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Energy Use of Residential Safety, Security, and Health Devices

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ABSTRACT

Miscellaneous electrical loads (MELs) are responsible for a significant fraction of energy consumption in buildings. This paper addresses one category of MELs: Safety, Security, and Health Devices (SSHDs). Common SSHDs include: electrical life safety equipment, smoke alarms, radon mitigation fans, and home oxygen concentrators. The installation or use of these devices is dictated by building codes, health providers, insurance companies, and other entities—none of which would ordinarily consider energy efficiency a priority. For this project, the most important residential devices were explored in terms of their governing regulations, functions, technologies, and energy use. The power consumption of 41 life safety SSHDs were measured. Individual power consumption of life safety devices is very small but many are typically required in every home. Devices performing the same functions have wide ranges in power use. Opportunities for reducing SSHD energy use were investigated, the results are summarized, and recommendations are made for further actions that could be taken to reduce SSHD energy use. SSHDs identified in this paper are responsible for at least one percent of current U.S. residential electricity consumption, but that number will climb steadily as existing buildings are upgraded and new types of SSHDs appear.

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1. Background and Introduction: Rising Electricity Consumption from Miscellaneous Electrical Loads

The miscellaneous uses of electricity consist of devices that do not easily fit into the conventional end uses of space heating and cooling, refrigeration, water heating, electronics, and lighting. This category has many different names, including “other,” “plug loads,” and “MELs” (for miscellaneous electrical loads). These miscellaneous loads are responsible for a significant fraction of energy consumption in buildings. The size of miscellaneous loads varies widely among countries because of differences in income (since discretionary income is often used to purchase these miscellaneous devices), building codes, and local conditions (Menezes et al. 2014). Estimates also differ because definitions of this category are inconsistent. For example, residential buildings in the United States and Malaysia have perhaps the largest reported fractions of energy consumption in the MELs category, at about 32 percent and 31 percent of total use, respectively (U.S. Department of Energy 2015b; Chong et al. 2015). In contrast, MELs consume only about 10 percent of total electricity use in European Union homes (Cao, Dai, and Liu 2016). MELs fractions in commercial buildings have a similarly wide range (Harvey et al. 2014), again reflecting differences in building stocks, cultures, and the variety of definitions for MELs.

Future MELs energy consumption is likely to grow in both absolute amount—as a result of building codes and new MELs continually entering the market—and fraction of total energy consumption, as building codes and minimum energy efficiency performance standards (MEPS) reduce consumption of space heating, lighting, refrigerators, and other conventional end uses. Figure 1 shows an investigation of several U.S. scenarios (U.S. Department of Energy 2015b). The scenarios in Figure 1 compare the energy use in the 2015 residential building stock (“Stock”) with energy use in four other categories: (1) residential buildings using ENERGY STAR® equipment (Energy Star), (2) best-available technologies in 2015 (Best Available), (3) technologies meeting the U.S. Department of Energy’s emerging technologies cost and performance goals (ET 2020), and (4) technologies operating at theoretical efficiency limits (Thermodynamic Limit). The analysis did not address energy savings in the “other” category, but emphasized that “finding ways to manage them will become increasingly important” (U.S. Department of Energy 2015a). Other policy documents (California Energy Commission 2017) have noted the unusual difficulties in obtaining energy savings in MELs.

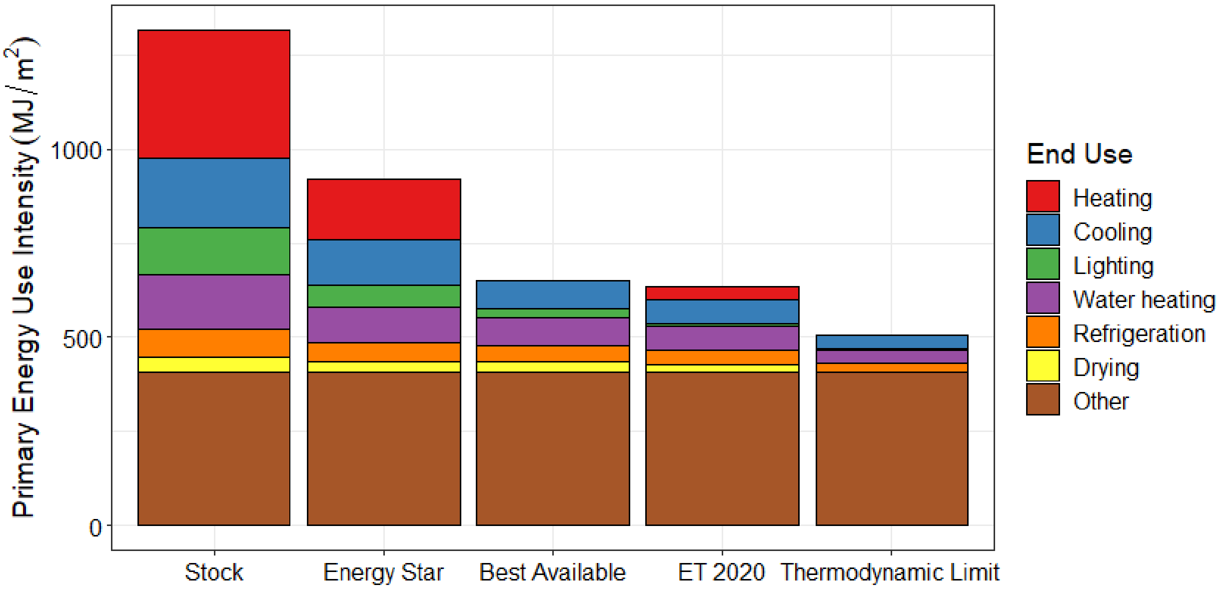

Figure 1. Forecasted energy consumption for core end uses (including heating, cooling, lighting, water heating, refrigeration, drying, and "other") and "other" end uses in five efficiency scenarios in residential buildings (adapted from (U.S. Department of Energy 2015b)).

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. Grouping by common characteristics facilitates gathering data and developing energy-saving strategies. Thus, "consumer electronics"—devices dedicated principally to information transformation—are now sometimes treated separately (Urban et al. 2017). Standby power consumption is another characteristic that could define a subset of MELs. Regulations in many countries have been established to reduce standby, notably the Ecodesign Directive in Europe (European Commission 2009). However, nearly all MELs have standby power consumption (De Almeida et al. 2011) and a growing fraction of conventional appliances draw power continuously, so standby power use is not a useful means of segmenting MELs. Another approach is to examine those devices purchased or installed by specific entities. For example, contractors install certain devices and components during construction. The category of "builder-installed" loads (Meier and Aillot 2016) is attractive from a policy perspective because they might be addressed through building codes. This paper identifies another segment of MELs, "Safety, Security, and Health", where the devices (and their markets) have unique features that make them suitable for targeted policies and programs.

This paper begins by defining "safety, security, and health devices" (SSHDs) and explaining why they deserve to be considered as a unique category of devices even if they are not together a distinct end use. Several prominent SSHDs are explored in terms of their governing regulations, functions, technologies, and energy use. This sample is not intended to be comprehensive, but it does illustrate the diversity of SSHDs and their features. Next, opportunities for reducing SSHD energy use are investigated. Finally, the results are summarized and recommendations are made for further actions to reduce SSHD energy use. This work builds upon an investigation performed in California (Meier, Alan et al. 2019). The SSHDs are discussed in the context of U.S. equipment codes, buildings, and regulations; however, many of the technologies and characteristics apply to other countries and regions.

2. Safety, Security, and Health Devices in Residential Buildings

An increasing number of energy-using devices are installed in homes to provide safety, security, and health functions. Example devices in the “safety” category include circuit breakers, arc-fault circuit interrupter (AFCI) and ground-fault circuit interrupter (GFCI) outlets and breakers,[2] smoke and carbon monoxide alarms, electric resistance ice/gutters/snow melt systems, back-up batteries to garage door openers, and flood and leak alarms. Example devices in the “security” category include surveillance systems, burglar alarms, illuminated address lights, electronic locks, and network communications equipment. Example devices in the “health” category include home oxygen concentrators, continuous positive airway pressure (CPAP) ventilators, ventilation fans, radon ventilation systems, air purification devices, and elevators. As opposed to being comprehensive, these device lists represent an illustrative set of commonly installed SSHDs in residential homes.

These devices are extraordinarily diverse; nevertheless, they share important features. First, they assure occupant safety and building integrity, with respect to both acute and chronic hazards. Second, most devices are installed at the time of construction (or renovation). Third, most use relatively small amounts of electrical energy. Finally, their energy efficiencies are not typically regulated. There is no widely accepted term to categorize these devices; we call them “safety, security, and health devices” (SSHDs). SSHDs are not a distinct end use, so it is difficult to draw clear borders between them and other devices. Moreover, many SSHDs are not characterized by all four common features. For example, oxygen concentrators are large energy consumers, and the efficiency of certain network communications equipment is regulated by the European Union. Nevertheless, SSHDs share characteristics that policymakers may find easier to address as a family than individually.

Over time, SSHDs will move from discretionary use to mandatory use. For example, a recent addition to this list is a battery to supply back-up power for automatic garage door openers. California law now 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 recent wildfires); however, maintaining the battery charge also adds several watts to the home’s electricity use. Homes connected to fiber optic communications networks use an optical network terminal (ONT) to maintain a data connection and to provide

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[2] Also called *earth leakage circuit breakers* and *residual current devices.*

Voice over Internet Protocol (VoIP) service. Some regulators have required service providers to offer a back-up battery to ensure emergency telephone service during power outages, and the charger for this battery consumes about 3 watts (W) (approximately 30 kilowatt-hours [kWh]/year). Surveillance systems—both wired and wireless—are emerging as a distinct product separate from other types of security systems. These systems, especially if equipped with multiple cameras and video recording capability, can draw as much as 25 W (~220 kWh/year) (Andrei et al. 2019). Some communities require homes to have illuminated street address numbers. These lights can draw as much as 8 W (~70 kWh/year), and most operate continuously because they lack switches or photocontrols (Meier et al. 2019). Home medical equipment will become both more pervasive and diverse in response to the rising costs of hospitalization and increasingly sophisticated automated health delivery equipment.

Policymakers have largely overlooked (or ignored) the energy consumption of SSHDs 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). Many SSHDs draw very little power, or the devices are not especially common (or both), so their aggregate energy consumption falls below the legislative thresholds. New technologies also have emerged that could enable lower energy consumption for many SSHDs. For example, advances in ambient energy harvesting and batteries may allow some devices to operate without any grid connection (Meier 2018). These trends suggest that SSHDs deserve renewed attention to determine if significant energy savings are now feasible.

In this paper, we evaluate the power consumption of a variety of SSHDs, which are listed in Table 1.

Table 1. Safety, Security, and Health Devices Evaluated in this Study

Device	Purpose
Ground-fault circuit interrupters (GFCI)	Protects people from electric shock, especially in the presence of exposed earth grounds such as plumbing
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
Home security systems	Detects and signals building intrusion ("burglar alarm")
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
Radon mitigation fans	Controls indoor radon gas levels

2.1 Residential SSHDs and Energy Efficiency Regulations

Most residential SSHDs are exempted from minimum energy efficiency performance standards (MEPS) in the United States, Europe, and elsewhere. The implicit assumption is that these regulations may impede a device's ability to provide life safety. In the United States, the 1975 Energy Policy and Conservation Act and subsequent amendments determine which products are covered (U.S. Department of Energy 1977). Specifically, it exempts the power supplies for certain continuously operating security or life safety alarms or surveillance systems from no-load mode minimum energy efficiency regulations. This exemption was extended to 2023 (115th Congress of the United States 2017). The European ecodesign regulations exempt external power supplies of medical devices (European Commission 2009). Similarly, the 2016 California Appliance Efficiency Regulations (Baez et al. 2017) exempts external power supplies that require Federal Food and Drug Administration (FDA) listing and approval as a medical device.

Many new “smart homes” require Internet connections to operate and therefore require contractors to install routers, home gateways, and other network infrastructure during construction. When installed to provide essential safety and security services, these devices may be considered SSHDs. Some of these devices are covered by mandatory and voluntary regulations in certain jurisdictions, such as the European Code of Conduct (Bertoldi and Lejeune 2020).

2.2 Existing Literature Pertaining to SSHD Energy Use

The existing literature on the power consumption of SSHDs is sparse and highly dispersed. Several factors explain the absence of literature, including the low per-device power consumption and difficulty in making measurements. 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 (California Energy Commission 2017). Table 2 summarizes the results of the literature search.

Table 2. Reported Power Consumption of Some Residential Safety, Security, and Health Devices

Source	SSHD	Results
Energy Consumption Analysis of Security Systems for a Residential Consumer (Andrei et al. 2019)	Security systems	Average 24-hour power consumption for the closed-circuit television (CCTV) system and anti-theft alarm system of 24 W and 5 W, respectively.
LG&E Watt Finders Guide (LG&E n.d.)	Smoke alarm	2 W
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.
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.
Eaton White Paper AP08324002E (effective July 2010) (Eaton Corporation 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.
Low-Power Mode Energy Consumption in California Homes (CEC-500-2008-035, September 2008) (Meier et al. 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.
Smoke Alarms Product Profile	Smoke alarms	Measurements of eight ionization and photoelectric units were 0.2 W to 0.5 W.

(Australian Greenhouse Office 2004)		

The findings provided in Table 2 come mainly from outdated sources. There are also discrepancies among the reports. Nevertheless, these sources indicate that SSHDs have a continuous, non-trivial power draw.

Based on the literature search and preliminary calculations, nine SSHDs were selected for further investigation: GFCIs, AFCIs, smoke alarms, CO alarms, home security systems, oxygen concentrators, CPAP ventilators, and radon mitigation fans. To our knowledge, none of these devices are covered by energy codes, although some are explicitly exempted. This study was confined to residential buildings.

3. Detailed Investigations of SSHD Energy Characteristics

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. 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 selected categories, the codes, market situation, energy use, and other relevant issues were reviewed.

The technical specifications and performance of many SSHDs are covered by health and safety codes and standards, which are often unique to each country. In the United States, the specifications are typically issued by the National Fire Prevention Association (NFPA), Underwriters Laboratories (UL), and the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE). These specifications are, in turn, typically adopted by state and local building codes. Table 3 summarizes the key health and safety codes applicable to the SSHDs.

Table 3. Residential Health and Safety Devices Required by U.S. 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

These codes do not explicitly address the devices' energy consumption, although the requirements can affect energy consumption in some cases.

Because many SSHDs are required by building codes and these codes change with time, the number of SSHDs incorporated into new construction has changed over the years. In order to estimate the total number of SSHDs in the U.S. it is necessary to estimate the number of SSHDs required in each year and how many new homes or apartments were constructed in that year. Annual residential and multifamily construction rates for 1973 – 2018 were obtained from the U.S. Census (U.S. Census 2020).

3.1. 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 (typically an imbalance of at least 6 milliamps [mA]) and disconnects the circuit before any injury can occur. The U.S. National Electric Code (NEC) first required residential outdoor receptacles to be protected by GFCIs beginning in 1975 (Roberts 2019). Since then, numerous other receptacles in the home have been covered by code, including receptacles in bathrooms, kitchens, garages, basements, and crawlspaces. The GFCI can be integrated into breakers, plugs, and outlets, but because outlets are cheaper (and more user friendly), builders and contractors tend to use them almost exclusively.

Using the assumptions for the number of GFCIs in new construction shown in Table 4 and annual residential and multifamily building construction estimates from Section 3.0, it is estimated that there are about 600 million GFCIs in U.S. homes and that the average new single-family house has eight GFCIs.

Table 4. Assumed number of GFCIs in new construction

Years	Residential GFCIs	Multifamily GFCIs	NEC Change
1975–1995	3	1.5	Required in all bathrooms

1996–2004	6	3.5	Added kitchen countertops
2005–2018	8	3.7	Added near laundry and utility room sinks

The primary purpose of an AFCI is to prevent fires. (This is in contrast to the GFCI, whose purpose is to prevent electrical shock.) The AFCI does this by continually analyzing the circuit waveform for characteristics known to be associated with electric 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 AFCI outlet will protect appliance cords and extension cords plugged into it. Using the number of AFCIs shown in Table 5 and building construction estimates from Section 3.0, it is estimated that there are about 140 million AFCIs in U.S. homes and that the average new house has four AFCIs.

Table 5. Assumed number of AFCIs in new construction

Years	Residential AFCIs	Multifamily AFCIs	NEC Change
2002–2007	2	2	Required for all bedroom outlets
2008–2018	4	3	Required for all outlets

According to the 2017 U.S. National Electrical Code (NFPA 70), circuits are required to be protected by GFCIs under certain conditions 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 (National Fire Protection Association 2017). Similarly, 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.

3.2 Smoke and Carbon Monoxide Alarms

Residential smoke alarms detect smoke and emit an audible alarm when smoke is detected. They employ two types of sensing technology: ionization, which uses a radioisotope to ionize air molecules, and photoelectric, which operates 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 number of smoke alarms shown in Table 6 and building construction estimates from Section 3.0, it is estimated that there are almost 200 million hardwired smoke alarms in U.S. homes and that the average new house has five smoke alarms.

Table 6. Assumed number of smoke alarms in new construction

Years	Residential Smoke Alarms	Multifamily Smoke Alarms	NFC Change
1976–1987	2	1	Require one on each floor
1988–2018	5	3	Added all bedrooms

The 2015 International Fire Code (International Code Council, Inc. 2014) requires smoke alarms in new construction to receive their primary power from the building wiring, have a battery backup, and 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 U.S. National Fire Alarm and Signaling 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 U.S. 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 (National Fire Protection Association 2018).

Carbon monoxide (CO) alarms detect the presence of CO gas, most commonly due to malfunctioning fuel-fired equipment such as furnaces, space heaters, and water heaters, but also from generators and automobiles. They are a more recent addition to homes than smoke alarms, and they were first required in New Jersey starting in 1996 (System Sensor 2016). One study (Gundel, Apte, and Nematollahi 1998) indicates that three types of CO sensors have been used: biomimetic, metal oxide sensor (MOS), and electrochemical cell, but we were only able to find electrochemical CO alarms for testing. Section 4.5 of the 2015 U.S. Standard for the Installation of Carbon Monoxide (CO) Detection and Warning Equipment (NFPA 720) (National Fire Protection Association 2015) 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, the 2015 International Fire Code® requires 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 state CO alarm legislation dates from System Sensor, U.S. Census annual construction estimates, and assuming the average newly constructed U.S. home has two CO alarms, it is estimated that there are about 7.3 million hardwired CO alarms in American homes.

3.3 Home Security Systems

Home security systems 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. One study of 10 home security systems found an average of 8.2 W (70 kWh/year) (Delforge, Schmidt, and Schmidt 2015). The U.S. Energy Information Administration (EIA) projects an annual energy consumption of 44 kWh for home security systems in 2020 (U.S. Energy Information Administration 2017). Finally, a security system in a Romanian home was found to draw 23.7 W and 4.8 W for the CCTV system and alarm system, respectively (Andrei et al. 2019). For this analysis, we used the 8.2 W power consumption estimate because it is likely a conservative estimate based on the ingrowth of video and internet connectivity features into the home security system space.

There are no reliable estimates of the number of installed home security systems. The EIA projects an installed stock of 49 million home security systems in 2020 (U.S. Energy Information Administration 2017). The 2019 Safety.com Home Security Report indicated that approximately 24 percent of survey respondents (approximately 28 million homes) had a professionally or self-monitored home security system (Ferron 2020). Parks Associates predicts that roughly 27 percent of U.S. households (approximately 32 million) would have security by 2021 (Ives 2018). For this analysis, we used the most conservative of these estimates to assume an installed stock of 28 million home security systems.

3.4 Oxygen Concentrators

At least 16 million Americans have chronic obstructive pulmonary diseases (COPD), such as bronchitis and emphysema (U.S. Department of Health and Human Services, National Institutes of Health, and National Heart, Lung, and Blood Institute 2018). 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, 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 concentrators have mostly replaced for home use. Oxygen concentrators are available as both stationary, mains-powered and portable, battery-powered devices. While we were not able to test any concentrators, we did review data sheets of five models from two companies with a range of capacities (see Table 7). The concentrators can deliver 1–10 liters/minute of oxygen and are rated at 70–590 W. De-rating an average power use of 340 W by 50% (ASHRAE 1997), we estimate that oxygen concentrators use an average of 1,500 kWh/year (assuming continuous operation). 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 oxygen delivery capacity, averaging 70 W/liter/minute. It is not known if the power consumption is proportional to the oxygen flow. It appears that, at best, power is weakly proportional; so, assuming the power applies 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.

About 18 percent of national health care (Medicare) patients with COPD used sustained oxygen therapy in 2010 (Nishi et al. 2015). Assuming the same rate for the 16 million Americans with COPD, this results in an estimate of 2.7 million oxygen concentrators in the United States.

Table 7. Power Use of Stationary Oxygen Concentrators

Concentrator	Capacity (l/min)	Rated 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

3.5 Continuous Positive Airway Pressure Ventilators

About 22 million Americans suffer from sleep apnea—a temporary cessation of breathing while sleeping (American Sleep Apnea Association 2020). Continuous positive airway pressure (CPAP) ventilators 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 (CapnLoki 2018). 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.

Based on product literature, CPAP ventilators are rated at 10–100 W (depending on the selected pressure, temperature, and humidity) but are used only when the patient is sleeping (assumed to be eight hours per day). Derating an average rated power of 56 W by 50% (ASHRAE 1997), we estimate that CPAP ventilators use an average of 77 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 (Smith 2015). By combining these factors, it is estimated that there are approximately 2.2 million CPAP ventilators in use in the United States.

3.6 Radon Mitigation Fans

Radon is a radioactive gas that occurs naturally in certain types of rocks and soils and can infiltrate homes through cracks and openings in the foundation. In 2013 the U.S. Environmental Protection Agency (EPA) estimated that there were 7 million homes in need of radon mitigation due to indoor air radon concentrations above the 4 picocuries per liter (pCi/L) action level (U.S. Environmental Protection Agency 2014). Based on radon ventilation fan sales data provided by the three major radon fan manufacturers, the same report estimated that in 2013 there were 1.2 million U.S. homes with operating radon mitigation systems. By extrapolating the EPA data, we estimate that the total has grown to 1.7 million homes by 2018.

In most homes requiring radon mitigation a single fan is operated continuously to negatively pressurize the area under the foundation in order to prevent infiltration of radon into the living area. The rated power consumption of available radon fans varies from 15 W to 169 W. Assuming a 50% de-rating factor, we estimate that the average radon fan uses 42 W, which when operated continuously results in an energy use of 370 kWh/year.

4.0 Detailed Analysis of Residential Life Safety SSHDs

Four categories of life safety devices were subjected to detailed measurement and analysis: GFCIs, AFCIs, smoke alarms, and CO alarms. All of them have been required in new homes for many years (typically in multiple 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 Internet-of-things [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 8 and Table 9 show the number of manufacturers and options that are readily available for each category of device. Two to five major manufacturers typically offer products that are readily available.

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. Table 9 lists some of the characteristics of the smoke and CO alarm market.

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 radio frequency (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 8. Manufacturers and Features of GFCIs and AFCIs

Device Category	Number of Manufacturers	Self Test*	Indicator Light*
GFCI outlet	4	Yes/No	Yes/No
GFCI breaker	4		Yes/No
GFCI plug	6		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

* "Yes/No" indicates products with and without the given feature for the device category were identified.

Table 9. Manufacturers and Features of Smoke and CO Alarms

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. These are summarized in Table 10. Only new products were tested.

Table 10. 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	-	-
GFCI plug	7	6	LED	-
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, WiFi

4.1 Measurement Procedure

It was necessary to construct a measurement fixture for each category of device to safely measure their power consumption because all of the residential life safety SSHDs were hard-wired. 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. Figure 2 shows a GFCI plug mounted in the junction box and a GFCI breaker mounted in one of the load centers.

Figure 2. An example measurement fixture showing the test setup for a GFCI breaker and a GFCI outlet.

Power was measured using a Chroma 66202 Digital Power Meter, which can measure power to 0.1 milliwatt (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. Data were recorded on a one-second basis using the Chroma Soft Panel software running on an attached PC. The recorded data 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).

To accurately and repeatedly measure the energy use of the residential life safety SSHDs, a test method based on IEC 62301 was developed (International Electrotechnical Commission 2011). 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 mode 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.

4.2 Findings

The measured power consumptions of the 41 life safety devices are displayed in Figure 3. The measurements for each of the 10 categories of devices are summarized in Table 11.

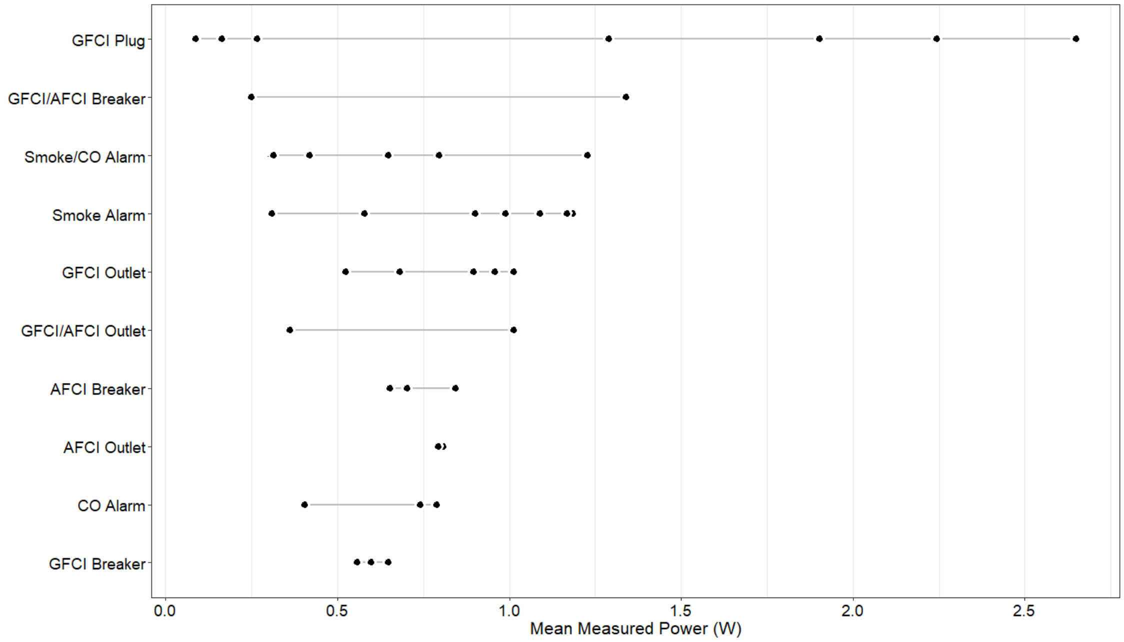

Figure 3. Measured Power Consumption of the Life Safety Devices

Table 11. Summary of Test Results for the Life Safety Devices

Device Category	N	Average Power (W)	Minimum Power (W)	Maximum Power (W)
GFCI plug	7	1.23	0.09	2.65
GFCI breaker	3	0.60	0.56	0.65
AFCI breaker	3	0.73	0.65	0.84
GFCI/AFCI breaker	2	0.79	0.25	1.34
GFCI outlet	5	0.81	0.53	1.01
AFCI outlet	2	0.80	0.79	0.81
GFCI/AFCI outlet	2	0.69	0.36	1.01
Smoke alarm	7	0.89	0.31	1.19

CO alarm	4	0.58	0.40	0.79
Smoke/CO alarm	6	0.62	0.31	1.23

All of these devices draw very little power. Most devices draw less than 1.5 W or 13 kWh/year, and some draw much less than that. This finding was expected; however, there was a wide range of power consumption within specific categories, which was unexpected. For example, the GFCI plug with the highest consumption draws 30 times more power than the GFCI plug drawing the least. The two GFCI plugs with the lowest measured power consumption were purchased in Japan. It appears that the configuration of the Japanese power supply is responsible for lower energy use. Japanese GFCIs meet different safety standards, but we were unable to determine if this had any bearing on device efficiency.

The ratios of maximum to minimum power for the other device categories ranged from about five to one. Older products were not measured. Anecdotal information indicates that newer products generally draw less power, so these results may be low for these devices in existing homes.

Note 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.

With two exceptions, the power consumption of all devices was highly stable. During each five-minute measurement period, the measured power consumption range averaged 24 mW, or 3 percent of average power consumption. Two of the devices measured exhibited a power range of 80 mW, which represents 26 percent of the average power consumption. Both of these devices were alarms manufactured by the same company and used wireless networking. The variation was a regular drop in power draw with a one-minute period, which we assume was related to the networking function. Figure 4 shows the power use during the test for two smoke alarms, one with wireless networking (sma07) and one without (sma03).

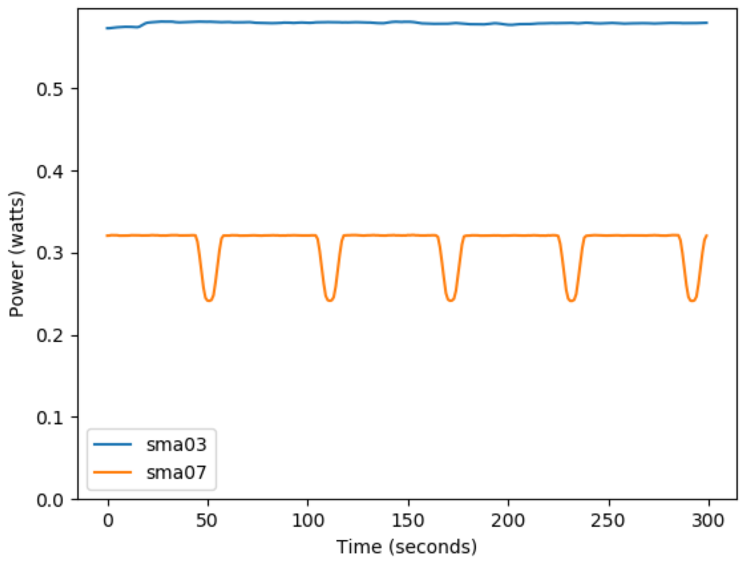

Figure 4. Power Consumption of Two Smoke Alarms During the Test. Alarm sma07 has Wireless Networking; sma03 Does Not.

We anticipated that device cost may have an effect on power consumption, as manufacturers may try to reduce costs by using cheaper components, fewer components, and less design effort. Figure 5 displays the relationship between retail prices and power consumption for the tested life safety devices. The two devices costing more than $75 are both sophisticated alarms and do use less than 0.5 W. Conversely, the three devices that use more than 1.75 watts are GFCI plugs and are quite cheap. But for the 36 other devices we see no correlation at all of power consumption to cost. In addition, no significant correlations of power consumption to manufacturer, category, or waveform were found.

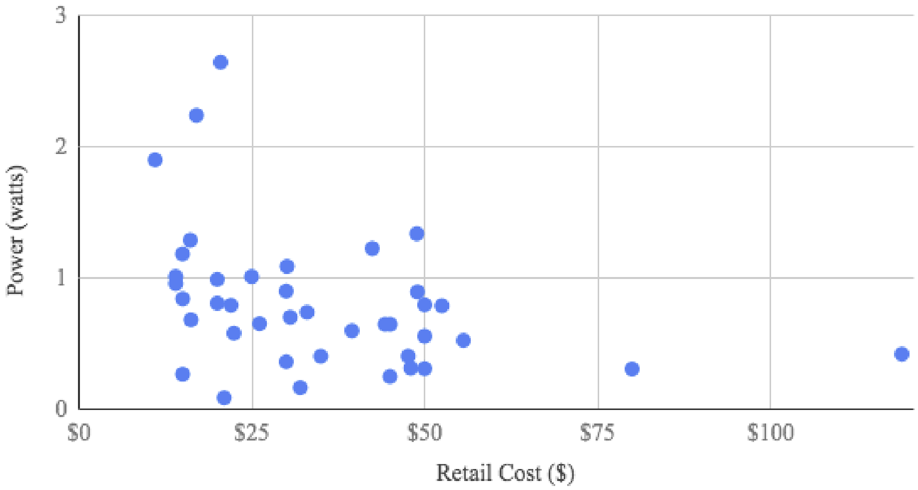

Figure 5. Life Safety Device Power Use as a Function of Device Cost

4.3 Teardowns

Based on data gathered during testing of the residential life safety SSHDs, five devices were selected for teardowns in an attempt to determine what design factors affected device power use (Table 12). 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 12. Life Safety Devices Selected for Teardown

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

* Resistance-capacitance divider

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 AFCI/GFCI outlet consumed less power than other GFCI outlets. It was found that in the more complex devices, buck converter power supplies were being used, probably made necessary by the presence of microcontrollers. The microcontrollers require better quality and regulated power, which cannot be provided by cheaper solutions such as using a resistive voltage divider. Buck converters are able to be much more efficient.

The findings from the teardowns suggest that inefficiencies in the power supplies are responsible for most of the power losses. This makes sense because battery-powered smoke alarms, which use the exact same detector circuits as mains powered alarms, can last 10 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. When the device is connected to line power, however, there must be additional power electronics to convert between 120 VAC and the low operating voltage of the device. To keep costs to a minimum, manufacturers have chosen simple, but inefficient, methods of achieving that voltage conversion.

5. Energy Use of SSHDs in U.S. Homes

The stock, sales, and annual energy consumption of residential SSHDs in the United States were calculated based on estimates of device saturation and building construction by year since 1980 (see section 3). Table 13 summarizes the central estimates, which have been rounded to one significant digit to reflect the uncertainties in the underlying data.

Table 13. Central Stock and Energy Consumption Estimates of SSHDs in U.S. Homes

Device	Stock (millions)	Sales (millions)	Unit Energy Use (kWh/year)	Stock Energy Use (TWh*/year)
GFCIs	600	50	7	4
AFCIs	100	10	6	0.9
Smoke alarms	200	20	8	2
CO alarms	7	2	5	0.04
Security systems	30	5	70	2
Oxygen concentrators	3	0.3	1,000	4
CPAP ventilators	2	0.4	80	0.2
Radon fans	2	0.3	400	0.6
			TOTAL	**10**

* TWh = terawatt-hour

Note: Values presented in this table are rounded to one significant digit to reflect the uncertainty in the estimates. Calculations of device-level and total stock energy use were performed using all available precision in the underlying estimates of stock and unit energy use.

Based on the total SSHD stock energy use (see Table 13) divided by the number of U.S. single homes, SSHDs in the average home use about 100 kWh/year. SSHDs in newly constructed homes will use about 200 kWh/year. Thus, these SSHDs in U.S homes are responsible for about 1 percent of U.S. residential electricity consumption. For comparison, refrigerators are responsible for about 7 percent of U.S. residential electricity consumption (Energy Information Administration 2018).

A single GFCI is responsible for only 7 kWh/year in today's average home. However, due to the number of GFCIs installed nationwide, we estimate their national stock energy consumption at 4 TWh/year, largest among the devices examined. Furthermore, this consumption will grow steadily for the next two decades through renovations and new construction. Figure 6 shows the historical rise in the number of GFCIs and all SSHDs in homes as a result of code changes. The electricity use of these SSHDs will climb by at least 10 percent per year in the foreseeable future as new homes represent a larger share of the stock, older homes are upgraded, and new SSHDs are introduced.

Oxygen concentrators have the second largest energy consumption among the devices examined, about 4 TWh/year. This was an unexpected finding, but not entirely surprising after considering the device's high electricity consumption and the 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 among the largest of the SSHDs investigated.

CPAP ventilators, the only other analyzed medical device, are responsible for much less national energy use, about 200 kWh/year. The uncertainties surrounding this number are relatively larger than for oxygen concentrators because there are more operational variables. CPAP ventilators 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 significantly more energy on the national scale than CPAP ventilators.

The values in Table 13 represent central, best estimates of stock and energy consumption for the evaluated SSHDs; however, the uncertainty associated with some of the values is significant. For instance, the rated power consumption of radon fans from three manufacturers can vary from 15 W to 169 W, or -82 percent to 99 percent of the central estimate. Similarly, the Romanian home security system previously discussed consumed over 28 W when the CCTV component is included, which is an increase of nearly 250 percent of the central estimate. Stock is also difficult to estimate precisely. As an example, because national stock data are unavailable for CPAP ventilators, the central stock estimate is based on estimates of the number of Americans suffering from sleep apnea, those who are actually diagnosed, and the number of diagnosed people actually using CPAP ventilators. Each sub-estimate value has uncertainty, and those uncertainties compound into a larger uncertainty for the estimated stock of CPAP ventilators. These uncertainties illustrate the challenges in evaluating SSHD energy use. The values provided in Table 13 are at best indicative of the national stock energy use of the evaluated SSHDs.

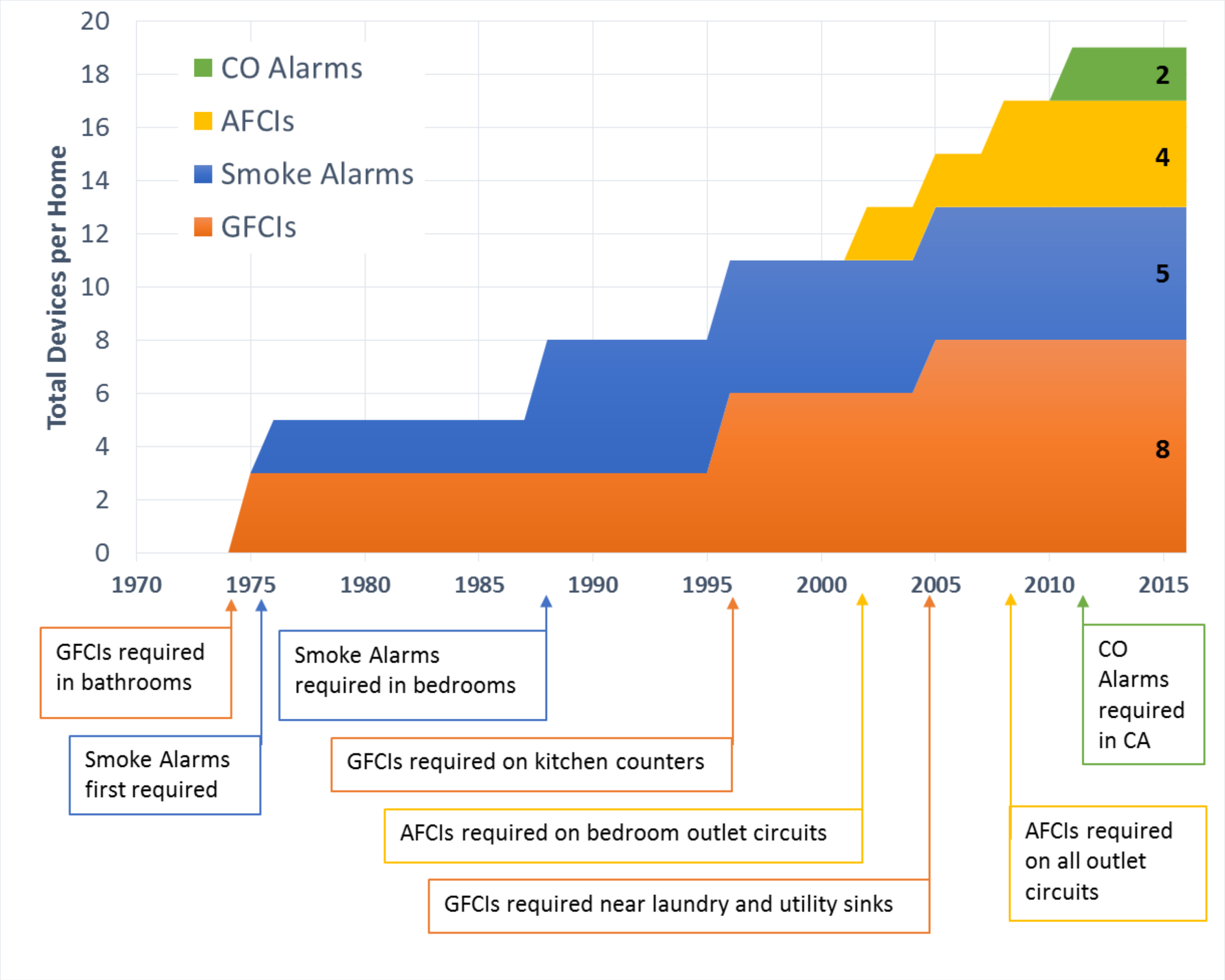

Figure 6. Growth in U.S. Residential Life-Safety Devices Required by Building Codes. (Estimated current number of individual devices per home are shown on right.)

6. Prospects for Energy Reductions in SSHDs

The stock and energy consumption of SSHDs in buildings will surely grow. More SSHDs will be installed as new homes 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 SSHD energy use soon exceeding 200 kWh/year for the average home. The battery back-up to open garage doors, recently mandated by California legislation, is an example of a response to a safety threat. This device alone will add up to 50 kWh/year for each new garage door in California. This feature will probably be incorporated in other regions even where not required by codes, so national consumption is likely to grow more rapidly. Surveillance systems, which provide security around homes, will also grow, especially those without expensive subscriptions. Complex systems can consume 250 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 because energy costs will be far less than the cost of 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 SSHD energy use.

6.1 Further Investigations

A sustained research effort should be undertaken to improve the energy efficiency of devices where health or safety considerations have historically prevented 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. Research questions for oxygen concentrators are provided below to illustrate the breadth:

- 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?

Further research is also needed to understand the usage of CPAP ventilators and the opportunities to save energy. For example, whether local sensing and algorithms can be developed to minimize heating/humidification energy. These algorithms might be co-developed with medical organizations.

With respect to GFCIs, 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 eliminate the need for external power. Devices relying solely on energy harvesting and on-board storage should be a priority. The higher costs of individual alarms would be more than offset by avoided costs of wiring. This solution, however, would require changing building codes.

6.2 Programmatic Activities

This study has shown that most SSHDs consume little energy, and therefore offer correspondingly small energy savings, even when reductions of 80 percent are possible. The efficiency improvements may still pay for themselves in reduced operating costs, but the high transaction costs limit the time consumers, contractors, and stakeholders will devote to making economic decisions. Governments, utilities, and other entities need to design programs that require little or no additional effort on the part of consumers, contractors, health providers, and other decision-makers to shift from current products to the most efficient available. The actions below illustrate the range of actions and participants needed to lower energy use in this category:

- 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
- Establish energy test procedures for SSHDs
- Educate healthcare 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.

Regulatory entities face an administrative problem related to SSHDs. Who should be responsible for promoting more efficient SSHD energy use? Presently nobody is. For example, building codes have the authority to mandate installation of GFCIs, but not to dictate their efficiency. No entity has responsibility for energy use of medical equipment. Even if this administrative responsibility cannot be established, 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

A category of MELs—devices that provide life safety, health, and security—was identified and investigated. The boundaries of SSHDs are not well-defined nor have their energy consumption characteristics been carefully investigated. The installation or use of these devices is dictated by building codes, health providers, insurance companies, and other entities—none of which would ordinarily consider energy efficiency a feature. The creation of this category enables targeted discussion of technologies, policies, and programs required to improve their energy efficiency.

The SSHDs investigated here are responsible for only 1 percent of U.S. residential electricity consumption, but this understates the total contribution of SSHDs since many devices were not included. In addition, the number of devices in this category will steadily climb as existing buildings begin to comply with new codes and as new types of SSHDs appear. At the same time, other SSHDs that were not included (such as modems, Wi-Fi access points, optical network terminals, and batteries for garage door openers) will shift from being elective to being required. This growth helps explain why MELs are projected to grow faster than any other traditional end use.

Reducing SSHD energy consumption is challenging. Most SSHDs consume little energy and therefore offer correspondingly small energy savings, even when reductions of 80 percent are available today. Higher efficiencies do not typically cost more, but the high transaction costs limit the time consumers, contractors, and others will devote to making economic decisions. Put another way, few consumers will search an hour for an SSHD that uses 5 kWh/year—about $1—less electricity. Worse still, the decision-makers are frequently not responsible for paying the ultimate electricity bills. For life-safety devices, higher priorities—safety and health—will determine their performance and design. Energy impacts rarely enter into the policy-making decisions for these devices (or, if they do, it is to exempt the devices from minimum energy efficiency standards).

Diverse strategies are required to reduce SSHD energy consumption. For some devices the best available models consume substantially less than typical models. This is the case for the best GFCIs, which use less than one-eighth compared to typical models. It appears that efficiencies of medical equipment could be greatly improved through better controls. Battery-charging systems for a host of devices can also be made more efficient. Completely new solutions, such as energy harvesting, could also offer energy savings. These are fruitful areas for further research and policies.

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