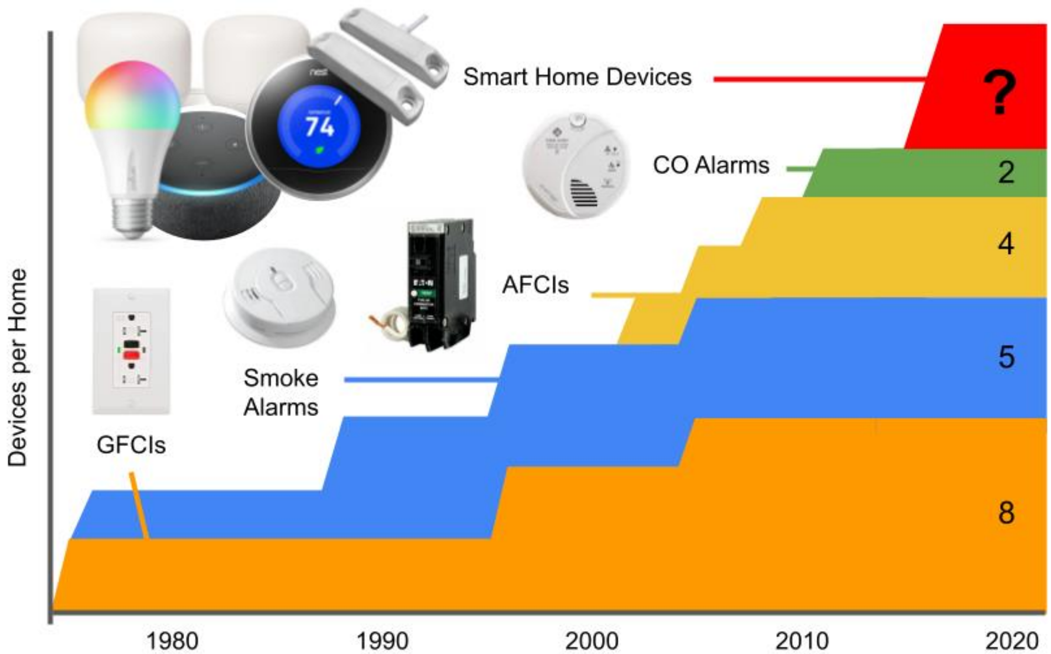
Emerging Technologies

Measuring Builder-Installed Electrical Loads

ET20SCE1050/DR19.07



Prepared by:

Emerging Products
Customer Service
Southern California Edison

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EXECUTIVE SUMMARY

PROJECT GOAL

Builder-Installed Electrical Loads (BIELs) are components and appliances installed by home builders to comply with health and safety codes, or to make homes more attractive to prospective buyers. These devices are installed in addition to the Heating, Ventilation, and Air Conditioning (HVAC) systems, water heaters, and other major appliances covered by energy efficiency standards. BIELs include: garage door openers; hot water recirculation pumps; washlets; hard-wired smoke detectors; HVAC system controls; security systems; remote-controlled skylights; and built-in appliances, like ovens.

BIELs consume energy even before homes are occupied, and often remain in place, consuming energy for the life of the home. Most BIELs are not covered by energy efficiency standards (and certain safety devices are explicitly exempt) and their energy consumption has been poorly documented. Earlier works measured home energy consumption before the occupants arrived. They found BIEL standby consumption was responsible for an average of 1,050 kilowatt-hours (kWh)/year in a small group of new California homes, which is about 13% of an average California home electricity bill.

Finally, purchasing decisions for these technologies are made by builders rather than consumers, so these diverse products can potentially be addressed together. For these reasons, it is important to understand their contribution to future residential electricity use.

This project's goal was to better understand how BIELs affect load shapes and electricity consumption in new "smart" homes, which contain smart loads (internet-connected appliances and devices) that can be controlled remotely via a gateway, mobile, or other networked device. This project studied unregulated BIELs, as well as regulated smart BIELs with unregulated networking components.

TECHNOLOGY APPROACH

LBNL surveyed construction practices and compiled a list (or "library") of electrical appliances, equipment, and components contractors often install. More than 100 devices were reviewed, but the list was ultimately reduced to the 38 that were most representative and non-repetitive, and that had available data. The library included each product's energy and power consumption, number of products in a typical home, and other relevant characteristics. Load shapes were also estimated. The focus was on smart or connected devices, to capture emerging trends. The library could be easily modified or updated.

In addition, LBNL conducted bench testing to categorize several loads' power scaling, standby consumption, and usage patterns. These loads included a Wi-Fi router, Wi-Fi mesh hub, irrigation controller, speaker system, and monitor. Although the bench-tested loads were all plug loads, builders currently install them in the most high-end homes. Additional bench testing was conducted to characterize the standby consumption of safety devices, including smoke alarms, Carbon Monoxide (CO) alarms, and Ground Fault Circuit Interrupter (GFCI) and Arc Fault Current Interrupter (AFCI) outlets and breakers. On average, the constant-on consumption of these devices was between 0.5 watts (W) and 1W.

The technical approach involved simulating BIEL energy and load shapes in six Southern California prototype new smart homes ranging from middle-income apartments to upscale houses. Each home was populated with BIELs appropriate to its size and climate.

Load impacts were estimated for each prototype. The results, shown in Figure ES-1, show spikes in the evening due to use of an induction range and clothes dryer. While standby consumption did not significantly vary, its cumulative impact was nevertheless substantial, especially in large, upscale homes. This approach was useful because the prototype homes could be easily adapted as new information was gathered, either about the products in the home or their electricity consumption. Laboratory measurements of several components were taken to better understand their behavior and to update the library.

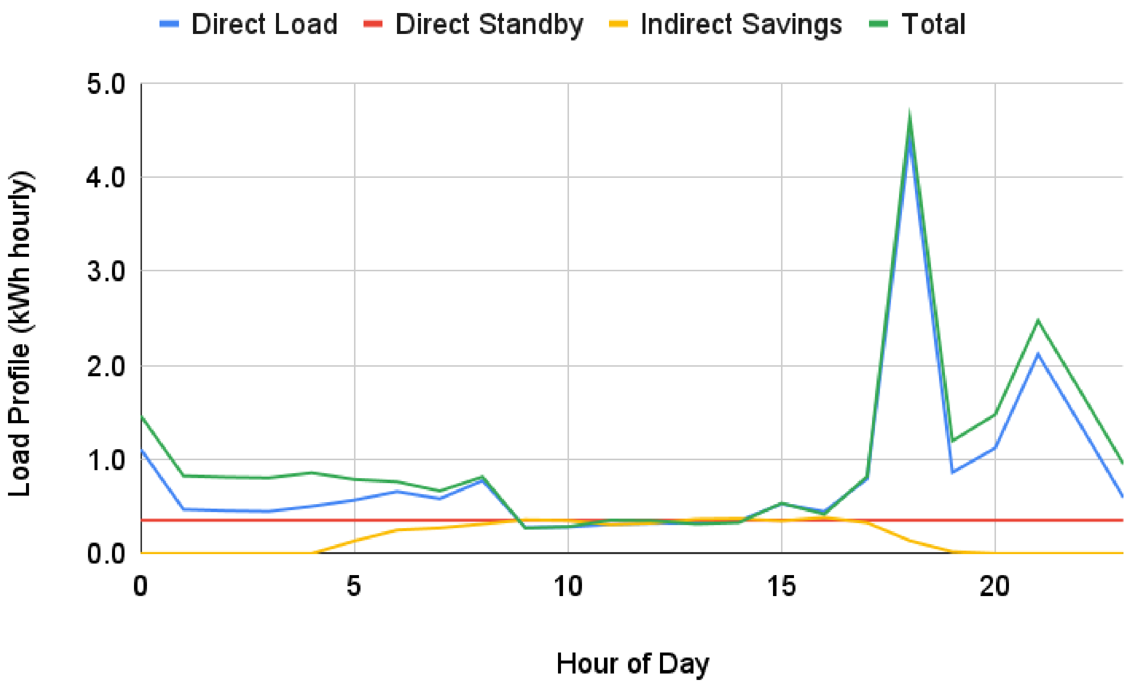

FIGURE ES-1. AGGREGATE LOAD SHAPES FOR A TYPICAL HIGH-END, SINGLE-FAMILY INLAND HOME IN SUMMER

PROJECT FINDINGS

Overall BIEL direct load impacts ranged from roughly 13.1 kWh/day in a small home, to 19.7 kWh/day in a large, upscale house (with peak demands of 2.5 kW and 4.5 kW, respectively). In the upscale house, 36% of total BIEL energy consumption was due to standby and constant-on devices. Unlike in previous studies, these figures accounted for the impacts of direct load and indirect savings while the homes were occupied. BIELs increased with floor area, but not with respect to climate (findings are summarized in Table ES-1). This study found newer smart home standby consumption was up to three times greater than the 1,050 kWh/year from previous studies. With a few exceptions (such as stoves) BIEL electricity use was flat, so it did not substantially increase demand at any particular time. When combined, these constant consumptions could add up to, at most, 360 W. Thus, BIELs (excluding those covered by Title 24 and federal energy efficiency standards) in new smart homes will not significantly contribute to future peak demand challenges.

TABLE-ES 1. SUMMARY OF ENERGY CONSUMPTIONS FOR THE SIX TYPICAL HOMES

	LOWEST DAILY CONSUMPTION/ SAVINGS (KWH/DAY)	HIGHEST DAILY CONSUMPTION/ SAVINGS (KWH/DAY)	PEAK TIMES
Direct Load	13.1	19.7	12 AM, 8 AM, 6 PM, 11 PM
Standby Consumption	2	9	Constant
Indirect Savings	0.3	4	4 PM

The indirect load impacts are larger and more variable. Smart controls connected to window shades greatly reduce solar gain (and, ultimately, cooling loads) by reliably closing during periods of high solar gain. The incremental benefits from such technologies will depend on the number of exposed windows and their orientation, combined with user behavior absent controls.

BIELs are responsible for a major fraction of the continuous (standby) energy consumption in new smart homes. The scenarios developed in this study showed that the continuous power consumption ranges from 100–360 W. For comparison, 360 W corresponds to roughly 45% of the electricity consumption of an average existing California residential customer. Even though electricity consumption of these devices is low on a per-unit basis, there are often many installations in each home. Our laboratory studies demonstrated a wide variation in the standby power consumption of these devices. Furthermore, devices such as Wi-Fi routers appear to operate very inefficiently in the range at which they operate, so even greater energy savings potential exists if their ability to power-scale can be improved.

PROJECT RECOMMENDATIONS

Many smart devices are already being integrated into new homes with systems like Alexa and Matter, and this trend is likely to sharply accelerate. Further field research should concentrate on this aspect. The actual level of BIELs is uncertain in both new and existing homes, so further field measurements are recommended to better estimate their overall impact. Field measurements in 30 diverse homes should be sufficient. Smart BIELs will be connected to networks, and their behaviors may change in unpredictable ways when interacting with other smart devices. Detailed examinations of even just a few homes would narrow the uncertainty. Further laboratory research should focus on improving the ability of BIELs to adjust power consumption efficiently in response to load. Depending on the findings new test procedures, minimum efficiency standards and building codes may be warranted.

To be sure, there are energy-savings potentials, and programs could be developed to target those savings. In addition, reducing BIELs has resiliency benefits during power outages: for homes equipped with batteries, lower consumption from BIELs extends the time a home can operate without grid power. Overall, however, this category of electricity use will not require major adjustments to load forecasts.

ABBREVIATIONS AND ACRONYMS

AFCI	Arc Fault Current Interrupter
BIEL	Builder-Installed Electrical Load
CO	Carbon Monoxide
dB	Decibel
DOE	Department of Energy
EV	Electric Vehicle
GFCI	Ground Fault Circuit Interrupter
HVAC	Heating, Ventilation, and Air Conditioning
IECC	International Energy Code Council
IoT	Internet of Things
kWh	Kilowatt-hour
LBNL	Lawrence Berkeley National Laboratory
Mbps	Megabits per second
MEL	Miscellaneous Electrical Load
MF	Multifamily
NREL	National Renewable Energy Laboratory
PV	Photovoltaic
RASS	Residential Appliance Saturation Study
SF	Single Family
TWh	Terawatt-hour
VAC	Volts of Alternating Current
VRF	Variant Refrigerant Flow

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FIGURES

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INTRODUCTION

MISCELLANEOUS ELECTRICAL LOADS: A GROWING FRACTION OF RESIDENTIAL ELECTRICITY USE

Miscellaneous Electrical Loads (MELs) are traditionally defined as any electrical loads that do not fulfill a core building service of HVAC, lighting, water heating, or refrigeration. MELs are mostly, but not exclusively, plug loads. As energy efficiency in lighting and HVAC has improved, MELs have become more numerous, and connected devices more commonplace. MELs are now responsible for 20%–40% of building electricity use (U.S. Department of Energy [DOE] 2021) where the range represents differences in definition and absence of measurements. Figure 1 shows recent national estimates, which were compiled from surveys, engineering estimates, and field measurements (U.S. DOE 2021). Much of the growth in electricity consumption appears to be in MEL end uses. Note the large "unspecified" consumption; this is electricity use that the DOE was unable to confidently allocate to specific end uses.

This growth coincides with an increasing focus on load shape, as well as just electricity use. There has been little investigation on the impacts of MEL load shapes, even though their combined electricity consumption is substantial. This end use is particularly dynamic. Also, some devices are connected to networks, and potentially could be controlled by local and remote entities. A better understanding of MEL energy and load impacts would be useful to policymakers and utility planners.

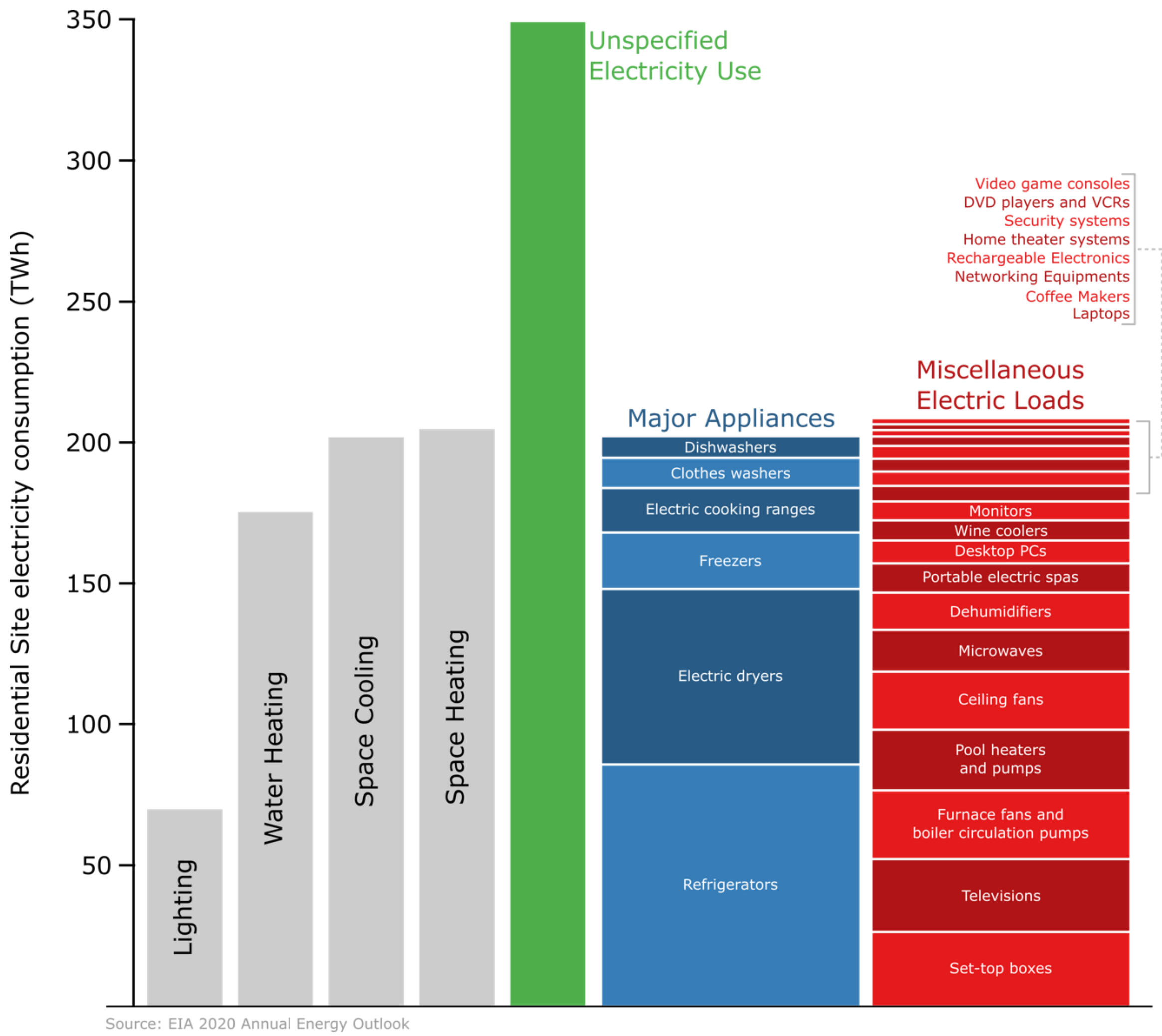

FIGURE 1. MELS IN RESIDENTIAL BUILDINGS (SOURCE: U.S. DOE 2021)

BUILDER-INSTALLED ELECTRICAL LOADS

Builder-Installed Electrical Loads (BIELs) are components and appliances home builders install for compliance with health and safety codes, or to make homes more attractive to prospective buyers. BIELs defy simple categorization, because they have many end uses. Their energy consumption is one component of the green "unspecified" consumption shown in Figure 1, but they also appear in the other categories. As shown in Figure 2, BIELs include devices in each major load category, as well as in regulated and unregulated spaces. This study focused on the energy use and load shape of particular BIEL subsets:

- Unregulated devices
- Unregulated networking components of regulated devices

Products in these subsets include garage door openers, hot water recirculation pumps, washlets, hard-wired smoke detectors, controls for HVAC systems, security systems, remotely-controlled skylights, and built-in smart appliances (like ovens).

The second target – network-related energy in regulated devices – arose from gaps in many energy test procedures used for minimum efficiency regulations. Those tests typically measure energy consumption without networking features enabled, which ignores a small but continuous power draw. An increasing number of white goods and HVAC controls have these network features.

This BIEL subset has not been carefully examined, partly because it crosses so many end uses, products, and responsibilities. However, anecdotal evidence suggests the standby consumption of these components may, together, cause electricity consumption as high as 1,000 kWh/year before the home is occupied. The common denominator is that the home builder or contractor selects and installs permanent appliances and components mostly in new homes. It made sense to study BIELs as a group, because there was a logical policy target – the builder – for incentives, education, and regulations.

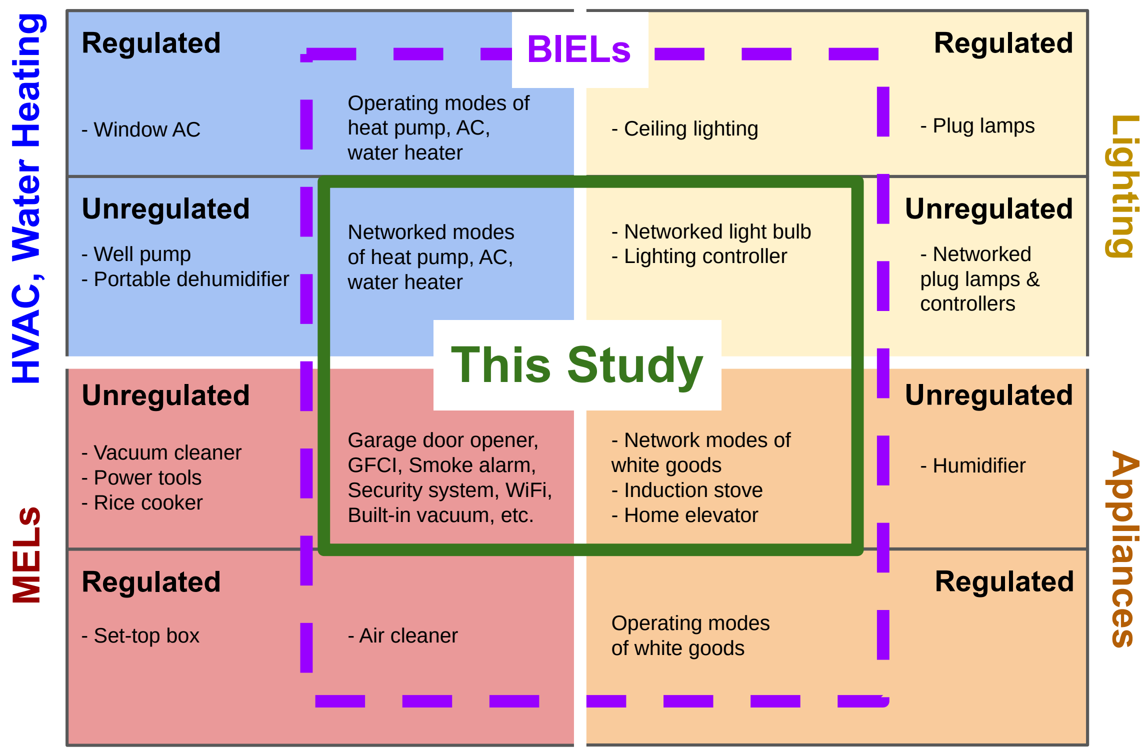

FIGURE 2. SCOPE OF STUDY WITH RESPECT TO END USES, BIELS, AND FEDERAL AND STATE EFFICIENCY REGULATIONS (SOURCE: LBNL)

Smart homes contain smart loads, which are internet-connected appliances and devices controlled remotely using a gateway, mobile, or other networked device (Sovacool and Furszyfer Del Rio 2020). Smart-home controls are often, but not necessarily, automated to respond to occupant needs (New York Times 2021). New homes, especially new smart homes, are outfitted with even more MELs that are not yet common in existing homes. This group includes Electric Vehicle (EV) chargers, communications infrastructure, batteries, and security equipment. These devices communicate through various protocols to in-home hubs, apps, or via the cloud.[1] Other equipment, such as recreational devices (pool pumps), code-required devices (continuous ventilation), and health devices (air cleaners) could potentially adjust operation and power consumption in response to utility signals.

Many of these devices are usually selected and installed by the home builder, but perhaps in consultation with future owners before they move in. They are also increasingly connected and communicating. Less is known about these devices, such as what they are, how much energy they consume, and their impact on load shapes. Some are evolving rapidly, too. Informal measurements by LBNL and others (Meier et al. 2020) suggest most of these devices have modest energy consumption; however, they may influence other devices' electricity consumption. Connected windows and shades, for example, affect cooling and lighting loads, and may have or cause unusual load shapes. Installation quality and extent of commissioning may also affect their energy usage. These devices' cumulative impact on new home electrical demand is therefore less understood.

These devices provide diverse services, but they are connected in the sense that the builder is responsible for their selection, installation, and commissioning. Builders and clients are uniquely challenged to make rational tradeoffs, because little consistent information is available on costs, features, energy and power consumption, and demand. In contrast, utilities have close connections with developers and builders, giving utilities a unique opportunity to influence decisions about equipment selection in future smart homes, either through information or incentives. The first step, however, is to understand the BIELs.

BIEL Definition

BIELs are appliances and components put into a home during the construction process and before people occupy it. Builders typically install these products because they are required by building codes, or to make the home more attractive to potential buyers or occupants. Many of the products are "hardwired," meaning an electrician must install them and they cannot be unplugged.

There is no clear boundary between *builder-installed* and *occupant-installed* devices. Many devices, such as smart thermostats and major appliances (like refrigerators, ranges, and clothes washers and dryers) may be installed either by contractors or by the occupants, after building completion. New types of products are often first installed by the existing home occupants, then later, builders begin installing them in new construction, and they become part of new-home packages. An example is structured wiring systems for entertainment and data. These systems began as retrofits, but builders quickly recognized new home buyers wanted them too (at least for upscale homes). We used an expansive definition to select products that *might eventually* be builder-installed, even if they are primarily occupant-installed today.

[1] ENERGY STAR® differentiates between "communicating" devices, which have two-way communication and controls inside buildings, and "connected" devices, which are linked to the internet.

BACKGROUND

EARLIER RESEARCH

In the past, builder-installed equipment and component electricity consumption was mostly overlooked. To be sure, appliances are regulated by federal and state efficiency rules, and have been intensively studied, but smaller or less-common components often required by building codes and other safety regulations were typically lumped into the "miscellaneous" use category and treated as insignificant ("in the noise"). Many safety devices are also legislatively exempt from efficiency regulations.

BIELs are difficult to study, because many are hardwired and cannot be easily metered like appliances. Even laboratory measurements are challenging, sometimes requiring a custom measurement jig. The alternative is to measure whole-home use of all BIELs together, which is relatively easy to do if the home has a smart meter. Meier and Alliot (2015) surveyed BIELs in nine new homes in Northern California which had been fully constructed but were not yet occupied by the owners. They had an average of 120 W (1,050 kWh/year) of BIELs. This corresponds to about 13% of an existing single-family home's electricity consumption in California: 7,600 kWh/year. These were ordinary subdivision homes, with no particular smart or advanced features to limit peak demand.

In a study of hourly readings from thousands of California residential smart meters, Delforge et al. (2015) found minimum power consumption averaged 164 W. Since these homes were occupied, the measurement captured BIELs and the continuous power consumption of occupant-installed devices.

Meier and Alliot (2015) measured power consumption of a limited number of safety devices falling into the BIELs category (additional analysis was performed for this project). The per-unit consumption of GFCIs, for example, was low; however, most homes had many of these components. In addition, a wide range of power consumption was observed for essentially identical devices.

Rainer et al. (2021) estimated the growth in the number of safety-related devices required for California homes. Figure 3 shows almost 20 devices must be installed by builders in new homes, although the number varies with home size and design. The most recent requirement is a backup battery for electrically-operated garage door openers, to ensure automobile egress during power outages.

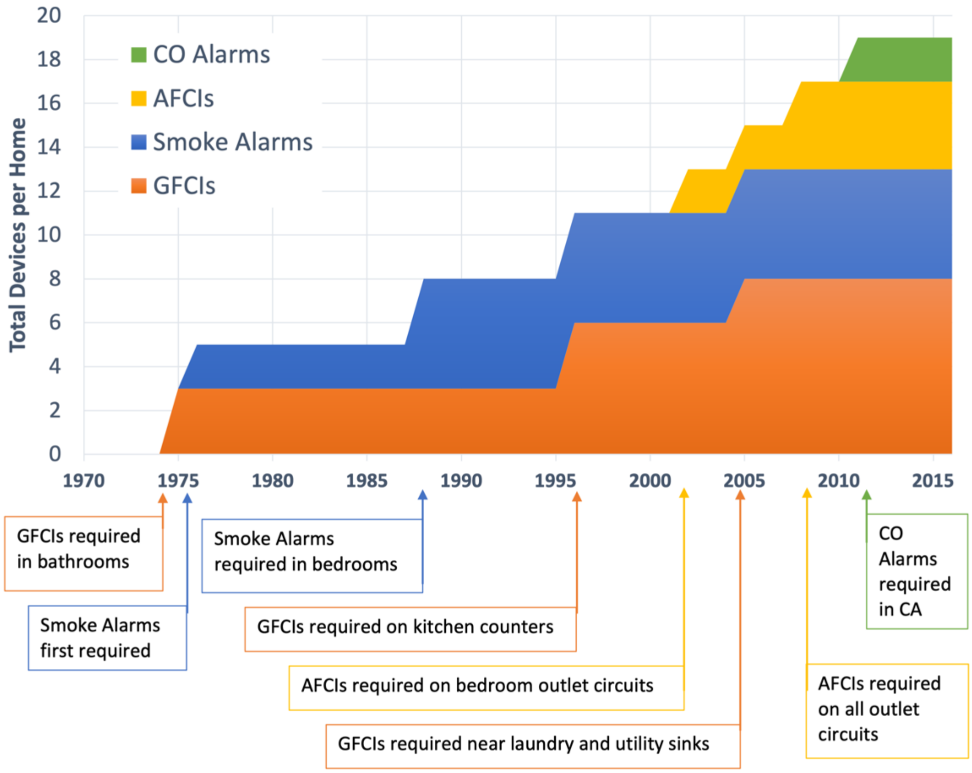

FIGURE 3. GROWTH IN U.S. RESIDENTIAL LIFE-SAFETY DEVICES REQUIRED BY BUILDING CODES AND OTHER ENTITIES (ESTIMATED CURRENT NUMBER OF INDIVIDUAL DEVICES PER HOME IS SHOWN ON THE RIGHT – SOURCE: RAINER ET AL. 2021)

New homes will probably employ many connected and smart features, which will translate to more builder-installed components and corresponding loads. However, no research has investigated these aspects. The contribution of BIELs to peak demand and opportunities for load shifting has also not been investigated.

PROJECT OBJECTIVES

The project objectives were to:

- Study BIELs associated with smart homes.
- Develop templated home models, with estimates of types of builder-installed devices and their power, load shape, and energy use.
- Predict load shapes and the energy use of new smart homes and new all-electric homes, with special focus on builder-installed equipment.
- Identify opportunities for load shifting, demand response, and energy savings.

Technical Approach

This project attempted to better understand the load shapes and energy use of new smart homes and all-electric homes, with a special focus on BIELs. We modeled homes using a bottom-up technical approach, which included:

- Developing a list of smart devices.
- Developing a portfolio of typical homes and their load characteristics.
- Creating a simple energy model to estimate the load shapes of other configurations.

First, we identified an extensive list of BIELs, and researched information related to their consumption profiles and indirect energy implications. This investigation focused on advanced products associated with leading-edge smart homes rather than conventional appliances and equipment such as air conditioners, heat pumps, and water heaters. Load shapes and data were supported in part by laboratory and field measurements. We then identified a set of typical homes, with estimates of types and quantities of builder-installed devices based on information derived from California developers.

Finally, we developed a simulation model to estimate each typical home's daily consumption, which we calculated based on typical rather than average load profiles. We chose typical profiles so the model would have discrete device quantities, and to make it easier to understand how load shifting can avoid worst-case scenarios. The simulation model was equipped with the flexibility to easily add data and test new homes.

LIST OF BUILDER-INSTALLED SMART PRODUCTS

LBNL compiled a library of electrical appliances, equipment, and components contractors often install. It contained 38 products and their energy and power consumption, number in a typical home, and other relevant characteristics.[2] Where possible, we also derived the typical load shape. The library is a "living" document, as we expect to revise it as further information is acquired. It will help utility planners better understand the products' energy and load implications.

The library of products shown in Appendix A is based on information derived from a wide array of formal and informal sources, and it evolved during the project. Our original plan called for obtaining "bills of materials" from developers, builders, and utility sources. We also originally planned to undertake onsite investigations and bring certain products into the laboratory for more detailed measurements. The pandemic made this approach unfeasible; instead, we relied on literature surveys, smart home builder websites, technology publications, manufacturer websites, ENERGY STAR-qualified product lists, interviews, and builder-supplied documents.

The process of compiling these products required many decisions. First, some products were both builder-installed and occupant-installed. We used an expansive definition to select products that might have been builder-installed, even if they were primarily occupant-installed at the time. As shown in Figure 2, the specific scope of our study included unregulated BIELs, as well as regulated BIELs with unregulated networking components. Second, the compilation focused primarily on networked smart products. However, we also included non-networked electricity-consuming products whose operation depended on external sensors and may have become networked in future models. An example was washlets (Japanese-style toilets with spray and dry features). Current washlet models have

[2] The number of products used in various calculations changed with the typical house. In addition, the electricity use of some appliances was divided into their direct loads and standby consumption.

considerable intelligence and remote controls (Figure 4), and prototype models have internet connections, to enable various health diagnostics.[3]

FIGURE 4. WASHLET WITH DEDICATED REMOTE CONTROL (NETWORKED MODELS WILL BE AVAILABLE SOON).

BIEL diversity complicates developing a systematic or comprehensive survey. For example, the product library data sources were inconsistent in how they reported energy consumption information, and in most cases, it was not reported at all. In addition, many smart devices involved network connections and bridges to link the devices to local hubs or the cloud. The descriptions were often unclear as to how many devices could be connected through a single bridge. Structured wiring systems present another example of products whose energy use can only be estimated through measuring an installed, populated system.

Our approach to calculating hourly consumption relied on typical values rather than averages. A typical load profile reflected a standard occupant's load usage on a normal day. This approach resulted in BIELs having zero active consumption for many hours per day (though still having standby consumption) when the home was unoccupied, or when the devices were not in use. By contrast, an average load profile represented the aggregate consumption of that load, averaged over all households with some direct consumption every hour, as it accounted for atypical user activity. Because it is difficult to study demand response using average load profiles, we opted for typical profiles.

Our approach to determining typical load profiles varied based on load. For most, we extrapolated typical profiles for a single home based on multiple sources of average load shape and typical usage pattern data. Other load profiles had unique methods of calculation. For example, indirect savings and load profiles from window shades were calculated based on output from the National Renewable Energy Laboratory's (NREL) PVWatts® calculator (NREL, 2021).

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[3] See, for example, Price (2021).

TYPICAL HOMES

To better understand these devices' energy and demand impacts, we created "typical homes" and populated them with smart devices from the library. A typical home more closely represented the most common set of characteristics. This was analogous to the "mode" rather than the "average." Using the most common was more realistic than assuming an average smart home, because:

- The home would contain no fractional products.
- The populations of future devices were still speculative, so no average existed.
- Using the typical home approach facilitated adding or removing devices.
- It made it easier for the reader or analyst to grasp assumptions.
- The typical homes could be moved to special climates or modified for special conditions.

The current population and saturation of smart devices is mostly speculation because few are widely available today and there is no information available about their adoption. The typical home approach is most appropriate under these circumstances.[4]

The Southern California region has diverse climates and housing types. To capture this diversity, typical homes with different features and locations were created. The configurations for these homes were based on information derived from California developers[5] such as Meritage, KB Homes, Lennar, K Hovanian, and City Ventures; construction data, surveys, interviews with home builders, real-estate publications, trade press (CNET 2021), and smart home product literature (Kohler, 2021). We also consulted International Energy Code Council (IECC) residential prototypes (Energy.gov, 2021a) and census data.

The pandemic hampered our efforts to gather information, but it also created new sources. In December, we attended the "Best of the West - Virtual Modern Home Tour" (Modern Architecture + Design Society, 2020). This tour showcased different new homes in Vancouver, Seattle, Silicon Valley, and San Diego. While much of the focus was on architectural design, it guided us on new home interiors: open concept kitchens and living rooms, amenities in outdoor spaces, and some basic appliances used in state-of-the-art new homes, like heat pump water heaters and air purifiers.

The pandemic also shifted consumer preferences. For example, upper-income families appeared to demand more rooms to serve as offices and gyms. Our methodology permitted easy incorporation of these trends as more data become available.

Ultimately, six typical homes were created (Table 1). The goal was to represent the diversity of new Southern California smart homes. The characteristics of the typical homes are discussed below. Appendix B has a device list and quantity for each home.

[4] This approach was also used by ENERGY STAR for its internal analyses and was prepared by LBNL.

[5] This includes Meritage, KB Homes, Lennar, K Hovanian, and City Ventures; direct interviews and inspections were not possible due to pandemic restrictions.

TABLE 1. TYPICAL HOMES FOR LOAD IMPACT MODELING

HOME PROTOTYPE	FLOOR AREA (FT^2)	BEDROOMS	BATHROOMS
Multifamily Typical	1,200	2	1
Multifamily High End	1,600	3	2
Townhouse	1,300	3	2
Senior Home	1,600	2	2
Single-Family Typical	2,400	3	2
Single-Family High End	3,200	4	3

BUILDING PROTOTYPES

Six prototype buildings were created for the Southern California region, consisting of a middle-income multifamily home (low rise), a high-end multifamily home (high rise), an attached townhouse, a single-family senior home, a single-family middle-income home, and a single-family high-end home. These prototypes resembled the homes shown in Figures 6 through 10. The prototypes were all assumed to be new construction buildings complying with California's 2019 Building Energy Efficiency Standards (California Energy Commission 2021) and the 2021 portfolio of federal appliance efficiency standards (Energy.gov, 2021b). The buildings had similar characteristics, such as energy-efficient appliances, solar panels, and mechanical ventilation. The prototypes differed in that high-end homes were larger in size and were assumed to have more amenities and smart technologies installed during construction. The goal of the project was to explore the impacts of builder-installed smart devices; however, assumptions were made regarding the behavior of conventional appliances in the typical homes, to capture indirect energy impacts from thermostats, home assistants, and other smart devices.[6]

The multifamily buildings had common areas separate from individual residential units. The extent of the common areas varied widely. Simple, low-rise apartments may have had outside walkways, while high rises had interior hallways, recreational facilities, garages, and laundries. However, the majority of the apartment buildings were low rise, with modest common areas. Most of the equipment in the common areas was specified by the architects and installed by the builders. Safety, health, and contractual obligations dictated many operating practices for lighting, HVAC, elevators, and other devices in the common areas.

We investigated BIELs in the multifamily buildings' common areas, with a focus on smart devices and their energy consumption characteristics. These devices included some lights, elevators, intercom systems, and shared Wi-Fi networks. In the end, we concluded these devices represented a relatively small fraction of total building electricity consumption, and small direct and indirect energy impacts. Energy savings was difficult to estimate, because many buildings were already controlled. Finally, they had uncertain load profiles, so their demand impacts were also uncertain. For all these reasons, we chose not to include them in our analyses.

[6] Bills of materials were originally expected to be important sources of information; however, they were rarely available, especially for cutting-edge homes.

MULTIFAMILY TYPICAL (MIDDLE INCOME)

The prototype was a second-floor unit in a three-story building (low rise) with 18 units and a ground-level parking lot.[7] The 1,200 square-foot prototype apartment had two occupants, two bedrooms, one bathroom, a balcony, and a western exposure. In this building, residents accessed the garages and their individual units via a smartphone app. This also enabled them to control the lights and thermostats inside their apartments.

Three mini-split heat pumps provided cooling and heating to the units, and ventilation was provided by energy recovery ventilators. The units came with high-efficiency clothes washers, dishwashers, heat pump dryers, and connected kitchen and bathroom appliances. Units with western and southern exposure had connected window shades to reduce afternoon solar gain. Each unit had a home voice assistant to allow tenants to control connected devices throughout their apartments. The building had rooftop solar, and EV charging in the garages. Appendix B shows the devices in this middle-income multifamily building.

FIGURE 5. MULTIFAMILY TYPICAL (MIDDLE INCOME)

[7] This is roughly comparable to a Title 24 low rise: https://energycodeace.com/download/35200/file_path/fieldList/FactSheet.HiRise.LowRise.MF.2019

MULTIFAMILY HIGH END

The prototype was a second-floor unit in a five-story building (high rise) with 16 units.[8] The 1,800 square-foot prototype apartment had three occupants, three bedrooms, two and a half bathrooms, a dining room, a balcony, and a western exposure. Building residents accessed their units via a smartphone app, which also enabled them to control lighting and thermostats in their apartments.

The building was equipped with a Variable Refrigerant Flow (VRF) system to cool and heat the units, and ventilation was provided by an energy recovery ventilator. The VRF allowed for multiple zones within each unit, each controlled by a connected thermostat. Each unit came with a high-efficiency clothes washer and dishwasher, heat pump dryer, heat pump water heater, and connected kitchen and bathroom appliances. The two full bathrooms had washlets and digital interfaces to control the shower and bathtub. The apartment used electrochromic windows, enabling the occupant to change the window tint based on the light outside or time of day. Each unit had a home voice assistant, allowing tenants to control connected devices throughout their apartments. The building had EV charging in the garages. Appendix B shows the devices in the high-income multifamily building.

FIGURE 6. MULTIFAMILY HIGH END

[8] This is roughly comparable to a Title 24 high rise: https://energycodeace.com/download/35200/file_path/fieldList/FactSheet.HiRise.LowRise.MF.2019

TOWNHOUSE

The townhouse was a 1,500 square-foot single-family attached home in an urban setting. The dwelling had four occupants (two adults and two children), three bedrooms, two baths, a two-car garage, an open-concept kitchen and living room, a top-floor deck, and a small bottom-floor patio. The home included rooftop Photovoltaic (PV), battery storage, and two EV charging stations in the garage. A multi-zone, high-efficiency central heat pump was used for heating and cooling, and an energy recovery ventilator provided ventilation. The townhouse had a high-efficiency clothes washer and dishwasher, heat pump dryer, heat pump water heater, central vacuum, and connected kitchen and living room appliances. A gray water system allowed reusing water from sinks and showers for the toilets. The main bathroom had a washlet and digital interfaces to control the shower and bath. A voice assistant was used to control the appliances and security system. Appendix B details the smart devices in the townhouse.

FIGURE 7. EXAMPLE TOWNHOUSE IN SOUTHERN CALIFORNIA (REPRESENTS APPROXIMATE PROTOTYPE SIZE AND STYLE).

SENIOR HOME

This prototype home allowed senior residents to age in place with minimal in-person home care. It was a one floor, 1,600 square-foot home in a retirement community. The home had two occupants, two bedrooms, two baths, and an attached garage. The home was equipped with solar PV and battery storage. A high-efficiency central heat pump was used for heating and cooling, and an energy recovery ventilator provided ventilation. The home also came with a high-efficiency clothes washer and dishwasher, heat pump dryer, and heat pump water heater. The home was equipped with motorized doors and sensors to measure if doors or windows opened unexpectedly. Other sensors monitored kitchen appliances like stoves and refrigerators, beds, and floors, and alerted a caretaker if anything unexpected occurred. A voice assistant allowed caretakers to communicate with residents throughout the day. Appendix B details the smart devices in the senior home.

SINGLE-FAMILY TYPICAL (MIDDLE INCOME)

The single-family detached prototype was a one-story, 2,400 square-foot home in a housing development. The home had four occupants (two adults and two children), three bedrooms, two baths, an attached two-car garage, an open concept kitchen and living room, and a sliding door leading to a small backyard with desert landscaping and a turf lawn. The home included rooftop PV, battery storage, and one EV charging station in the garage.

FIGURE 8. SINGLE-FAMILY TYPICAL (MIDDLE INCOME)

A high-efficiency central heat pump was used for heating and cooling, and an energy recovery ventilator provided ventilation. The home came with a high-efficiency clothes washer and dishwasher, heat pump dryer, heat pump water heater, central vacuum, connected kitchen and living room appliances, and a gray water system to reuse water from sinks and showers for the toilets. A voice assistant was used to control the appliances, security system, doors, and windows, and the garage door could be controlled by a smartphone app. Appendix B details the smart devices in the middle-income smart home.

SINGLE-FAMILY HIGH END

The high-end detached prototype was a 3,200 square-foot home located in a luxury housing development. The home had four occupants (two adults and two children), four bedrooms, three bathrooms, an attached two-car garage, and an open concept living room and kitchen, with access to an entertainment patio and outdoor pool. The backyard was landscaped with a connected irrigation system. The home included rooftop PV, battery storage, and two EV charging stations in the garage.

FIGURE 9. SINGLE-FAMILY HIGH END

A multi-zone, high-efficiency central heat pump was used for heating and cooling, and an energy recovery ventilator provided ventilation. The home also came with a high-efficiency clothes washer and dishwasher, heat pump dryer, heat pump water heater, central vacuum, connected kitchen (Figure 10) and living room appliances, and gray water system for reusing water from sinks and showers for the toilets. It also had connected weather stations and pool monitoring equipment to control the irrigation system, a robotic pool cleaner, and a robotic lawnmower. A voice assistant was used to control the appliances and security system, and the doors, windows, and garage door could be controlled by a smartphone app. Finally, a home energy monitoring system was used to track the home's energy use over time. Appendix B details the smart devices in the high-income smart home.

FIGURE 10. CONNECTED REFRIGERATOR WITH MULTIMEDIA INTERFACE

FIELD AND LABORATORY MEASUREMENTS

Field and laboratory measurements were performed to supplement the characteristics and load profiles in the device list. MELs, including a Wi-Fi router, Wi-Fi repeater hub, and garden irrigation system, were measured in a typical residential environment. While these are traditionally occupant installed, they are increasingly builder installed as part of smart-home packages. We recorded each MEL load profile over multiple days.

We also measured several other MELs, including a Wi-Fi router, sound bar, and monitor in the lab to see how their power-scaling curves were affected by standby power. While they were not BIELs at the time, their power-scaling characteristics could be similar to interactive displays and speakers we expect to be builder-installed in future homes. Lab measurements were performed in the LBNL Connected Devices Laboratory, shown in Figure 11.

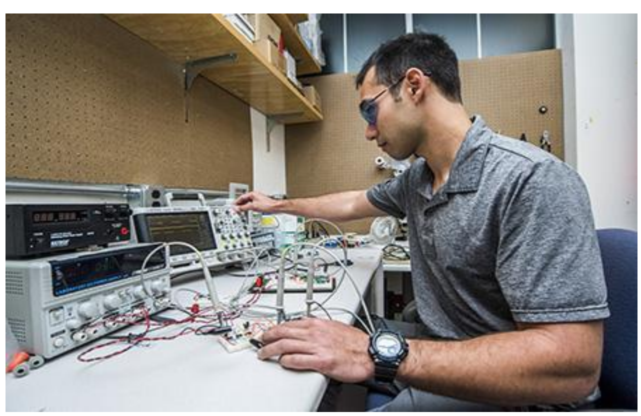


FIGURE 11. LBNL CONNECTED DEVICES LABORATORY

Field and laboratory measurements were taken with a Chroma 66202 power meter, which measures AC or DC voltage, current, and power to 0.1 milliwatt (mW) resolution. It could also report other potentially interesting quantities, such as frequency, power factor, crest factor, and maximum/minimum voltage/current. With an attached Windows machine, the Chroma meter's driver software (Softpanel) could log all the meter's measurements at a given sampling interval over a given period of time.

LAB MEASUREMENTS – POWER SCALING

The device library made it apparent that standby consumption would play a major role in overall smart BIEL energy consumption. While some BIELs had a constant-on operation, others were a mix of direct load and standby consumption. To help understand the impact of standby consumption, we measured the power scaling characteristics of several other devices: a Wi-Fi base station, a monitor, and a sound bar. While not explicitly BIELs, similar versions of these devices could eventually become builder installed.

Device power-scaling curves described how their power consumption varied with useful output, which varied by function. Wi-Fi router output was measured as the data rate it provided to the user. Monitor output was measured as brightness. Sound bar output could be measured as volume setting or decibel (dB) sound intensity. An ideal device power-scaling curve appeared as a line showing it drew no power when providing no useful output; however, most devices deviated from this and showed standby characteristics.

Estimating potential energy savings from improved power scaling required two calculations. First, the power savings at each level of output had to be measured (or estimated). Second, the corresponding time in which the device operated at each level of output, typically stated in hours/year, had to be measured. Annual savings from improved power-scaling technology was the product of power savings and hours at each service level.

At the time, no standards existed to measure power scaling, and product data sheets lacked related data. We measured input power with high accuracy. The level of output was measured differently depending on the load. For the WiFi router, it was measured in Megabits per second (Mbps) download speed through the router's software. For the sound bar and monitor, the level of output was the discrete volume or brightness settings.

SIMULATIONS

We developed a BIELs Analysis Tool to fully understand overall home consumption and load-shifting potential, because there was no existing source or reference detailing whole-house aggregate consumption. The tool was intended to reveal how consumption profiles may vary based on home type, climate, and season. It also identified opportunities to reduce overall consumption, either indirectly through smart energy management or by eliminating standby consumption and improving power scaling.

The BIELs Analysis Tool was a Google Sheets calculator that modeled 38 BIELs' aggregate weekday load profile in a typical home. Many of the BIELs had separate profiles for direct and standby loads. Several of the devices varied by season and climate zone, and the load profiles differed from those commonly used in building simulations and load forecasts because they represented single, real-life homes rather than a collection of homes. For example, the tool modeled a clothes dryer as a power spike at its rated load for a couple of hours per day, and only the standby use in all others. By contrast, a load forecast would have modeled some usage every hour.

The tool was populated with information on the typical homes and pre-filled BIEL quantities, but users could easily adjust how many of each BIEL they had in their modeled homes. Users could also easily add new BIELs to the tool as necessary.

RESULTS

LIST OF BUILDER-INSTALLED SMART PRODUCTS

The power and energy data shown in Appendix A were from the products' direct energy use. Certain products, like smart thermostats and automatic window shades, had significant indirect impacts on home HVAC energy, and most appliance test procedures could not fully capture the impact of connected functionality on appliance energy use and overall efficiency.

Notable appliances with high energy consumption include induction ranges, bathtub spas, clothes dryers, and refrigerators. All of these appliances can consume in excess of 1 kWh/day. In addition, washlets, battery systems, air purifiers, structured wiring panels, security systems, and elevators consume between 0.5 and 1 kWh/day. Notable appliances with low direct energy consumption include water/freeze alarms, thermostats, smoke and CO alarms, light bulbs, home voice assistants, motion-activated faucets, and remote-controlled curtains. Each of these appliances is individually expected to consume no more than 50 Wh/day. Some of these devices, such as remote-controlled curtains and motion-activated faucets, draw so little power that they are offered either with batteries or a 120 Volts of Alternating Current (VAC) adapter.

FIELD AND LABORATORY MEASUREMENTS

FIELD MEASUREMENTS – LOAD PROFILES

We measured several smart BIELs in the field to validate their load profiles. These devices were a Wi-Fi base station (Figure 12), a Wi-Fi repeater hub (Figure 13), and a garden irrigation system (Figure 14). Sample devices were selected based on relevance and availability, and indicated the degree to which smart BIELs could come to be dominated by constant-on or standby consumption.

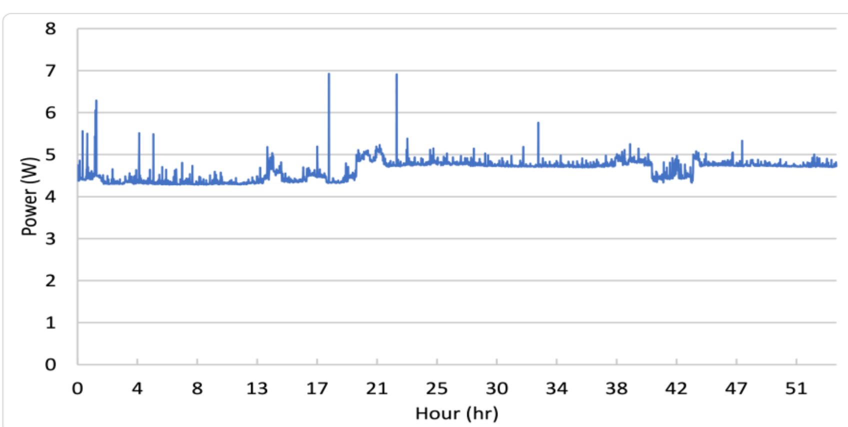


FIGURE 12. WI-FI BASE STATION LOAD PROFILE (CONSUMPTION USUALLY BETWEEN 4 - 5 W, EVEN DURING PEAK DATA TRANSFER PERIODS)

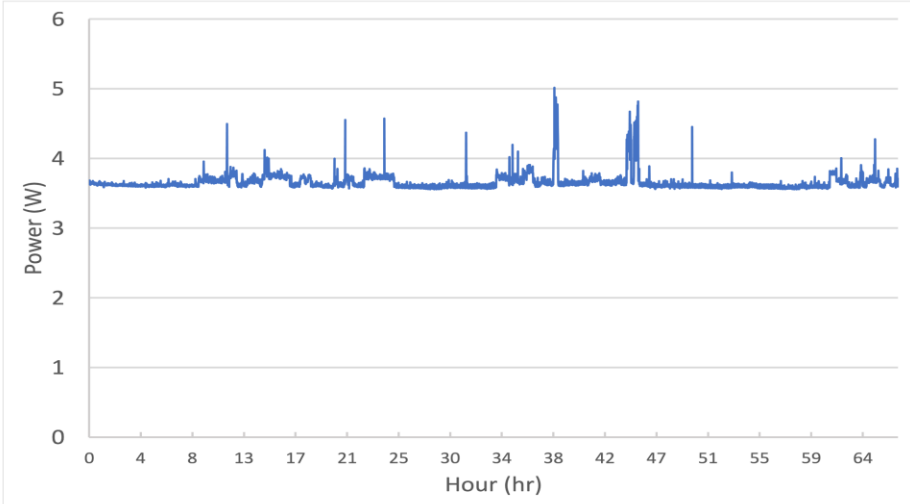


FIGURE 13. WI-FI REPEATER HUB LOAD PROFILE (CONSUMPTION USUALLY BETWEEN 3 - 4 W, EVEN AT NIGHT)

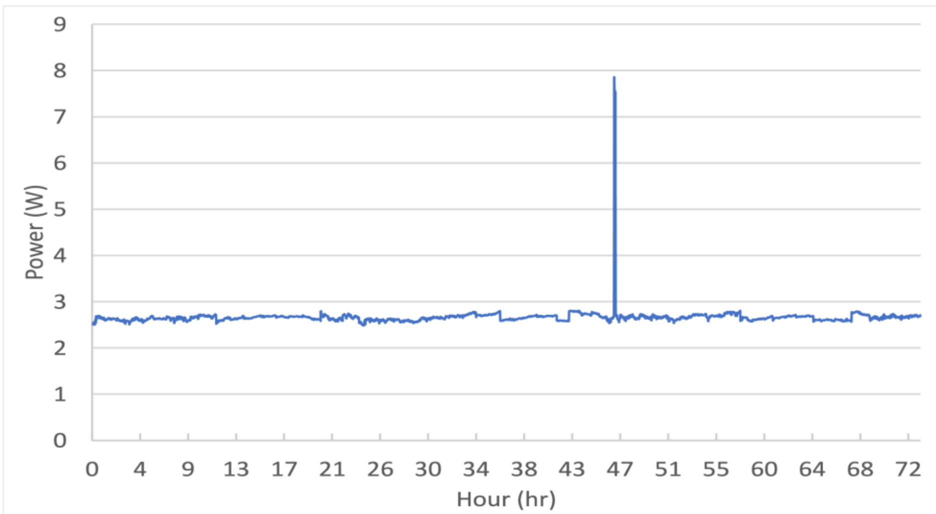


FIGURE 14. GARDEN IRRIGATION SYSTEM LOAD PROFILE (CONTROLLER ACTIVATES SYSTEM FOR 10 MINUTES EVERY TWO DAYS)

LAB MEASUREMENTS - POWER SCALING

The Wi-Fi router profiled in Figure 15 had relatively-high standby consumption when there was no network traffic. Figure 16 shows a typical Wi-Fi router, field tested from its reporting application. The typical profile was acquired from a live field measurement over a typical day, with two occupants working from home during the day and streaming TV at night.

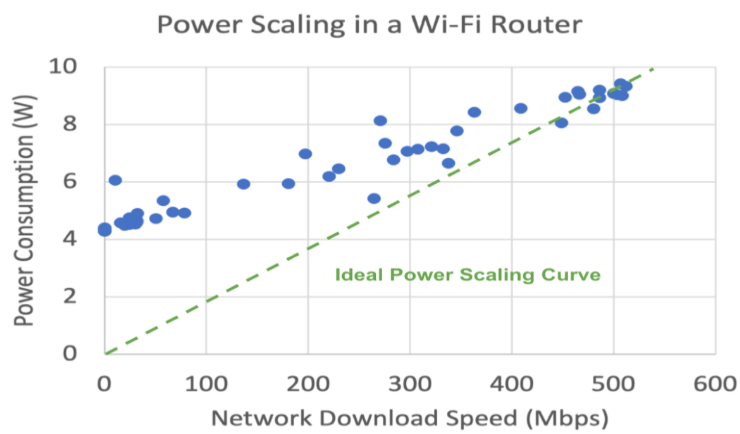


FIGURE 15. RELATIONSHIP BETWEEN WI-FI ROUTER OUTPUT (MEASURED IN DATA THROUGHPUT, MBPS) AND POWER CONSUMPTION (SOURCE: LBNL MEASUREMENTS)

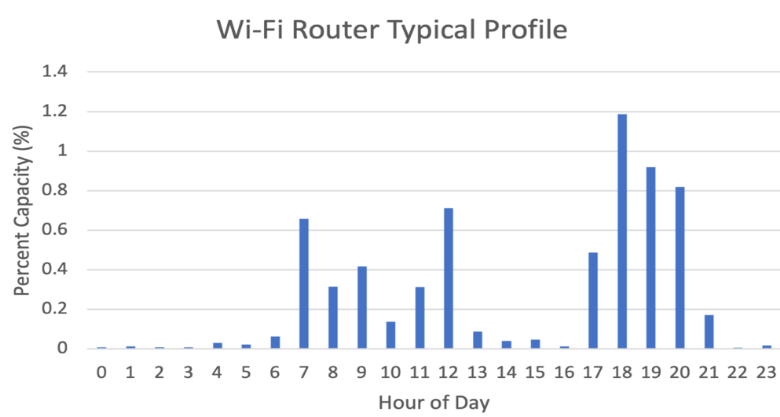


FIGURE 16. CAPACITY UTILIZATION OF A TYPICAL WI-FI ROUTER OVER A DAY (SOURCE: LBNL MEASUREMENTS)

The router in this field test operated nearly all of the time below five megabits per second (Mbps); that is, 1% of capacity. This speed was far from ideal power scaling. While the Wi-Fi router's peak consumption occurred in the evening, it had a relatively low impact on peak demand, due to its relatively low point on the power-scaling curve.

There is surprisingly little published data on device power scaling behavior. Manufacturers are principally concerned about the device's behavior near capacity, where overheating may occur or other components may be stressed (they may also be concerned about no-load behavior if the product must comply with European, Korean, and other standby power regulations). Despite the general lack of published data, power scaling is relevant to many types of devices, and such data can be measured easily in a lab. For example, Figure 17 shows the measured power-scaling profile of a computer monitor, which like the Wi-Fi router, also had a linear characteristic with a significant no-load power. The power-scaling profile of a sound bar, shown in Figure 18, had a nonlinear relationship between volume setting and power consumption, which may have been due to magnetic saturation at high current. The volume setting was tested separately and confirmed to be nearly linear with the dB sound intensity.

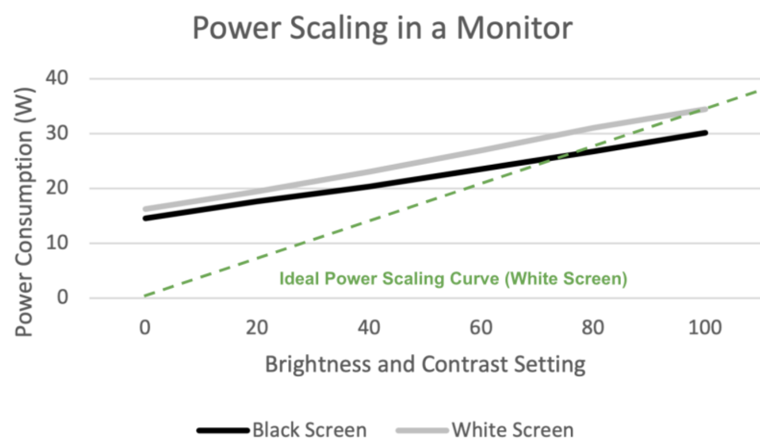


FIGURE 17. RELATIONSHIP BETWEEN MONITOR BRIGHTNESS AND POWER CONSUMPTION FOR BLACK SCREEN AND WHITE SCREEN (BRIGHTNESS AND CONTRAST WERE INCREASED TOGETHER - SOURCE: LBNL MEASUREMENTS)

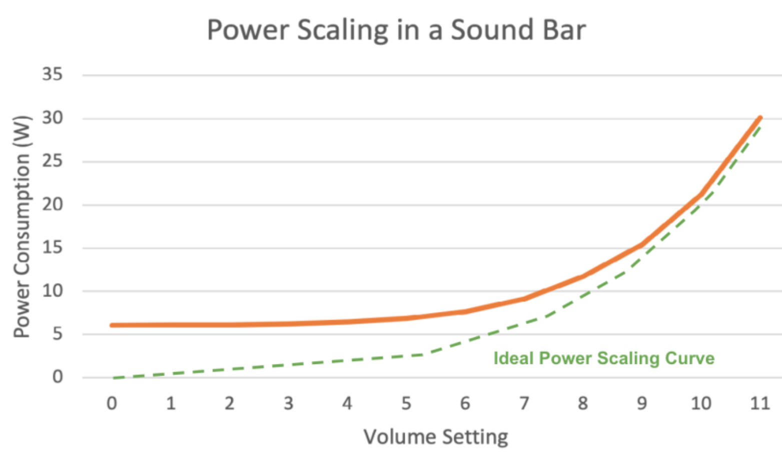


FIGURE 18. RELATIONSHIP BETWEEN SOUND BAR VOLUME SETTING AND POWER CONSUMPTION (TEST WAS CONDUCTED WITH A 440 HZ PURE-SINE TONE - SOURCE: LBNL MEASUREMENTS)

LAB MEASUREMENTS - SAFETY DEVICES

Several types of BIEL are dedicated to safety, and they must therefore remain operational at all times. These include GFCIs, AFCIs, smoke detectors, and CO detectors. We measured the constant-on power of several BIELs in each safety device category. These devices, shown in Table 2, have an average constant-on power of between 0.6 W and 0.9 W (Rainer et al. 2021). While individually insignificant, this constant-on power consumption can ultimately add up when there are many devices in numerous homes. For example, a home with 20 GFCI outlets may draw a constant 20 W and consume nearly 500 Wh daily. The simulation data in the following section indicates how the consumption of constant-on loads compares with direct load.

TABLE 2. SUMMARY OF TEST RESULTS

DEVICE CATEGORY	N	AVERAGE POWER (W)	MINIMUM POWER (W)	MAXIMUM POWER (W)
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

There is a wide range in power consumption among these devices. For GFCI breakers, the highest consumer requires five times as much power as the lowest. Many types of safety BIELs have antiquated power supplies, and these products have remained unchanged for decades. A product teardown revealed that many of the largest energy-consuming devices use a resistive divider voltage supply.

We ultimately found these types of safety devices have a flat, constant load shape. As such, they are not high-priority candidates for load shifting. The best solution to consumption in safety BIELs is to simply lower the constant consumption by studying best practices and updating standards. While the reliability and safety offered by these devices should never be compromised, this study reveals an opportunity for significant energy savings by simply switching to more efficient products.

SIMULATIONS

The following two screenshots (Tables 3a and 3b) show the preset model homes and the spreadsheet's tabs, respectively. The second screenshot (Table 3b) is a fragment of the bottom of the spreadsheet, which displays the tabs corresponding to the climates, home information, and devices.

TABLE 3A. MODEL SCREENSHOT SHOWING PRESET MODEL HOMES

1	Device Name	Quantity	Quantity	Quantity	Quantity	Quantity	Quantity
2		**Senior Home**	**SF Home Typic**	**SF Home High-**	**Townhouse**	**MF Home Typic**	**MF Home High-**
3	Lights	70	70	85	50	30	50
4	Ceiling Fans	2	3	4	2	1	5
5	Garage Door Openers	1	1	1	1	1	1
6	PV Inverters	1	1	1	1	0	1
7	Home Battery	1	1	1	1	0	1
8	Dishwashers	1	1	1	1	1	1
9	Smart Washing Machines	1	1	1	1	1	1
10	Heat Pump Dryers	1	1	1	1	1	1
11	Induction Ranges	1	2	2	2	2	2

TABLE 3B. MODEL SCREENSHOT SHOWING CLIMATES, HOME INFORMATION, AND DEVICES

30	Built-in Vacuums	0		1			12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
31	Air Purifiers	2	1				0.0	0.0	0.0	0.0	0.0	0.0	0.0	45.0	45.0	0.0	0.0
32	Air Purifiers Standby	2		1			1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
33	Graywater Systems (pump/filtrat	0	1				4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2
34	Home Fountain/Pond Pumps	0	1				20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
35	Structured Wiring Panels	0		1			30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
36	Integrated USB/120 VAC Outlets	20		1			0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
37	Home Energy Monitoring Systen	0		1			5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
38	Motion-Activated Faucets	1		1			0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
39	Elevators	1	1				40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0

WinterCoastal | SummerCoastal | WinterInland | SummerInland | HomeInfo | DeviceNotes

The BIELs Analysis Tool categorized energy consumption as being either direct load, direct standby, or indirect savings. *Direct load consumption* was the BIEL's useful energy consumption when it was being directly used by the occupant (for example, the oven's energy consumption). *Direct standby* was the consumption of a constant-on load when it was not being used by the occupant (for example, the standby power consumption of a smart oven in sleep mode). *Indirect savings* was the energy the smart BIEL saved (for example, the reduced cooling load from smart blinds that could automatically block sunlight). The BIELs Analysis Tool's output was a typical daily load profile chart highlighting the aggregate consumption or savings of each category.

The BIELs Analysis Tool modeled typical weekday home energy consumption profiles. A total of 24 cases were parametrically modeled along the following parameters:

- Season
  - Summer
  - Winter
- SCE Climate Zone
  - Coastal - Los Angeles
  - Inland - Riverside
- Type of Home (from Table 1)

The BIELs we modeled for direct load, direct standby, and indirect savings are listed in Appendix A. The full set of simulation results is shown in Appendix C.

Indirect HVAC impacts are not fully captured in the tool. For example, smart shades reduced solar gain and air conditioning loads. We made a simple estimate of the impacts based on a typical window. A more accurate estimate would require an hourly load simulation model of the prototypes, along with a much more detailed specification of the building locations, orientations, and HVAC systems. Thus, the indirect HVAC load impacts should be treated as indicative of their magnitude rather than exact values.

EXAMPLE BIELS ANALYSIS TOOL OUTPUT

The BIELs Analysis Tool output the daily BIEL load profile over a 24-hour period, categorized by device type. It showed how significant direct standby and indirect impacts could be compared to direct load. For example, in Figure 19, the coastal single-family unit was dominated by direct loads during the winter. The large spikes were caused by direct load from cooking in the evening, followed by running the clothes dryer at night. In many homes, the dishwasher would be set to automatically run after midnight. Note that these three peaks were caused by appliances that could be occupant-installed loads, so this was a maximum-case scenario. The small "bumps" in the morning were caused by lighting.

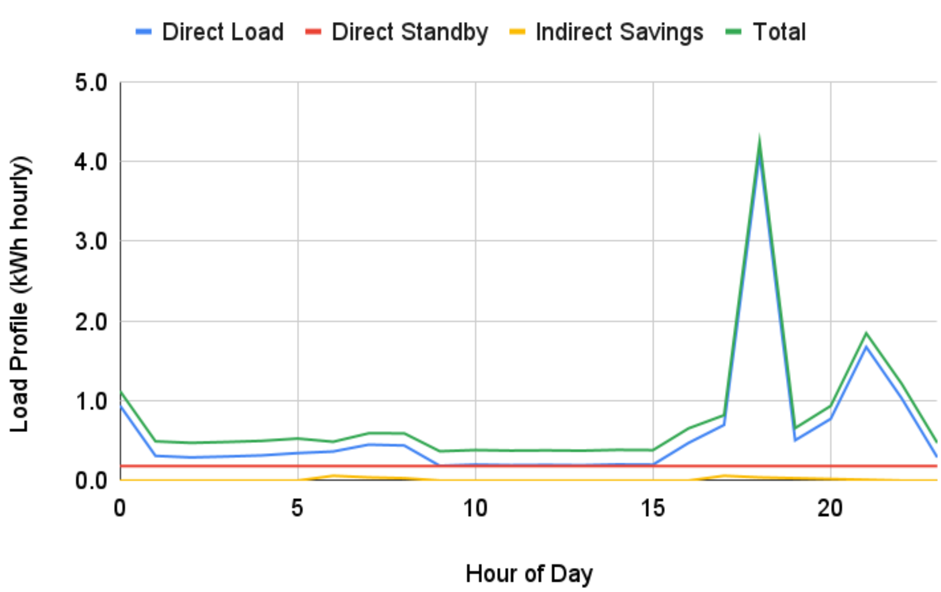


FIGURE 19. WINTER BIEL LOAD SHAPE FOR A TYPICAL SINGLE-FAMILY COASTAL HOME

By contrast, an inland high-end single-family unit (Figure 20) had more smart connected devices, and its typical summer consumption profile had a much greater contribution from standby and indirect savings, as shown in orange. The savings was principally from air conditioning; the smart shades prevented solar gain, and ceiling fans provided cooling air movement. The largest savings occurred in summer inland homes at about 4 PM, when smart shading cut solar gain.

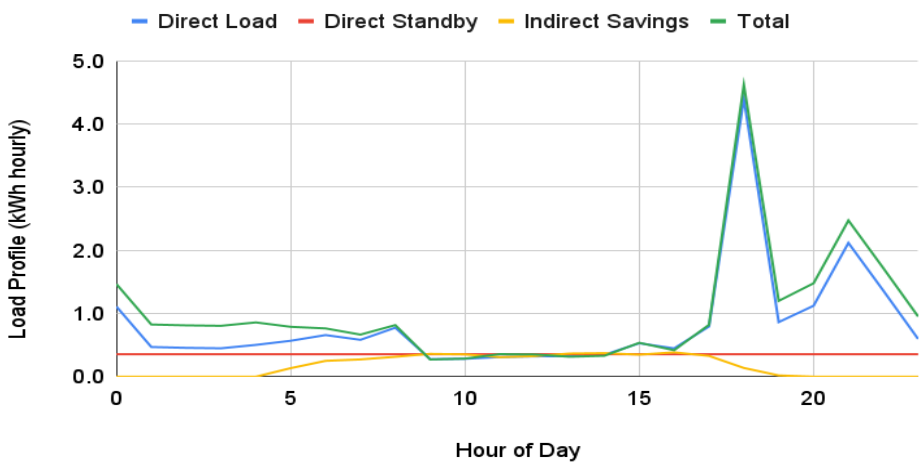


FIGURE 20. TYPICAL SINGLE-FAMILY HIGH-END INLAND HOME SUMMER LOAD SHAPE

These two examples illustrate how the tool depicted future changes in BIELs consumption patterns and quantified the extent to which these changes would affect overall consumption.

DISCUSSION

OVERALL BIEL LOAD IMPACTS

The methodology we used to construct these load shapes relied on our estimated future smart home characteristics (home size and builder-installed devices and their locations). For this reason, the results should be treated as indicative rather than quantitative. But the transparent nature of the methodology means readers can easily understand the origin of a number and load shape. If they disagree with the choices used here, they can explore the impacts by entering their own values into the BIELs Analysis Tool.

Prototype smart home BIEL load shapes are displayed in Appendix C and summarized in Table 5.

TABLE 5. ENERGY CONSUMPTION SUMMARY FOR THE SIX TYPICAL HOMES

	LOWEST DAILY CONSUMPTION/SAVINGS (KWH/DAY)	HIGHEST DAILY CONSUMPTION/ SAVINGS (KWH/DAY)	PEAK TIMES
Direct Load	13	20	12 AM, 8 AM, 6 PM, 11 PM
Standby Consumption	2	9	Constant
Indirect Savings	0.3	4	4 PM

Six home prototypes were modeled in two climate zones, for winter and summer (24 charts total). These charts depict direct loads, direct standby, indirect savings, and total power consumption for every hour. Since HVAC and discretionary products were not included, these values represent only a fraction of a future smart home's total electrical demand. Not surprisingly, high-end homes consumed more than average homes. The single-family buildings consumed more than the multifamily buildings per dwelling unit. As previously mentioned, consumption from common spaces in multifamily buildings was not included in the study, since it was far lower than the aggregate consumption of the dwelling units.

Total BIEL load impacts in all regions followed similar trends of low, constant demand during most hours punctuated by a midnight peak, morning peak, and much-higher peaks in the early and late evening. The 1 kW midnight peak was entirely due to the smart dishwasher, which was scheduled to run at midnight. The morning peak may have also consumed up to 1 kW in a high-end inland home, but was barely visible in most cases. The evening peak began at about 3 PM, but climbed sharply at about 6 PM. The peak varied from about 2.5 – 4.5 kW, depending on home type and climate zone. Elevated consumption continued for a few hours, with a second peak at 9 PM. These peaks were mostly direct loads caused by thermal loads, most notably cooking and clothes drying. Here, too, these peaks were caused by appliances that could be occupant-installed loads, so this was a maximum-case scenario.

Constant demand could be as high as 360 W for larger, high-end homes (compared to about 100 W for an average home). While almost every BIEL had some standby consumption, much of it could be attributed to always-on heating systems, such as heated washlets or under-sink, on-demand water heaters. Since the load was both flat and small, the load impacts were small. BIEL annual standby energy use represents a significant increase in a future home's electricity consumption. At 360 W, their annual electricity consumption is almost 3,200 kWh — roughly half of an average California total residential customer's electricity use. New communications protocols, such as "Matter" (Stacey on IoT 2021) are appearing, and could reduce smart product network burdens and power requirements. Alternatively, these networks could force connected devices to reside in higher power modes, resulting in higher energy consumption. However, further research is necessary to determine how to best reduce on-demand heating consumption.

Although indirect savings can be as high as 800 W during midday, they usually are barely visible compared to the large direct loads caused by cooking and other devices. These savings are still significant, and they show how smart devices can influence the behavior of a home's envelope and, ultimately, cut air conditioning loads.

Opportunities for Energy and Demand Savings

From a programmatic perspective, BIELs are attractive targets for energy savings, because all of the purchasing decisions are undertaken by a single entity: the builder. Thus, a single program could, in principle, capture this wide range of products. But there are also huge technical and practical challenges. Some obstacles include small power savings per product, absence of recognized testing and labeling requirements, and unclear linkages to indirect savings. These features make it difficult to structure an incentive program. Nevertheless, some opportunities exist to reduce energy, and these are discussed below.

There are several ways to maximize indirect home BIEL-related savings. One example is an automatic shade that closes to block solar irradiation in the conditioned space during the summer. Ceiling fans are another load that can indirectly reduce the cooling burden. Smart thermostats can also help save energy by reducing what would otherwise be wasteful occupant thermostat regulation.

All types of homes in our study has significant standby power consumption, which would likely grow as more smart devices were acquired. Cross-cutting technical solutions may be able to achieve broad reductions. These strategies include improving power conversion efficiencies, and power management and scaling. Some technologies, such as wake-up radios and coordinated scheduling, can eliminate standby consumption altogether (Gerber et al. 2019). These opportunities can only be realized through research, innovation, and commercializing the solutions.

Lower BIEL standby power consumption translates to longer battery-supported operation during power outages, which may create another incentive to minimize BIELs.

Failure to reduce BIEL energy use is a unique lost opportunity. It is especially important to minimize BIELs at the time of installation, because they will remain there for the life of the building. In addition, the occupants cannot easily switch them to conserve electricity.

Broader Opportunities for Load Shifting and Demand Response

BIEL load shape coincides somewhat with the California duck curve (Gerke et al. 2020) and therefore contributes to an imbalanced grid. In other words, installing these smart technologies in buildings is likely to slightly exacerbate California's grid problems; however, the contribution will be small compared to that of HVAC and discretionary loads. Nevertheless, it deserves attention. The load with the highest peak coincidence is the induction stove, and its use is driven by behavior. Consumer information programs may be the only way to shift this peak.

In one case, window shade and smart device controls contributed to load reduction during critical periods. The reductions were small; however, we assumed only one shaded window, so greater savings would be possible in some homes. Builder incentives might encourage more installations (or higher-quality installations). If the controls were linked to the network, grid signals could actuate the shades and provide grid services.

Kitchen appliances are selected by either the builder or the future occupants, depending on the circumstances of design, construction, and sale. In either event, the induction stove and other built-in appliances are used during critical late-afternoon periods. None of these appliances currently have any load-shifting capabilities; however, load shifting could be built into future models. For example, redesigned refrigerators could store thermal mass, and dishwashers could pre-heat water (in addition to postponing operation). All of these modifications would require close coordination with appliance manufacturers.

Heat pump clothes dryers are now entering the market, and are a target for both load shifting and energy efficiency. They offer energy savings, and shift their usage to later in the evening (because they extend drying time). New homes have the opportunity to install completely new solutions, possibly as builder-installed items. For example, the "Clothes Styler" (Winke 2021) can shift clothes from the conventional, wash-dry-iron sequence to a steam cycle that might occur with a conventional dryer. The Clothes Styler is currently a niche consumer product in the United States, but is widely used in Korea. These are already Wi-Fi enabled. It is not clear, however, whether this product would displace washing machine, dryer, and dry cleaner energy use and demand, or add to it.

Laboratory Measurements

Laboratory measurements revealed many smart devices had significant standby consumption and poor ability to scale their power consumption with the level of useful output. In the field test, the Wi-Fi router and irrigation system operated at a low percentage of their maximum output capacity. However, as shown in Figures 13, 14, and 15, their power consumption was nearly constant over the period of performance. This was further clarified by characterizing Wi-Fi router power scaling. As shown in Figure 16, the Wi-Fi router typically operated at a relatively low data rate compared to its maximum capacity. At low power, it deviated significantly from an ideal power scaling curve. Other devices, such as the sound bar and monitor, had similarly poor power-scaling characteristics.

Overall, we suspect both power scaling and standby consumption will continue to degrade as many BIELs acquire more internal decision-making capabilities and are connected to networks ("become smart"). Unfortunately, there is no literature to compare these results with other products, because researchers have not yet begun to address this issue.

IMPLICATIONS OF THIS INVESTIGATION

Overall, BIEL load impacts in new smart homes are likely to be modest. A few loads, such as induction stoves, will significantly add to these homes' demand — and at times that are unfavorable to the grid — but these impacts are expected and, to some extent, unavoidable. On the other hand, the energy impacts may be significant. Future smart homes will use more electricity in standby modes.

CONCLUSIONS

This project examined BIEL demand and electricity impacts, but not HVAC and major appliance load impacts. By examining BIELs alone, we can better understand their impacts.

BIELs use electricity directly and, in some cases, indirectly by inducing energy consumption in other devices. The most frequent forms of induced (or indirect) energy use are related to heating, cooling, and lighting. This study separated each device's electricity use into these direct and indirect impacts, because their load shapes and amounts were often very different. This distinction between direct and indirect impacts applies not just to BIELs, but also to other new, connected appliances.

Overall direct BIEL load impacts amounted to roughly 13.1 kWh/day in a small home, to 19.7 kWh/day in a large, upscale house (2.5 kW and 4.5 kW peak loads, respectively). Note that unlike previous studies, these figures accounted for the impacts of direct load and indirect savings while the homes were occupied. In our modeling, BIEL load impacts increased with floor area, but not with respect to climate. This study found newer smart home consumption to be up to three times greater than the 1,050 kWh/year result from previous studies. With a few exceptions (such as stoves) BIEL electricity use is flat, and therefore does not substantially increase demand at any particular time. Thus, BIELs (excluding those covered by Title 24 and energy efficiency standards) in new smart homes will not significantly contribute to future peak demand challenges.

Indirect load impacts were larger and more variable. Smart controls connected to window shades greatly reduced solar gain (and, ultimately, cooling loads) by reliably closing during periods of high solar gain. The incremental benefits from such technologies will depend on the number of exposed windows and their orientation, combined with user behavior absent controls. Ultimately, a unified simulation would be needed to capture all of these effects.

BIELs are responsible for a major fraction of continuous (standby) power consumption in new smart homes. Scenarios developed in this study showed continuous power consumption ranged from 100–350 W. For comparison, 350 W corresponds to roughly 45% of an average California residential customer's electricity consumption. Even though these devices' electricity consumption was low on a per-unit basis, there are often many installations in each home. Our laboratory studies demonstrated a wide variation in device standby power consumption. Furthermore, some of them appeared to run very inefficiently in their operating range, so even greater energy savings potential exists if their ability to power-scale could be improved. For these reasons, we conclude that BIELs do not represent a significant variable load. To be sure, there is energy-savings potential, and some programs could be developed to target those savings. Reducing BIELs in homes equipped with batteries also extends the time a home can operate without grid power. This feature greatly improves resilience during power outages. Overall, however, this category of electricity use will not require major adjustments to load forecasts and energy efficiency programs.

Improved BIEL power scaling could save energy, as demonstrated in the measurements described earlier. However, the absence of power-scaling data for most types of MELs and BIELs makes it impossible to estimate the amount of potential. Thus, two avenues of future research are suggested. First, further measurements of power scaling need to be conducted. Second, for appliances with poor power scaling behavior, techniques should be investigated to improve their part-load performance. Depending on the findings, new test procedures, minimum efficiency standards, and building codes may be warranted.

During our investigations, two transformational events occurred in California: the pandemic, and extensive wildfires. Both are already influencing consumers with respect to energy-using equipment. For example, consumers are buying more office and exercise products as a result of staying home more. The wildfires have stimulated a huge increase in air filtration equipment and sensor purchases. These trends have not yet translated to widespread adjustments to builder-installed products in new homes, but they are likely to happen. We expect to capture this trend as we update the device library.

RECOMMENDATIONS

This study explored the nature and level of electricity consumption caused by BIELs, with emphasis on the equipment appearing in the newest smart homes. The findings can inform load forecasts and energy efficiency programs.

There is inadequate information on the actual population of BIELs in homes, and especially the growth of new BIELs in smart homes. These devices are not recorded in California Residential Appliance Saturation Studies (RASSs) or sales statistics, because they are too small or new (or both). This lack of information translates into large uncertainties in load shapes and electricity consumption. Thus, audits of popular new home categories (similar to the typical homes used in this report's modeling) could greatly reduce the uncertainty of BIEL loads and electricity consumption.

Few of the smart BIELs appeared to have significant load impacts; but this study relied heavily on measuring individual devices (instead of measuring multiple devices in actual homes) so further studies should focus on whole-house field measurements of consumption and load shapes. The actual level of BIELs is uncertain in both new and existing homes, so further field measurements are recommended to better estimate their overall impact. Field measurements in 30 diverse homes should be sufficient.

Many smart devices are currently being integrated into new homes with systems like Alexa and Matter, which are already being installed by builders. This trend is likely to sharply accelerate. The extent to which these networks will be linked to demand response and load shifting is not yet clear. These investigations need to be coupled with careful inventories of products installed, their modes, and the times the devices run in each mode. Smart BIELs will be connected to networks, and their behaviors may change in unpredictable ways when interacting with other smart devices. Specifically, policymakers need to understand which devices fail to revert to low power modes when connected to the network, and target them for further actions. Demand control and other grid signals add further uncertainties. Whole-building energy and network monitoring is therefore essential.

BIEL standby electricity use is significant and deserves further scrutiny, because there appear to be opportunities to save electricity. This report identifies two strategies deserving further research. The first involves improving device standby consumption and power scaling. Using a wake-up radio and systematically integrating smart energy management into the home network are promising research directions. A second opportunity involves finding more ways to indirectly reduce consumption by using smart controls. These opportunities are best investigated in the laboratory, where competing technologies can be compared and electricity savings more confidently estimated. Ultimately, new products incorporating these technologies could be used to create a program targeting home builders and contractors.

APPENDICES

APPENDIX A: LIST OF BUILDER-INSTALLED SMART PRODUCTS

APPLIANCE	LOCATION CATEGORY	SERVICE CATEGORY	NAMEPLATE POWER CONSUMPTION	ENERGY CONSUMPTION (WH/DAY)
Lights	All	Lighting	10 W Standby: 0.5 W	25
Ceiling Fans	Living Spaces	HVAC	25 W Standby: 1.2 W	100
Garage Door Openers	Garage/Utility	Convenience	1.1 kW	31
PV Inverters	Garage/Utility	Electrification	5 kW Standby: 1 W	24
Home Battery	Garage/Utility	Electrification	5 kW Standing Loss: 20 W Standby: 7.5 W	488
Dishwashers	Kitchen	Cleaning	650 W	650
Smart Washing Machines	Laundry	Cleaning	1.2 kW Standby: 1 W	290
Heat Pump Dryers	Laundry	Cleaning	7.2 kW Standby: 0.9 W	1,700
Induction Stove Top Individual	Kitchen	Food	1.8 kW Standby: 3 W	1,800
Smart Refrigerators	Kitchen	Food	200 W	1,600
GFCI/AFCI Breaker	Breaker Panel	Safety	Standby: 0.8 W	19.2
Smoke/CO Alarms	Living Spaces	Safety	Standby: 1 W	24
Doorbells	Entry	Safety	Standby: 2.8 W	68
Door Locks	Entry	Safety	Usually battery-powered	Not Applicable
Security Systems	All	Safety	Standby: 25 W	600
Water/Freeze Alarms	All	Safety	Standby: 1 W	24
Thermostats	Living Spaces	HVAC	Standby: 2 W max	24
Home Voice Assistants	Living Spaces	Convenience	3.1 W Standby: 1.7 W	45
Washlets (depends on heater)	Bathroom	Hygiene	Standby: 30 W	1,000
Smart Plugs/Strips	Living Spaces	Convenience	Standby: 1 W	24
Irrigation Controls	Garage/Utility	Landscape	Standby: 3 W	72

Appliance	Location Category	Service Category	Nameplate Power Consumption	Energy Consumption (Wh/day)
Vacuums	Garage/Utility	Cleaning	1.8 kW	300
Air Purifiers	Living Spaces	Cleaning	Standby: 1 W Active: 45 W	660
Graywater Systems (pump/filtration)	Garage/Utility	Landscape	200 W	100
Home Fountain/Pond Pumps	Outdoor	Landscape	20 W	480
Structured Wiring Panels	All	Entertainment	Standby: 30 W	720
Integrated USB/120 VAC Outlets	All	Convenience	Standby: 0.06 W	1.4
Home Energy Monitoring Systems	Living Spaces	Safety	Standby: 5 W	120
Motion-Activated Faucets	Bathroom	Convenience	Standby: 0.5 W	12
Elevators	Living Spaces	Safety	2 kW Standby: 40 W	960
Bathtub/Spa with Electronic Controls	Bathroom	Hygiene	Jets: 990 W Standby: 7 W	660
Under-Sink Tankless Water Heater	Kitchen	Hygiene	Standby: 15 W	360
Hot Water Recirculation Pump	Garage/Utility	Convenience	Standby: 1 W	24
Water Softener	Garage/Utility	Hygiene	8 W	192
Heated Towel Warmers	Bathroom	Hygiene	75 W	450
Smart Device Gateway	Garage/Utility	Networking	Standby: 0.5 W	12
Networking Equipment (e.g. modem, router)	Living Spaces	Networking	Standby: 10 W	240
Window Shades	Living Spaces	HVAC	Standby: 1.5 W	48

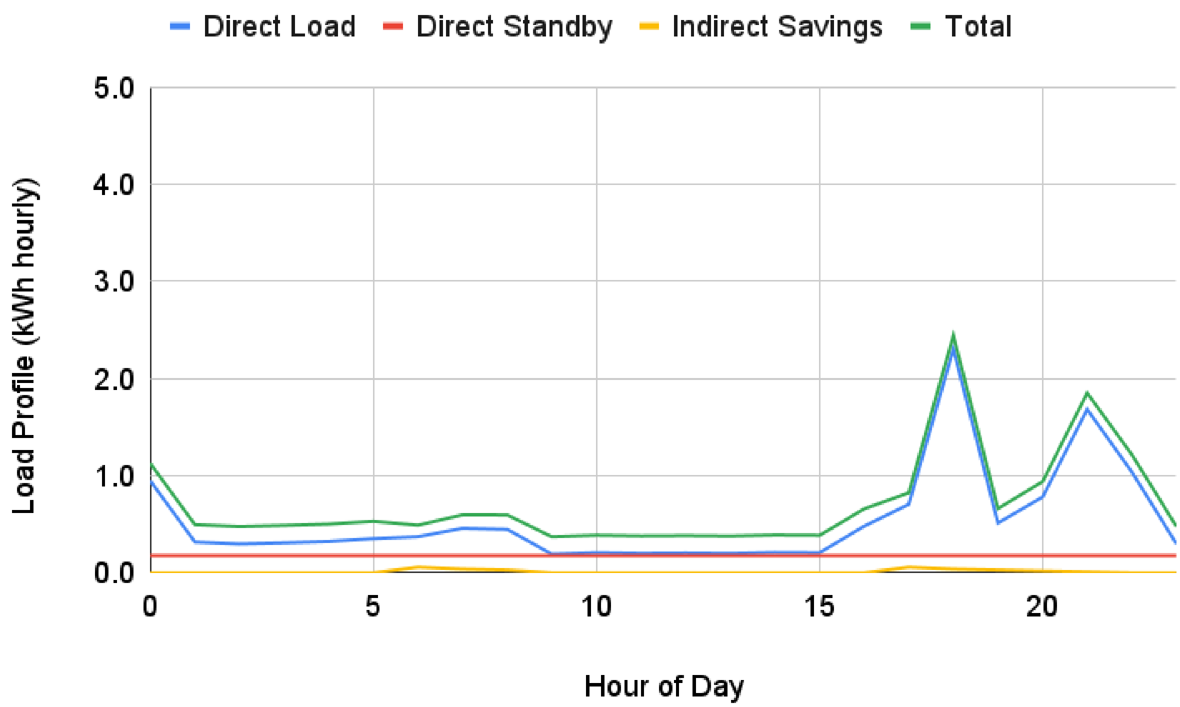
APPENDIX B: SMART DEVICES IN TYPICAL HOMES

Devices	Senior Home	SF Home Typical	SF Home High End	Townhouse	MF Home Typical	MF Home High End
Lights	70	70	85	50	30	50
Ceiling Fans	2	3	4	2	1	5
Garage Door Openers	1	1	1	1	1	1
PV Inverters	1	1	1	1	0	1
Home Battery	1	1	1	1	0	1
Dishwashers	1	1	1	1	1	1
Smart Washing Machines	1	1	1	1	1	1
Heat Pump Dryers	1	1	1	1	1	1
Induction Ranges	1	2	2	2	2	2
Smart Refrigerators	1	1	1	1	1	1
GFCI/AFCI Breaker	16	24	32	13	12	16
Smoke/CO Alarms	6	6	8	6	3	5
Doorbells	1	1	1	1	1	1
Door Locks	2	3	3	1	1	1
Security Systems	1	0	1	1	0	1
Water/Freeze Alarms	5	5	6	5	2	4
Thermostats	1	2	4	1	1	4
Home Voice Assistants	1	1	2	2	1	1
Washlets	1	1	3	1	1	3
Irrigation Controls	0	0	1	0	0	1
Air Purifiers	3	3	4	3	2	4
Graywater Systems (pump/filtration)	1	1	1	1	0	1
Home Fountain/Pond Pumps	0	0	1	0	0	0
Structured Wiring Panels	0	0	1	0	0	1
Integrated USB/ 120 VAC Outlets	60	60	80	50	20	32
Home Energy Monitoring Systems	0	1	1	0	0	1

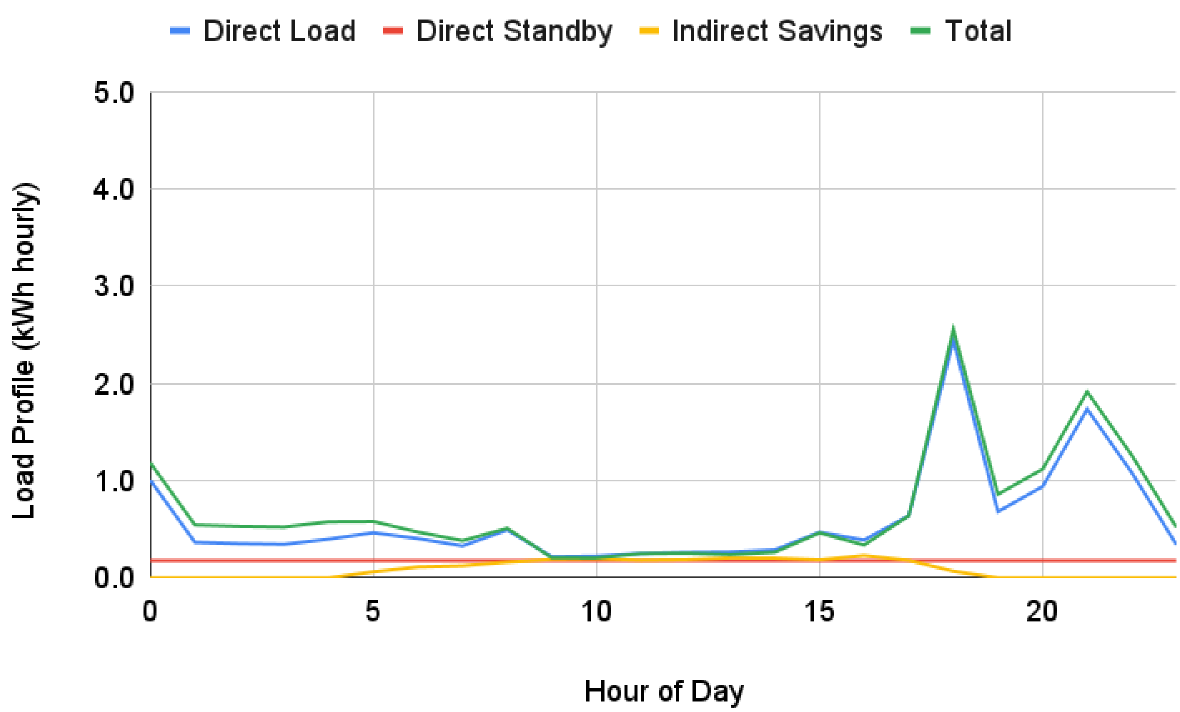
Devices	Senior Home	SF Home Typical	SF Home High End	Townhouse	MF Home Typical	MF Home High End
Motion-Activated Faucets	2	2	3	1	1	2
Elevators	0	0	1	0	0	0
Bathtub/Spa with Electronic Controls	1	1	1	1	1	1
Under-Sink Tankless Water Heater	1	1	2	1	1	2
Hot Water Recirculation Pump	2	4	5	2	2	3
Water Softener	1	0	1	0	0	1
Heated Towel Warmers	0	0	2	0	0	2
Intwine Connected Gateway	1	1	1	1	1	1
Networking Equipment (e.g., modem, router)	1	2	3	1	1	2
Window Shades	5	5	9	3	4	7

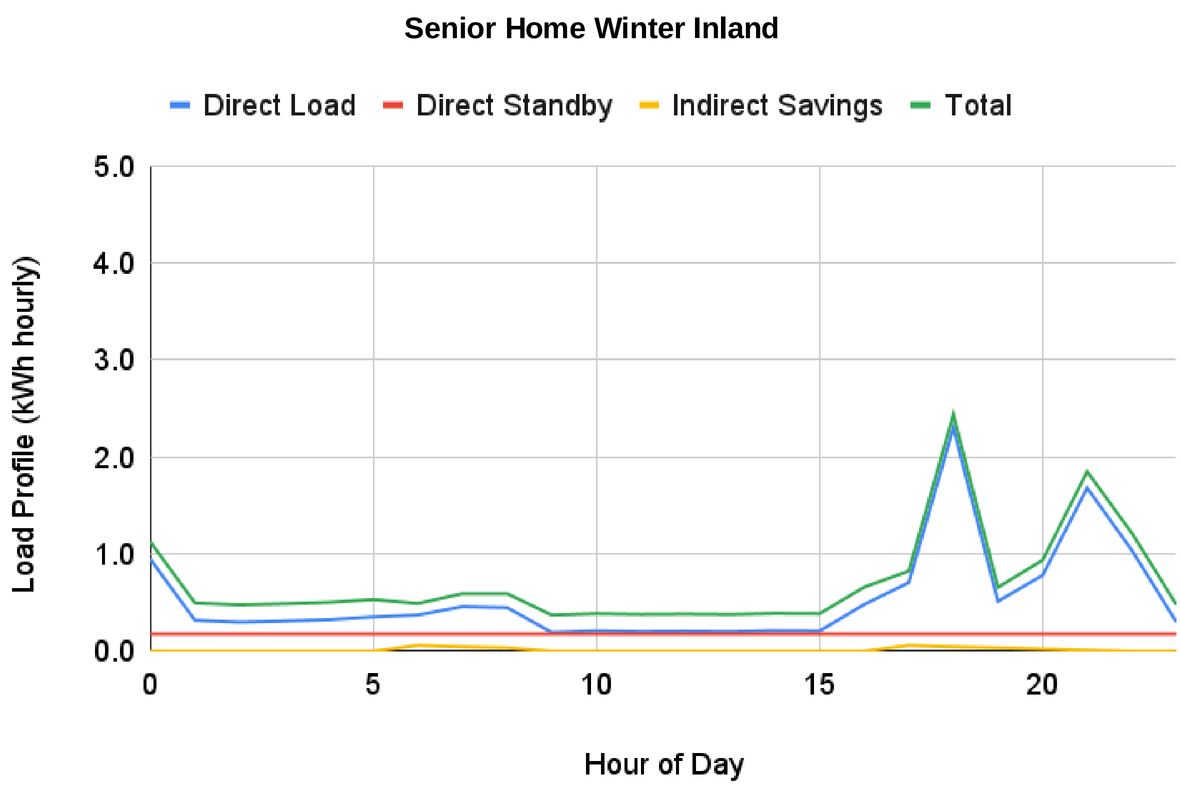
APPENDIX C: AGGREGATE LOAD SHAPES BY CATEGORY

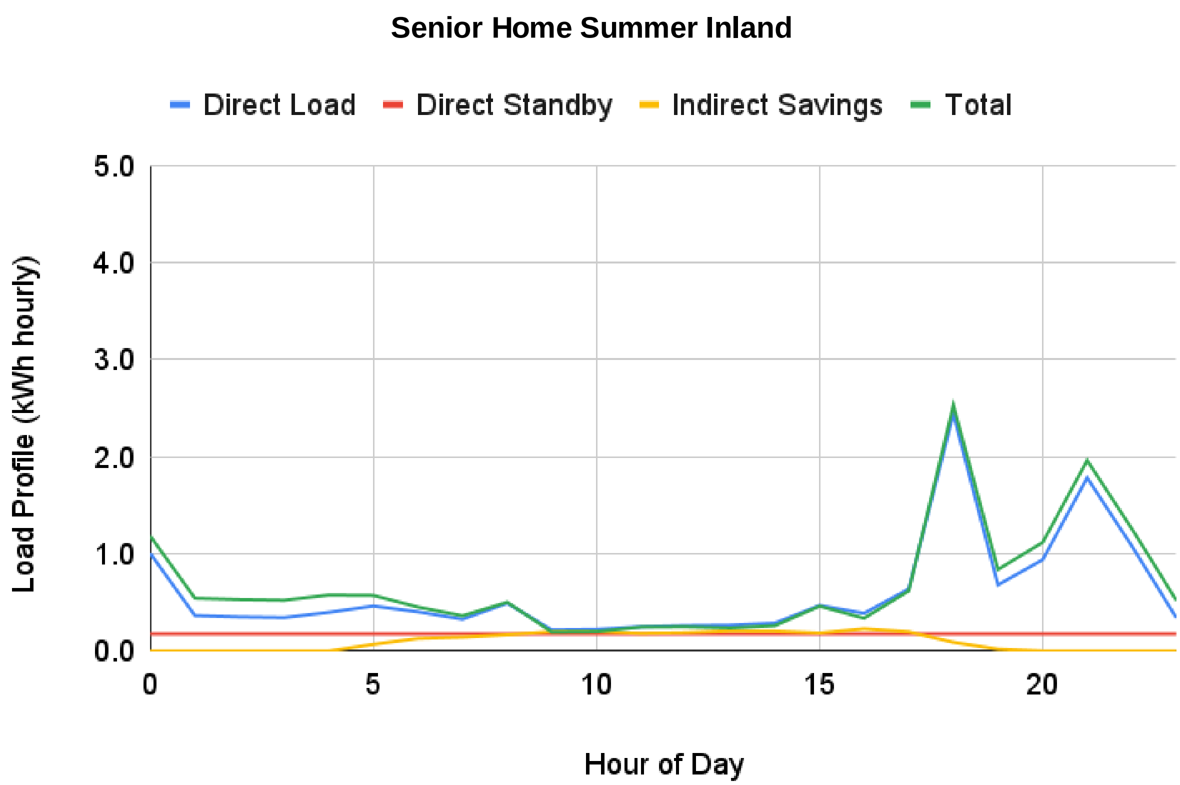
Senior Home Winter Coastal



Senior Home Summer Coastal




Senior Home Winter Inland
Direct Load
Direct Standby
Indirect Savings
Total
Load Profile (kWh hourly)
5.0
4.0
3.0
2.0
1.0
0.0
0
5
10
15
20
Hour of Day


Senior Home Summer Inland
Direct Load
Direct Standby
Indirect Savings
Total
Load Profile (kWh hourly)
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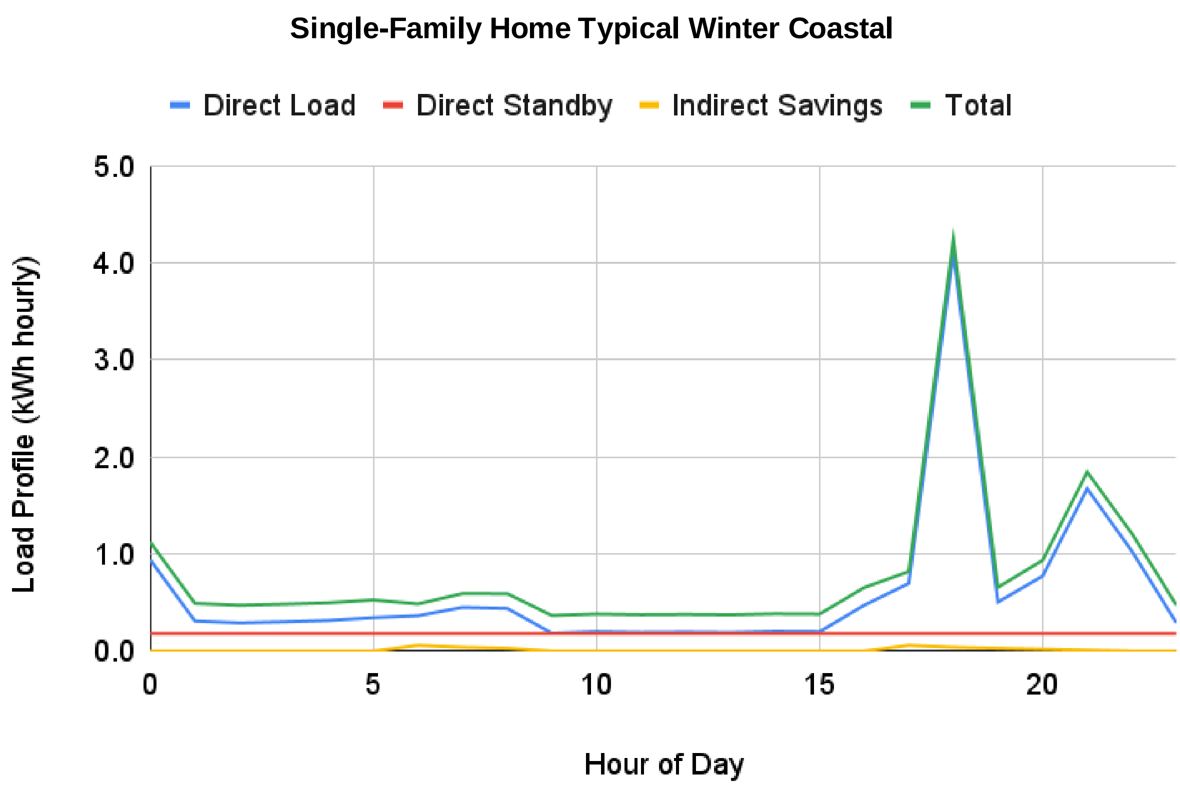
Hour of Day


Single-Family Home Typical Winter Coastal
Direct Load
Direct Standby
Indirect Savings
Total
Load Profile (kWh hourly)
5.0
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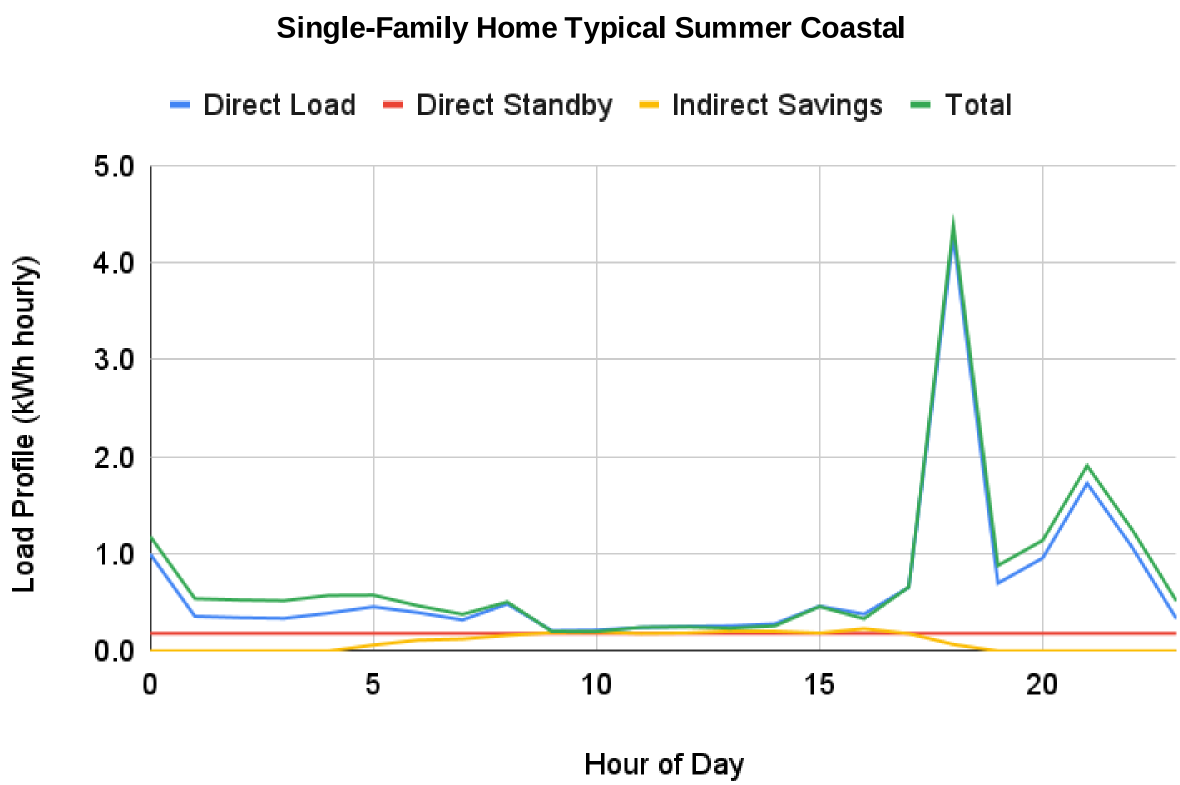
Hour of Day


Single-Family Home Typical Summer Coastal
Direct Load
Direct Standby
Indirect Savings
Total
Load Profile (kWh hourly)
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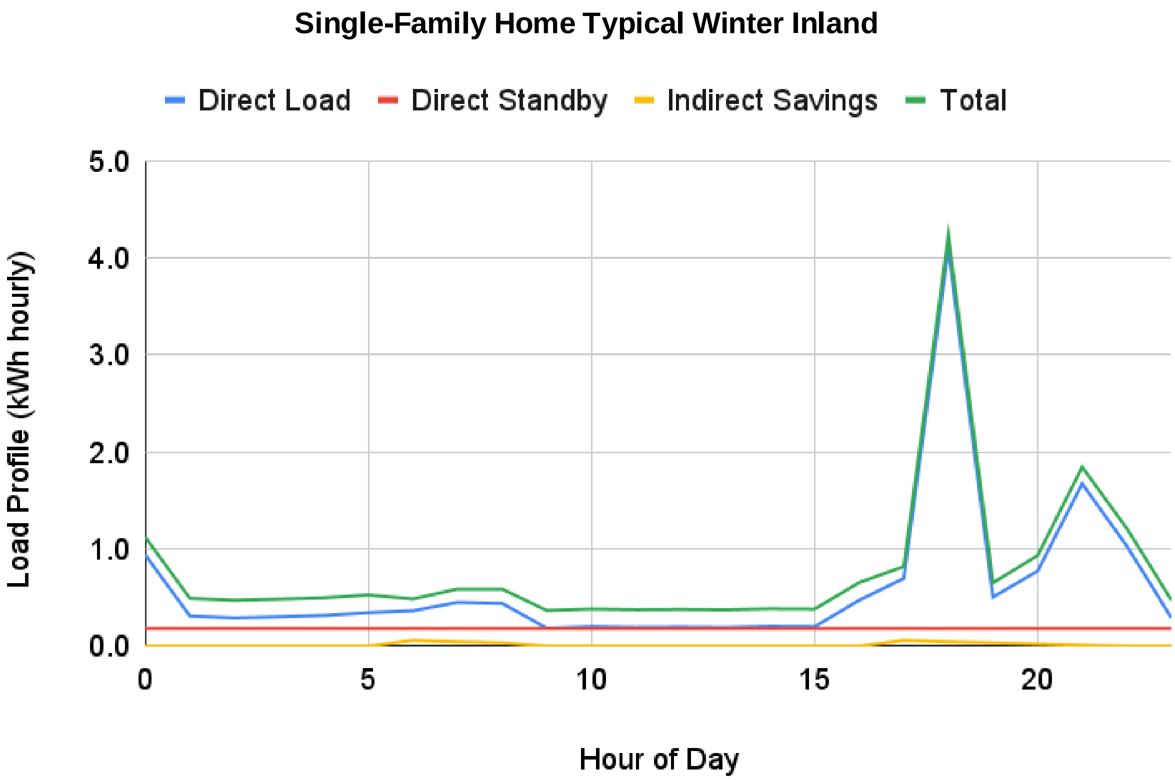
Hour of Day


Single-Family Home Typical Winter Inland
Direct Load
Direct Standby
Indirect Savings
Total
Load Profile (kWh hourly)
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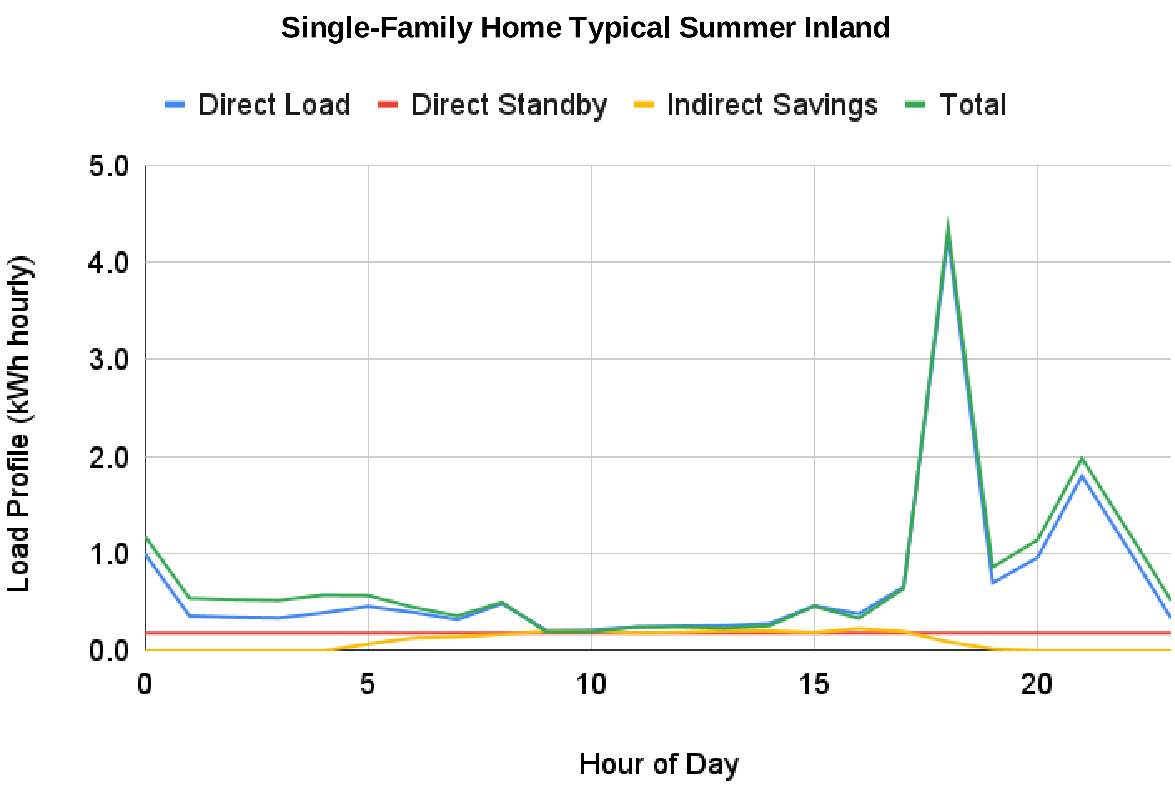
Hour of Day


Single-Family Home Typical Summer Inland
Direct Load
Direct Standby
Indirect Savings
Total
Load Profile (kWh hourly)
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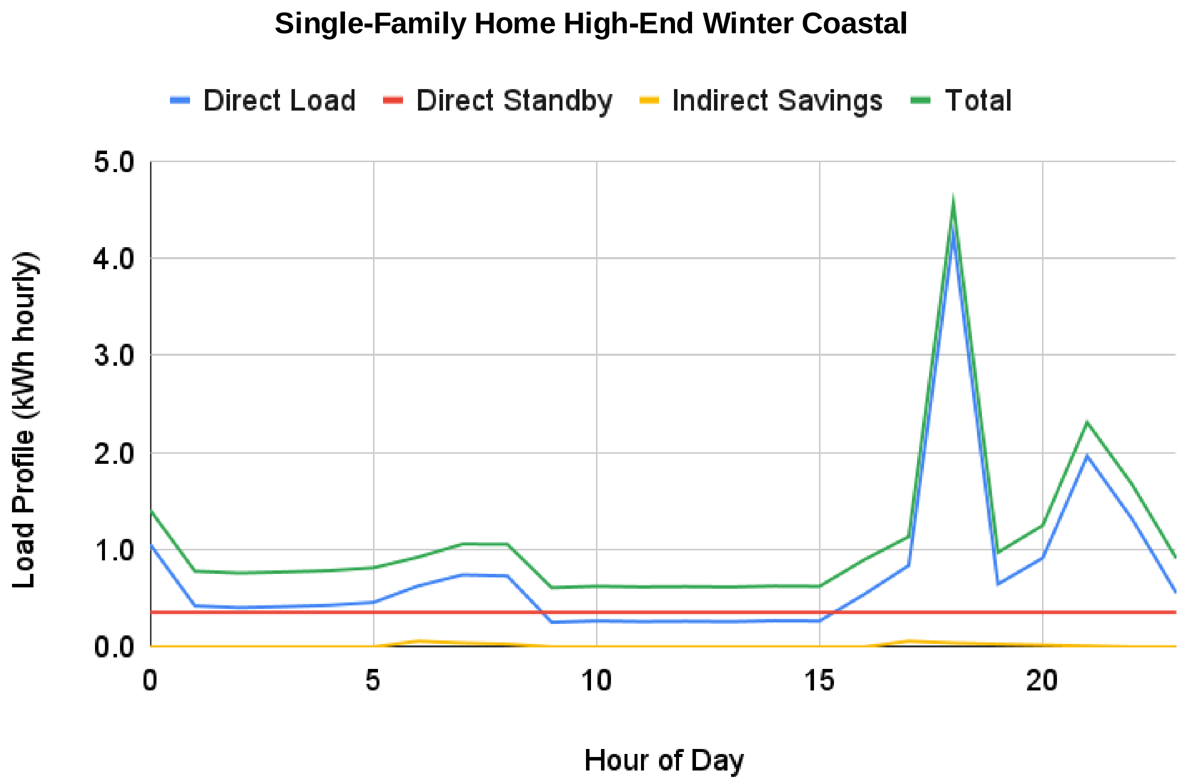
Hour of Day



Single-Family Home High-End Winter Coastal
Direct Load
Direct Standby
Indirect Savings
Total
Load Profile (kWh hourly)
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2.0
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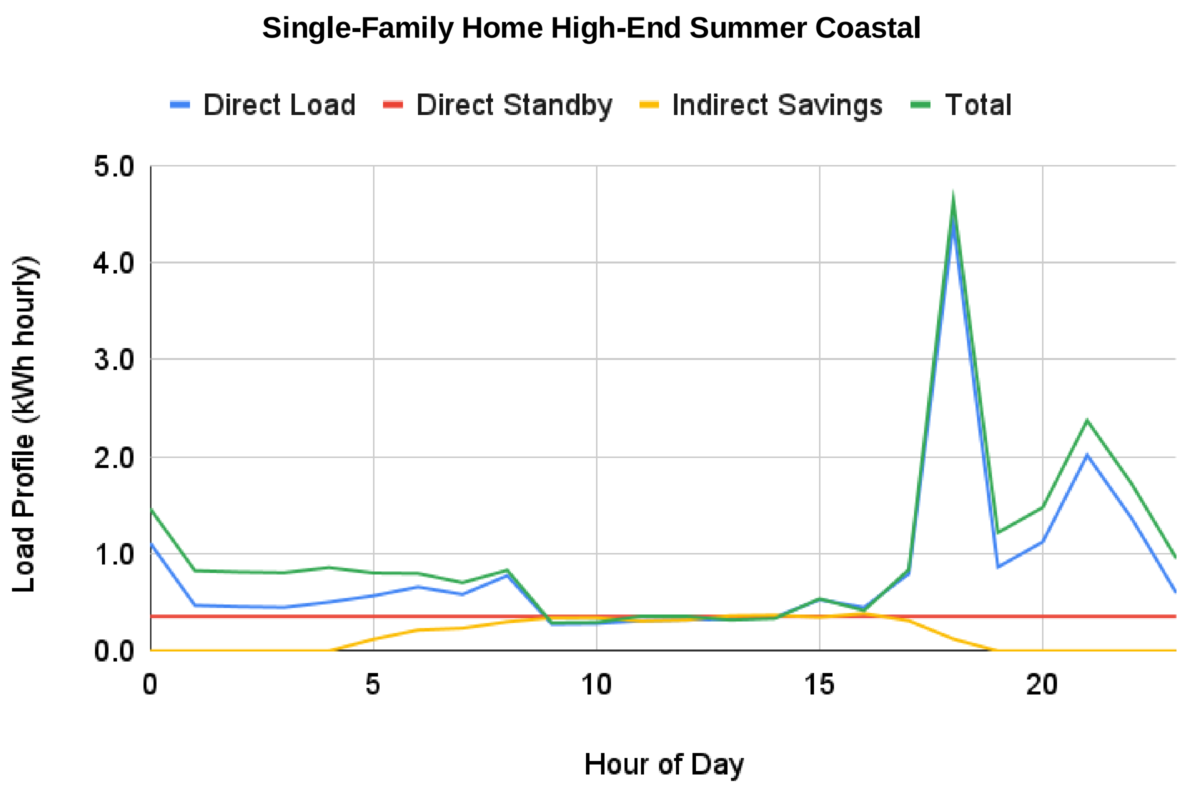
Hour of Day



Single-Family Home High-End Summer Coastal
Direct Load
Direct Standby
Indirect Savings
Total
Load Profile (kWh hourly)
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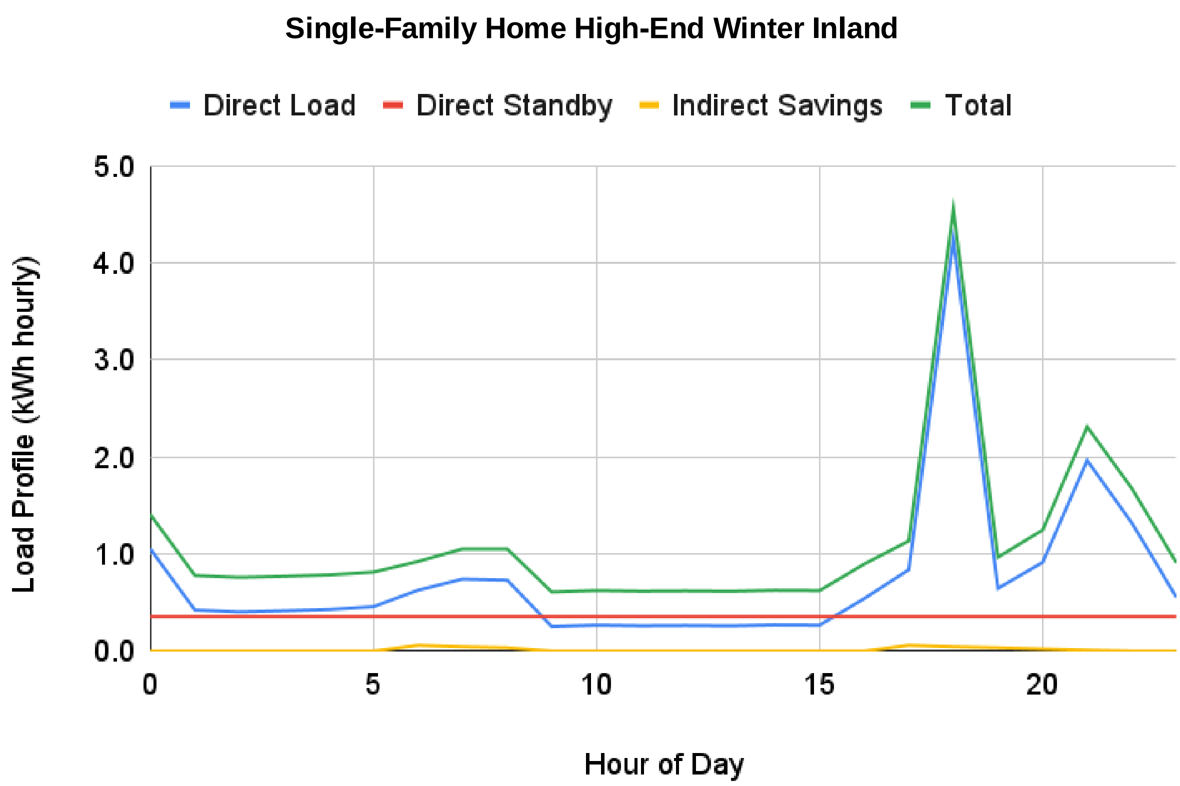
Hour of Day


Single-Family Home High-End Winter Inland
Direct Load
Direct Standby
Indirect Savings
Total
Load Profile (kWh hourly)
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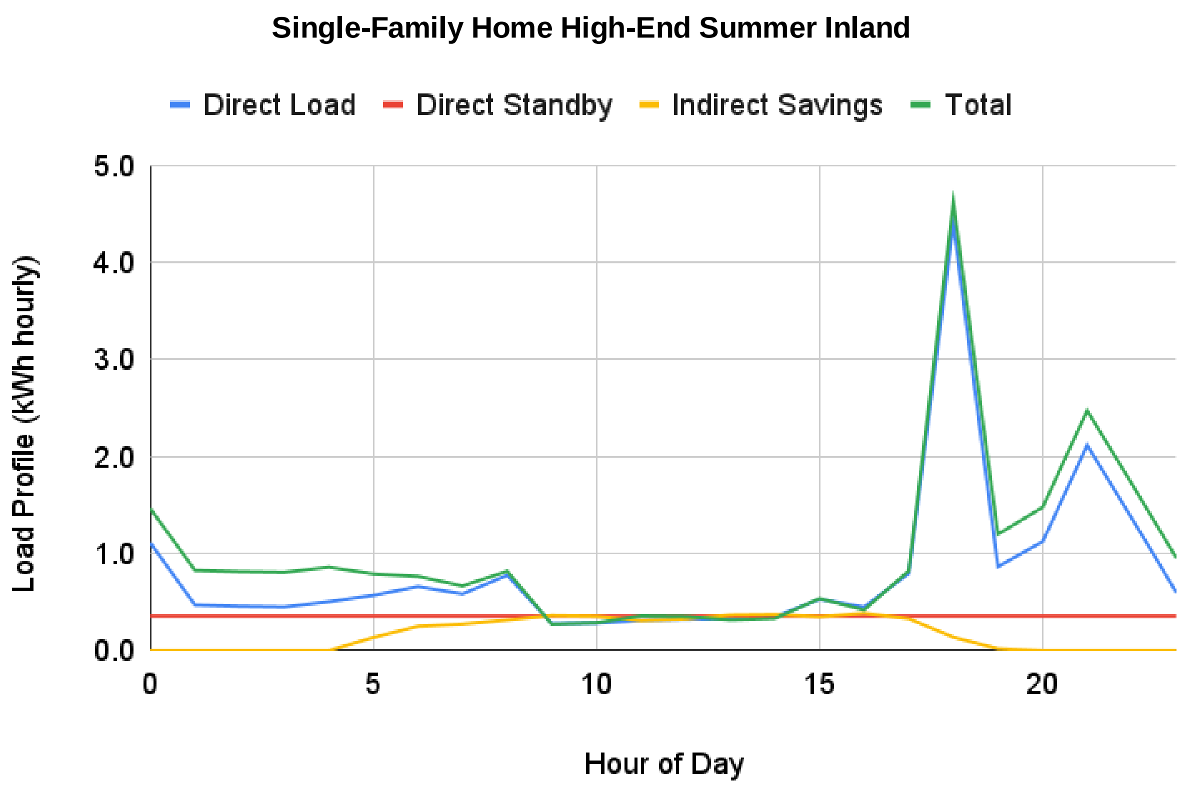
Hour of Day


Single-Family Home High-End Summer Inland
Direct Load
Direct Standby
Indirect Savings
Total
Load Profile (kWh hourly)
5.0
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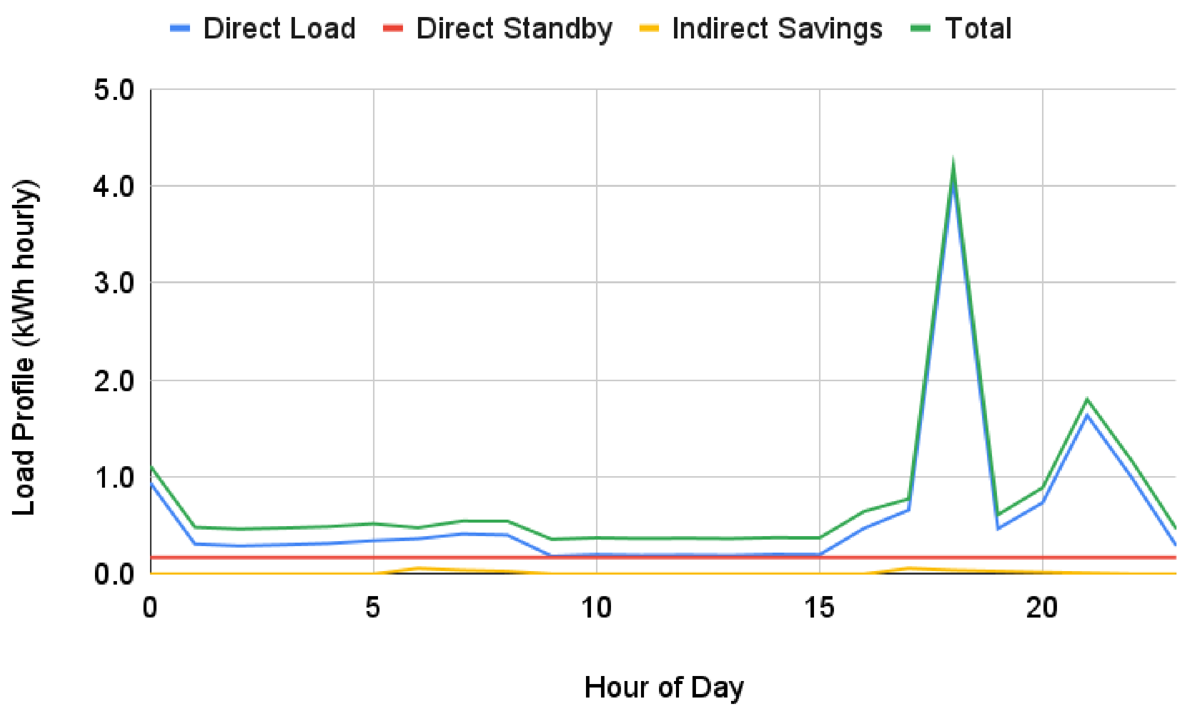
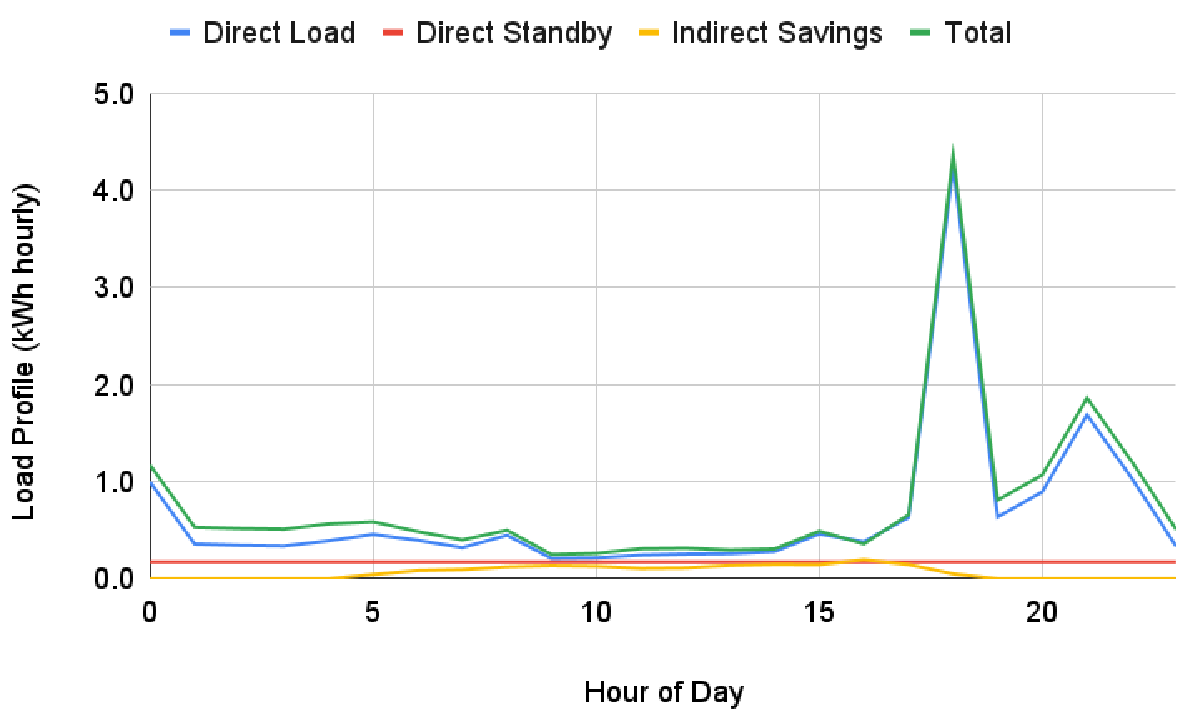
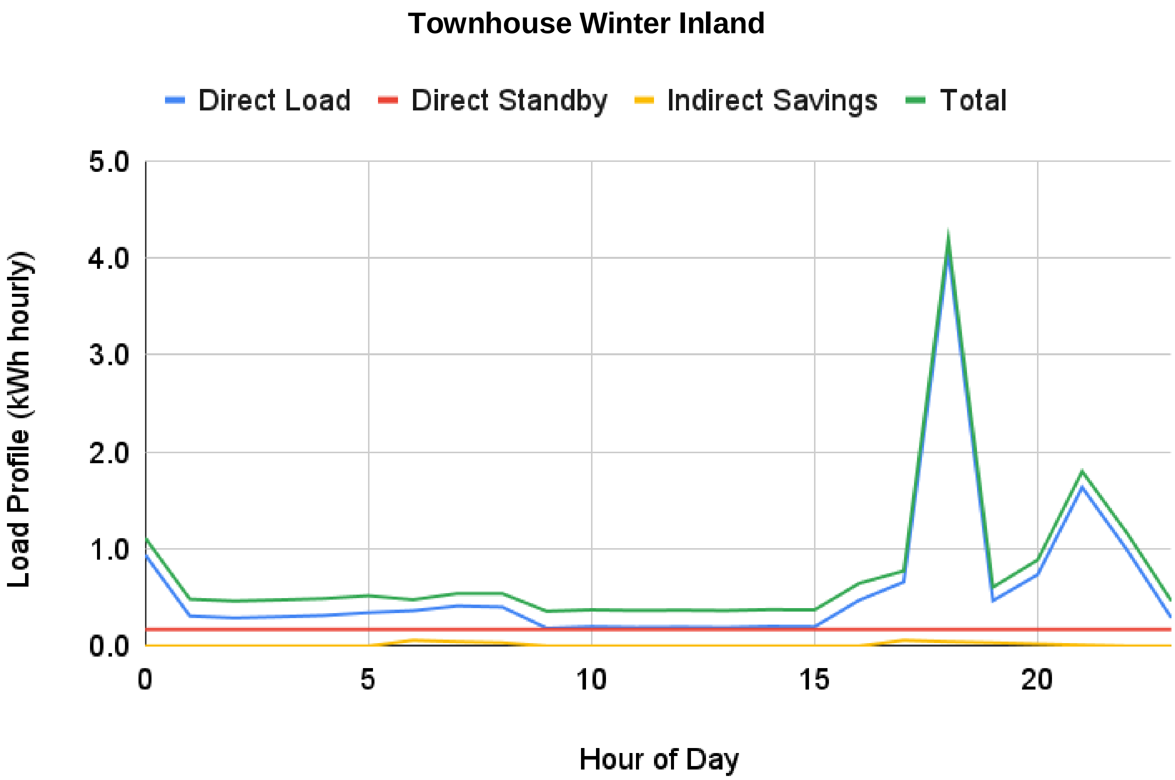
15
20
Hour of Day

Townhouse Winter Coastal



Townhouse Summer Coastal




Townhouse Winter Inland
Direct Load
Direct Standby
Indirect Savings
Total
Load Profile (kWh hourly)
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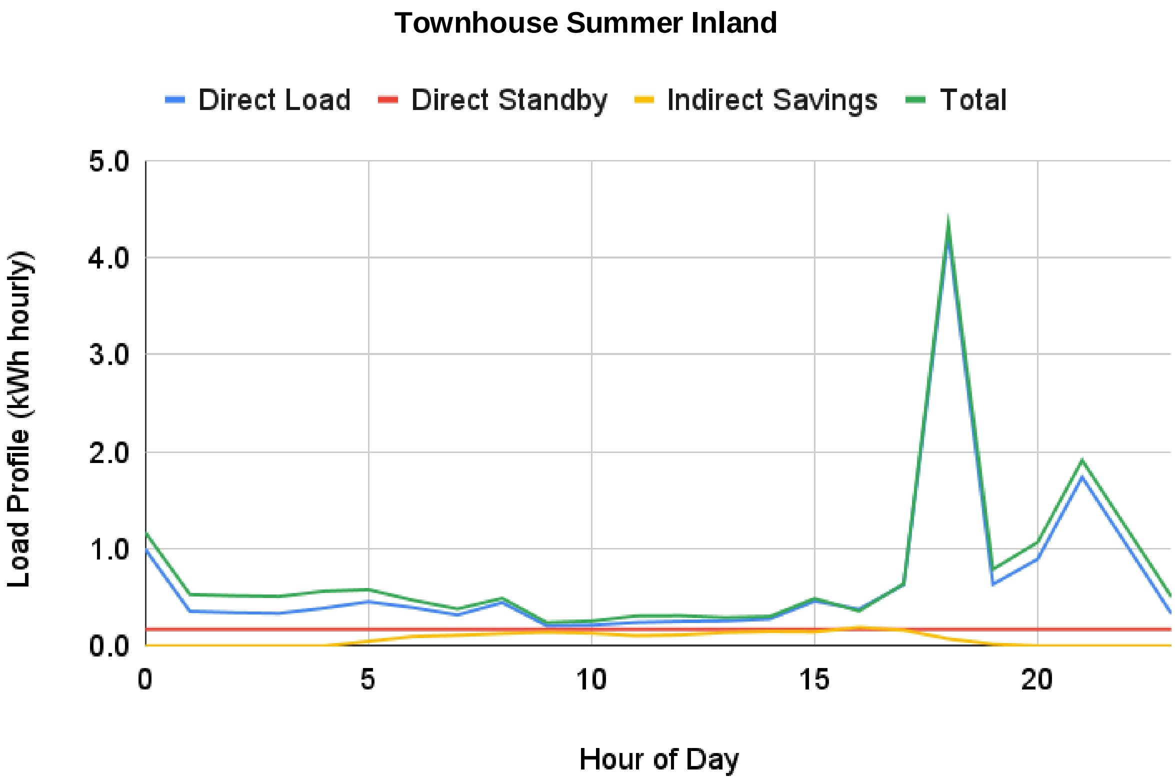
Hour of Day


Townhouse Summer Inland
Direct Load
Direct Standby
Indirect Savings
Total
Load Profile (kWh hourly)
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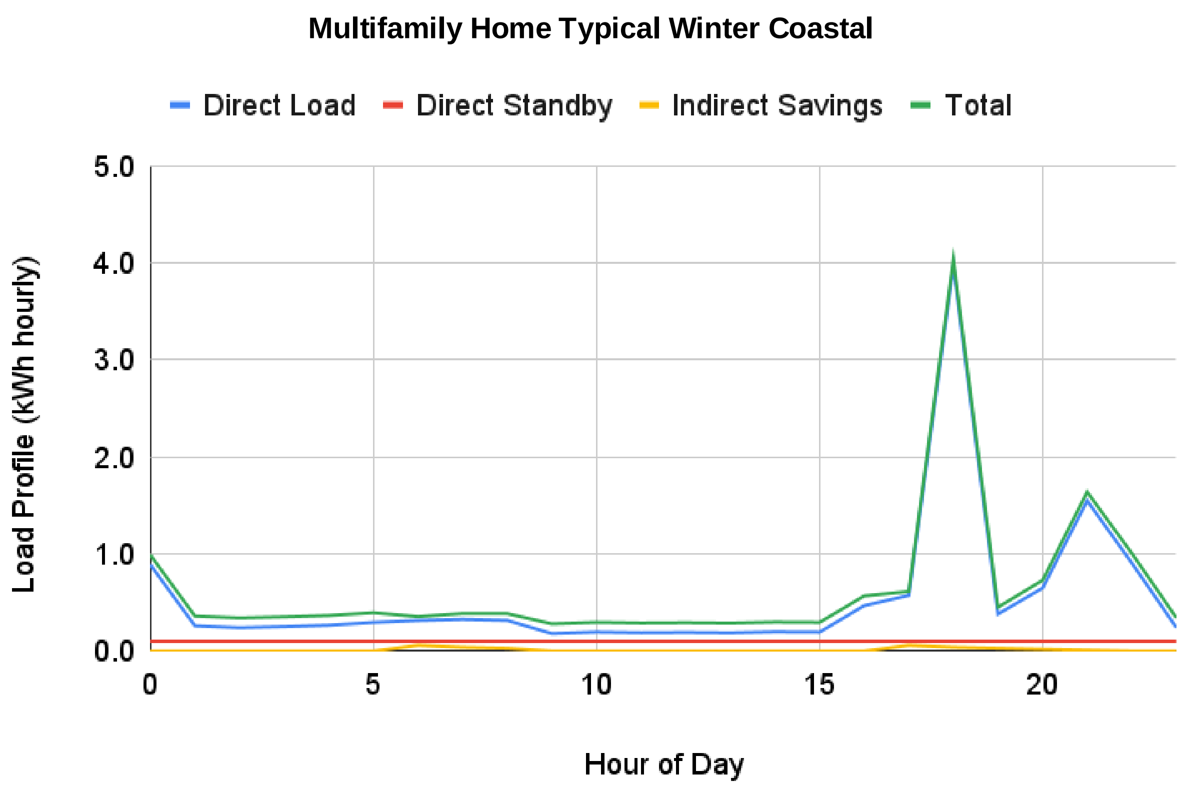
Hour of Day


Multifamily Home Typical Winter Coastal
Direct Load
Direct Standby
Indirect Savings
Total
Load Profile (kWh hourly)
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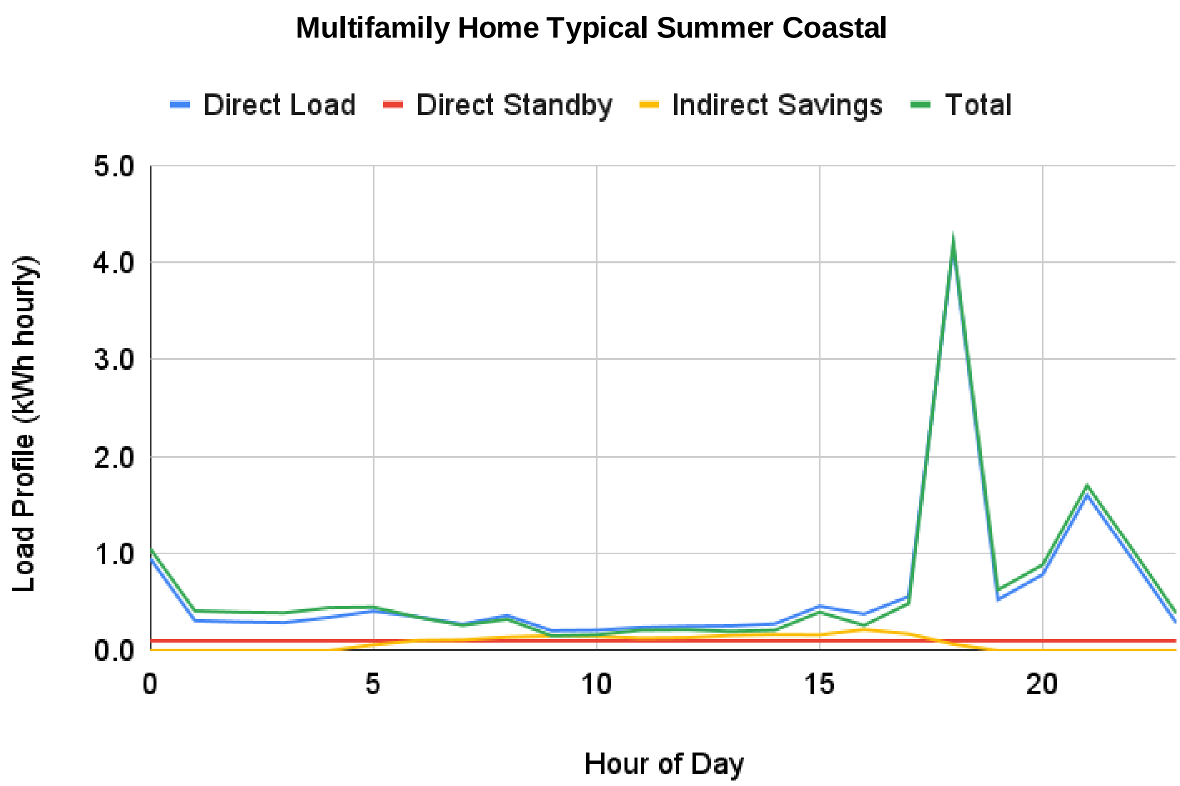
Hour of Day


Multifamily Home Typical Summer Coastal
Direct Load
Direct Standby
Indirect Savings
Total
Load Profile (kWh hourly)
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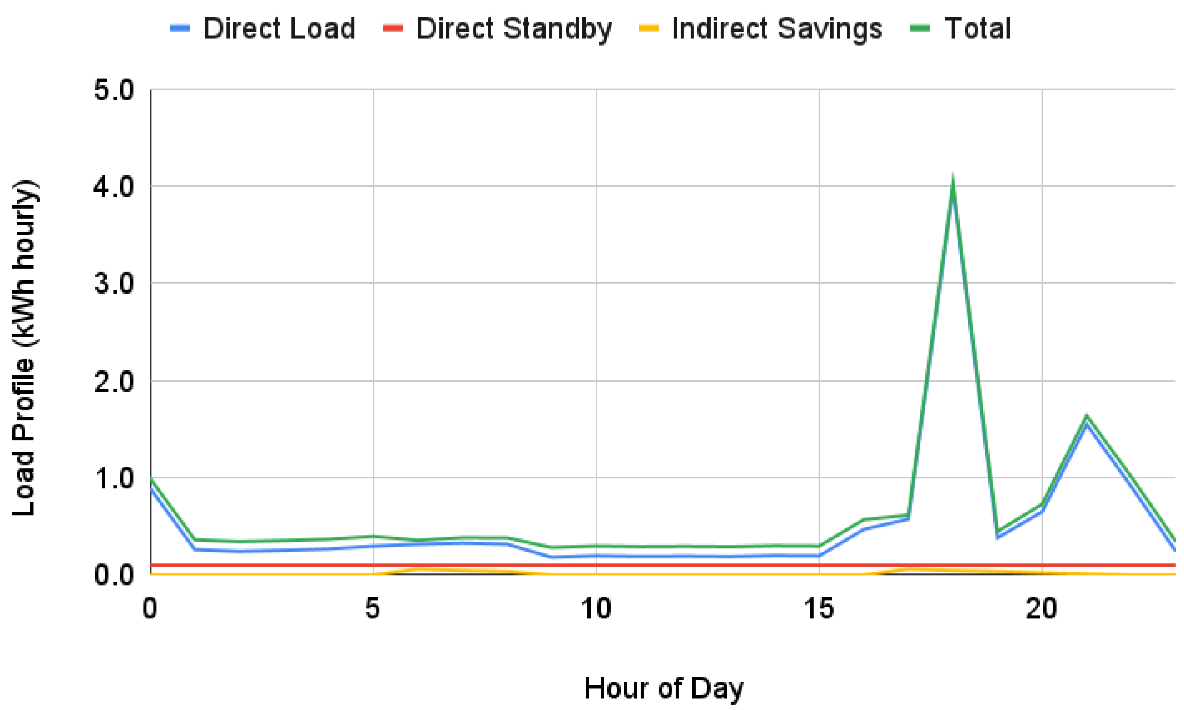
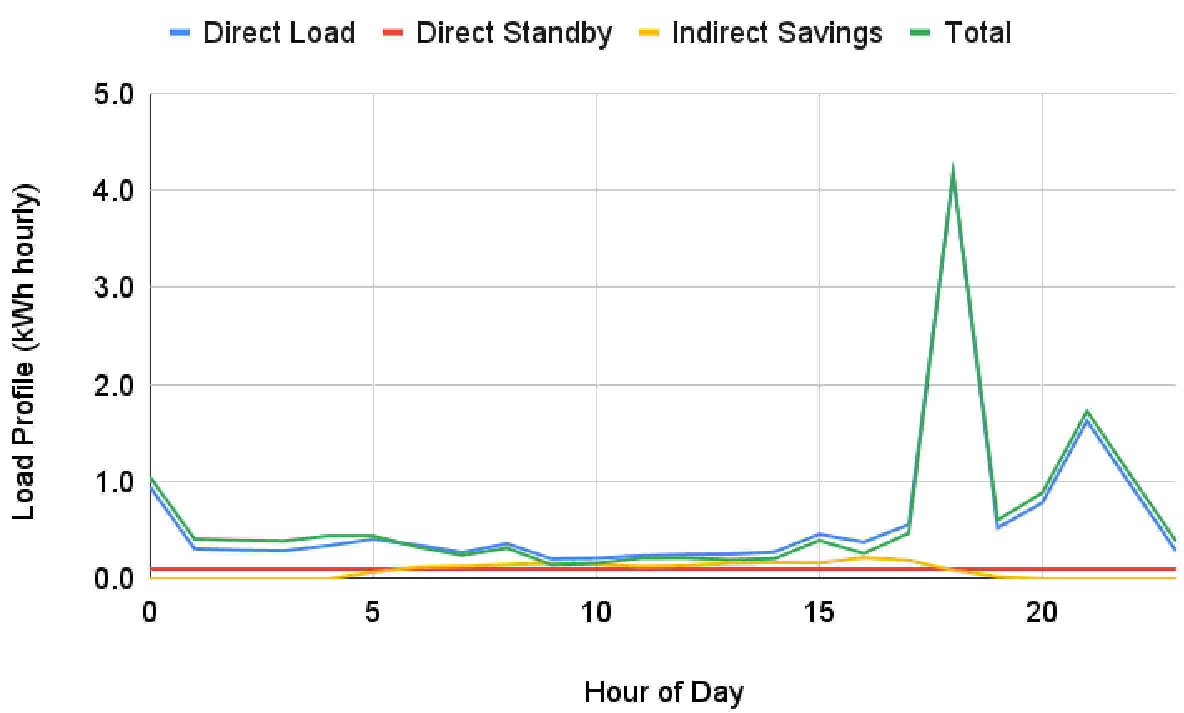
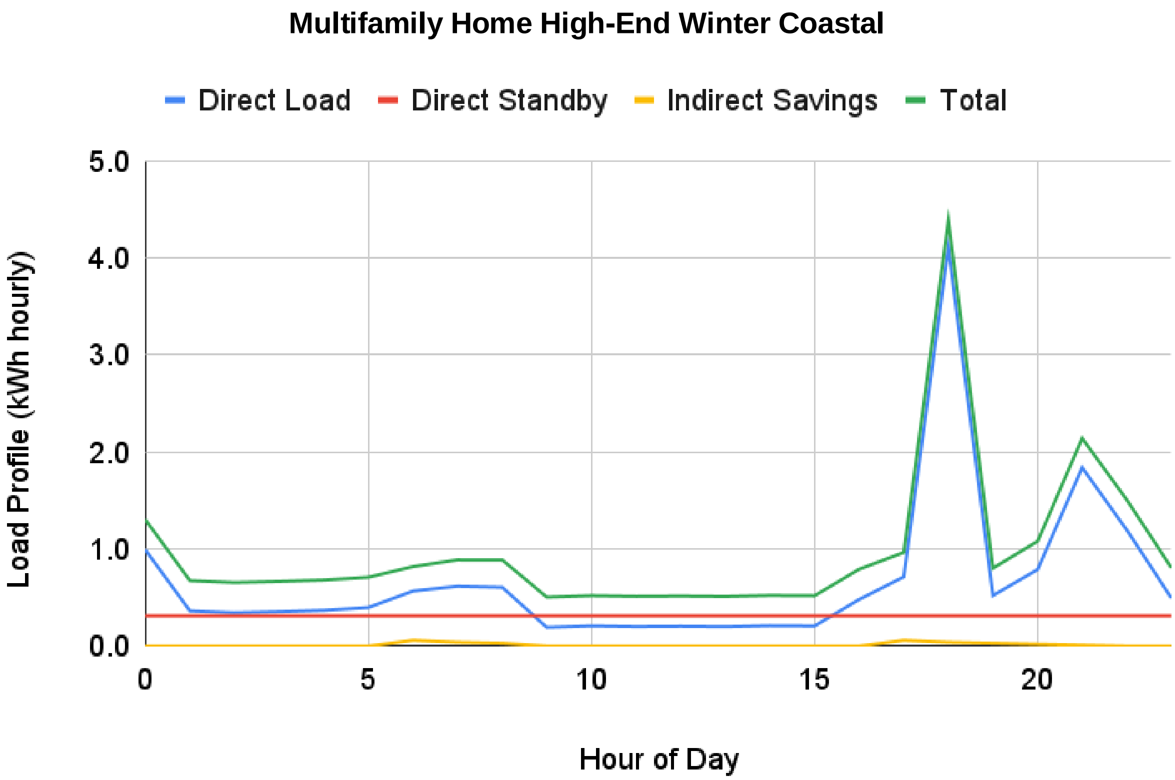
Hour of Day

Multifamily Home Typical Winter Inland



Multifamily Home Typical Summer Inland




Multifamily Home High-End Winter Coastal
Direct Load
Direct Standby
Indirect Savings
Total
Load Profile (kWh hourly)
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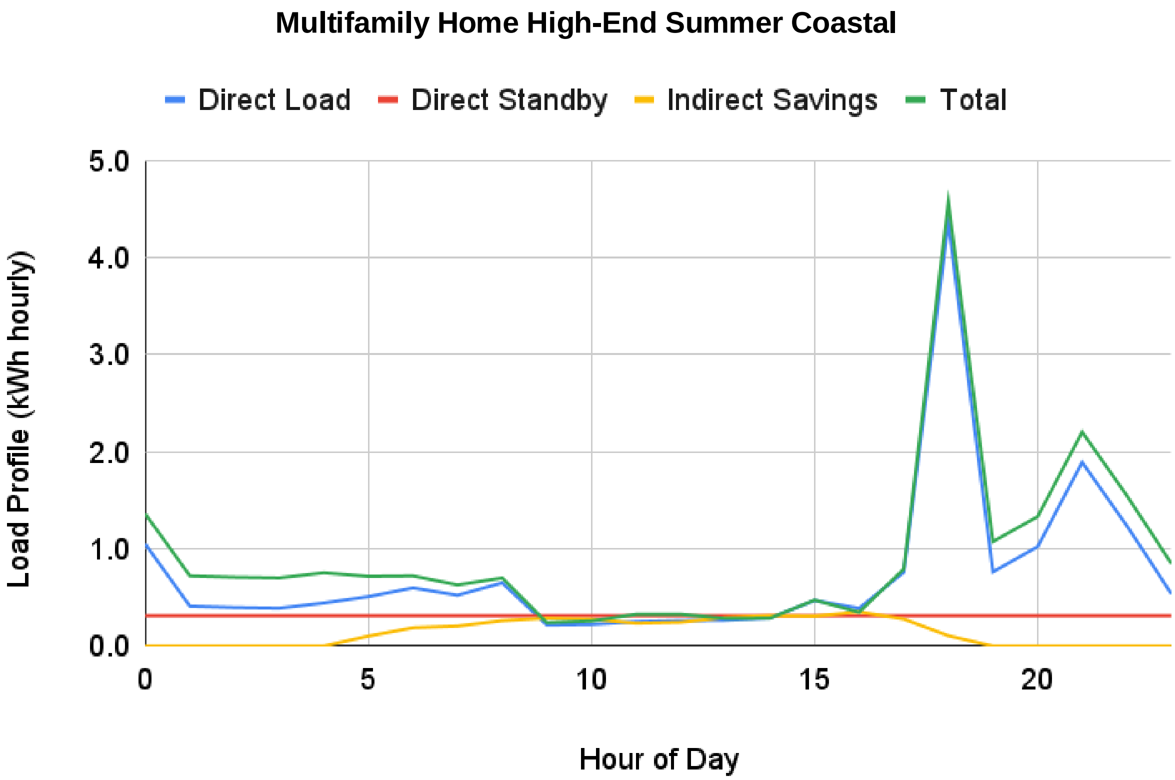
Hour of Day


Multifamily Home High-End Summer Coastal
Direct Load
Direct Standby
Indirect Savings
Total
Load Profile (kWh hourly)
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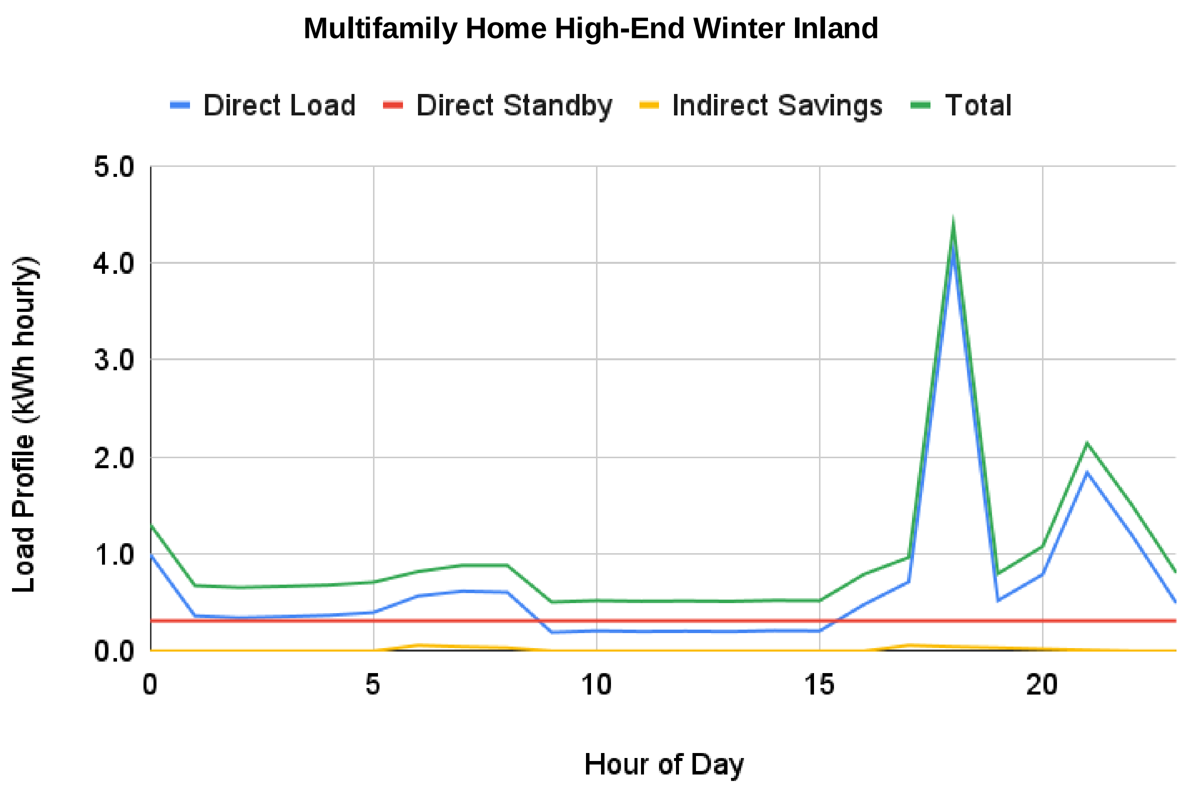
Hour of Day


Multifamily Home High-End Winter Inland
Direct Load
Direct Standby
Indirect Savings
Total
Load Profile (kWh hourly)
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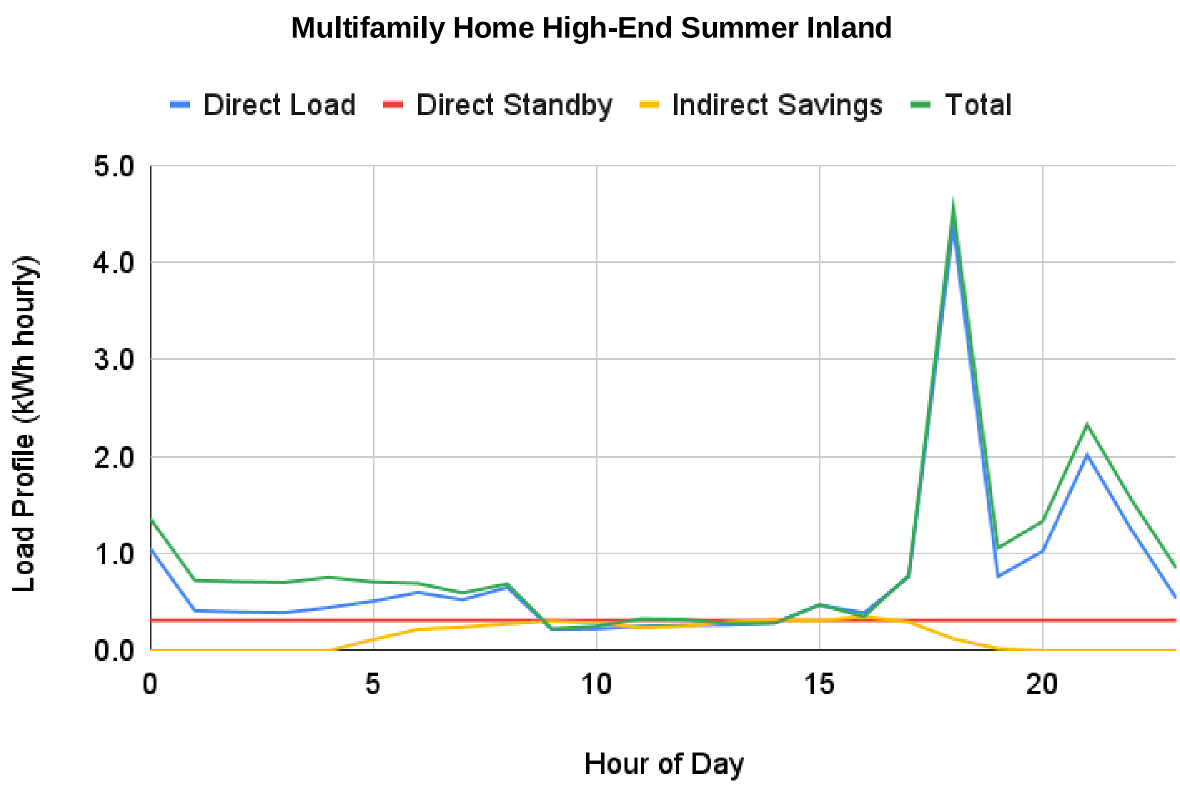
Hour of Day


Multifamily Home High-End Summer Inland
Direct Load
Direct Standby
Indirect Savings
Total
Load Profile (kWh hourly)
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Hour of Day

APPENDIX D: ADVANCED TOOL USAGE

The BIELs Analysis Tool is a spreadsheet calculation. Users can set the quantity of a certain BIEL in a modeled home, or add new types of BIELs to the model. The spreadsheet (Table 4) has the following format:

TABLE 4. BIELS ANALYSIS TOOL - SCREENSHOT SHOWING SAMPLE MODEL INPUTS

	A	B	C	D	E	F	G	H	I	J	K
1	Device Name	Quantity	Direct Load? (Y=1)	Direct Standby? (Y=1)	Indirect Savings? (Y=1)	Climate Affected	0.0	1.0	2.0	3.0	4.0
2		**Senior Home**									
3	Lights	70	1				0.0	0.0	0.0	0.0	0.0
4	Lights Standby	14		1			0.5	0.5	0.5	0.5	0.5

This screenshot illustrates an entry for one home type (Senior Home), energy use categories for each BIEL in the home, climate dependencies, and the first five hours of the load profile.

To set the quantity of a certain BIEL in the home, modify Column B ("Quantity"). The BIELs Analysis Tool comes with preset homes, which can be found in the "HomeInfo" tab.
To upload a preset home, copy the appropriate column from the "HomeInfo" tab into Column B, and all the preset BIEL quantities will be copied.

To add a new BIEL, fill in Columns A – AD on a new row:

1. Column A: Enter the new device name.
2. Column B: Enter the BIEL quantity in the current home model, but eventually update the "HomeInfo" tab with quantities for each preset home.
3. Columns C–E: Specify whether the BIEL profile is direct load, direct standby, or indirect savings. Enter "1" into the corresponding column and leave the other columns blank.
4. Column F: This column is optional, but enter "Y" to indicate the BIEL profile is affected by the climate zone or season.
5. Columns G–AD: Enter the load profile for each hour of the day, starting at midnight.

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