

At Long Last: Realizing the Promise of Non-intrusive Load Monitoring

Jennifer McWilliams, Lullit Getachew, Chris Dyson, DNV

ABSTRACT

Accurate remote load sensing offers the potential to transform residential energy efficiency delivery by targeting customers with information tailored to their needs, as well as facilitating visibility into load-shifting potential for utilities. Non-intrusive load monitoring (NILM) has shown promise to deliver this capability since its conception in the 1980s, but putting it into practice has proved challenging, particularly when using low-frequency smart meter data. Several NILM equipment manufacturers have opted to collect their own high-frequency electrical data downstream of the meter at the electrical panel main. The promise of such NILM solutions has hitherto not been independently evaluated and is the focus of this paper.

This paper provides findings from recent studies in Rhode Island and California to answer the following important questions:

- What are the features and functionalities offered by various NILMs solutions in the market today?
- At a foundational level, are NILM solutions able to accurately identify the appliance stock in a household?
- How do NILM solutions fare when compared to the ground truth as determined by end use metering?
- How do participants interact with the NILM device?
- What is the customer satisfaction with the Sense device and perception of the change, if any, in their energy consumption behavior in response to the Sense device?
- Lessons learned from NILM installations

Introduction

The concept of non-intrusive load monitoring (NILM) is 30 years old, first conceived at the Massachusetts Institute of Technology (MIT) with funding from the Electric Power Research Institute (EPRI) (Hart 1992). The basic idea of NILM is to disaggregate total household power consumption into its constituent end-use loads, allowing low cost, non-intrusive monitoring of the loads. Particularly in jurisdictions where electricity has Time of Use tariffs, the information provided by NILMs is valuable to electricity consumers to understand the end uses and related costs of their energy consumption to aid in energy and cost saving decisions. The information also has value to electric utilities to understand the constituent loads on their electric grid to inform decisions related to their demand side management programs including energy efficiency rebates and demand response incentives.

When smart meters were widely deployed, many companies developed NILM algorithms aimed at the electric utility market to disaggregate high-frequency (~1 minute) smart meter data, but the success of these has been limited as described in Pacific Gas and Electric's (PG&E) study that found many end-uses were not accurately identified by the three NILMs investigated (PG&E

2016). Because of disaggregation difficulties, many of the utility facing NILMs have diverged from their initial intent to disaggregate individual customer end uses, and instead offer utility clients a customer portal to enhance energy consumption awareness and facilitate demand response without disaggregating the customer data.

NILMs only realize their full potential when the algorithm is able to correctly identify electric end-uses so several companies endeavored to improve the algorithm by measuring total power at more frequent intervals, on the order of one megahertz or millions of samples per second. The focus of this paper will be the accuracy of this newer, higher frequency measurement type of NILM employed by energy monitors such as Mirubee¹, Neurio², Wattie³ and Sense⁴.

Improving NILM disaggregation algorithms continue to be an active area of research. A team from Southeast University in Nanjing, China recently used a neural network model to improve NILM disaggregation performance (Liu, 2021). Their method generated accurate results when tested on the Reference Energy Disaggregation Data (REDD) set developed at MIT (Kolter, 2011). It still remains to be seen if this model can disaggregate the many varieties of waveforms experienced by buildings not included in the REDD data set.

This paper summarizes results related to the energy monitor accuracy gleaned from two studies that DNV performed for utility clients interested in investigating NILM equipment. The first is a program evaluation and market study of Sacramento Municipal Utilities District's (SMUD) residential electrification programs. Part of the evaluation presented here includes a NILM technology overview and a comparison of home energy loads detected by the Sense energy monitor to measured HVAC and water heating energy consumption (DNV 2020). The second is an evaluation of National Grid's (NG) Residential Home Energy Monitoring System Pilot study designed to help the client understand customer perceptions of NILM technology installed through their pilot program (DNV 2021). The pilot program made a Sense energy monitor available to participating National Grid Rhode Island residential customers. The customer perceptions from that report related to the accuracy of the Sense NILM equipment are presented below.

Methodology

This section describes the methodology used in each of the two studies. Both of these studies are evaluations of utility pilot programs and used standard evaluation techniques for monitoring and verification of electrical loads (used in the SMUD study) and survey questionnaire design (used in the NG study).

SMUD Residential Electrification Program

The NILM technology overview was intended to be internationally comprehensive, including those products marketed to utility companies that perform data analytics on smart meter data (provided by the utility) and those products, often customer facing, that use hardware

¹ Purchased by Wibeee <https://wibeee.com/>

² Purchased by Generac <http://investors.generac.com/news-releases/news-release-details/generac-announces-acquisition-neurio-technology-inc>

³ <https://www.wattie.io/>

⁴ <https://sense.com/sense-home-energy-monitor>

to collect data from the home or from the smart meter directly. As the only U.S. based energy monitor that measures total home power at a sub-second sampling rate, the Sense energy monitor was selected and installed in nine homes as part of this one-year pilot study. To preserve anonymity the homes were labeled with letters A through I. These homes were selected based on homeowner interest and electrical load center suitability from those that had participated in an electrification program where heat pump water heaters and air source heat pump HVAC systems that provide heating and cooling were installed. Hard measurements from current transducer (CT) loggers served as the ground truth for comparing heat pump water heater and HVAC load estimates from the Sense disaggregation estimates.

As part of the experiment design, to assess the effect of homeowner interaction on the effectiveness of the disaggregation algorithm, we allowed only some of the homeowners to interact with the Sense web or smart phone applications. The Sense application was given to four homeowners and it was not provided to five homeowners (to represent disinterested customers).

NG Residential Home Energy Monitoring System Pilot

This pilot program, which started in 2018, provided Sense monitors at no cost to a subset of NG residential customers. NG promoted the program to five customer groups: 1) Demand response participants, 2) Home Energy Assessment participants, 3) High bill complaint customers, 4) Low to moderate income customers, and 5) A randomly selected group of customers who did not belong to the other four customer groups. Of the 801 customers who expressed interest in the program, NG selected 337 to receive the free Sense monitor. DNV was contracted to perform a process evaluation focused on the research objectives shown in Table 1.

These research objectives were achieved through analyzing responses to a series of questions posed to program participants and non-participants through a web survey. The survey included screener questions (verifying residence, and receipt of the device for participants and recall of offer for non-participants). Only if a customer in the sample frame passed these screeners could the survey move them to the next questions. The results presented below focus only on the information provided by program participants related to their reasons for getting a Sense monitor, how they interacted with the monitor, and their satisfaction with the device.

Table 1. Sample design and research objectives for the Residential Home Energy Monitoring System Pilot program evaluation

Customer Group Surveyed	Key Research Objectives	Sample Size
Program Participants	- Identify drivers of participation and participant expectations - Understand participant interaction with the Sense monitor - Understand changes in energy consumption behavior due to the Sense monitor - Assess program satisfaction and benefit	99
Interested Nonparticipants	Understand nonparticipant energy consumption behaviour	133
Invited Uninterested Nonparticipants	- Identify barriers to program participation - Understand nonparticipant energy consumption behavior	211

Ninety-nine participants and 344 nonparticipants completed the web surveys.⁵ The nonparticipants included 133 “interested nonparticipants”: These were customers who had expressed interest in the Sense Monitor in 2018 but who were not selected for the program; and 211 “uninterested participants”: These were customers who had never responded to NG’s 2018 email promoting the program.

The survey response rates were significantly higher among participants and interested non-participants (32% for each) than uninterested non-participants (only 3%). The 32% participant response rate is much higher than participant survey response rates (typically in the 10%-15% range) that DNV has observed from other recent program evaluations it has conducted or reviewed leading us to believe that the participant survey results in this study are reasonably representative of the larger participant population.

The evaluation team asked the participants several questions about how they interacted with the monitor. These questions covered how many household members were using the monitor, how they accessed it, how frequently they were looking at it, whether the frequency with which they looked at it had changed over time, and what were their reasons for looking at the monitor less frequently or more frequently than they once did. The evaluation team also asked the participants how accurate they thought the Sense monitor was at reporting their home’s actual energy consumption, and which of their appliances or devices they thought the monitor was not accurately reading.

Results

The results from the two studies are presented below, starting with the technology overview, next the results of the SMUD pilot installations to assess the accuracy of the Sense load disaggregation technologies, and finally the NG customer web survey responses regarding their Sense equipment.

NILM Technology Overview Results

Although the SMUD study focused on hardware-based NILMs, the features of smart meter based NILM technologies were also surveyed and are shown in Table 2. The target consumer of these technologies is generally a utility who may use the information internally or use it to provide a service for their customers. The technology company name is listed in the left column with a brief description of their services in the next column. All the technologies provide an energy consumer engagement application through the web or a smart phone application. The final three columns list differentiating features: whether the application provides real time visualization, recommendations to the customer such as energy or cost savings opportunities, and whether it allows demand response through direct load control.

⁵ The 344 nonparticipants were those who completed the full nonparticipant surveys. There were an additional 489 nonparticipants who completed the initial survey questions but were screened out of the rest of the survey because they did not recall National Grid reaching out to them about the program.

Table 2. Basic features of smart meter based NILMs

Name	Description	Visualization	Recommendations	Demand Response
Bidgely	Utility smart meter AI solutions. Offers additional services with EnergyHub hardware (such as demand response)		x	x
C3 Energy	Offer a wide range of AI- based service offerings for utility operations	x	x	
Ecotagious (Uplight)	Customer engagement platform for utility demand side management			x
EnergyHub	Demand response management for utilities and customers	x		x
Enertiv	Primarily a commercial building service offering	x	x	
Grid4C	Utility smart meter AI solutions	x		
Midori	Italian homeowner facing application and in-home display of disaggregated smart meter data.	x	x	
Onzo	Utility smart meter AI solutions			x
Opower	Customer interface for utility-run behavioral based energy savings programs		x	
Plotwatt	Targeted to commercial property portfolio managers.		x	

Like the smart meter-based technologies, all of the hardware-based solutions provide an energy consumer engagement application through the web or a smart phone application and going further, most of these apps provide real time visualization of the data. The target customer for these technologies is generally a homeowner or a business energy manager. Table 3 shows the basic features of the hardware based NILM devices with name and description in the first two columns as in the previous table. The final three columns indicate whether the technology captures higher resolution data than typical utility meter (< 1 minute), whether the application provides recommendations to the customer such as energy or cost savings opportunities, and whether it allows demand response through direct load control. In the context of PG&E's earlier findings, the aim of this study was to investigate the ability of high resolution NILM devices to accurately identify individual electric end uses in the home.

Table 3. Basic features of hardware based NILMs

Name	Description	High Resolution	Recommendations	Demand Response
Chai Energy	Over free service using Green Button, but also have hardware to access smart meter data		x	x
Exibea (ELIQ)	Primarily a customer engagement platform		x	
Green Running	Have NILM hardware called VERV https://verv.energy/		x	
Home Detector Sensor Network	Integrated IAQ, energy and security smart home solution. Based in France		x	
Homepulse	Uses various sources of data for services. Based in France		x	x
Mirubee (Wibee)	Spanish Company. Similar technology to Sense	x	x	
Neurio	Canadian Company similar to Sense	x	x	x
Powerley	Rely on AMI data for services. Have an application for estimating appliance load with magnetic field.			x
Schneider Electric Wiser Energy	Energy monitoring hardware. Software less sophisticated	x		
Sense	Disaggregates at the premise, no additional submetering except in Solar package	x		
Smappee	Energy monitoring hardware. Disaggregation algorithm less sophisticated. Allows for circuit level submetering, gas and water metering	x	x	
Smart Impulse	Targeted at commercial building owners. Based in France		x	
Verdigris	Primarily offer monitoring and targeting services for commercial buildings	x	x	x
Voltaware	NILM Device sold via utility partners	x	x	
Wattie	Similar to Sense; Based in Sweden	x		

Sense Monitor Load Monitoring Accuracy Results

The Sense smart phone app or web view displays total consumption and other direct-metered loads such as sub-metered solar production visually in real time, as shown in Figure 1 for four days in April. Individual disaggregated appliance load profiles can be accessed through a

drill-down menu and viewed in separate display windows. All the visual displays have a zoom feature to view the load profile from a macro (monthly) to a micro (sub-minute) level.

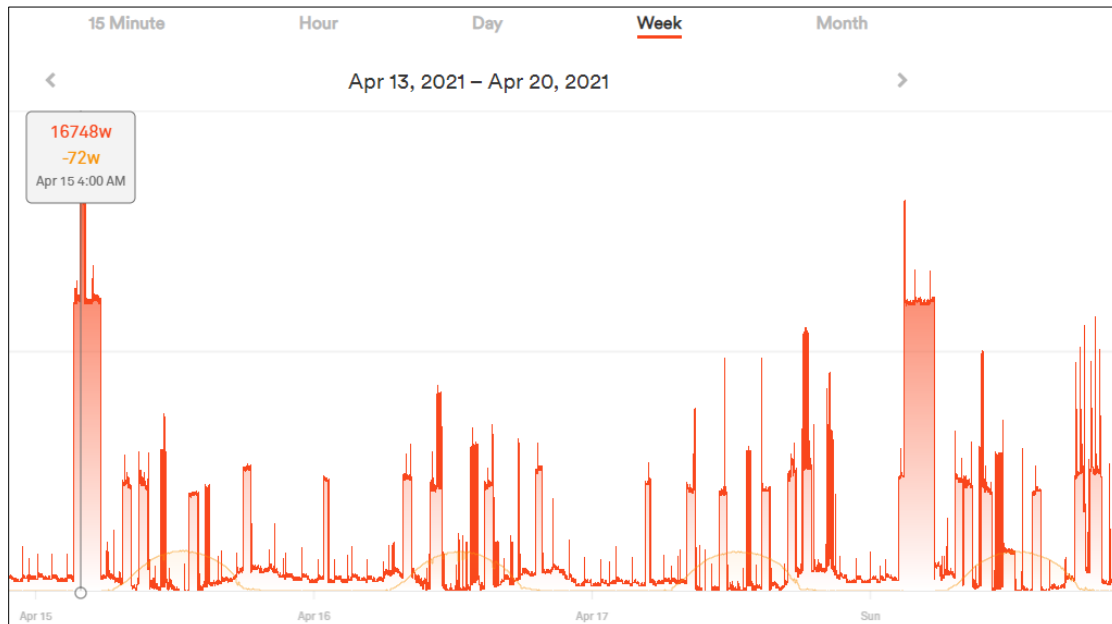


Figure 1. Sense visual display of total consumption and solar production

As the Sense monitor discovers appliances it labels them in a general manner, such as “Heat 1”, “Heat 2”, “Heat 3” and “Motor 1”, “Motor 2”, etc. The homeowner is able to re-label these appliances in the application, but most of the participants in the study did not do so. Homeowner interaction with the Sense application do not seem to have much influence on the ability of the device to detect the major appliances, however, this study only enabled homeowner interaction, it did not track the frequency or depth of interaction. Homes A and B with owner interaction did not lead to more accurate major appliance identification than Sites E and F without homeowner interaction.

We examined the data from the nine sites where monitoring equipment was installed to see if the Sense could accurately identify the HVAC equipment and water heaters at each of the sites. As the largest electric load in the house, we expect the Sense monitor to be able to identify air conditioning systems. The monitor was able to identify all five air conditioning (AC) systems that were paired with gas heating, though at two sites the single air conditioner was identified as two separate AC systems. We similarly expect the Sense monitor to be able to identify both the heating and the cooling operation of HVAC heat pumps. The monitor had more trouble identifying the HVAC heat pumps (HP) that it never identified as a heating system and identified as AC in only two of the four sites.

Of the four heat pump water heaters, two were clearly identified as water heaters, one was identified as a heater and one was not identified. The one conventional electric water heater was identified as a water heater. Table 4 shows the homes, labeled Site A through Site I, whether the homeowner was allowed to interact with the Sense application, the type of space cooling and

water heating equipment, whether the monitor was able to identify the equipment and whether the loads assigned to the equipment were accurate.⁶

Table 4. Sense monitor HVAC and water heat appliance identification

	Interaction with App	Space Cooling			Water Heating		
		HVAC type	Able to identify	Accurate	WH type	Able to identify	Accurate
Site A	Yes	HP	as AC	partly	HP	As Heater	no
Site B	Yes	HP	no	N/A	gas	N/A	N/A
Site C	No	HP	no	N/A	gas	N/A	N/A
Site D	No	HP	as AC	no	elec	yes	N/A
Site E	No	AC	yes, but 2	partly	HP	yes	partly
Site F	No	AC	yes	mostly	HP	yes	mostly
Site G	Yes	AC	yes	unknown	HP	no	N/A
Site H	Yes	AC	yes, but 2	unknown	gas	N/A	N/A
Site I	No	AC	yes	unknown	gas	N/A	N/A

The accuracy of the monitor's disaggregated loadshapes was determined by comparing them to direct measurements of the loads made using CTs. At sites G, H and I there were no robust CT measurements of the AC load available to compare to the Sense monitor loads.

At two sites (A and E) the HVAC disaggregated loads were accurate in timing but not in the total power assigned to the load. At site E the load was represented by two AC systems even though only one system was present in the home. Figure 2 shows the AC data at Site A where the label "Smp-AC" indicates the measurement from a CT and "Nse-AC" indicates the estimated load that Sense assigned to the AC system. Each pixel indicates a point in time with the hour of the day on the x-axis and the day of the year on the y-axis. The color of the pixel indicates the power in kW shown in the scale on the right of each image. Light blue indicates missing data. The nearly identical pattern in the two images shows that the Sense monitor correctly identified the timing of the AC equipment, but the very different scales at the right show that the monitor underestimated the power consumed by the AC equipment. Figure 3 shows Site D where the Sense monitor was inaccurate in both timing and magnitude and Figure 4 shows site F where the Sense monitor was mostly accurate in both timing and magnitude. When inaccurate, the Sense tended to underestimate the power consumed by the AC.

⁶ It is worth noting that, although not studied here, the Sense monitor can be paired with Belkin Wemo plug-through energy measurement devices to improve the accuracy of load disaggregation by directly measuring the electric load plugged through the Wemo.



Figure 2. Site A: comparison of AC loads from measured CTs and Sense monitor showing agreement in timing of the load through the nearly identical pattern visible throughout the image and particularly apparent in the red circled section. The measurements were not in agreement in power magnitude shown in the scale on the right circled in purple. Notice that full scale for the CT measurement on top of the figure is 3 kW whereas full scale for the Sense monitor is 1.5 kW.

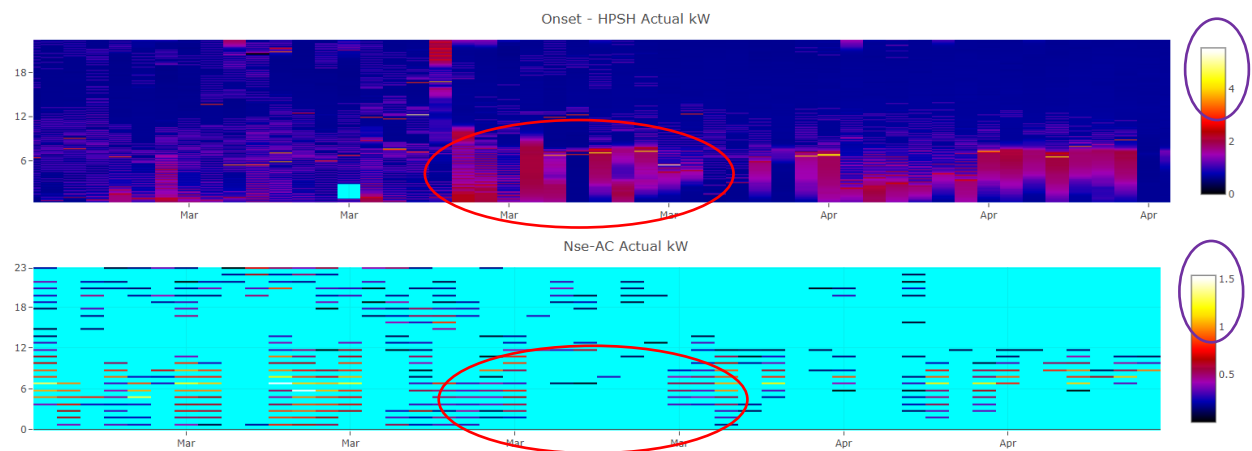


Figure 3. Site D: comparison of AC loads from measured CTs and Sense monitor showing inaccurate timing and power magnitude. The inaccurate timing can be seen most clearly in the distinctly different patterns of operation visible in the red circled areas. The inaccurate power magnitude can be seen in the full scale for the CT measurement shown on the top right where the full scale value is above 4 kW whereas the full scale for the Sense monitor on the bottom is 1.5 kW.

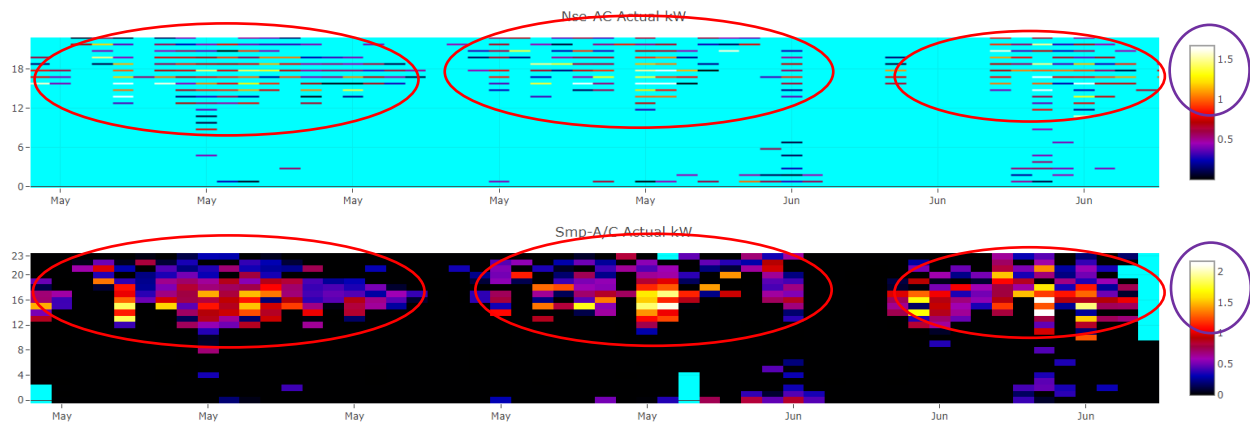


Figure 4. Site F: comparison of AC loads from measured CTs and Sense monitor showing mostly accurate timing and power magnitude. The pattern from the Sense monitor shown on the top in the figure is nearly identical to the pattern from the CT measured load shown in the three red circled areas. Maximum full scale shown on the right of each plot circled in purple is similar at 1.5 kW for the Sense monitor and 2 kW for the measured CTs.

Water heater results are shown for site A, E and F in Figures 5, 6, and 7 respectively where the monitor at Site A shown in Figure 6 captures the 6am cycling behavior of the water heater but misses the 6pm water heater operation. The water heater draws 0.3 kW when running in heat pump mode and draws 3 kW in electric resistance mode. Most of the operation is in heat pump mode and the Sense monitor captured the correct order of magnitude for most of the early morning hours. It does not capture the electric resistance mode of the HP water heater.

In Figures 6 and 7 the full scale of the Sense monitor equipment is larger than that of the CT measurements showing that the Sense monitor is over predicting the water heater power draw. It may be affected by the high frequency power spikes when the heat pump compressor turns on. The cycling pattern picked up by the Sense at Site E shows resemblance to the CT measurements, but at Site F the cycling behavior looks almost identical from the two devices.

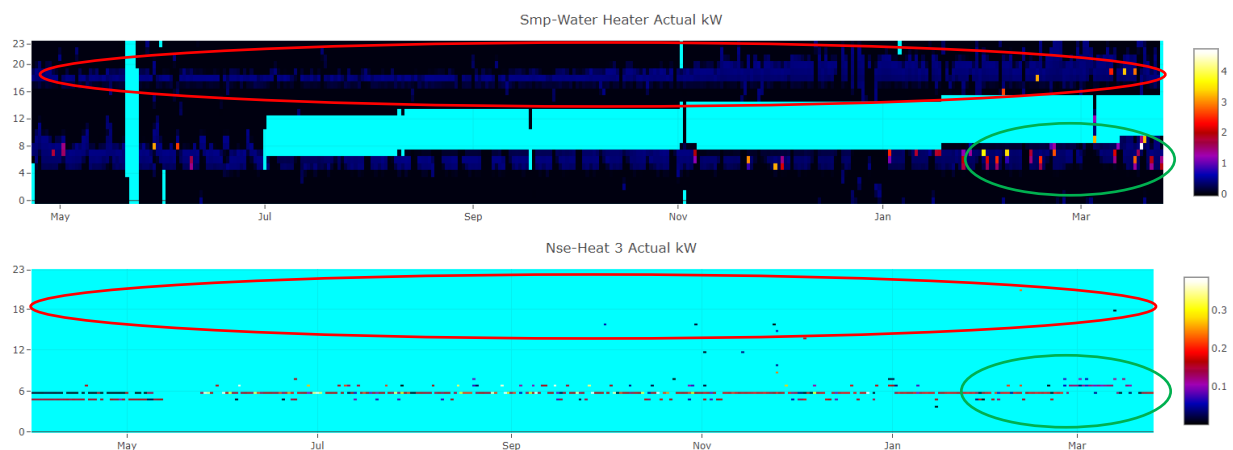


Figure 5. Site A: comparison of water heating loads from measured CTs and Sense monitor showing inaccurate load disaggregation, both in timing and in magnitude. The red oval indicates evening water heater operation that is completely missed by the Sense monitor. Also, the Sense monitor does not capture the electric resistance operation shown by a green oval where the CTs measure 3-4 kW and Sense indicates only 0.1-0.2 kW.

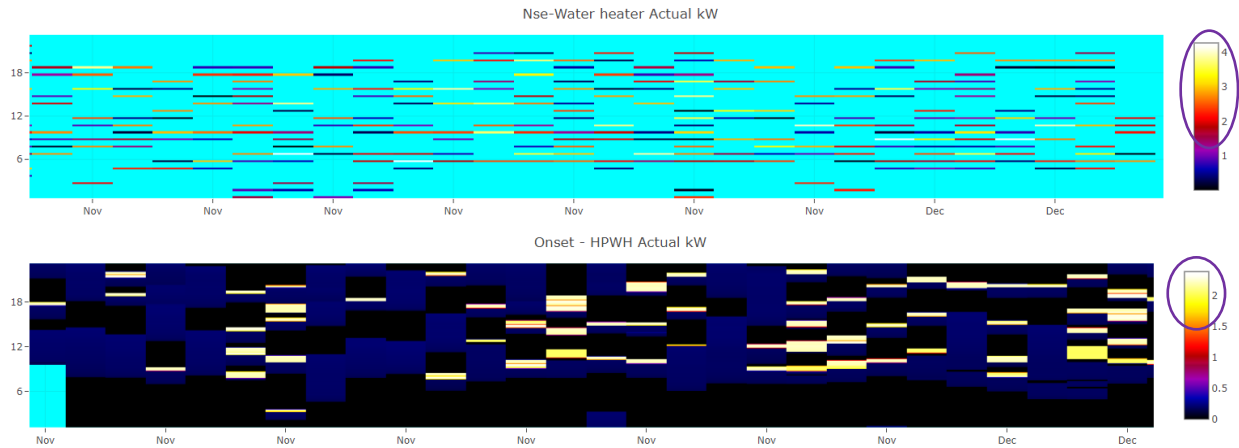


Figure 6. Site E: comparison of water heating loads from measured CTs and Sense monitor showing mostly accurate timing with the overall pattern being very similar on the two plots, but inaccurate power magnitude shown in the scale on the right. Indicated with purple circles, full scale is 4 kW for the Sense monitor, but only 2 kW for the measured CTs.

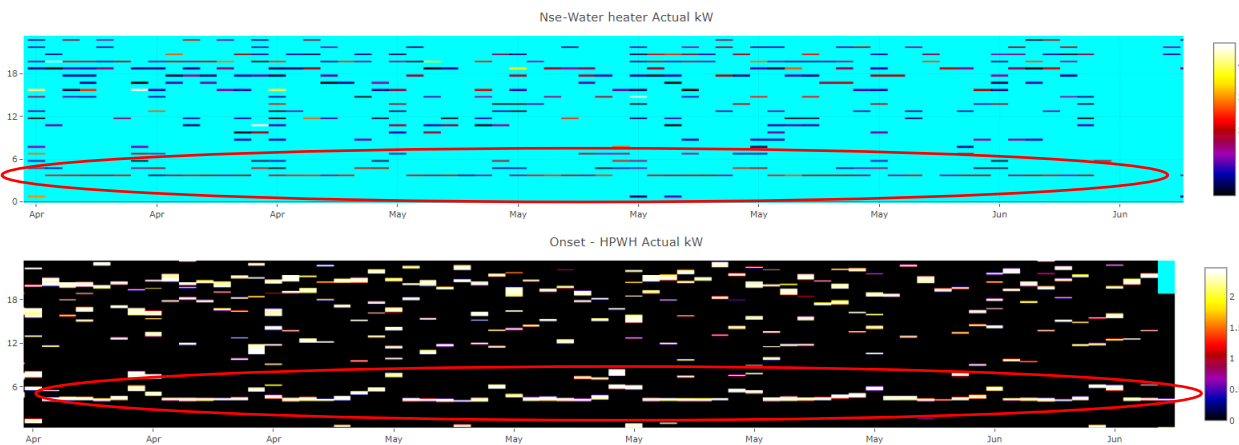


Figure 7. Site F: comparison of water heating loads from measured CTs and Sense monitor showing mostly accurate timing with the overall pattern being very similar on the two plots. Notice the weekday water draw at 4:00 AM circled in red at the bottom of both plots. The power magnitude shown by full scale at the right of the plots is 4 kW for the Sense monitor, but it rarely operates there. The blue to red colors on the plot indicate it operates in the 1-2 kW range most of the time. The yellow-white color of the CT measurements in the lower plot indicate that it operates close to full scale most of the time near 2 kW.

NG Residential Home Energy Monitoring System Pilot Results

The results of the National Grid process evaluation of their Residential Home Energy Monitoring System Pilot study are summarized in the following paragraphs.

The most-cited drivers of participation in the Sense monitor program were curiosity about how much energy the devices in their house were using and a desire to learn how to reduce their energy consumption. When a separate question asked how the monitor compared to their expectations, slightly less than half the participants (45%) said they had expectations about the kind of information they would receive from the monitor and when asked if the monitor did not

meet, met, exceeded expectations, 45% said it was less useful than expected, 33% said it met expectations and 21% said it exceeded expectations.

The evaluation team asked the participants several questions about how they interacted with the monitor. The participant interaction with the device was generally done by one household member and the frequency of interaction for slightly over half the respondents (53%) was on a daily or weekly basis. The majority (56%) said that they look at it less frequently than they did when they first received the device.⁷ The primary reasons they look at the monitor less frequently than they once did are shown in Figure 8.

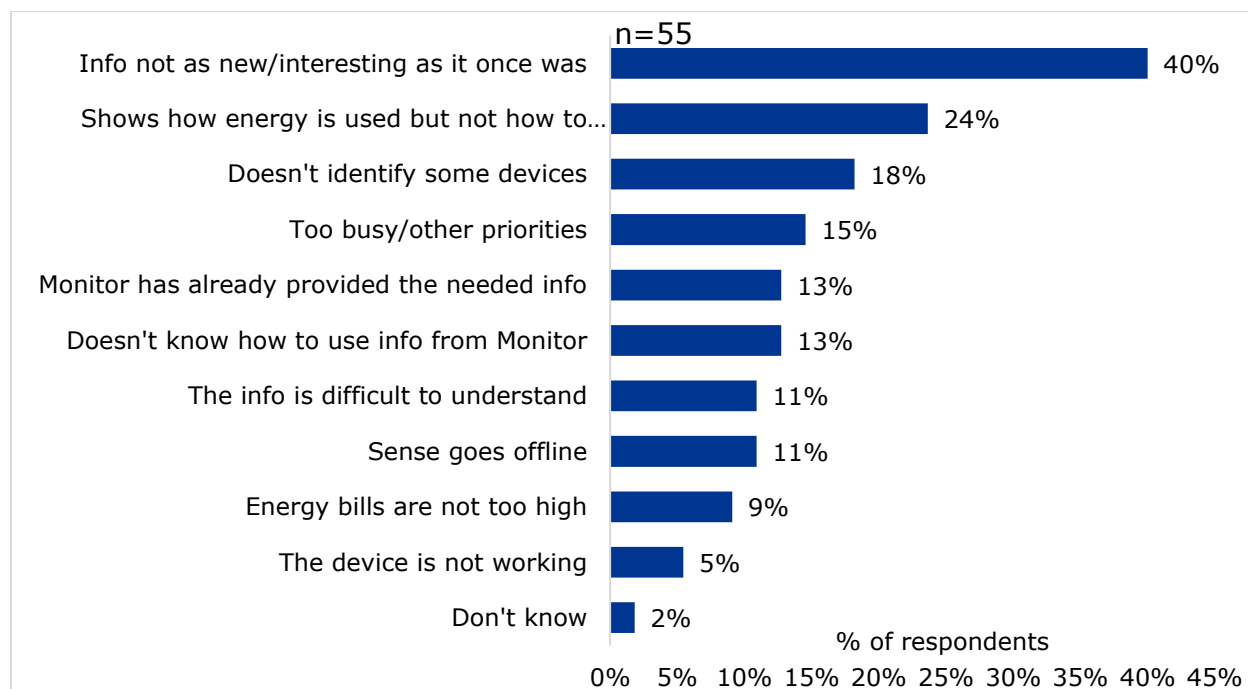


Figure 8. Why participants look at the monitor less frequently than they once did
Note: Percentages exceed 100% because respondents could choose multiple options.

The evaluation team asked the participants how accurate they thought the Sense monitor was at reporting their home's actual energy consumption. Figure 9 shows that nearly two thirds of the participants thought that monitor was accurate for all or most of their devices and appliances and only 2% of the respondents thought the monitor was totally inaccurate.

⁷ The Sense Monitors were installed in April-May 2018 and the participants were surveyed in October 2020

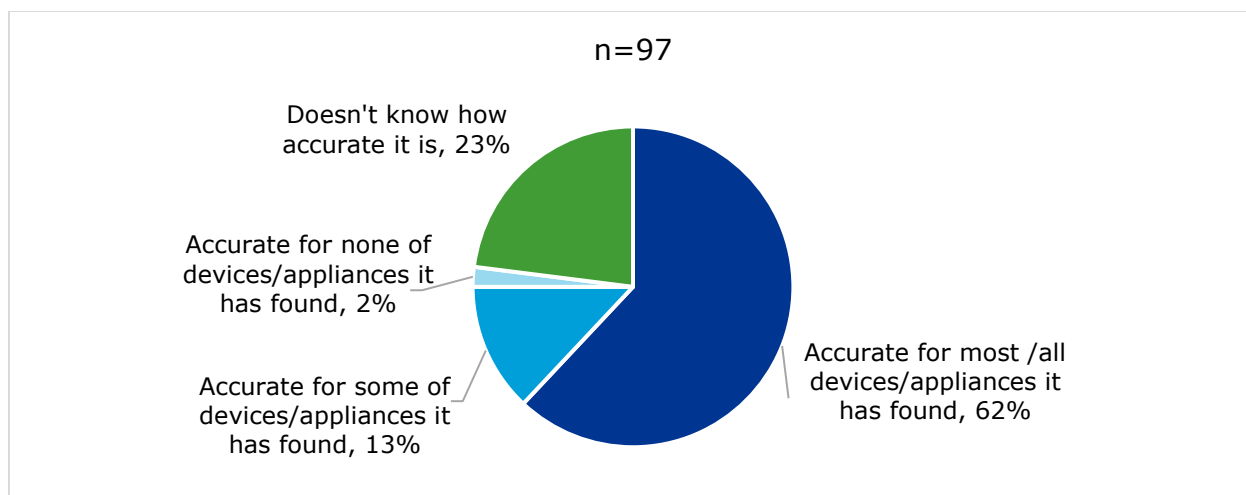


Figure 9. Participant response to the question regarding how accurately the Sense monitor reports home energy consumption

The team asked the participants which of their appliances or devices they thought the Monitor was not accurately reading. Figure 10 shows that they identified a wide variety of appliances/devices with air conditioners, furnaces, and refrigerators being the most cited. This is consistent with the conclusions of the research discussed earlier.

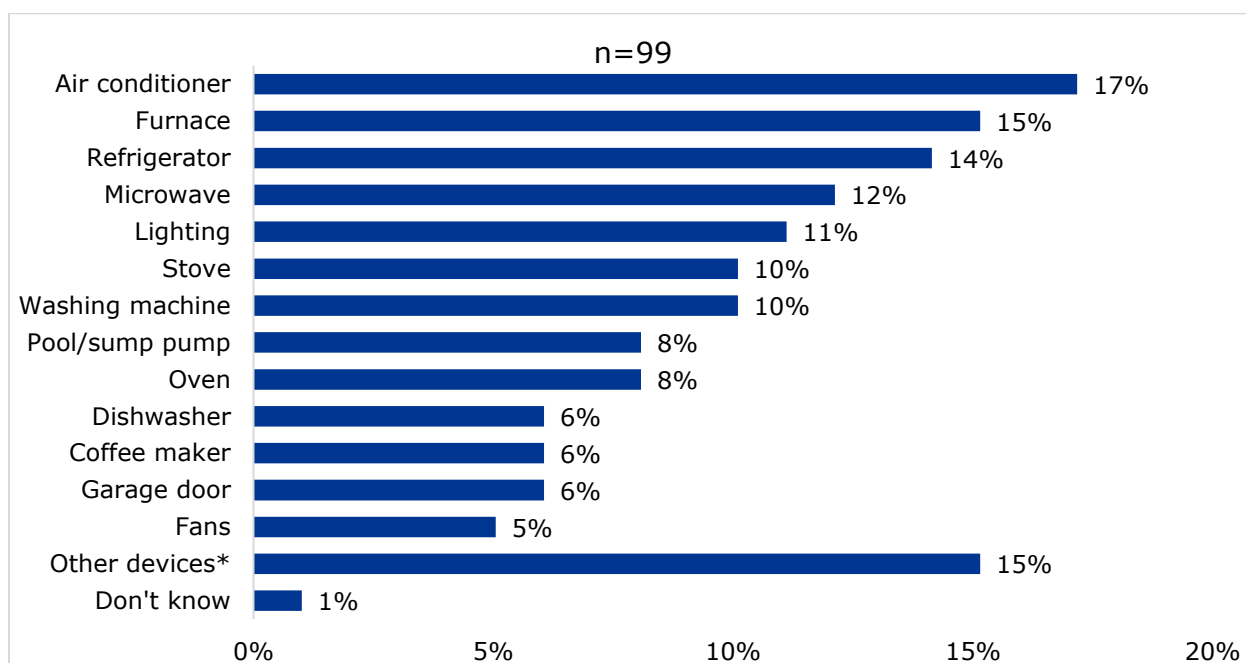


Figure 10. Participant responses regarding which appliances or devices they thought were not measured accurately by the Sense monitor

There was evidence that the Sense monitor influenced lighting upgrades and lighting behavior changes in the participants. The team asked the 36 participants who had reported both using the Sense monitor to observe their lighting and recently upgrading their lighting: “How influential was the information provided by the monitor in your decision to install this more

energy-efficient lighting?” Two-thirds of them (67%) said that the information from the Monitor was highly influential in their decision.

In addition, when asked whether the Sense Monitor had shown them the impacts of this new energy-efficient lighting on their electric consumption, 75% of them said that it had. It is reasonable to assume that this “feedback mechanism” – e.g., seeing the immediate evidence of the new energy efficient lighting on their electric consumption -- would encourage these participants to purchase more energy efficient lighting.

Sixty-five of the respondents said they were using the monitor to learn about how and when they were using heating and cooling in their house. Twenty-nine percent of the participants said they had upgraded the energy efficiency of their HVAC equipment. For the participants there was evidence that the Sense Monitor had influenced these HVAC upgrades. The team asked the participants “How influential was the information provided by the monitor in your decision to install this more energy-efficient heating, cooling or water heating equipment?” Fifty-six percent said that the information from the Monitor was highly influential in their decision.⁸ In addition, when asked whether the Sense Monitor had shown them the impacts of this new energy-efficient HVAC equipment on their electric consumption, 61% of them said that it had.

Most participants who reported energy-saving lighting actions gave the Sense monitor some credit for these actions. When the team asked them: “How influential was the information provided by the monitor in your decision to reduce your lighting use?”, 64% said it was highly influential. In addition, when asked whether the Sense monitor was able to show them the impacts of reducing their lighting use, 80% of them said that it had.

The evaluation team asked the participants both why they were satisfied and why they were less than satisfied with the Sense Monitor. Satisfied participants cited their fascination with smart technologies and their appreciation of being able to identify where they needed to reduce their electric load. One participant said he was able to use the information from Sense to better size his backup generator. Less-than-satisfied participants said their monitor had performance problems including taking too long to recognize some of their appliances/devices and not providing accurate information. Other participants said that insufficient information was provided on how to use the monitor and that the monitor did not provide information on how to reduce their electric use.

Barriers to participation for those nonparticipants that recalled the program solicitation email (only 21% recalled it) were split half and half between being too busy and not having enough information about whether the monitor would benefit them.

Conclusion

Both these studies showed evidence that the Sense monitor does not accurately disaggregate the various appliance loads in a home. The monitor is able to identify an air conditioner in the home most of the time, but the power draw and exact cycling behavior assigned to that appliance may not be accurate. Participant interaction with the device did not appear to improve the accuracy of the appliance identification, though that could be an artifact of particular homeowner behavior in the very small SMUD pilot study.

⁸ These included the 22% of respondents who said the Monitor information was “extremely influential” and 33% of respondents who said it was “Very influential.”

Homeowner survey responses indicated that the Sense monitor accurately identified appliance operation most of the time. Even though the Sense monitor did not meet expectations of most participants, they still reported it being useful to inform their energy saving equipment purchases and energy saving behaviors

The results of these studies show that the Sense disaggregation algorithms still have room for improvement. Although the Sense monitor is not perfect at identifying the electric loads in a home, it is still useful for homeowners to learn about their energy consumption and may help them to adopt energy saving equipment and habits. If the Sense monitor provided energy saving recommendations based on the collected information as some participants wished, it could be an even more powerful tool for lowering residential energy consumption.

References

- DNV. 2020. *Residential Space and Water Heating Electrification Measurement, Verification and Market Characterization Study Report*. Unpublished report for Sacramento Municipal Utility District.
- . 2021. *Process Evaluation of the Residential Home Energy Monitoring System Pilot*. Unpublished report for Rhode Island National Grid.
- Hart, G. W. 1992. "Nonintrusive Appliance Load Monitoring." In *Proceedings of the IEEE* 80 (12): 1870–1891. New York, NY: IEEE. ieeexplore.ieee.org/document/192069.
- Kolter, J. Z. and M. Johnson. 2012. "REDD: A Public Data Set for Energy Disaggregation Research." In *Proceedings of the SustKDD workshop on Data Mining Applications in Sustainability*. Beijing, China: Association for Computing Machinery. <http://redd.csail.mit.edu/kolter-kddsust11.pdf>
- Liu, Y., J. Wang, J. Deng, W. Sheng, and P. Tan. 2021. "Non-Intrusive Load Monitoring Based on Unsupervised Optimization Enhanced Neural Network Deep Learning." In *Frontiers in Energy Research*. 9:718916. <https://www.frontiersin.org/articles/10.3389/fenrg.2021.718916/full>
- PG&E (Pacific Gas and Electric). 2016. *EPIC 1 Project 18 – Demonstrate SmartMeter Enabled Data Analytics to Provide Customers with Appliance-Level Energy Use Information*. San Francisco, CA: Pacific Gas and Electric. www.pge.com/pge_global/common/pdfs/about-pge/environment/what-we-are-doing/electric-program-investment-charge/PGE-EPIC-Project-1.18.pdf.