Smart Home Demand Response: Real-Time Energy Use and Enhanced Customer Engagement

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ABSTRACT

Reducing energy demand during peak periods can deliver carbon emissions savings, reduce customer bills, and support grid reliability. As electrification initiatives progress and renewable energy resources are added to the grid, the optimal timing of demand reduction efforts will continue to shift, requiring enhanced customer communication methods and adaptable program designs. This paper summarizes a first-of-its-kind behavioral demand response program that leverages smart home energy monitor technology. Customers are alerted to summer and winter "Energy Conservation Events" through push notifications, emails, and text messages. A smartphone app enables participants to view their device-level energy use in real-time, identifying appliances and equipment that can be turned off or down during these events. Smart plugs that can be controlled through the monitor app give customers the ability to remotely disable associated loads through the same application. A quick analysis of monitor data enables our team to deliver estimated demand reduction results to participants within 48 hours of each event, providing a fast feedback loop. Initial estimates indicate that this program delivers nearly 50% greater per-participant demand reduction than existing behavioral approaches. This paper describes the program, including recruitment, installation, process and impact evaluation methodology, and results to date.

Background

The landscape of energy efficiency is rapidly changing. As equipment efficiency standards continue to evolve, programs that target improving individual equipment efficiencies are becoming less cost-effective. Consequently, operational, behavioral, and market transformation efforts are gaining more traction. Program delivery and marketing have also evolved as utilities continue to place increasing importance on customer relationships and satisfaction. In addition to these programmatic changes, connected technology has continued to develop at breakneck speeds, and smart home devices (i.e., internet-connected and able to operate interactively and autonomously) are now flooding the residential market (Statistica 2022). Many of these devices purport to deliver energy savings; however, these savings are largely untested, preventing smart home devices from taking a larger role in programs and portfolios.

One technology that has seen great advancement in recent years is residential home energy monitors, which not only communicate overall energy use to customers, but also give them real-time feedback on the disaggregated energy use of specific devices within their homes. Early research suggests that direct, overall energy use feedback can produce whole-home energy savings of between 5% to 15% (Darby 2006). Lesic et al. (2018) found that customers tend to underestimate the electricity use of high consumption appliances and overestimate the use of low consumption appliances, which suggests that even greater savings should be obtainable with the addition of appliance-level granularity.

Home energy monitors present a personalized and detailed behavioral opportunity compared to existing, more generic approaches and recommendations. In addition to only being generally representative of energy use (versus providing specific household consumption feedback) many existing approaches have a long feedback loop. Changes to behavior and equipment may take many billing cycles before becoming measurable, if evident at all. Home energy monitoring technology also presents an opportunity to combine behavioral approaches with sustained customer engagement that can be used to suggest specific energy-saving actions and potentially raise program awareness, satisfaction, and participation.

Introduction

In its decision of December 20, 2016, the Public Service Commission of Wisconsin (PSC) stated that it was "particularly interested in examining the role broadband access could play in expanding access to energy efficiency programs and services". The PSC also directed "the development of additional Focus program offerings for rural Wisconsin that would support more equitable distribution of Focus benefits throughout all areas of the state, and also be designed to seek the additional benefits…by tying the use of the internet to increased energy efficiency measures." This decision created the opportunity and demand for new types of broadband-connected energy efficiency programs in the Wisconsin market.

Wisconsin Power and Light (WPL) and Cadmus designed the Home Energy Monitor Program to assess the feasibility of using energy disaggregation technology as a tool to inform and develop new energy-saving programs for Wisconsin homes. The technology utilized in this program is the Sense Monitor, a high-frequency whole-home energy meter that captures the shape of energy-use profiles by sampling 1,000 times per second. It is installed at the home's electric panel and uses machine-learning algorithms to disaggregate electric sub-loads throughout the home in which the device is installed. Sense Labs identifies the unique electric load signature of lights, appliances, and other end-use devices and labels them for viewing within an app that can communicate directly with the customer. This communication capability enables the technology to sidestep some of the traditional hurdles of residential load disaggregation. When a new device is detected, the app asks the customer to verify its identity, which increases detection reliability. The customer also receives regular reminders that have the potential to increase the persistence of associated behavioral savings.

The program is currently wrapping up its fifth phase (Phase V) of operation. Each phase was designed to investigate a different subset of the customer population and/or application of the technology. The original phase (Phase I) of the program targeted 100 customers in rural areas to determine the feasibility of mitigating some of the inequities in access that have traditionally resulted in rural customers being underserved by energy efficiency programs. Phase II included 100 additional device installations in rural, suburban, and urban areas to better represent demographics within the WPL service territory. Phase III was constructed to test the ability of enhanced messaging campaigns to increase participation in Focus on Energy programs and deliver residential energy savings. Phase IV of the program focused on income-qualified customers, with the objective of gaining a better understanding of the device-level energy use and appliance efficiency of this high-priority customer segment. The fifth and final phase is intended to test the demand response applications of the technology. This paper will present results from the most recent phase of the program.

The overall program has three primary objectives: derive estimates of the energy savings achievable through the replacement or servicing of inefficient equipment, identify behavioral effects produced by homeowner's awareness of energy use and engagement with the device app, and assess the impact that might be achieved with demand response initiatives.

Program Implementation

Participant Selection and Recruitment Survey

Participants were recruited from rural, suburban, and urban zip codes, to represent the general population of WPL customers. All selected participants were required to live in the WPL Energy service territory and have access to a broadband internet connection. In phases I, II, IV, and V, Cadmus selected households with slightly above average annual energy consumption as an attempt to ensure greater opportunities for implementing energy efficiency measures. Some filtering of potential participants based on energy consumption in each phase also removed outliers that could bias the results of the pilot. For phases I, II, IV, and V, Cadmus created histograms of annual consumption and bound selection to annual household energy consumptions between 10,000 kWh and 16,000 kWh, approximately the 3rd quartile of energy use. For phase III homes with annual energy use falling in the middle of the distribution were selected, to test whether "Always On" loads (the monitor's designation for unvarying plug loads, see Walton, R., 2019) were correlated with overall energy use. Homeowners in WPL territory with annual energy consumption in the chosen ranges were sent recruitment surveys that included questions such as the following:

- Age of home
- Square footage
- Home type (e.g., ranch)
- Number of full-time occupants
- Distance between electrical panel and Wi-Fi router
- Access to an app-compatible device (i.e., smartphone or tablet)
- Internet latency

The recruitment surveys yielded sizeable populations of eligible participants. Nine hundred customers were contacted over the six years of the program to schedule Sense Monitor installations. One hundred customers participated in each of phases I through IV, and five hundred customers were recruited for phase V of the program. Table shows the research objectives and participant selection criteria for each phase of the program.

Table 1. Research Objectives and Implementation Status by Phase

Phase	Participants	Research Objectives
I	100 Rural	Primary: Remote Audit / Behavioral Savings / Appliance Demand Characteristics
II	100 Mixed (Rural, Suburban, Urban)	Primary: Objectives listed above, plus Circuit-Level Monitoring / Appliance Replacement
III	100 Sense Monitor / 100 Alternative Energy Monitor	Primary: Objectives listed above, plus Enhanced Customer Messaging / Compare Monitoring Products
IV	100 Low-Income	Primary: Objectives listed above, plus Understand the Energy-Savings Potential of Low-Income Participants
V	500 High Energy Use	Primary: Demand Response and Smart Device Integration

Source: Cadmus.

Technology Deployment

Cadmus schedulers contacted eligible participants and coordinated installation visits with a Cadmus field technician and licensed electrician. While the electrician installed the Sense Monitor in the participant's electric panel, the Cadmus technician worked with the participant to sign the customer agreement, deliver a gift card incentive, and connect the Sense Monitor to the homeowner's Wi-Fi network. Cadmus technicians also collected field data on the characteristics and model numbers for major appliances in the home. Additional data was collected on the square footage of the home and the percentage of light fixtures using incandescent, CFL, and/or LED bulbs.

Demand Response Events

In the Phase V demand response events for all program participants, Cadmus automatically enrolled Phase V participants and gave Phases I through IV participants the ability to opt-out of these events via a secondary recruitment survey. Additionally, Cadmus coordinated with Sense to deliver a recruitment survey to customers in Alliant Energy territory who bought a Sense Monitor independent of the program: we sent this survey once in 2022 and again in 2023, and successfully recruited 39 previous nonparticipants.

After two internal test events, the first official event launched on August 16, 2022, with 551 participants. Cadmus manually triggered the first events based on local weather data. Cadmus and Alliant Energy continued to implement conservation events in the winter and summer of 2023. Savings results from the first six conservation events are discussed in the Impact Evaluation section of this paper, and participant satisfaction is discussed in the Process Evaluation section.

Evaluation Activities

Multiple evaluation activities were undertaken each year to assess pilot design, implementation, customer satisfaction, behavior changes, and energy-related outcomes. These activities included interviews with program actors and technicians, customer surveys, analyses of disaggregated energy use data, and billing analysis. This paper describes a selection of those activities and their most recent results. Complete evaluation reports (Kramer et al., 2019, Hicks et al., 2020, Hicks et al. 2021, and Hicks et al. 2023) can be accessed online via the PSC Electronic Records Filing system).

Customer Surveys

Cadmus contacted participants via email and offered them an incentive for completing online surveys. The number of complete responses in our most recently fielded surveys was 137 Phase III and IV participants who were asked about overall program experience (68.5% response rate), and 555 participants from Phases I through V (61.7% response rate) who were asked about their experience participating in demand response events. Surveys were designed to gather data on a variety of topics, including satisfaction with WPL, estimated monthly energy savings, behavioral changes due to participation in the pilot.

Behavioral Energy Savings Estimation

Cadmus used monthly billing data to examine changes in electricity consumption between the periods before and after participants received a Sense Monitor for Phase I through Phase IV participants. To conduct this evaluation Cadmus procured the following data to conduct the impact analysis:

- Monthly billing data for Phases I through IV participants as well as for a group of nonparticipants. Available billing data generally ranged from January 2017 to June 2022.
- Daily weather data from the National Oceanic and Atmospheric Administration (NOAA)
- Sense Monitor participation/installation dates

Participants were removed if they had fewer than 300 days of pre-period billing data, or if they had no post-period billing data available. Cadmus had to remove participants from the analysis for a variety of reasons; attrition by phase ranged from 13% to 26%. The primary reasons for removing participants from the analysis were that we did not receive their billing data or they did not create an account for their monitor.

Due to the nature of the pilot program, there is not a designated randomized control design where participant and non-participant groups are designated prior to the delivery of the treatment. Cadmus used a quasi-experimental design to attempt to control for changes in energy consumption unrelated to the installation of the Sense Monitor. Cadmus selected a matched comparison group using billing data from non-participants using a propensity score matching approach.

Propensity score matching produced a set of non-participants that are similar to the participants in relation to the chosen explanatory variables, in this case pre-period consumption, weather conditions, and geographic location. Cadmus confirmed that none of the differences were statistically significant using analysis of variance (ANOVA).

Cadmus evaluated savings for phases (I,II,III, an V) using a difference-in-difference model specification. Difference-in-difference models estimate savings by comparing the changes in pre- to post- energy consumption between treatment and comparison groups. The difference between this difference is the estimated savings.

Device Load Shape Construction

Cadmus analyzed the Sense Monitor data to characterize the hourly load shapes for various device categories. We compared average hourly demand for all days to demand on Midcontinent Independent System Operator (MISO) peak days.

Demand Response Event Analysis

Cadmus analyzed event savings and appliance usage during the six demand response events conducted in 2022 and 2023. Analysis included a review of event participation, demand reduction estimates, and device usage analysis during called events.

Results

Participant Survey

Satisfaction with Energy Savings. Survey respondents answered whether they have observed a decrease in their monthly energy costs since receiving their respective monitor: 28% of respondents (n=100) said they had observed energy savings since installation. Of the 10 Phase IV Sense Monitor respondents who observed a decrease in their monthly energy costs, 30% noticed a decrease of between $5 and $10 and 30% noticed a decrease of between $10 and $15. Of the 18 Phase III Sense Monitor respondents who observed a decrease in their monthly energy costs, 39% noticed a decrease of between $5 and $10 and 39% noticed a decrease of between $10 and $15. Nearly all respondents were satisfied with the decrease in energy costs after accessing the app.

Respondents who did not notice a decrease in their monthly energy costs cited several reasons:

- They did not make any behavior changes or had already optimized their usage;
- Rising inflation and the increase in energy costs impacted their monthly bills; or
- Issues with their energy monitoring device did not allow them to save energy.

Behavioral Changes. Cadmus asked respondents about their energy-saving habits before and after participating in the program. The most common actions taken to reduce energy usage prior to monitor installation were turning off lights (29%), adjusting thermostat settings (21%), and washing laundry with cold water (17%; Figure 1). After the monitor was installed, deliberate actions to save energy increased, with the most common energy reduction actions being unplugging electronic devices or appliances while not in use (68%), turning off lights in unoccupied rooms (62%), and using energy-saving or “sleep” features of electronic devices such as computers and TVs (56%).

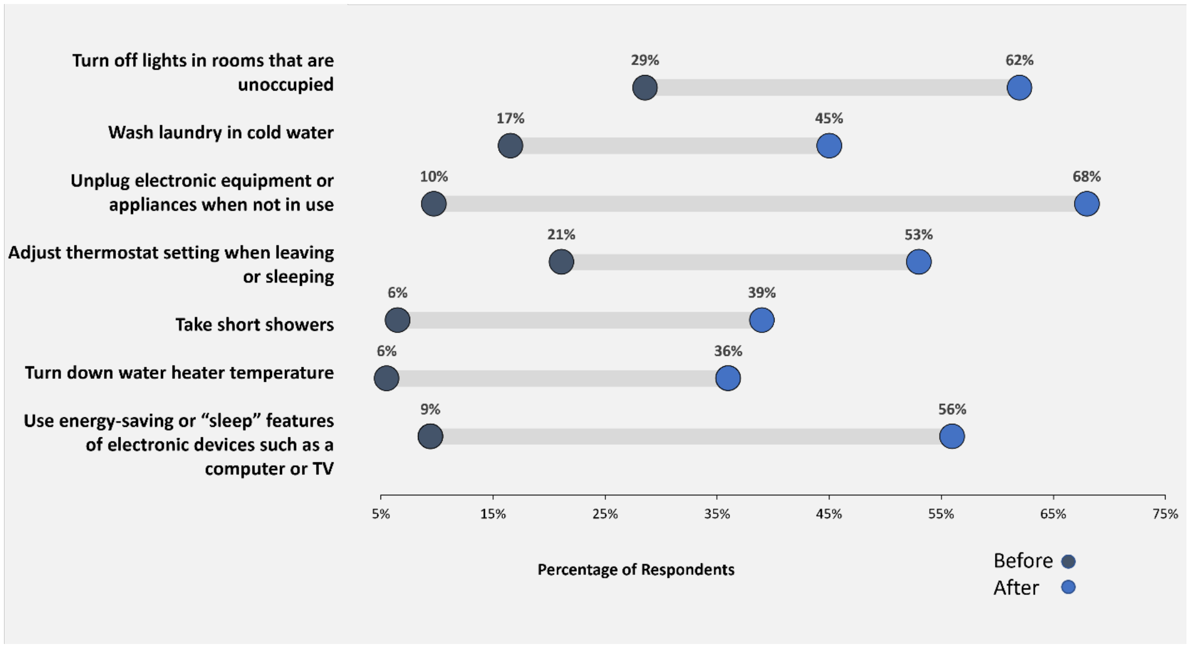

Figure 1. Energy-saving behaviors. *Source:* Cadmus.

Demand Response Program Satisfaction. Cadmus surveyed participants of the demand response events to gauge their satisfaction with the demand response program. Of the 422 participants who responded to the survey in 2023, 60% joined the program in Phase V.

Overall, respondents were motivated to participate in the demand response events to save energy, save money, and earn incentives. Figure 2 shows respondents’ reasons for participating in events (note that 67 participants selected all the reasons). These reasons were similar across all the program phases.

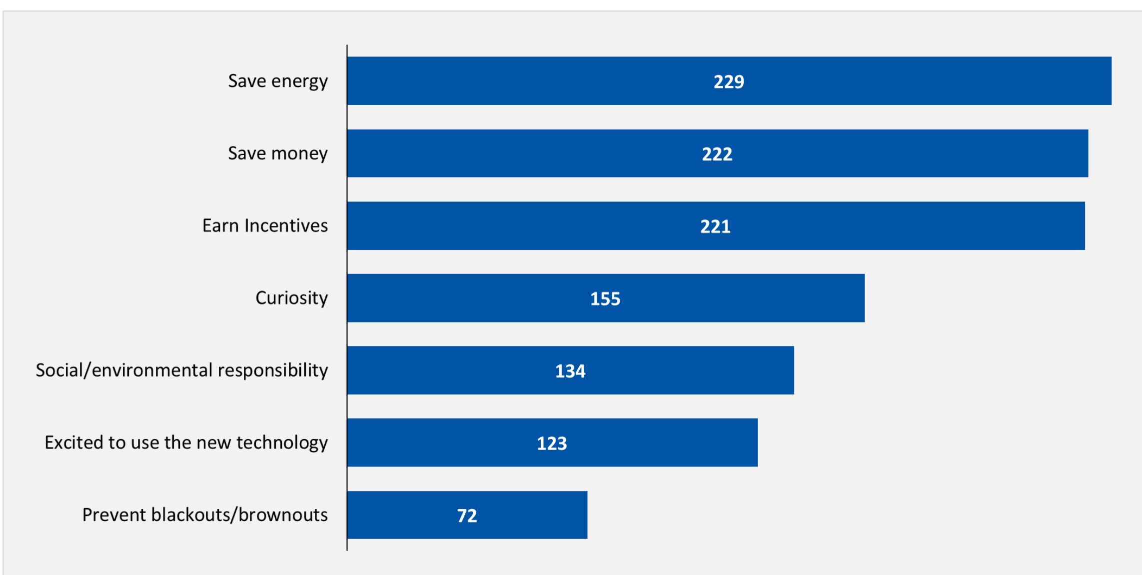

Figure 2. Reasons for Participating in Demand Response Events. *Source:* Cadmus.

Participants are notified about events through email, and may also receive notifications about events through their Sense App. A higher percentage of respondents recalled the email notifications they received (96%) than recalled the Sense App notifications (56%).

Respondents were asked if they used the Sense Monitor to find which devices in their home could be turned off during a conservation event. Nearly two-thirds of respondents used the Sense Monitor to identify devices in their home. Forty-six respondents (9%) suggested that the Sense Monitor could be improved to better identify home devices that a respondent could turn off during a conservation event. The most common devices that survey respondents turned down or off were lights, a washer or dryer, and a TV or computer. Figure 3 shows the average demand reduction per device-type that participants adjusted during a demand response event. When asked, 97% of respondents indicated that they would participate in future conservation events.

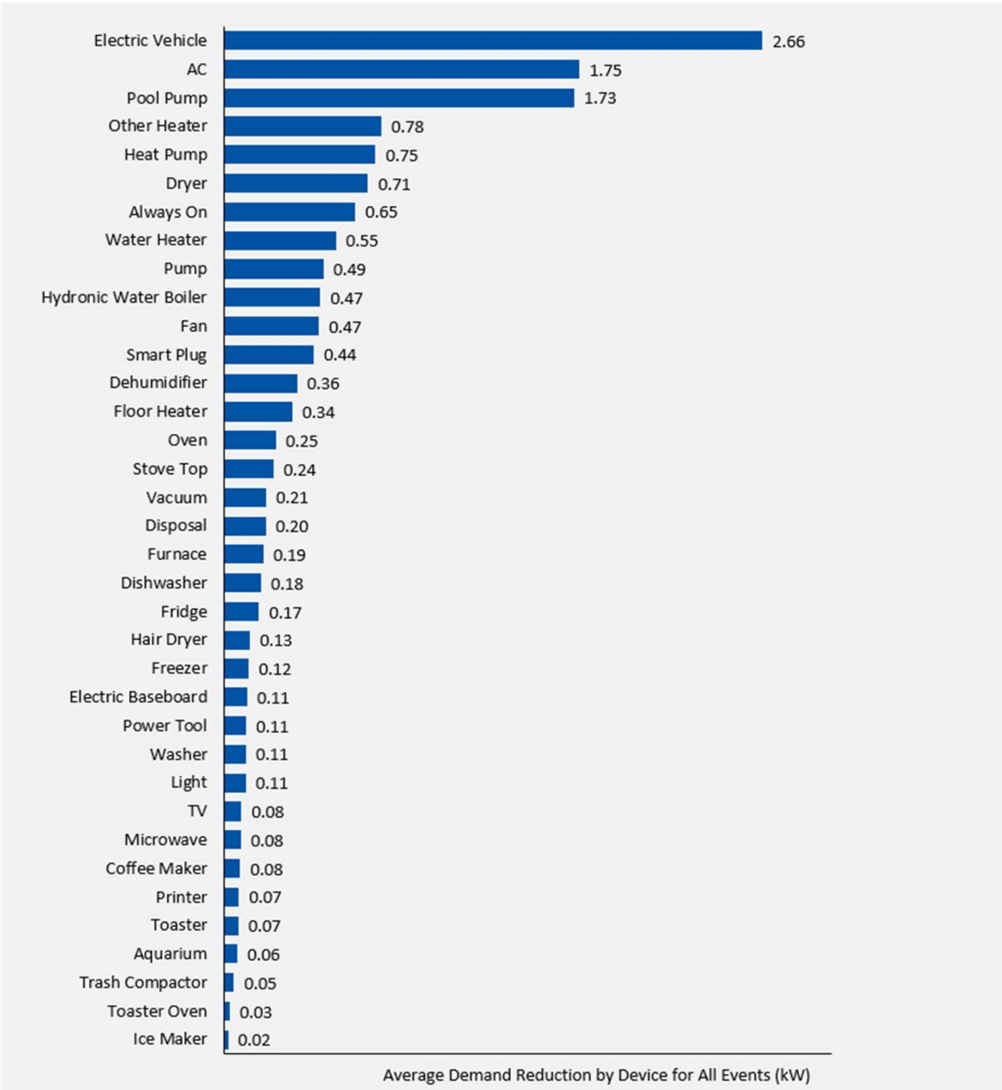

Figure 3. Average Demand Reduction by Devices Turned Down/Off During an Event. *Source:* Cadmus.

Behavioral Energy Savings

Billing Analysis. Table 2 shows the 2022 savings estimates by phase, ranging from 3.2% (Phase III) to 7.6% (Phase II). Only the result for Phase II was statistically significant at the 90% confidence level, as the confidence intervals for the other phases include 0 kWh. Cadmus was unable to detect statistically significant savings for most phases largely due to the relatively small size of the treatment effect and the small sample sizes in each phase. However, Cadmus also estimated savings across all phases and found statistically significant savings of 4.5%.

Table 2. Savings Estimates by Phase

Group	N	Annual Per-Participant Savings (kWh)	90% Confidence Interval (kWh)	Percentage Savings	Annual Program Savings (MWh)
Phase I	89	387.6	±733.3	3.3%	34.5
Phase II	90	752.9	±485.3	7.6%	67.8
Phase III	79	289.9	±461.4	3.2%	22.9
Phase IV	78	322.3	±682.6	3.4%	25.1
All Phases	**336**	**454.2**	**±296.5**	**4.5%**	**152.6**

Source: Cadmus.

Device Load Shapes

Figure 4 shows the average whole-home demand by season. The difference between all days and MISO peak days is most pronounced during the mid-afternoon peak use hours in the summer. Differences between average days and peak days during winter and shoulder seasons (fall and spring) are smaller. During fall the difference is most pronounced in the evening hours. During winter the differences are relatively constant throughout the day. Spring shows little difference in demand on MISO peak days compared to all days. The overall load shape of summer can likely be largely attributed to air conditioning use.

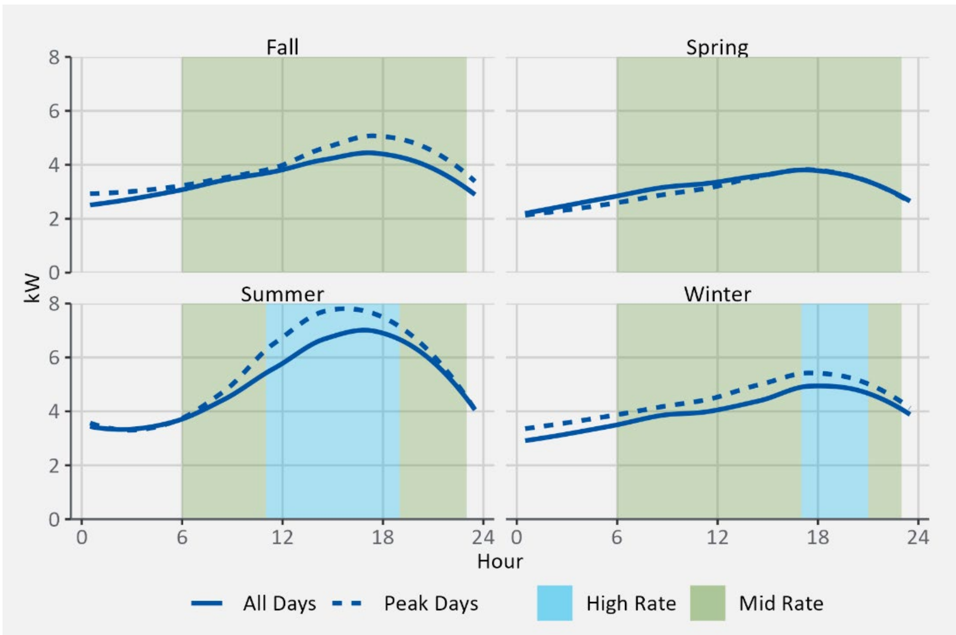

Figure 4. Average 24-Hour Load Shape for Total Consumption. *Source:* Cadmus.

One interesting device type to compare across seasons and MISO peak days is water heaters (Figure 5). The overall bimodal demand is higher in the colder months of winter than in the warmer months of summer, as expected. However, the demand on MISO peak days is lower compared to all days in the summer, while it is higher in the winter. This may be because summer MISO peak days are more likely to occur on the hottest days, when using hot water (for example, to shower) may be less appealing to customers. Similarly, winter MISO peak days are more likely to occur on the coldest days, when hot water may be more desirable.

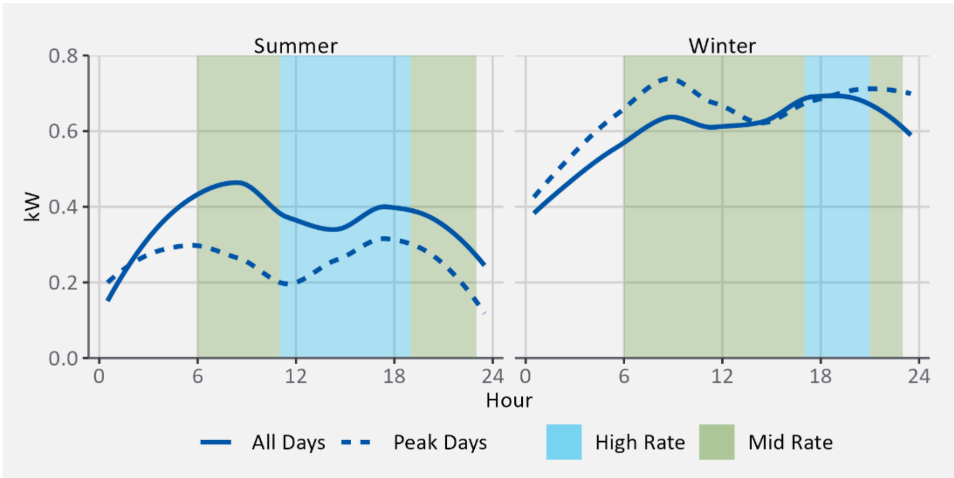

Figure 5. Average 24-Hour Load Shape for Water Heaters. *Source:* Cadmus.

The demand shape for EV charging is relatively stable throughout the year and has little meaningful difference between all days and MISO peak days. The demand is lowest in the middle of the day, when customers are likely using their EVs away from the home, and is highest at night, when customers are most likely to be charging their EVs. Figure 6 shows the load shape for EV charging for summer and winter.

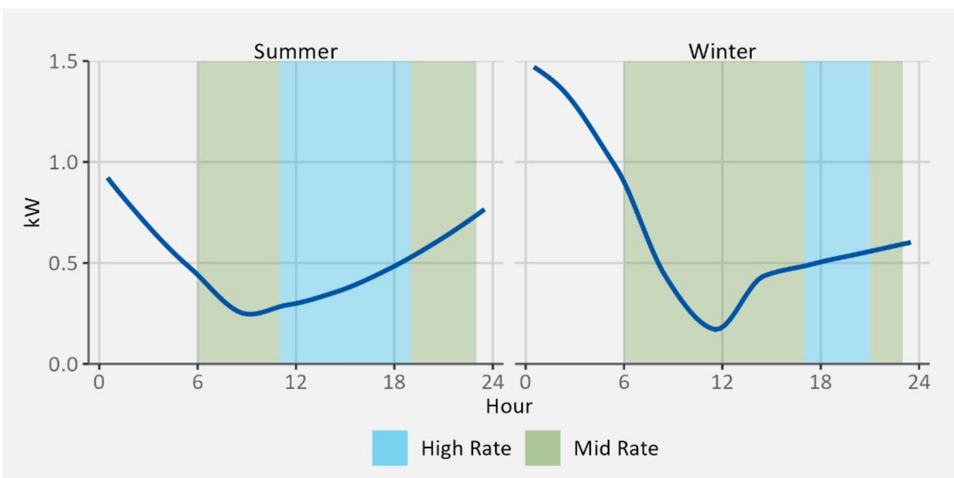

Figure 6. Average 24-Hour Load Shape for Electric Vehicle Charging. *Source:* Cadmus.

Figure 7 depicts the demand profile of an EV on two of the 2022 MISO peak days. EV consumption was identified by 29 unique Sense Monitors during 2022. A single EV charger contributed more than 6 kW of demand during peak hours on the June peak day and more than 11 kW of demand during peak hours on the July peak day.

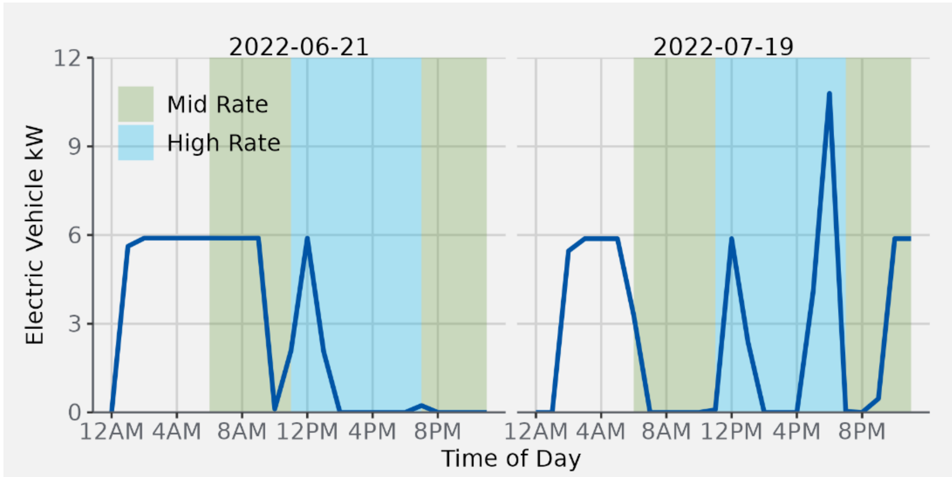

Figure 7. Electric Vehicle Demand Profile on Two Peak Days. *Source:* Cadmus.

Demand Response Event Analysis

Event Participation. Cadmus launched the demand response component of this program in the summer of 2022, with the first three events taking place in summer 2022. The first three events included Phases I through IV and a portion of the Phase V monitors installed at the time. Phases I through V are represented in the other event seasons. In winter 2023, three more events took place, with the last nine events taking place in summer 2023.

Event Demand Reduction Analysis. Cadmus calculated demand reduction estimates for each participant using a baseline from historical energy use data on days with similar weather conditions. Table 3 details the median and mean savings for the number of participants who actively participated in the demand response events. Participation increased between summer 2022 and winter 2023 because installations increased between event periods. Increased savings in the August and September 2023 events illustrate the effect of heatwave temperatures on the participants' ability to save during events.

Table 3. Savings Estimates by Phase

Event Date	**Event Window**	**Number of Participants**	**Mean Savings (kWh)**	**Median Savings (kWh)**	**Average Event Weather in Degrees Fahrenheit**
Aug 16, 2022	2 p.m. -6 p.m.	568	2.18	1.56	78
Sep 8, 2022	2 p.m. -6 p.m.	651	2.12	1.60	81
Sep 20, 2022	2 p.m. -6 p.m.	647	3.87	3.01	79
Jan 25, 2023	4 p.m. -8 p.m.	752	2.07	1.49	31
Feb 15, 2023	4 p.m. -8 p.m.	757	1.66	1.25	34
Feb 28, 2023	4 p.m. -8 p.m.	747	2.27	1.76	32
Jul 26, 2023	3 p.m. -5 p.m.	727	2.23	1.99	82
Jul 27, 2023	3 p.m. -5 p.m.	699	2.15	1.75	90
Jul 28, 2023	3 p.m. -5 p.m.	695	1.97	1.49	87
Aug 20, 2023	4 p.m. -8 p.m.	720	2.84	2.39	86
Aug 21, 2023	4 p.m. -8 p.m.	718	1.17	1.08	80
Aug 22, 2023	2 p.m. -6 p.m.	718	2.76	2.20	85
Aug 23, 2023	2 p.m. -6 p.m.	717	6.13	5.34	96
Aug 24, 2023	2 p.m. -6 p.m.	712	3.95	3.09	90
Sep 5, 2023	2 p.m. -6 p.m.	722	3.65	3.09	85

Source: Cadmus.

Cadmus also identified the devices with the most significant demand reduction during the demand response events. Figure 9 provides the top demand reducing devices during summer events and Figure 10 provides the top demand reducing devices during winter events.

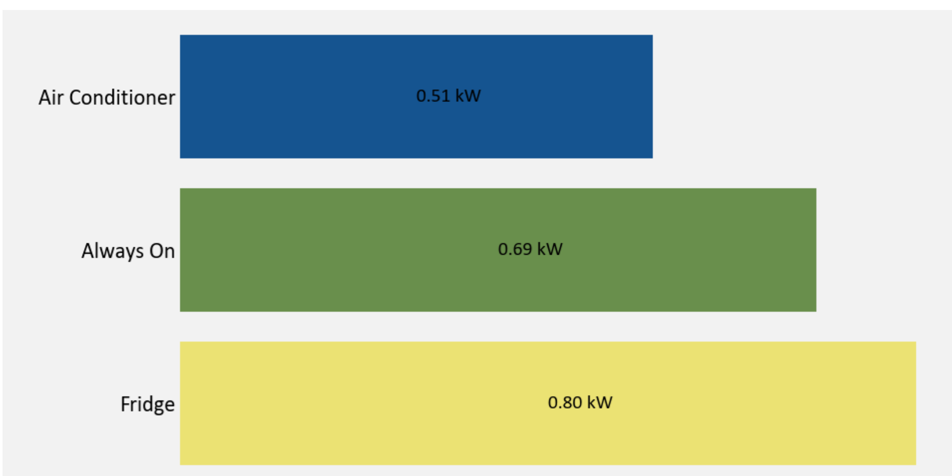

Figure 9. Top Demand Reducing Devices during Summer Events. *Source:* Cadmus.

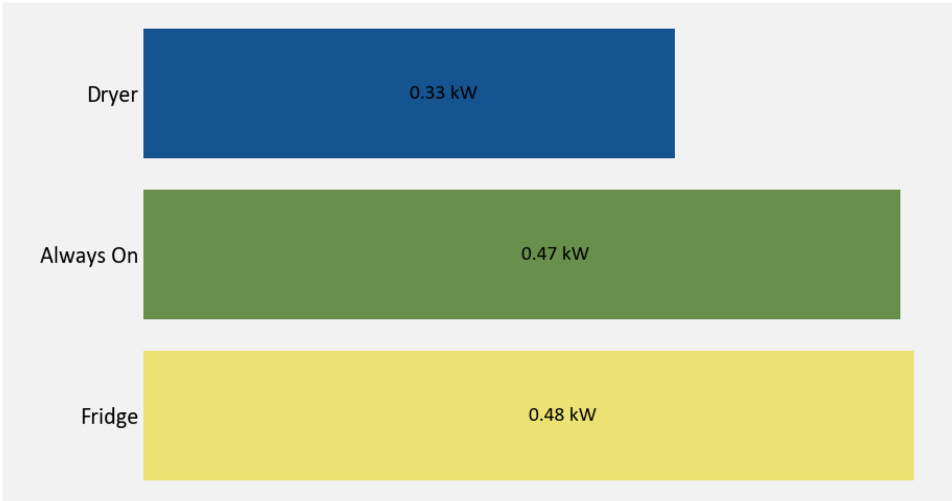

Figure 10. Top Demand Reducing Devices during Winter Events. *Source:* Cadmus.

Phase V introduced the installation of smart plugs in coordination with the Sense Monitor installations. The smart plugs sync with the monitor and allow for remote control of one appliance. Participants were encouraged to install their smart plugs on high energy-use appliances (such as EV chargers and dehumidifiers). The number of smart plugs used during demand response events is shown in Table 10 for Phase V participants.

Table 5. Number of Phase V Smart Plugs Used during Each Event

Event	Smart Plugs Used
1	55
2	63
3	66
4	57
5	47
6	44

Source: Cadmus.

Conclusions

Device-level home energy monitoring delivers opportunities and insights in several areas of interest such as behavioral and resource acquisition energy savings, customer engagement, and demand response initiatives. The results of a subset of evaluation activities, conducted to assess pilot design, implementation, customer satisfaction, behavior changes, and energy-related outcomes are summarized below. These findings will continue to be updated as additional data becomes available.

Participant Survey Findings

- Nearly two-thirds of respondents used the Sense Monitor to identify devices in their home during demand response events. The most common devices that survey respondents turned down or off were lights, a washer or dryer, and a TV or computer.
- When asked, 97% of respondents indicated that they would participate in future conservation events.
- After participating in the program, deliberate actions to save energy increased, with the most common new energy reduction actions being unplugging electronic devices or appliances while not in use (68%), turning off lights in unoccupied rooms (62%), and using energy-saving or "sleep" features of electronic devices such as computers and TVs (56%).

Energy Use Data Analysis Findings

- A billing analysis of total household consumption before and after program participation indicated that participants saved 4.5±3% of annual energy use. This is above the savings typically found for residential behavior programs. This is the first time the study had enough participants to measure statistically significant savings.
- The difference in MISO peak-day demand and non-peak-day demand is greatest in the summer. This difference is most pronounced during the afternoon peak hours and appears to be largely driven by air conditioner use.
- Energy monitoring devices can be used to deliver significant demand reduction during peak hours. This is the first demand response program that leverages real-time customer access to device-level energy use information and delivers results within 48 hours of each event. The first year of demand response events resulted in measurable demand reductions that exceed the typical impacts of behavioral demand response programs and rival those of smart thermostat demand response programs. The average demand reduction from events called in the summer was 0.68 kW, and in the winter was 0.49 kW.

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