between the DC power supply and the SSL product to derive input DC power. Similar measurements are specified for DC-powered LEDs in LM-82-12, which characterizes LED light engines and LED lamps at varying temperatures.

The ENERGY STAR program has established a test method for Large Network Equipment (LNE), including PoE switches and routers, and is applicable to both AC- and DC-powered network equipment (U.S. EPA 2015). This test method specifies measuring current, voltage, and power, between the tested unit and the power source. However, the ENERGY STAR method for Small Network Equipment (SNE) excludes DC-powered equipment.[5]

Health and Safety

In addition to energy test methods, other non-energy test methods may still apply to zero-standby solutions. These include safety, health, and radiation standards and their underlying test methods.

The health effects from wireless devices and systems that rely on RF or microwave radiation to function are still debated (Lin 2016). Test methods have been established to measure exposure. It is not clear that zero-standby devices contribute incrementally more radiation than other devices with higher standby power levels. Indeed, efficiency measures taken to enable lower standby may also contribute to lower radiation.

None of these test methods appear to pose major obstacles to zero standby solutions, although some of them may be new to manufacturers (e.g., lasers). Nevertheless, manufacturers will still need to devote resources to comply with them.

Some zero standby solutions require energy storage with batteries and capacitors, which will have materials impacts. Life cycle assessments of batteries have been undertaken for a wide range of technologies, though most have focused on large units suitable for utility or electric vehicle applications (Larcher and Tarascon 2015) but some assessments of super capacitors for electronics applications have been investigated (Smith et al. 2018). Procedures for performing life cycle assessments have become more standardized; however, they have not yet evolved into internationally recognized test methods directly applicable to zero-standby products and materials.

2. Codes and Standards

Scope

In the same way that current test methods no longer apply, current codes and standards will no longer capture new behaviors of zero-standby technologies. The current codes and standards are reviewed as they apply to zero-standby technologies and identify areas where gaps may exist.

Low-power and direct DC products can fall under three distinct regulatory categories: (1) regulated by energy codes, (2) exempt from energy codes, and (3) required by building

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[5] SNE differs from LNE primarily due to the number of physical network ports (11 or less for SNE, 12 or more for LNE), and whether it is mounted on standard equipment racks or not.

codes. In the first category, codes and standards regulate the standby energy use of products that are used in buildings. In the second category, energy codes can specifically exempt products, including many medical devices and home security products, from minimum efficiency requirements. In the third category, building health and safety codes require specific products but are silent with respect to their energy consumption. Examples include GFCIs and smoke alarms. Thus, low-standby technologies must be designed in a complex, potentially inconsistent regulatory environment. Some of the complexities and inconsistencies are discussed below.

Energy Codes and Standards

Numerous entities have current energy codes and standards for plug loads that consider their low-power mode use, including the DOE, the Energy Commission, and ENERGY STAR (voluntary), which are summarized below.

California Energy Commission Codes and Standards

The Energy Commission, via Title 20, has test methods and standards for a variety of plug load appliances, as summarized in Table 19. Note that the Energy Commission covers more appliances than those provided in Table 19; however, the appliances provided in Table 19 are limited to those with low-power-mode measurements and/or standards.

Table 19: Low-Power-Mode Testing and Standards in California Appliance Energy Standards

Appliance Category	Title 20 Standards Section	Low-Power and Off Mode Measurements
Gas and Oil Space Heaters and Electric Residential Boilers	1605.1(e) 1605.3(e)	Measures off mode and standby mode using IEC 62301. The efficiency standard for boilers is based on the annual fuel utilization efficiency (AFUE). Maximum standby loss and maximum consumption during standby are specified for natural gas and liquefied petroleum gas (LPG) boilers rated at least 300,000 Btu/h and duct furnaces, respectively.
Room ACs, Room AC Heat Pumps, Packaged Terminal ACs, and Packaged Terminal Heat pumps	1605.1(b)	Measures total energy use during a defined cycle and period, which includes low-power modes.
Water Heaters	1605.1(f)	Total site standby energy (including electrical) is measured over the standby period, which is roughly the period of time between two water draws. A standby heat loss coefficient for the storage tank is calculated and incorporated into the calculation for the uniform energy factor (UEF). The efficiency standard for water heaters is based on the UEF.

Hot Water Dispensers	1605.1(f)(4)	Only measures standby energy use over a 24-hour period. The result is reported as the standby loss (in watts).
Televisions	1605.3(v)(2)	Measures off mode and standby modes using IEC 62301 procedures.
Washing Machines	1605.1(p)	Calculates an integrated modified energy factor (IMEF) which uses the per-cycle combined low-power mode energy consumption (averaged over a year) as measured by IEC 62301 procedures.
Dishwashers	1605.1(o)	IEC 62301 procedures are used to measure off mode and various low-power modes to calculate the annual combined low-power mode energy consumption.
Refrigerators, Refrigerator-Freezers, and Freezers	1605.1(a) 1605.3(a)	Measures total energy use during a defined cycle and period, which includes low-power modes. However, many newer, electronic features (displays, Internet connection, etc.) may be switched off during the test, thus lowering the apparent non-active power consumption. California regulations also cover wine chillers with a modified Energy Expended equation.
Lights	1605.1(k) 1605.3(k)	For lamps capable of operating in standby mode (e.g., smart lamps), measure standby power using IEC 62301 procedures. California has additional requirements for standby power in Table K-1 to ensure: that the lamp is connected to only one network, that it be measured for not less than 60 minutes, and that it be measured at a lamp that is 10 meters from the hub.
External Power Supplies	1605.1(u) 1605.3(u)	Standby- and no-load power measurements taken at different loading conditions. Instantaneous power readings can be used if the power draw is stable; otherwise, IEC 62301 procedures are used.
Battery Chargers	1605.3(w)	Unit energy consumption (UEC) calculation requires measurements of standby and off-mode power consumption, which are taken as the time series integral of the power consumed over a 10-minute test period, divided by the period of measurement. The annual UEC for standby and off modes incorporates an assumed daily hours of operation based on product class. Maintenance mode and no-battery mode power consumption limits are specified for large battery charger systems, small battery charger systems, inductive charger systems, and battery backup and uninterruptible power supply (UPS) systems (only requirement for maintenance mode).
Audio and Video Equipment	1605.3(v)(1)	Test method for standby-passive mode is IEC 62087:2002(E). Maximum power consumption is specified for compact audio products in audio standby-

		passive mode and DVD players and recorders in video standby-passive mode (Table V-1 of section 1605.3(v)(1)).
Computer Monitors	1605.3(v)(4)	The test method for sleep mode and off mode is IEC 62301.
Computers	1605.3(v)(5)	The test method is the ENERGY STAR Program Requirements for Computers, Final Test Method with modifications, and it is carried out according to the requirements in IEC 62623.

U.S. Department of Energy Appliance Standards

The Energy Independence and Security Act of 2007 (EISA) requires DOE to take standby power use into account.[6] Therefore, a number of appliances covered by the DOE Appliance and Equipment Standards program have required low-power mode consumption measurements and/or standards in place. A summary of these standards, as codified in the Code of Federal Regulations (CFR), is provided in Table 20.

Table 20: Low-Power Mode Testing and Standards in Federal Appliance Energy Standards

Appliance Category	CFR Standards Section	Low-Power and Off Mode Measurements
Gas and Oil Space Heaters and Electric Residential Boilers	10 CFR 430.32(e)	Measures off mode and standby mode using IEC 62301 procedures. The efficiency standard for boilers is based on the annual fuel utilization efficiency (AFUE).
Washing Machines	10 CFR 430.32(g)*	Calculates an integrated modified energy factor (IMEF) which uses the per-cycle combined low-power mode energy consumption (averaged over a year) as measured by IEC 62301 procedures.
Dishwashers	10 CFR 430.32(f)	IEC 62301 procedures used to measure off mode and various low-power or standby modes to calculate the annual combined low-power mode energy consumption.
Refrigerators, Refrigerator-Freezers, and Freezers	10 CFR 430.32(a)	Measures total energy use during a defined cycle and period, which includes low-power modes. However, many newer, electronic features (displays, Internet connection, etc.) may be switched off during the test, thus lowering the apparent non-active power consumption.
External Power Supplies	10 CFR 430.32(w)	Power supplies (with some exceptions)

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[6] Section 310(3) of EISA 2007; Pub. L. 110-140 (codified at 42 U.S.C. 6295(gg)) amended the Energy Policy and Conservation Act (EPCA) to require that energy conservation standards address standby mode and off mode energy use.

		manufactured on or after February 10, 2016, must meet standards for maximum power in no-load mode (10 CFR 430.32(w)(ii)).
Battery Chargers	10 CFR 430.32(z)	Unit energy consumption (UEC) calculation requires measurements of standby and off-mode power consumption, which are taken as the time series integral of the power consumed over a 10-minute test period, divided by the period of measurement.
** Clothes washers manufactured on or after March 7, 2015, and before January 1, 2018, have different IMEF standards than those manufactured on or after January 1, 2018.		

ENERGY STAR

In addition to Energy Commission and federal standards, ENERGY STAR has voluntary standards covering low-power modes for many appliances. Table 21 summarizes the ENERGY STAR low-power mode requirements.

Table 21: Low-Power Mode Testing and Standards in ENERGY STAR Product Specifications

Appliance Category	Relevant Qualification Criterion	Description
Clothes Dryers	Combined energy factor (CEF)	CEF is the ratio of the test load weight (lbs) to the sum of the standby and off mode energy consumption and the per-cycle energy consumption (kWh). The CEF must be greater than or equal to a specified minimum (based on product type).
Audio and Video Equipment	Sleep mode power	Sleep mode power must be less than a specified maximum (based on product function).
Computers	Desktops, notebooks, tablets, and thin clients: Typical energy consumption (E_{TEC}) Workstations: Weighted power consumption (P_{TEC}) Small-scale servers: Off mode power	E_{TEC} and P_{TEC} are the time-weighted energy and power consumption across modes (including off and sleep modes), respectively. These metrics must be less than maximums that are based on product type and function. The off mode power consumption of small-scale servers must be less than 1 W (or 1.4 W for products having a wake-on-LAN feature enabled by default).
Displays	Computer monitors: Typical energy consumption (E_{TEC}) Signage displays: Sleep mode power All displays:	E_{TEC} is the time-weighted energy consumption across on and sleep modes. This must be less than or equal to a specified maximum (based on monitor area). Sleep mode power for signage displays must be less than or equal to a specified minimum equal to 0.5 W plus allowances for

	Off mode power	product features. Off mode power for all displays having off mode must be less than or equal to 0.5 W.
Game Consoles	Standby mode power	Standby mode power must be less than or equal to 0.5 W.
Telephony	Off mode power	On mode power, less an off mode power incentive (calculated as 0.25 multiplied by the difference in on and off mode power consumption), must be less than or equal to a specified maximum (based on product features).
Televisions	Standby-passive mode power and standby-active, low-mode power	Standby-passive mode power must be less than or equal to 0.5 W. Standby-active, low-mode power must be less than or equal to 3 W.
Connected Thermostats	Network standby average power consumption	Network standby average power consumption must be less than or equal to 3 W.
Room Air Cleaners and Purifiers	Standby mode power	Standby mode power must be less than or equal to 2 W.
Electric Vehicle Supply Equipment	No vehicle mode power	No vehicle mode power must be less than 2.6 W plus allowances for the network connection with wake capability and high-resolution display.

Health and Safety Codes

Building codes may require installation of devices to limit risks of electrocution, fire, and other health and safety hazards. A summary of the residential health and safety devices required by building codes is presented in Table 22. Responsibility for these devices is divided among various organizations. In general, Underwriters Laboratories (UL) defines the operation and test methods for all aspects of a device's performance. State and local building codes dictate the numbers and locations of the devices in homes and typically reference codes developed by the National Fire Protection Association (NFPA). Changes to these products that reduce their energy use need to be compatible with the relevant UL standard, but would not affect how they are treated by the relative NFPA code. As mentioned earlier, the number of life safety devices in homes has been steadily increasing since they were first required in the 1970s (see Figure 63).

Table 22: Residential Health and Safety Devices Required by Building Standards

Device	Code/Standard	Purpose
Ground-Fault Circuit Interrupter (GFCI)	NFPA 70 UL 943	Protect people from electric shock
Arc-Fault Circuit Interrupter (AFCI)	NFPA 70 UL 1699	Protect building from fires started by arcing wires
Smoke Alarm	NFPA 101 UL 217	Warn occupants of fire and smoke
Carbon Monoxide (CO) Alarm	NFPA 720 UL 2034	Warn occupants of dangerous CO levels

Other Health Considerations

As previously discussed, new behaviors and materials associated with very-low-power devices are liable to introduce new health effects that must be considered. In this section, some of the requirements for these devices are discussed.

Devices that emit electromagnetic radiation are subject to regulation by the Federal Communications Commission (FCC) and, in some cases, the FDA. The FCC is required by the National Environmental Policy Act of 1969 to evaluate the effect of emissions from FCC-regulated transmitters on the quality of the human environment. In 1996 the FCC adopted maximum permissible exposure limits for field strength and power density for the transmitters operating at frequencies of 300 kHz to 100 GHz, as well as specific absorption rate limits for devices operating within close proximity to the body (Federal Communications Commission 2015). The Center for Devices and Radiological Health of the FDA is responsible for regulating manufacturers of electronic products that emit (or could emit) radiation; however, by law the FDA does not regulate radiation-emitting products before they can be sold. If devices are found to emit potentially harmful levels of radiation, the FDA then has the authority to step in and require the manufacturer to notify consumers, replace the device, and/or recall the device (U.S. FDA 2018).

Additionally, the FDA helps regulate products employing lasers, which could be used to supply energy in zero-standby energy-harvesting devices. Laws, regulations, and standards exist to help manage any hazardous effects from each of the four laser classes the FDA recognizes (U.S. FDA 2019).

For some products—and especially those incorporating some form of energy storage—considerations must be taken for end-of-life material disposal. The Restriction of Hazardous Substances (RoHS) and Waste Electrical and Electronic Equipment (WEEE) directives exist in the European Union and thus can influence U.S. products that are also sold abroad. In addition, there are various local waste disposal regulations, such as California's Electronic Waste Recycling Act of 2003.

Finally, many medical devices are currently exempt from energy standards. As an example, power supplies and certain battery chargers classified as devices for human use under the Federal Food, Drug, and Cosmetic Act, and requiring FDA listing and approval as a medical

device, are exempt from California's appliance efficiency regulations (California Energy Commission 2017).

None of these standards appear to pose major obstacles to zero standby solutions, although some of them (e.g., lasers) may be new to manufacturers. Nevertheless, manufacturers will still need to devote resources to comply with them.

3. Discussion

Aspects of zero standby technologies that will complicate their coverage by test methods and standards are discussed below. This discussion is based on the investigations described above.

Zero-Standby Solutions

Previously, it was explained how IEC 62301 is used to measure the power consumption in low-power modes for a variety of plug loads. Table 23 lists the aspects of IEC 62301 that must be modified in order to accommodate new standby operating characteristics. The two modifications having the greatest energy impact appear to be boundary definitions and addressing the presence of energy storage. Some of the solutions require a separate transmitter (or possibly just a remote control) that provides power designed to be harvested. The transmitter would most likely be a separate device with its own power consumption. The presence of energy storage—a battery or capacitor—complicates the test method because the state-of-charge must be considered during measurements. In both cases, some approaches might be adapted from existing test methods, such as those for battery chargers and wireless charging. For example, harvesting a transmitted signal's energy is a form of wireless charging (albeit an extremely weak form).

Table 23: IEC 62301 Test Method Changes Required to Account for Zero-Standby Solutions

Test Aspect	Reason for Modification
Power supply (assumes mains or AC powered)	The power supply options must include DC. DC should include conventional DC power as well as "Managed DC" (e.g., USB and Ethernet).
Modes	Certain modes, such as disconnected, off, and network connected, will require new definitions to accommodate energy harvesting of communications signals.
Boundary conditions for DC-powered products	Define whether to include energy consumption of remote power supplies (AC-to-DC and DC-to-DC) feeding the product.
Environmental conditions for energy-harvesting products	Power consumption may vary with environmental conditions such as the amount of light or range of temperature. Include standard environmental conditions to obtain consistent values for energy contributed by the environment (deliberate or incidental) and greater control of the test room.
Duration of power measurements	The presence of batteries and capacitors to store energy may require much longer (or different) testing conditions.
Instruments for power measurements	Lower power consumption may require greater resolution (below 1 mW).
Mobile operation (and intermittent connection to mains power)	The expectation of frequent and extensive mobile operation needs to be taken into account.
Type of energy harvesting	To fairly test the product, the type(s) of energy harvesting must be identified. This information will enable the tester to appropriately set the test conditions and procedure.

These are substantial modifications and may require a comprehensive review. Ultimately, the best potential approach may be to start over and devise an entirely new energy test method (or methods).

Earlier investigations have shown that some zero-standby solutions will include energy storage and energy harvesting (Meier 2018). Several prototypes were developed that rely on harvesting the energy from an infrared or laser signal, and then charging a capacitor with the harvested energy. The stored energy is sent as a wake-up drive signal to the gate of a footer switch. In the prototypes, this footer switch is an N-type MOSFET that connects the grounds of the device (plug load) and the device's power supply. Before the footer switch is activated, no power is consumed by the device because its ground is not connected to the supply ground. Such prototypes could allow a device to operate with zero standby consumption for essentially indefinite periods of time.

Standzero (a term derived from "standby-zero") is the elapsed time a product can operate while disconnected from grid-supplied electricity (Meier and Siderius 2017). Thus, standzero has the dimension of time. The standzero concept is already familiar to hundreds of millions of users of smartphones and other portable electronics because it is similar to the operating time until recharging is required. Homes with optical networks where telephone service is also included must have batteries whose standzero time is specified (typically a few hours). Users of portable oxygen concentrators know the standzero times of their units, because their lives may depend on it.

Products with any amount of standzero time will employ some form of energy storage (e.g., battery or capacitor). Additionally, devices may harvest ambient energy from lighting, infrared signals, vibration, or other means. Figure 65 depicts a possible implementation of these technologies. The test method will therefore need to specify an initial state for the energy storage as well as standardized environmental conditions for the energy harvesting.

Figure 65: Rendering of Possible Components of a Standzero Device, Including Energy Harvesting Means, Energy Storage, and Logic to Control Electricity Flow Between Mains, Storage, and Harvested Energy
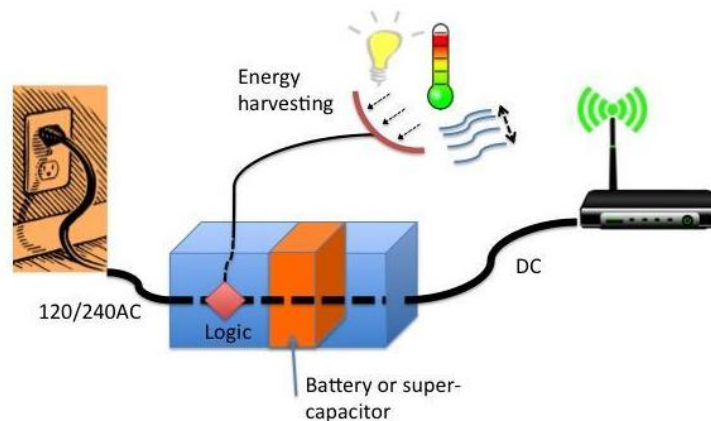
No accepted method for measuring standzero exists today, even though related metrics are widely used to describe performance in numerous appliances (examples provided above). A standzero test method will need to specify an initial state for the energy storage (e.g., battery state of charge) as well as standardized environmental conditions (e.g., incident lux or temperature) for any energy harvesting capability. The dynamics of standzero operation must be considered in the test method. For some products, standzero operation will be an intermittent behavior, whereas in others standzero operation will be the dominant type of behavior. Some devices will have sufficient energy harvesting and storage capability to always power its minimum load in standzero fashion. Such an appliance would have an infinite standzero time.

To address some of these considerations, one can draw upon existing test procedures. This might be an extension of an existing test method (such as IEC 62301) or a completely new test method. For instance, IEC 62257-9-5[7] contains test methods for off-grid lighting product

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[7] Recommendations for renewable energy and hybrid systems for rural electrification - Part 9-5: Integrated systems - Selection of stand-alone lighting kits for rural electrification

performance after mains charging, electromechanical charging, and solar charging (a given product would necessarily be powered by one of these means). Prior to performing these test procedures, the product's battery is brought to a specific state of charge (essentially its fully discharged state) before the specified charging and performance measurement takes place. Similarly, the storage component of appliances with standzero capability needs to be brought to a standardized state (e.g., fully charged or fully discharged) prior to subjecting the appliance to environmental stimuli (i.e., energy harvesting) and measuring the standzero time. Additionally, the solar charge test in IEC 62257-9-5 specifies standard conditions for how the product is to be charged based on product-specific energy harvesting characteristics. Any standzero test would also need to specify standard environmental conditions from which the appliance can harvest energy. As an example, one might imagine that the test procedure for a standzero-capable television that harvests visible light require the television to be placed under lighting conditions (e.g., lux levels) typical of a household's living room. Of course, there are many nuances to consider, but some examples of the issues involved in specifying test procedures for standzero technologies are listed below:

- Combination of a time performance test with measurement of power (the measured time with 0 watts power draw)

- Specification of environmental conditions of the test

- Definition of the state-of-charge of the battery or capacitor

- Duration of the test, including characterization of any periodic standzero intervals

The test boundary for zero-standby technologies also requires clarification. Many zero-standby solutions harvest power from an external source (such as a laser or radio signal). How should these sources be included in the standby measurements? A future test method must provide guidance. Development of a standzero test method is additionally challenging because there is no obvious precedent on which to build.

Finally, low-standby products such as thermostats, smart speakers, and video cameras have network connections functioning in their lowest modes. The network connection can induce energy consumption by equipment upstream, all the way to the cloud. The network consumption is typically small, on the order of 0.06 kWh/GB transmitted (Aslan et al. 2017), but how the data are used and stored can induce a wide range in upstream power consumptions. These impacts were not investigated in this report.

Direct DC-powered Devices

DC-powered devices will no longer have a dedicated power supply converting mains AC to DC. This complicates testing since the device power consumption must be measured in terms of DC rather than AC. How should power supply losses (both fixed and variable) be captured when no dedicated power supply exists?

Although most energy test methods, such as IEC 62301, specifically exclude DC-powered products, most of their elements could be transposed into a DC test method or could be modified to accommodate both AC and DC products. The chief issue is whether to account for the upstream AC-to-DC transformation losses. Consider a product such as a router, which has two versions that are identical save that one is mains-powered and the other is direct-DC powered (from a USB or other source). The DC model would always consume less energy because the power supply losses do not get captured. This would be accurate in the case where

the DC power is provided by a native source such as PV, but as is more typical (at least currently) there would be losses at the AC-to-DC conversion.

One method to improve comparability is to calculate a net-energy consumption for DC products; that is, the difference between the combination of product and power supply and the power supply alone. ENERGY STAR adopted this approach for its imaging equipment specification (U.S. EPA 2014). ENERGY STAR assumed that the power supply's consumption does not change in the two conditions (i.e., with and without a load).[8]

Life Safety Devices

Life safety devices were examined in considerable detail because they are unique in the aspect that they are required by code. The growth of these devices (Figure 63) and their concomitant energy use is significant. The measurements both in new homes and the lab indicate that the cumulative impact of these products in new homes can exceed 200 kWh/year. It is not clear if these products should be treated within building codes or in minimum efficiency standards (e.g., within California Title 24 or Title 20). This growing collection of products deserves attention by policymakers.

4. Conclusions

Test methods, codes, and standards do not yet capture the unique features of ZNE plug loads and products with zero or very-low standby power. Those unique features span energy consumption behavior, materials, and health and safety. Establishing test methods and standards is especially challenging because each product has a small environmental footprint— drawing less than a few watts of power and consisting of only a few grams of materials—but the cumulative impact of billions of these products is enormous.

The most important findings and recommendations are summarized below:

- For nearly all energy test methods, the boundaries of measurement need to be re-considered to reflect new behaviors of the technologies. The boundaries include upstream energy use, environment, and duration of measurement.

- All test methods and standards need to take into account that more and more products will operate for long periods unconnected to the grid. This phenomenon is not just limited to portable electronics: think EVs and autonomous vacuum cleaners. The testing dilemma is how to define (and measure) standby modes when "disconnected" may be a common configuration.

- Energy test methods for DC products need to be updated to reflect the anticipated increase in higher-power DC products. The ultimate goal should be comparable treatment of AC and DC products.

- Future zero-standby solutions may require manufacturers to comply with new health and safety requirements. For example, lasers might be used to enable energy harvesting. None of these requirements appear insurmountable.

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[8] This assumption may fail when the product begins communicating with the power supply so that the power supply adjusts its behavior depending on product mode. Power over Ethernet and USB make communication much simpler.

- For DC products, the boundaries of the measurements need to be better defined; for example, how should upstream DC power supplies be treated?

- For mobile products and those with standzero capability, test methods need consistent procedures of accounting for energy storage and environmental energy harvesting.

- Life cycle assessments of materials associated with low-standby technologies need further investigation. Most studies of energy storage, for example, focus on much larger products.

- As some appliances approach zero grid energy, what is an appropriate energy test method?

- Health and life safety devices are presently exempt from most energy standards and codes. The project results suggest that the aggregate energy use for these products is growing.

Adoption of zero and near-zero standby solutions will require research along several avenues to help understand the implications of this transformation. Some recommendations to those related to test methods, codes, and standards are listed below:

- Develop consistent energy bookkeeping procedures to reflect the network-related energy consumption induced by a product. Devices may not be using grid power for operation, but they may be inducing upstream energy use by virtue of their high communications/data/cloud processing load. In other words, when a product either transmits or receives a byte of data in the course of controlling its operation, how much additional energy consumption is induced in the local network and in the cloud?

- The low-power mode test method, IEC 62301, may require entirely new sections describing procedures to measure behavior of devices with energy harvesting and storage. Greatly extending the measurement interval to capture harvesting and storage/discharge behavior will probably not be sufficient. IEC 62301 should also be extended to include standzero, that is, to define measurement methods to characterize unplugged behavior. These modifications will require research in addition to administrative updates.

- Define a consistent method based on smart meter data to determine a new home's standby losses before occupancy begins. Once defined, this measurement could be used in local or statewide energy codes (e.g., "not to exceed 100 watts").

This chapter described the test methods, codes and standards that apply to a set of products in the midst of rapid technological evolution. Even if the exact direction of the transformation of plug loads is not clear, appropriate test methods, codes and standards will provide a transparent framework for evaluation by manufacturers, policymakers, and consumers.

CHAPTER 6:
Supplemental Research

1. Introduction

Several research activities did not neatly fit in the earlier chapters and are presented here. Further GFCI measurements were undertaken when additional devices were obtained from Japan. The back-up batteries for garage door openers were studied because legislation in late 2018 made them mandatory. A subcontractor created a prototype of a DC power network with storage and renewable power which built upon findings from several chapters in this report. Plug loads in commercial buildings were also examined. Some of this research is continuing through support from other sources.

2. Further GFCI measurements

The original measurement plan included GFCI and combination GFCI/AFCI devices, both as outlets and breakers. Two GFCI plug adapters available in Japan (Figure 66) were obtained late in the project. These adapters are used for installing appliances that require GFCI protection (such as washing machines and washlet-toilets) on circuits that do not have a GFCI. The measured devices had much lower power use than any of the GFCI devices tested so far. Therefore, for comparison, five U.S. GFCI plug devices were tested to check if the low power use was related to the device type or the country of origin.

Figure 66: Japanese GFCI Plug Adapters

A summary of the GFCI plugs tested is shown in Table 24. Three of the U.S. devices were plug adapters similar to the Japanese models; that is, they plug into a standard 120 V outlet and provide a single GFCI protected outlet, while the other two were add-ons to the plugs, which are designed to be installed at the end of an appliance cord to provide GFCI protection to the appliance (Figure 67).

Table 24: GFCI Plug Measurements

Device ID	Plug Type	Origin	Reset Mode	Cost ($)	Average Power (W)	Power Factor
GFP48	Adapter	Japan	Last	21	0.09	0.74
GFP49	Adapter	Japan	Last	32	0.17	0.72
GFP50	Replacement	U.S.	Powered	17	2.24	0.98
GFP51	Adapter	U.S.	Last	15	0.27	0.99
GFP52	Adapter	U.S.	Powered	11	1.90	0.71
GFP53	Adapter	U.S.	Tripped	16	1.29	0.69
GFP54	Replacement	U.S.	Powered	20	2.65	0.99

Figure 67: GFP52, a Plug Adapter (left), GFP50, a Replacement Plug (center), and GFP51 (right)

The behavior of the devices after loss of power also differed. While all GFCI outlets tested returned to the state they were in before the loss of power (they are persistent), four of the U.S. plug devices exhibited different behaviors: one model always started in tripped (no power) mode, while the other three always started in powered mode. Also note that both replacement devices start in powered mode; this may be a feature when used on devices such as pumps or refrigerators.

The average power use of the U.S. GFCIs was 1.67 W. One model, however, drew just over 0.25 W. The Japanese models drew much less power. Both drew less than 0.20 W, with one model drawing only 0.09 W (or 5 percent of an average U.S. GFCI).

Efficiency does not appear to cost more. Models GFP50 and GFP51 are produced by the same Chinese manufacturer (Shenzhen Nandao Electromachinery Co.), and their cost is within $2 of

each other, yet one uses more than eight times more power than the other. One possible explanation is that GFP51 may also be sold in the EU market and needs to meet the 0.5 W European Union standby standard. There is also no correlation between price and efficiency among the Japanese units: the most efficient Japanese unit costs significantly less and draws half as much power.

3. Back-Up Batteries for Garage Door Openers

Some garage doors are equipped with back-up batteries to enable operation during power failures. California recently enacted legislation (Dodd 2018) requiring all new garage doors to be equipped with back-up batteries. This action was in response to several deaths during recent wildfires where people were unable to exit their garages when the power was interrupted. This legislation mandates the installation of a new plug load—the battery charger—in many California homes. The energy implications of this new SSHD were investigated to provide data for policymakers. It was also envisioned that the door opener could be incorporated into a DC network and energy storage services shared by several devices.

Five garage door openers with battery back-up systems were acquired and tested. No energy test procedure exists for these devices, so a simple procedure was developed. Power use was measured with a fully charged battery connected and without a battery connected. Preliminary results are listed in Table 25.

Table 25: Standby Power of Five Garage Door Openers with Batteries (Preliminary)

	Battery				Garage Door Opener Power (W)		
Device	Type	Capacity (Ah)	Nominal Voltage	Charged Voltage	Float Charge (mA)	With Battery	Without Battery	Difference
GDO55	Li-ion	4	18	20.48	-	14.617	14.119	0.498
GDO56	lead-acid	5	12	15.03	200–250	-	-	5.623
GDO57	lead-acid	5	12	13.36	25	8.491	8.178	0.313
GDO58	lead-acid	4.5	12	12.86	3–4	12.237	3.493	8.744
GDO59	lead-acid	5.4	12	13.35	1	7.53	7.538	-0.008

Note: Ah = ampere hour

The addition of a battery back-up increased electricity use an average of roughly 3 W. However, the values ranged from 0 to almost 9 W. The consumption appears to be sensitive to conditions and configuration, so a more complex testing method is needed. (This is often the case for devices with batteries.)

The battery must be replaced periodically—some manufacturers recommend every two years, though consumers report two to five years—which has its own cost and materials burden. The annualized costs of the electricity for recharging and batteries are about the same.

4. Low-Voltage DC Home Networks

Earlier in this report it was noted that low-voltage DC networks had potential benefits in homes. These DC networks could save energy by providing direct DC power to efficiently operate several communications, lighting, and other plug loads. By equipping the network with a small, dedicated PV collector and a battery, the system also could provide power to key services during a power interruption. Ultimately, it might be able to supply modest demand response when dual-power appliances are available. The system normally operates with power from the PV and battery; when no solar energy is available and the battery is depleted, power could be drawn from the grid. (However, power would flow only in one direction.) A DC network would save energy because it would connect the PV sources to the batteries with a very small voltage adjustment. This provides extremely high efficiencies, since a system like this is designed to closely match the voltages of a PV source to that of the storage batteries. This report identified garage door openers, optical fiber boxes, medical equipment, and sump pumps as devices that would benefit from such a system. Later, as dual-powered appliances (that is, capable of operating on either AC or DC) are developed, other small loads could be attached.

As a proof of concept, a small DC network was created based on PoE. Figure 68 shows a block diagram for the system. The present network is connected with USB-PD (Power Delivery); however, it could be upgraded to PoE.

Figure 68: Block Diagram for a Residential Low-Voltage DC Network
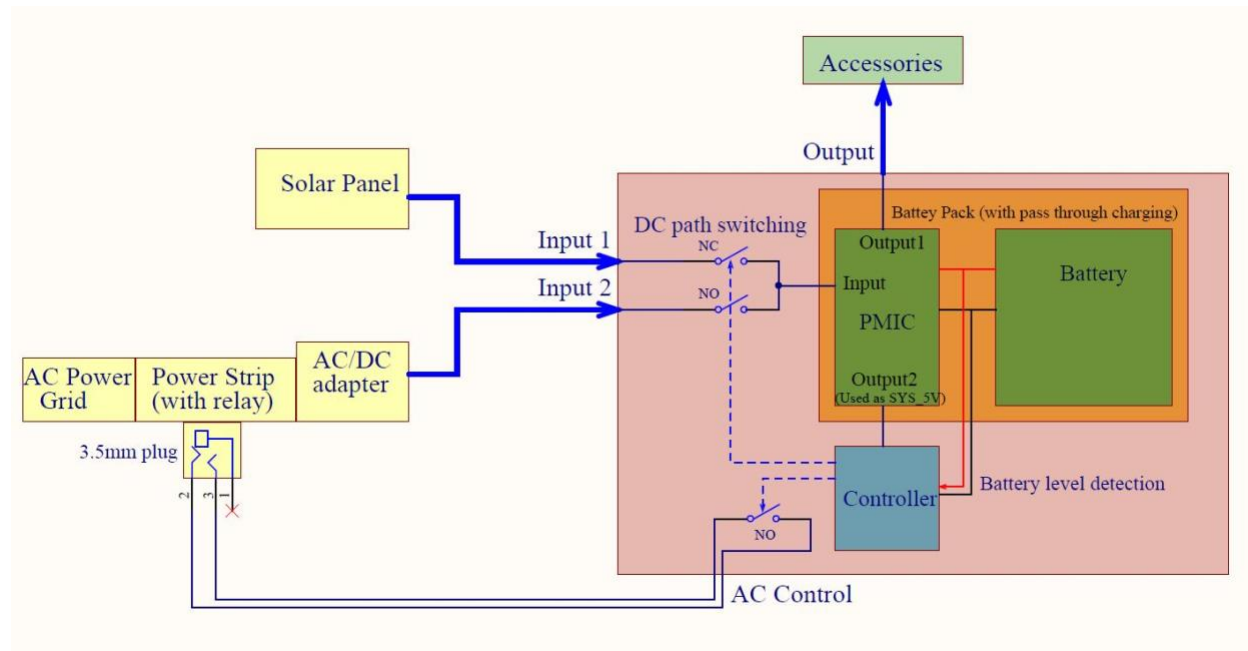
Source: Belkin

Components were either fabricated or acquired, and a bench model of the proposed system was assembled (Figure 69). One intended feature will be scalability; that is, the ability to add storage and PV capacity as the number of devices connected to the network grows.

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Figure 69: Bench Assembly of a Low-Voltage Residential DC Network with Two Loads
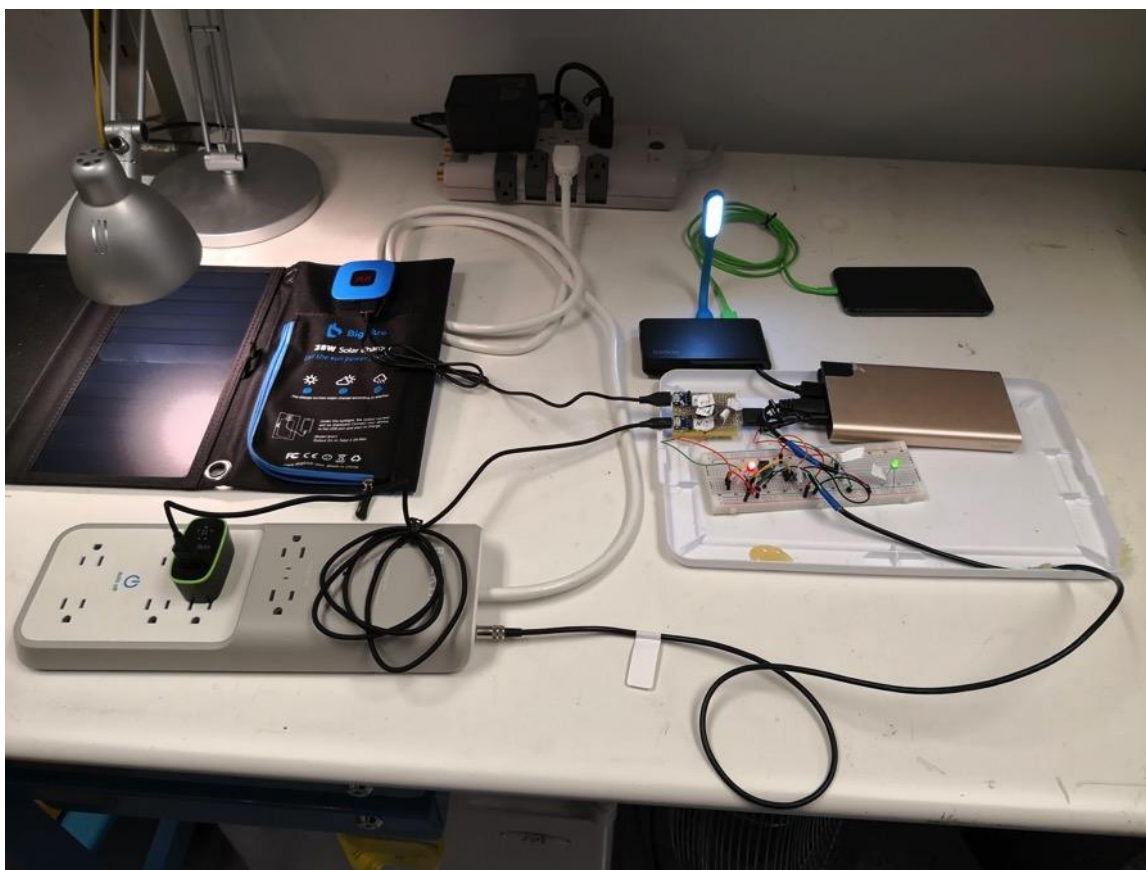
Source: Belkin

The system is currently under test. Early results indicate that its primary goals were achieved; that is, collecting solar energy, storing, and managing its distribution to various loads, and interacting with the grid.

5. Plug Loads in Commercial Buildings

Plug loads in commercial buildings differ substantially from those in homes. To be sure, there is some overlap—many commercial buildings have kitchens, for example—but they also have unique devices and usage patterns. This research focused on residential buildings but undertook two studies of plug loads related to commercial buildings.

Plug Loads in a Zero Net Energy Commercial Building

The energy performance of a ZNE office building in Northern California was investigated from the perspectives of simulation, measurement, verification, and code compliance. Simulations of the building's energy use were undertaken during the design stage to demonstrate code compliance, and measurements of actual energy use were taken for six months after occupancy. Total energy use determined from simulations was nearly equal to that determined by measurements, but actual HVAC and lighting energy use were lower than the simulations by 34 percent and 26 percent, respectively. Actual plug energy use was more than 800 percent higher than the results from the simulations. Reconciliation of simulations and actual energy use was made more complicated by the inconsistencies in categories. Water heating energy

disappeared as a separate end use because decentralized, plug-in units replaced a central unit and became a plug load. An "other" energy use was not present in the energy simulation, whereas energy measurements included it. Details of this investigation are published in Koyanagi and Meier (2017).

Laboratory Measurements of Plug Load Devices Specific to Commercial Buildings

There is surprisingly little documentation about the energy consumption of life safety equipment installed in commercial buildings. Many of the devices are difficult to measure because they are hard-wired. Some of the most common devices were measured to determine if their consumption is significant, and the measurements are summarized in Table 26.

Table 26: Measurements of Commercial SSHDs

Device	Description	Cost ($)	Average Power (W)	Power Factor
elt45	Emergency Egress Light	20	1.98	0.60
exl46	Combination Exit/Emergency Egress Light	89	3.22	0.83
exs47	Exit Sign	58	2.92	0.78

These are relatively low-power consumptions but, like in homes, dozens of these devices may be present in a commercial building.

CHAPTER 7:
Project Benefits

1. The Role of the Electric Program Investment Charge (EPIC)

For most plug loads, manufacturers face the dilemma that consumers will pay little attention to energy-saving improvements. Most products do not (and probably will not) have energy labels to alert customers to efficient products. This market arrangement discourages research into more-efficient technologies. EPIC funding is needed to make advances in these three related areas for the detailed reasons described below.

For zero-standby power supplies and devices, power supply and device manufacturers have shown increasing interest in energy efficiency and the role of power supplies in ZNE buildings, but their approach has been to implement incremental, rather than holistic improvements. In addition, power supply and device manufacturers are skilled in conditioning and managing power but not in energy harvesting, storage, and communication. Since power supply and device manufacturers are unlikely to fund the changes explored in this research, EPIC funding is needed to push the envelope of what is possible. Some of the prototypes developed for this project are shown in Figure 70. These are being shown to manufacturers for possible commercialization.

Figure 70: Standby Reduction Prototypes

(a) IR-based Zero Standby Supply   (b) Laser-based Zero Standby Supply   (c) Wake-up Radio

Credit: Daniel Gerber

For DC-powered products, manufacturers and other DC power advocates, such as the Emerge Alliance, have been trying for years to increase adoption of DC power in buildings. EPIC funding is needed to overcome at least three barriers. First, the lack of devices that are optimized for standard DC power is a key barrier to market adoption. Second, the overall energy benefits have not yet been demonstrated over the range of anticipated products. Third, stakeholders have not identified benefits that ZNE can bring to reducing plug loads. An important step in eliminating these barriers is to demonstrate to manufacturers the versatility of DC powering. Some of the prototypes developed for this project are shown in Figure 71. These are being shown to manufacturers for possible commercialization. A complete low-voltage DC network was also created and prototyped (and is illustrated in the Supplemental Research chapter, below). A California-based manufacturer is already evaluating it for commercialization.

Figure 71: Direct-DC Prototypes
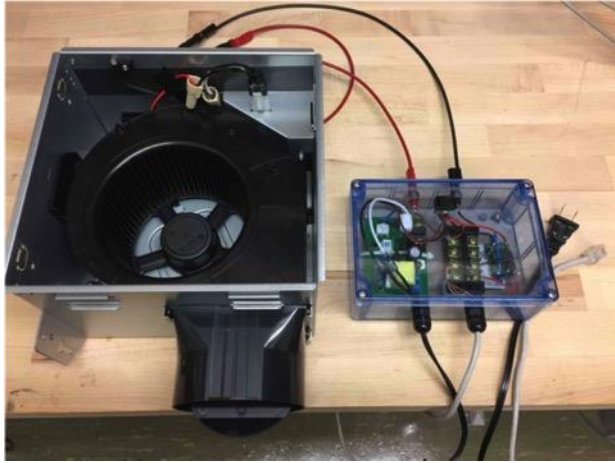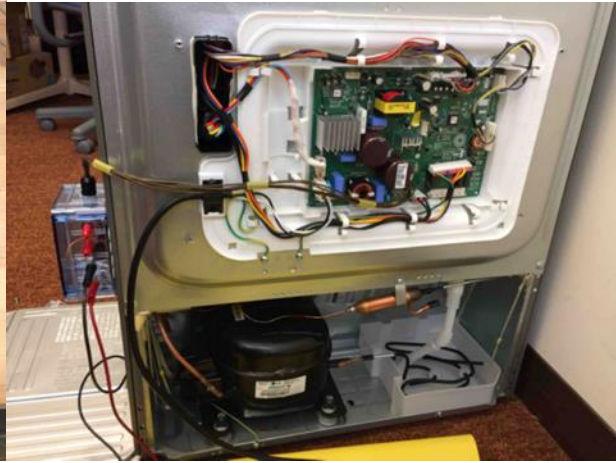
(a) Direct-DC Fan   **(b) Direct-DC Refrigerator**

Credit: Daniel Gerber

For products providing security, safety, or medical services, EPIC funding is especially necessary. First, these manufacturers' products have not been challenged to improve efficiency because they are exempt from standards. (Many manufacturers don't even know how much power their products draw.) Second, dealing with medical equipment requires special attention to safety, so manufacturers stick with proven solutions. Third, solutions often lie "outside the box." For example, smoke alarms could be powered with PoE. Finally, few researchers have studied these devices, so there is not even a good sense of the scale and nature of the problem (and solutions).

2. Anticipated Energy Use

As described in Chapter 1, plug loads comprise at least 25 percent of energy use in U.S. buildings (U.S. Department of Energy 2015). The Energy Commission estimates that in 2014, plug loads consumed 28 percent of residential energy use (21.9 GWh) in investor-owned utility (IOU) territories. The Energy Commission projections indicate that this will grow by 150 percent in 10 years, reaching 33.3 GWh by 2024 (CEC 2015). In a California study, plug loads were responsible for 40 percent of a commercial building's energy use; continuous energy use— caused mostly by plug loads—exceeded 40 percent in about half the residences in a study of 25,000 homes. In California, electricity demand attributed to plug loads is about 50,000 GWh/year, although estimates differ because definitions of plug loads vary. And the energy used by plug loads is growing, as the number and variety of devices proliferate. The "Internet of Things" is increasingly the "Internet of Plug Loads."

3. Energy Savings Resulting from this Research

This research explored three lines of inquiry, as detailed in chapters 2, 3, and 4:

1. Reducing standby energy consumption
2. Energy-saving opportunities of using direct current in buildings
3. Safety, security, and health devices

The energy savings will be achieved in thousands of different types of products and use cases. This complicates the estimation of savings, but not the confidence that savings are possible. Table 27 below provides estimates of potential benefits to ratepayers after full implementation, in electricity savings, cost savings, and demand and emissions reductions. The assumptions are listed below the table.

Table 27: Project Impacts: Electricity and Cost Savings, Demand and Greenhouse Gas (GHG) Reduction in California

	Electricity Savings (GWh/year)	Cost Savings (M$/year)	Demand Reduction (MW)	GHG Emissions Reduction - CO_2e (MT/year)
Reducing Standby Energy Consumption				
Zero standby	1,822	309	208	665
Higher mode savings	182	31	21	67
Energy-Saving Opportunities of Using Direct Current in Buildings				
DC networks	1,200	204	140	136
Power supply efficiency savings	1,122	190	128	409
More efficient appliances	557	95	64	203
Safety, Security, and Health Devices				
Builder installed residential	863	147	99	315
Builder installed commercial	154	24	18	56
Medical	121	19	14	44
TOTAL	**6,021**	**1,019**	**692**	**1,895**

Assumptions:

- Base case is the number of households or commercial floor area in 2014 plus new construction until 2024.

- Task 2 savings are based on the number of products in no-load, low-mode, or controllable by generic sensors, eliminating no load use, assuming 60 percent of the products will have been replaced by 2024.

- The Task 3 base case is the number of consumer electronics products operating with power supplies, and efficient appliances are represented by refrigeration products, savings are based on reducing conversion losses, and improved efficiency due to DC operation (ranging from 8 to 10 percent). DC network savings are 200 kWh/home, for 50 percent of homes in California.

- The Task 4 base case is from field measurements and savings projected from the most efficient GFCIs available on the market (40 percent); medical energy use is based on plug load surveys in medical buildings and savings assumed to be 60 percent, with 10 percent of products affected by 2024.

- Demand reduction was calculated assuming savings occurred at a constant rate.

- Insufficient detail on product categories may have caused minor double-counting of energy savings.

- Energy savings are valued at $0.17/kWh for residential and $0.16/kWh for commercial, and reduced carbon emissions are estimated assuming 0.73 lbs/kWh.

In summary, this project will reduce electricity use by about 6,000 GWh/year, and will save ratepayers about $1.02 billion/year. In addition, electrical demand will be reduced by 690 MW, and GHG emissions will be reduced by 1,900 million tons of CO_2e/year.

The principal California market segments affected by this research will be the residential and commercial sectors. Note that the estimate includes only office buildings within the commercial sector; this is a conservative assumption. The technologies described in this report apply to both new and existing buildings. However, the ZNE technologies principally target new construction. The projected savings are conservative because there are already examples of 50 percent savings for some applications. These assumptions are reasonable given the uncertainty in the definitions of plug loads and the rate at which the energy-saving technologies will be taken up by the market. Many of plug load devices have relatively short lifetimes—fewer than 10 years—which means that savings resulting from this research will accelerate in a relatively rapid timeframe as legacy equipment is retired and replaced with new, more-efficient devices. A significant fraction of the potential energy savings can be attained once these strategies are implemented.

4. Secondary Benefits from Energy Savings

Because of the avoided energy use resulting from this project, a number of secondary benefits accrue to both customers and the grid:

- Customers will receive lower bills, and the net energy cost savings will accumulate

- Costs associated with building new generation will be delayed or reduced; this will in turn reduce operations, maintenance, and capital costs

- Savings from plug loads may reduce peak loads in both summer and winter

- Lower plug load energy consumption may alleviate electric system power flow congestion

5. Utility and Ratepayer Benefits

The project will benefit California investor-owned utility (IOU) electricity ratepayers with respect to the EPIC goals in the following ways:

Greater reliability. Reduced electricity demand by plug loads, achieved by the innovations proposed in this project, will avoid reliance on the least reliable generation sources at the margin. The project also will improve power factor, which will improve system reliability. There may be additional reliability from reduced peak demand, although the extent of these benefits has not been determined.

Greater resilience and energy security. As described in the Supplemental Research chapter, during power outages a low-voltage DC network could provide electricity to maintain key services, such as medical devices, lighting, and communications. During normal conditions, a home DC network would save grid electricity by directly powering some appliances and avoiding as much as 300 kWh/year of grid-supplied electricity.

Lower costs. Less energy consumed by plug loads translates into lower utility bills, both in terms of reduced kWh and kW. These savings will be, to some extent, offset by increased costs of products, although, in the case of DC-powered devices, components are removed from the device, thus potentially leading to lower costs. For life safety devices, it was shown that GFCI power consumption could be reduced by 80 percent. However, the innovations proposed in this project will provide new features beyond only saving energy, so any incremental costs will be spread among these features.

Increased safety. Consumers are safer when more devices can be switched to locally generated power during grid outages. This is especially true for consumers relying on critical medical devices. The low-voltage DC power envisioned for more products also reduces public exposure to hazards from electrical shocks. Connecting garage door openers to a DC network ensures that more doors will be able to open during a power outage/wildfire and potentially save lives.

New technologies. One immediate barrier to DC adoption is the lack of DC-compatible devices. This project created new devices, and demonstrated the feasibility and versatility of DC powering to manufacturers. These products can now be included in demonstration projects, in which the overall energy benefits of DC power can be quantified for consumers, manufacturers, and other stakeholders.

Benefits to the grid. This research will have only modest impacts on the grid because many plug loads operate continuously or not particularly at peak. However, battery-reliant plug loads can be recharged on DC circuits utilizing stored solar energy or discharged into dual-power appliances during peak hours. This will introduce the opportunity to shift some system load.

6. Cost/Benefit Ratios

The anticipated benefits and costs of the project are summarized in Table 28 below. The benefits are (conservatively) based on five years of accumulated savings. Costs were calculated only for the residential sector because it makes up almost 90 percent of plug load energy use. Each California household has 50 eligible devices, or 700 million devices in all households. If the incremental cost is $0.50/device, then the residential costs are $0.35 billion.

Table 28: Anticipated Benefits and Costs

Perspective	CEC/EPIC Perspective	Consumer
Benefit	$4.3 billion	$4.3 billion
Cost	$1.6 million	$0.35 billion
Benefit/Cost Ratio	~2,700	~12

Source: LBNL

The benefits from the consumer's perspective may ultimately be much higher because they pay this incremental cost to obtain other features. Consumer costs do not include savings from avoided investments in PV or other renewable technologies to meet ZNE targets.

CHAPTER 8:
Technology/Knowledge Transfer

1. Target Audience

The project has a diverse audience for technology transfer. Some of the key audiences are: consumers, manufacturers, researchers, and policymakers. The project team's technology transfer activities and target audiences are described in Table 29.

Table 29: Target Audiences

Audience	Target Message and Activity
Manufacturers of plug load devices, power supplies, DC power, and life safety products	The goal was to disseminate research results and create prototype demonstrations of zero-standby technology power supplies and devices and direct DC devices. This was accomplished through collaborations and discussions with project partners and individual manufacturers. California-based manufacturers include Belkin, Power Integrations, and Delta. One member of the project team is on IEC 62301, the technical standard covering measurement of standby power.
Codes and Standards authorities	The goal was to identify product-level standards, test procedures, and enhancements to building codes that need to be created or updated. Team members met with staff from the Energy Commission standards office, EPA ENERGY STAR, and the DOE Buildings Technology Office.
Utilities	The goal was to convey relevant research results for absorption into efficiency and incentive programs. This occurred through multiple face-to-face conversations and presentations with staff from most California utilities. One California utility has agreed to fund follow-on investigations of builder-installed loads.

Policymakers	The goal was to inform policymakers of key issues related to plug loads and possible solutions. This was accomplished through presentations at large international conferences on energy efficiency in the United States and Europe.
	The Technical Advisory Committee (TAC) was composed of representatives from manufacturers, technical experts, EPA ENERGY STAR, and the Energy Commission: Katharine Kaplan, EPA; Michael Lubliner, Washington State Energy Office; David Chen, Power Integrations; and Ken Rider, California Energy Commission. The TAC had access to the earliest results from the project and advised on technology/knowledge transfer strategies, as well as being early adopters of the study findings themselves.
Consumers and Customers, both existing and potential	The goal was to expand awareness of the energy consumption of plug loads and efficiency opportunities through demonstrations of devices and through publications in consumer-facing magazines, websites, etc. For example, articles were published in *Home Energy Magazine.*

2. Publications and Presentations

At the time this report was prepared, at least 14 articles had already been published and at least four presentations had been made. Table 30 shows a list of publications and presentations. Note that most conference papers were accompanied by a presentation, but these were not listed.

Table 30: Publications and Presentations

Publications
Fares, Robert, Marina Sofos, Jared Langevin, Robert Hosbach, Alan Meier, Joshua Butzbaugh, and Paul Ehrlich. 2018. "Improving Characterization of Miscellaneous Energy Loads in Energy Demand Models." In *Proceedings of the ACEEE 2018 Summer Study on Energy Efficiency in Buildings.* Pacific Grove, Calif.: American Council for An Energy Efficient Economy (Washington, D.C.).
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Meier, Alan. 2018. "Zero Standby Solutions." Poster presented at the Building Technologies Office Peer Review, Crystal City, Virginia, April 30.

Rainer, Leo, Aditya Khandekar, and Alan Meier. 2018. "Builder Installed Electric Loads: The Energy Mortgage on a New House." In *Proceedings of the ACEEE 2018 Summer Study on Energy Efficiency in Buildings*. Pacific Grove, California: American Council for An Energy Efficient Economy (Washington, D.C.).

Presentations

Fares, Robert, and Alan Meier. 2018. "Introduction to Miscellaneous Energy Loads (MELs) and BTO's MELs Characterization Efforts." Presented at the Building Technologies Office Peer Review, Crystal City, Virginia, May 1.

Meier, Alan. 2017. "Cloud-Enabled Energy Efficiency—an Opportunity or a Threat?" Invited Lecture, Canon Institute, Tokyo, September 4.

Meier, Alan. 2017. "Delivering Energy Services Through the Web: California's Experiences." In *Reframing Urban Energy Policy—Challenges and Opportunities in the City of Seoul.* Seoul, Korea: Seoul Metropolitan Government.

Meier, Alan. 2017. "ZNE Ready Plug Loads." Presented at the EPIC Plug Load Collaborative Meeting, Sacramento, California, September 27.

CHAPTER 9:
Conclusions and Future Work

1. Conclusions

The aim of this project was to develop technologies that will reduce the energy use of plug loads (which are also called miscellaneous electrical loads—MELs). Lower energy use by this category will reduce building electricity use, carbon emissions, and consumer costs. When these products achieve very-low-energy use, consumers will be able to more economically tap renewable energy sources and achieve greater energy security from energy interruptions.

The scope of the discussions in this report demonstrate that no single technology can reduce plug load energy use because they are so diverse. Furthermore, limited resources prevented intensive studies of all major devices; instead the project focused on areas where the research team felt significant innovations were possible or where the team had unique expertise. In addition, some technical solutions can be applied to families of products. The approach adopted in this project was therefore multi-pronged and consisted of three steps:

1. Identify plug loads and evaluate current technologies
2. Develop lower-energy alternatives
3. Commercialize solutions

Activity was undertaken in all steps. However, the diversity of plug loads means that, for some devices, only the first step was accomplished. In others, however, commercialization is already underway. Deploying new technologies is as important as developing them in the first place. For that reason, this report also considered the codes, standards, and other policies that affect energy use of plug loads.

The conclusions are organized by chapter, followed by overall conclusions.

2. Zero Standby Solutions

Improvements to power supplies have drastically reduced standby consumption over the last 20 years. However, the need for standby power reduction persists due to the increasing population of devices with standby modes and the proliferation of IoT devices. Since modern electronics are diverse in application and requirements, the strategy of this project was to create a portfolio of solutions to tackle standby consumption. Several such solutions were presented and prototyped. Each solution in this particular report makes use of a sleep transistor, which is a solid-state standby-killer switch that can connect or disconnect the main device from its power supply.

The first solution demonstrates the value of burst mode for lightly loaded converters. This work developed a stand-alone controller that could enhance any converter with burst mode. Essentially, it disables the converter for one to two seconds, and reactivates the converter when the output voltage falls below a certain voltage.

The second and third solutions use optical energy harvesting, with an intended application in remote line-of-sight devices such as DVD VCRs, lights, fans, and curtains. One of these optical techniques uses IR energy harvesting to activate a footer switch and wake the device. However, the prototype had limited activation range due to the wide beam angle of the IR LED. This

limitation could not be overcome, so another optical technique was developed, where the receiver instead harvests visible light energy from a laser pointer. The laser prototype was demonstrated to activate a device at a range of 25 m. However, its drawbacks are in the accuracy required to hit an individual photodiode with a laser pointer.

The fourth solution uses a wake-up radio to activate a sleep transistor. The wake-up radio is an ultra-low-power microwatt receiver whose sole purpose is to wake the device. It is often capable of being programmed and addressable. The prototype used the AS3932 125 kHz wake-up radio. Its range is limited to 3 m due to its use low-frequency magnetically coupled wireless communication. Nonetheless, it demonstrates the principle of using a wake-up radio in conjunction with burst mode and a sleep transistor. Other techniques in literature have demonstrated the AS3932 at a range of 50 m.

This work demonstrates zero or near-zero standby power as being technically feasible in several families of products. These solutions have both advantages and drawbacks and will require further technical improvements and reductions in cost before they can be commercialized. In addition, the portfolio of solutions will need to be broadened before standby power use can be confidently—and economically—eliminated. There is reason to be optimistic, however, since many of the technologies investigated here barely existed a decade ago.

3. DC Power

Buildings with DC power have attracted considerable attention recently, but the development of highly efficient DC-ready loads has lagged (with the exception of mobile electronics). This work categorized the types of loads whose efficiency directly benefits from a DC input. DC-connected loads can be designed to connect directly to DC distribution, thus providing the most benefit in efficiency and cost. Examples include variable speed motor loads (HVAC, refrigeration, water heating) and wireless loads. DC-converted loads require a DC-DC converter front end, which is usually an improvement in efficiency and cost over equivalent AC-DC converters. Examples include LED lighting and computers. Finally, DC-indifferent loads such as resistive heating elements or outdated fixed speed motors benefit equally from DC or AC distribution.

Several types of loads were studied, and several were modified or prototyped as direct-DC. These loads include a wall adapter, bath fan, refrigerator, task lamp, and zone lighting rig. The main focus of each design is to leverage DC input to eliminate or improve the efficiency of the conversion stages.

This project obtained new insights during the design, development, and measurement phases. These insights were specific to the categories examined, namely, electronics, motor loads, and lighting. In electronics, DC input can allow for the downsizing or elimination of wall adapters. The efficiency benefits generally favor DC, though the comparisons must be made with careful attention to the distribution voltage and conversion process. In motor loads, the most efficient type of BLDC motor is designed such that its internal DC capacitor bus naturally operates at the DC input voltage. Although there is very little loss across a diode bridge rectifier, a PFC boost rectifier is notably less efficient. In lighting, task lamps that connect to a DC charging station with programmable power supply capability can use the charging station as the LED driver. Zone lighting can benefit greatly from series remote drivers, but further research must validate their feasibility. In all loads, DC input can allow for a great reduction in the size of the DC capacitors, and will also improve power quality. Further study is required to determine the full value of these secondary effects.

4. Safety, Security, and Health Devices (SSHDs)

This investigation identified a unique category of energy-using devices that provide life safety, health, and security to buildings. Their installation or use is dictated by building codes, health providers, insurance companies, and other entities. None of these entities would ordinarily consider energy efficiency as a priority feature.

While not particularly large today, SSHD energy use will steadily climb as existing buildings begin to comply with new codes and new types of SSHDs appear. Also, these estimates understate their total contribution because devices from other categories are now appearing or shifting from elective products into SSHDs (such as modems, Wi-Fi routers, FiOs boxes, and batteries for garage door openers). This growth helps explain why MELs are projected to grow faster than any other end use.

There are diverse strategies to reduce future SSHD energy consumption (or at lessen growth rates). For some devices, such as GFCIs and mechanical ventilation systems, the best-on-market models consume less than half as much power as typical models. It appears that efficiencies of medical equipment could be greatly improved through better compressors and controls. Battery-charging systems for a host of devices can also be made more efficient. Completely new solutions, possibly relying on customized ICs, could also offer energy savings.

At the same time, reducing the energy consumption of SSHDs is challenging. Most SSHDs consume little energy and therefore offer correspondingly small energy savings, even when reductions of 50 percent are technically feasible. The efficiency improvements may still pay for themselves in reduced operating costs, but even though they will pay for themselves, consumers, contractors and others will not spend time or money implementing the changes because the payoff is so small. Few people will devote an hour searching for an SSHD that uses 5 kWh/year—about $1—less electricity.

However, the case for improved efficiency of GFCIs is much stronger. Efficiency does not appear to cost more. The average power use of a sample of U.S. GFCIs was 1.67 W. One model, however, drew just over 0.25 W. Two models produced by the same Chinese manufacturer had similar costs, but one draws over eight times more power than the other. And the Japanese models drew even less power: an average of less than 0.20 W, with one model drawing only 0.09 W (5 percent of the U.S. average).

A second obstacle is that higher priorities determine the performance and characteristics of many SSHDs. These range from safety—electrical and fire—to health. Energy impacts rarely enter into the policymaking decisions for these devices (or, if they do, it is to exempt the devices). A coordinating council might help by raising the profile of energy use in these devices.

An important element of this investigation involved careful measurement, inspection, and teardown of SSHCs. With this information, it was hoped to first identify how these devices actually used energy and then propose lower-energy solutions. Unfortunately, these devices were more resistant to teardowns and detailed measurements than expected. As a result, fewer savings opportunities were identified than anticipated.

5. Test Methods

Test methods, codes, and standards do not yet capture the unique features of plug loads with zero or very-low standby power. Those unique features span energy consumption behavior, materials, and health and safety. Establishing test methods and standards is especially challenging because each product has a small environmental footprint—drawing less than a few

watts of power and consisting of only a few grams of materials—but the cumulative impact of billions of these products is enormous. This is the product space occupied by the Internet of Things.

For nearly all energy test methods, the boundaries of measurement need to be reconsidered to reflect new behaviors of the technologies. The boundaries include upstream energy use, environment, and duration of measurement. All test methods and standards need to consider that more and more products will operate for long periods unconnected to the grid. This phenomenon extends beyond today's portable electronics to electric vehicles and vacuum cleaners. The testing dilemma is how to define (and measure) standby modes when "disconnected" may be a common configuration.

Higher-power DC products are appearing in the market, but energy test procedures have not been updated to reflect this market shift. The ultimate goal should be comparable treatment of AC and DC products.

Future zero-standby solutions may require manufacturers to comply with new health and safety requirements. For example, lasers might be used to enable energy harvesting. Similarly, life cycle assessments of materials associated with low-standby technologies need further investigation. Most studies of energy storage, for example, focus on much larger products.

Fortunately, none of these requirements appear insurmountable.

Health and life safety devices are presently exempt from most energy standards and codes. Our research suggests that these products' energy consumption is growing.

6. Recommended Future Work

Introduction to Future Work

This project covered several, distinct research areas so the recommended future work is necessarily diverse. The goal here is to point to both broad areas and specific projects. The future work described below is not meant to be comprehensive or exhaustive but based on the findings from this project. The future work is roughly divided by the tasks in the project. However, not everything falls neatly into these groups and some material spans more than one task. The reader should refer to specific chapters to better understand the context of the recommendations.

Zero Standby Solutions

No single technology will eliminate standby power use. However, several technologies appear promising for specific applications or use cases. To advance them toward commercial development and incorporation, the following future work is recommended:

- Optimize wake-up radio, possibly including integration with the router. In addition, industry should consider burst mode for powering wake-up radios.

- Develop a scheduling algorithm in the router for devices to perform intermittent updates or data transfer.

- Explore more DC alternatives, such as a power server that can be controlled to current limit or turn off devices in standby.

- Investigate energy harvesting and storage combinations optimized for specific use cases.

- Explore lifetime batteries for certain devices.

- Recommend industry to develop and popularize burst mode. This includes including enabling pins on converter packages and designing burst mode controllers that can grant burst mode capability to normal converters.

- Design networks with occupancy sensors that can enable devices to shift themselves into lower power modes.

In the long run, coordinated improvements in efficiency, energy harvesting, and energy storage will be the best strategy to achieving zero standby power use.

DC Devices
This project demonstrated the potential for DC networks in providing energy savings, safety, and resiliency. Further research should recognize the multiple benefits of DC power (rather than simply focusing on energy savings). For this reason, many of the recommendations below focus on robust integration of products rather than the products themselves. Future work might include the following activities:

- Perform detailed loss analysis of AC boost converters to determine losses in PFC boost AC/DC converters.

- Develop integrated DC networks of high-priority communications and safety devices, supported by storage and stand-alone PV.

- Improve DC network power distribution management and data (including energy price) exchange, and define a standard mechanism for 380 V DC.

- Integrate important safety and security devices into a DC network, such as sump pumps, garage door openers, etc.

- Standardize communication protocols for managing power distribution and key application layer protocols for safety and critical load devices.

- Develop energy and performance test procedures for DC devices.

- Work with manufacturers to develop dual-powered AC-DC devices

- Work with appliance industry partners to develop high-power 380 V DC "behind the wall" loads such as HVAC, refrigeration, EV charging, hot water, and washer/dryer.

- Work with solar industry partners to allow a 380 V DC bus to connect power optimizers, storage, and loads.

- Assess the relative efficiency of "direct PV" devices for sale today that power an end-use device directly from a PV panel, possibly with a battery included (e.g., air conditioners).

- Improve a prototype of a series remote driver and get it evaluated by industry.

Safety, Security, and Health Devices
A sustained research effort should be undertaken to improve the energy efficiency of devices where health or safety considerations prevent innovations. This research needs to be carefully

linked to the health and safety communities to understand the service needs, identify technical solutions, and field-test prototypes. The first three targets should be oxygen concentrators, mechanical ventilation systems, and CPAPs.

The most efficient GFCI measured drew only 5 percent of the power of the average GFCI used today. There appears to be no relationship between the cost of a GFCI and its efficiency. Guidelines or standards should be explored.

For smoke and CO alarms, research should be undertaken to obviate the need for a power supply. This could be accomplished through a "10-year" battery, possibly combined with energy harvesting. This solution will require changing building codes but might reduce overall costs if wiring costs can be eliminated.

Some safety devices, notably garage door openers, may benefit from connection to a new DC network. These networks offer important other benefits, such as resiliency to power outages and reduced environmental burdens caused by battery replacements.

Most SSHDs consume little energy and therefore offer correspondingly small energy savings, even when reductions of 50 percent are technically feasible. The efficiency improvements may still pay for themselves in reduced operating costs, but even though they will pay for themselves, consumers, contractors and others will not spend time or money implementing the changes because the payoff is so small. Government, utilities, and other entities need to design programs that require little or no additional effort on the part of consumers, contractors, and other decision-makers to shift from current products to the most efficient available. California (and other entities) face an administrative problem related to SSHDs.

The problem is different for mechanical ventilation systems because occupants switch off the systems and expose themselves to poor indoor air quality to avoid thermal discomfort and noise. Here the goal is to increase ventilation, which leads to higher electricity consumption. More precisely, the goal is to convince occupants to take other measures to reduce their exposure to indoor air pollutants. Some of this research crosses into social science and public policy.

Codes and Standards

The evolution of plug loads will no doubt continue, and possibly at faster rates than ever. Test methods, codes, and standards will need to be continuously updated so as to provide a transparent framework for evaluation by manufacturers, policymakers, and consumers.

Over the long run, it will be necessary to develop consistent energy bookkeeping procedures to reflect the network-related energy consumption induced by a product. Devices may not be using grid power for operation, but they may be inducing upstream energy use by virtue of their high communications/data/cloud processing load. In other words, when a product either transmits or receives a byte of data in the course of controlling its operation, how much additional energy consumption is induced in the local network and in the cloud?

In the near term, the method for testing low-power modes, IEC 62301, may require entirely new sections describing procedures to measure behavior of devices with energy harvesting and storage. Greatly extending the measurement interval to capture harvesting and storage/discharge behavior will probably not be sufficient. IEC 62301 should also be extended to define measurement methods to characterize unplugged behavior. These modifications will require research in addition to administrative updates.

GLOSSARY

Term	Definition
AC	Alternating Current
AFCI	Arc Fault Circuit Interrupters
API	Application Programming Interface
ASCII	American Standard Code for Information Interchange
BLDC	Brushless DC
BLE	Bluetooth Low Energy
Burst Mode	Control that bursts operation of a power converter to handle low load
Cascode	A set of stacked transistors, whose purpose varies with application
CEC	California Energy Commission
CO	Carbon Monoxide
CPAP	Continuous Positive Airway Pressure
DC	Direct Current
DC-connected	Direct-DC load whose internal DC stage can directly connect to the distribution
DC-converted	Direct-DC load that requires a DC/DC converter to interface with the distribution
DC-indifferent	Direct-DC load that does not benefit from DC distribution
Direct-DC	Internally DC load with a DC input
DOE	U.S. Department of Energy
EMAN	Energy Management
EMI	Electromagnetic Interference
EPIC	The Electric Program Investment Charge, created by the California Public Utilities Commission in December 2011, supports investments in clean energy technologies that benefit electricity ratepayers of Pacific Gas and Electric Company, Southern California Edison Company, and San Diego Gas & Electric Company.
EPRI	Electric Power Research Institute
EVSE	Electric Vehicle Supply Equipment
GFCI	Ground Fault Circuit Interrupts
GWh	Gigawatt-hour
Hz	Hertz

IC	Integrated Circuit
IoT	Internet of Things
IOU	Investor-Owned Utility
IP	Internet Protocol
IR	Infrared
kHz	Kilohertz
LBNL	Lawrence Berkeley National Laboratory
LED	Light-Emitting Diode
MELs	Miscellaneous Electrical Loads
MHz	Megahertz
MOSFET	Metal-oxide semiconductor field-effect transistor. A transistor that switches on (closed) if a voltage is applied at the gate.
mW	Milliwatt
Native-DC	Internally DC load with an AC input
NMOS (N-type)	MOSFET with N-type doping. Turns on with a positive gate voltage
OSHA	Occupational Safety and Health Administration
PFC	Power Factor Correction
PMOS (P-type)	MOSFET with P-type doping. Turns on with a negative gate voltage
PoE	Power over Ethernet
PPS	Programmable Power Supply
PV	Photovoltaic
QC	Quick charge
RF	Radio frequency
Smart Grid	An electricity supply network that uses digital communications technology to detect and react to local changes in usage
SSHD	Safety, Security, and Health Device
USB	Universal Serial Bus
USB-PD	USB Power Delivery
V	Volt
VFD	Variable Frequency Drive
WuR	Wake-up Radio
ZNE	Zero Net Energy

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APPENDIX A:
DC Capacitor Voltage in BLDC Motors

Brushless DC (BLDC) motors are designed with an intended AC input voltage to the stator windings. See Figure A-1. The AC winding voltage is important because it dictates the inverter's DC input voltage from the DC capacitor bus. Direct-DC loads can be DC-connected if the nominal DC capacitor bus voltage is the same as the DC distribution voltage. This section shows how a motor's input voltage can be designed independently of its power rating, and can ultimately be designed such that the DC capacitor bus can seamlessly connect to the DC distribution.

Figure A-1. Winding Area Diagram for Two Motors with Equal Input Power and Magnetic Flux. The winding area in both motors is roughly equal. (a) A high-voltage motor that requires 12 windings, but they can be relatively thin. (b) An equivalent low-voltage motor only requires 3 windings, but they must be thick enough for the relatively high winding current.

(a)   (b)
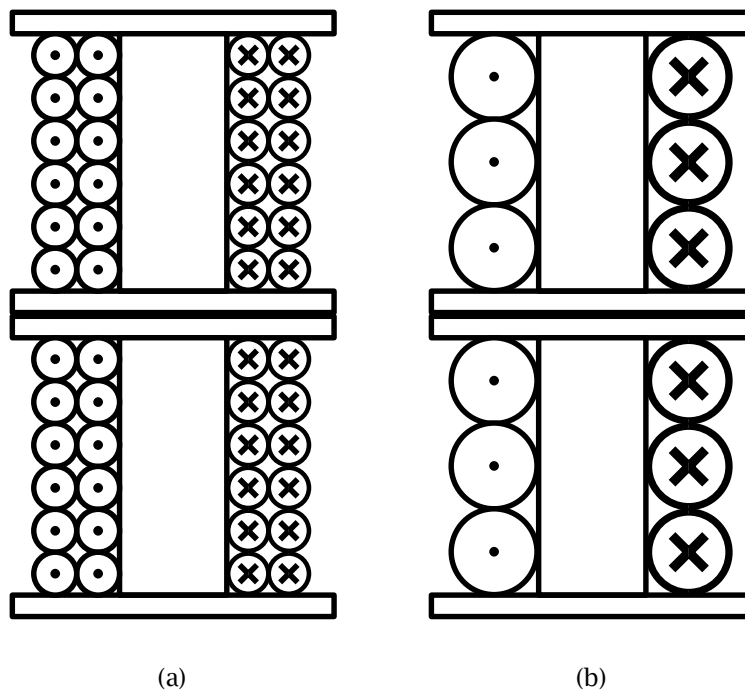
For a given application, assume that the motor's electrical input power P_{const} is specified and constant. Also assume that the motor's magnetic flux Φ_{const} is constant and is directly related to the mechanical output power. The relations between the electrical stator windings and the magnetic core are:

$$P_{const} = VI \tag{1}$$

$$\Phi const = \frac{NI}{R_{tot}} \tag{2}$$

$$E = N \frac{d\Phi_{const}}{dt}, \tag{3}$$

where V and I respectively are the winding's input voltage and current, N is the number of windings, R_{tot} is the total reluctance of the magnetic core, and E is the back EMF generated in the windings.ρ

Consider a comparison between motors 1 and 2, which both have the same input power $P_1 = P_2$, and magnetic flux $\Phi_1 = \Phi_2$. However, the main difference is that the winding voltage of motor 1 is designed to be K times greater than that of motor 2. Since $V_1 = KV_2$, Eq. 1 assures that $I_1 = \frac{1}{K}I_2$. If the two motors are specified with the same magnetic flux and core parameters, then Eq. 2 requires that $N_1 = KN_2$. In other words, the motor 1 requires K times as many windings, but the windings only pass $\frac{1}{K}$ times as much current. Finally, Eq. 3 follows that $E_1 = KE_2$, but since $V_1 = KV_2$, then each motor has proportionally as much voltage headroom, and each motor can attain the same maximum speed.

The overall result is that high-voltage motors use less current and have more stator windings than low-voltage motors of the same input power and flux. Since the low-voltage motor requires thicker windings capable of passing a higher current than the high-voltage motor. Nonetheless, the low-voltage motor requires fewer windings and so the overall winding packing window is comparable between the two motors, as shown in Fig. 21.

Finally, the losses in the high and low-voltage motors are also equivalent. The core loss is equivalent because the flux Φ is the same between the motors. For winding loss, the factor K falls out of the equations:

$$P_w = I^2 R_w \tag{4}$$

$$R_w = \rho \frac{L}{A}. \tag{5}$$

The wire loss power P_w and resistance R_w are dependent on the wire length L, cross sectional area A, and resistivity ρ. As shown in Fig. 21, the number of turns $N_1 = KN_2$ requires motor 1 to have a smaller area $A_1 = \frac{1}{K}A_2$, and greater length $L_1 = KL_2$. As such, motor 1 has a greater wire resistance $R_1 = K^2 R_2$. Nonetheless, the winding current $I_1 = \frac{1}{K}I_2$, and so the overall winding loss power $P_1 = I_1^2 R_1 = (\frac{1}{K}I_2)^2 (K^2 R_2) = P_2$.

APPENDIX B:
Supplementary Material for Chapter 4

APPENDIX B-1:
Life Safety Devices Purchased for Detailed Analysis

Device ID	Manufacturer	Cost	Options
Smoke alarms			
SMA05	A1	$14.97	Ionization, R/G LED, Wired Interconnect
SMA07	A1	$49.97	Photoelectric, LED status ring, RF Interconnect
SMA36	A1	$19.97	Photoelectric, R/G LED, Wired Interconnect
SMA02	A2	$29.96	Photoelectric, R/G LED, Wired Interconnect
SMA03	A3	$22.40	Photoelectric, R/G LED, Wired Interconnect
SMA44	A3	$30.09	Dual, R/G LED, Wired Interconnect
SMA42	A6	*	Ionization, R LED, No Interconnect, No battery backup
CO alarms			
COA08	A1	$32.97	Electrochemical, R/G/Y LEDs, Wired Interconnect
COA11	A1	$52.47	Electrochemical, R/G LEDs, Wired Interconnect, digital display
COA09	A2	$34.96	Electrochemical, R/G LEDs, Wired Interconnect
COA37	A3	$47.60	Electrochemical, R/G LED, No Interconnect
Smoke / CO alarms			
SCA12	A1	$49.97	Photoelectric/electrochemical, R/G LED, Wired Interconnect
SCA43	A1	$47.97	Ionization / electrochemical, R/G LED, Wired Interconnect, Voice
SCA15	A1	$79.97	Photoelectric/electrochemical, LED status ring, RF Interconnect
SCA13	A3	$44.25	Photoelectric/electrochemical, R/G LEDs, Wired Interconnect
SCA14	A4	$42.41	Proprietary sensor, R/G LEDs, Wired Interconnect
SCA16	A5	$119.00	Split-spectrum/electrochemical, LED status ring, Wifi Interconnect
GFCI outlets			
GFO17	O1	$13.97	R/G LED, Self-test

Device ID	Manufacturer	Cost	Options
GFO18	O2	$48.95	R/G LED, Self-test
GFO38	O3	$13.97	R LED, Self-test
GFO39	O4	$16.18	Replacement indicator, Self-test
GFO40	O5	$55.60	R/G LED, Self-test
GFCI breakers			
GFB22	B1	$39.48	None
GFB23	B2	$49.97	None
GFB24	B3	$45.00	None
Device ID	**Manufacturer**	**Cost**	**Options**
AFCI outlets			
AFO25	O1	$19.98	R/G LED
AFO26	O3	$21.98	R/G LED
AFCI breakers			
AFB27	B1	$30.53	None
AFB28	B2	$15.00	R LED
AFB41	B3	$26.11	None
AFCI / GFCI outlets			
AGO30	O1	$24.97	R/G LED, Self-test
AGO31	O3	$29.97	R/G LED, Self-test
AFCI / GFCI breakers			
AGB34	B2	$44.97	R LEDs
AGB35	B3	$48.85	R LED

* Device SMA42 was an old alarm from an existing home and so did not have a purchase cost.

APPENDIX B-2:
SSHD Test Method

1. Turn on Chroma and start *Chroma 66200 Soft Panel* program
   a. Click on **Scan Device**
   b. Click on **Open** and choose *Base.Mea*
   c. Click on **Recording** and then **Open** and choose *rpd.Rpt*
2. Open SSHD Testing google sheet, *Tests* tab.
3. Un-LOTO the test fixture
4. Measure Devices
   a. Remove device from packaging and mark with ID
   b. Record model number on *Test* tab
   c. Take a picture of the back and front of the device
   d. Install device in test fixture and plug test fixture into the Chroma
   e. Click on **Recording** to open the *Recording* window
   f. Click **Browse** in *Soft Panel Recording* window and name file using the device ID
   g. Click **Record Start**
   h. When recording is finished click on **Back** to close the *Recording* window
   i. Press **Alt + PrtScn** with *Soft Panel* window active
   j. Click on **Select**, select the waveform graph with the mouse, and click on **Crop**
   k. Open *Paint* program and click on **Paste**
   l. Click on **Save** and save PNG file using the device ID
   m. Check the data file and image file and add any notes to the *Test* tab
   n. Disconnect the test fixture from the Choma and remove the device
   o. Repeat as necessary
5. LOTO the test fixture when finished with testing

APPENDIX B-3:
Selected SSHD Test Results

Device ID	Voltage (VAC)	Current (amps)	Mean Power (watts)	Min Power (watts)	Max Power (watts)	Power Stdev (watts)	Power Factor	Distortion Power Factor	Displacement Power Factor	Regression Slope (watts/sec)
sma02	125.5	0.058	0.901	0.887	0.907	0.0047	0.124	0.939	0.132	5.99E-05
sma03	125.3	0.0397	0.58	0.573	0.582	0.0015	0.116	0.962	0.121	-1.14E-05
sma05	125.0	0.0731	1.185	1.168	1.192	0.0051	0.13	0.958	0.135	4.71E-05
sma07	125.4	0.0055	0.31	0.241	0.322	0.0241	0.447	0.484	0.924	-2.52E-04
coa08	125.2	0.0149	0.74	0.735	0.744	0.002	0.397	0.942	0.422	1.53E-05
coa09	125.6	0.0285	0.404	0.399	0.406	0.0013	0.113	0.934	0.121	-2.00E-05
coa11	125.1	0.0154	0.789	0.77	0.795	0.0055	0.408	0.947	0.431	-2.49E-05
sca12	125.3	0.0721	0.797	0.783	0.806	0.0054	0.088	0.932	0.095	-4.23E-05
sca13	124.6	0.0486	0.648	0.64	0.65	0.0018	0.107	0.962	0.111	2.06E-06
sca14	125.4	0.1101	1.227	1.216	1.238	0.0076	0.089	0.918	0.097	-9.43E-06
sca15	125.5	0.0054	0.307	0.239	0.318	0.0235	0.45	0.488	0.922	-6.60E-04
sca16	125.8	0.0065	0.42	0.412	0.43	0.003	0.513	0.513	1.001	3.12E-05
gfo17	125.3	0.0083	1.013	0.998	1.017	0.0029	0.977	0.992	0.984	-9.98E-06
gfo18	125.2	0.0076	0.895	0.88	0.9	0.0042	0.94	0.982	0.957	1.49E-06
gfb22	125.2	0.0048	0.599	0.59	0.6	0.0023	0.994	0.996	0.998	3.15E-05
gfb23	125.4	0.0084	0.558	0.556	0.559	0.0005	0.528	0.882	0.598	4.04E-06
gfb24	125.4	0.0052	0.648	0.635	0.651	0.0035	0.993	0.989	1.003	1.42E-05
afo25	125.6	0.0082	0.809	0.8	0.812	0.0032	0.784	0.868	0.903	-4.92E-05
afo26	125.6	0.0519	0.793	0.787	0.799	0.0031	0.122	0.322	0.377	1.97E-05
afb27	125.2	0.0065	0.702	0.697	0.703	0.001	0.856	0.876	0.977	1.37E-05
afb28	125.6	0.0577	0.843	0.832	0.849	0.0034	0.116	0.489	0.238	-2.69E-05
ago30	125.8	0.01	1.012	0.996	1.015	0.003	0.806	0.903	0.892	-1.83E-05

Device ID	Voltage (VAC)	Current (amps)	Mean Power (watts)	Min Power (watts)	Max Power (watts)	Power Stdev (watts)	Power Factor	Distortion Power Factor	Displacement Power Factor	Regression Slope
ago31	125.7	0.0047	0.362	0.36	0.363	0.0006	0.614	0.677	0.906	5.69E-06
agb34	125.3	0.0058	0.249	0.248	0.249	0.0002	0.345	0.850	0.405	-1.13E-06
agb35	125.4	0.0531	1.339	1.322	1.347	0.0055	0.201	0.380	0.529	-3.71E-05
sma36	124.9	0.0702	0.99	0.977	0.992	0.0019	0.113	0.964	0.117	1.69E-05
coa37	125.1	0.0392	0.405	0.4	0.406	0.0012	0.082	0.930	0.089	-1.71E-05
gfo38	125.9	0.0076	0.958	0.942	0.963	0.0038	0.996	0.995	1.002	5.47E-05
gfo39	125.2	0.0076	0.682	0.672	0.686	0.0029	0.718	0.889	0.808	-1.02E-06
gfo40	124.8	0.0042	0.525	0.519	0.529	0.0023	0.993	0.993	1	1.63E-05
afb41	125.1	0.0053	0.653	0.644	0.656	0.002	0.985	0.993	0.992	4.58E-06
sma42	124.8	0.0132	1.167	1.149	1.172	0.004	0.709	0.894	0.793	5.37E-05
sca43	125.4	0.0051	0.314	0.314	0.315	0.0002	0.495	0.542	0.912	5.70E-07
sma44	125.7	0.0726	1.09	1.077	1.094	0.0033	0.119	0.932	0.128	1.51E-05