# Can We Find the End Use in Smart Metering Data?

*Michael Baker, SBW Consulting, Inc., Micah Fuller, Pacific Gas and Electric, Gina Hicks, SBW Consulting, Inc., Santiago Martin Rodriguez-Anderson, SBW Consulting, Inc.*

## ABSTRACT

A test was conducted to determine whether one-minute interval measurements of a home's total electrical use could be disaggregated into standardized end uses, without having to provide information about each home, e.g., demographics, appliance and equipment inventory, or building characteristics. One-minute total energy use measurements were obtained for 166 homes. Direct end use measurements were also obtained for six of these homes. Three vendors of commercially available disaggregation products were hired to estimate end uses for all homes without knowing which homes had direct end use measurements. The vendors were asked to disaggregate electric end use for a period of 5 months starting from the beginning of December 2014. During this period, disaggregation estimates from all vendors were found to have large estimation errors for almost all of the end uses, sometimes failing to even identify an end use while other times significantly overestimating end use energy consumption. Estimates from one vendor matched or came close to matching the end use measurements for some important end uses such as air conditioning, cooking, lighting, and refrigeration, but had large errors for other end uses. While vendor estimates were most accurate for end uses aggregated over the 5-month analysis period, accuracy markedly degraded for individual months or homes.

## Introduction

Using so-called smart meters, many utilities can now collect, from each of their customers, measurements of electrical use for intervals as short as one minute. Pacific Gas and Electric (PG&E) has deployed such meters. The data available from these meters has many possible applications. One of which is to provide customers with information that may help them operate their homes more efficiently. In particular, PG&E wanted to determine whether the one-minute interval measurements of total electrical energy supplied to a home could be accurately disaggregated into end uses, without relying on any other information about each home, e.g., demographics, appliance and equipment inventory, or building characteristics. If this proved possible, PG&E would be able to routinely provide their customers with information about how much they were spending on end uses such as refrigeration or space cooling. PG&E sponsored the test described in this paper to determine whether any of the companies that offer smart meter data analysis services (referred to in this paper as vendors) could provide accurate end use estimates given only smart metering data collected from PG&E residential customers.

One-minute total energy use measurements were obtained for 166 homes. Direct end use measurements were also obtained from six of these homes (referred to in this paper as test sites). Approximately 60 devices or circuits were monitored in each of the test sites. Three vendors were selected to test their ability to accurately estimate end uses for the test sites. The meters serving each of the homes participating in this study were modified so that they could continue to record normally for billing purposes, but could also provide measurements of electric energy use for each minute.

Homes participating in the study were assigned an arbitrary identifier that masked their identity. The Vendors did not know which homes were the test sites, nor were the vendors provided any information about the characteristics of any of the homes. Data was provided on 87 homes to two of the vendors and on 85 homes to the third. There was substantial overlap in the homes assigned to the three vendors, so end uses for some homes were estimated by more than one vendor. Each vendor was asked to provide estimates for a standardized set of electrical end uses at the hourly level for each of their assigned homes over a 5-month period from December 2014 to April 2015. The direct end use measurements were aggregated to the hourly level. The accuracy of the vendor estimates was determined by comparing them to the direct end use measurements for the test sites.

## Characteristics of Test Sites

PG&E requested volunteers for this test from its employees and contractors. Owners of 37 homes expressed interest in the study. To be selected, the home had to be a primary residence and be served by a PG&E electric meter. Gas end uses also had to be served by a PG&E gas meter. Each homeowner provided information about the home's location and the characteristics of the structure, occupants and energy using equipment. All but nine of these homes were eliminated for the following reasons:

1. Solar electric. Some homes were eliminated because they had solar electric generation and were net metered. For such a home the meter readings would not equal to the sum of the end uses within the home and the variation of use over time would in part be due to the variation in output from the solar electric system.
2. Combined space and water heating systems. It was not feasible to separately measure heating and cooling energy for these systems.
3. Remodeling plans. PG&E wanted to collect a full year of both gas and electric end use data from the test sites. Measurements would be substantially more complicated if the homeowners completed remodeling projects during this period.
4. Antiquated wiring. A number of homes had outlets that lacked a ground wire. This along with other information such as photographs of electrical panels was used to determine whether the wiring in the home was antiquated and not suitable for this test.

Device/circuit inventories were completed for nine homes. This included a complete inventory of all electric and gas powered devices served by the PG&E meters. Electric devices were included in the inventory if they were permanently connected to a circuit, i.e., hard-wired, or the homeowner reported that the device was always plugged into the same outlet. We ignored devices that were occasionally plugged into an outlet or were often plugged into different outlets. All electric circuits in each home were traced so that each device could be associated with a specific circuit. These inventories were compiled, analyzed and used by PG&E in selecting six test sites. The selected test sites have the following characteristics:

1. Climate zones. Two of the test sites were in or near San Francisco and the other four were in or near Stockton, California. Stockton is hotter in the summer season. It has approximately five times as many cooling degree days as San Francisco.
2. Floor Area. The test sites were of similar size, with floor area ranging from 2,100 to 3,000 square feet.

3. Year Built. Five out of six of the test sites were more than 15 years old. One was built in 2007.
4. Occupants. Five out of six test sites had two adult occupants. Of these, only two had occupants that were children (one each). One home had five adult occupants and no children.
5. Heating and Cooling. All test sites had gas space heating equipment, either central or wall units. Four of the test sites had central air conditioning.
6. Cooking. Two of the test sites only had electric cooking equipment. The other four had a mix of gas stove tops and electric ovens. None of the test sites had a gas oven.
7. Refrigeration. Four test sites had one refrigerator. One of them had two and one home had four.
8. Water Heating. All test sites heated water with a single gas fired water heater.
9. Clothes Washing and Drying. All test sites had a single electric clothes washer, five test sites had a single electric clothes dryer, and one home had a gas clothes dryer.
10. Pools and Spas. Two of the test sites had a pump for a swimming pool or spa.
11. Electric Vehicle Charging. Two test sites had an electric vehicle charger for the entire study while one home added a charger during the study.
12. Television. Three test sites had one television and three had two televisions.

## Definition of Electric End Uses

During the design of this study, we searched for but were unable to find any national or international standards for classifying energy using equipment by end use. However, clear definitions were needed to guide the vendor estimates of end use and our direct measurements of end uses in the test sites. Table 1 shows the descriptions of each end use provided to the vendors.

Table 1. Definition of electric end uses provided to the vendors.

| End Use | Description of end use provided to vendors |
|---|---|
| Space Heater | Plug-in heater, baseboard, wall (with and without fan), fan (in gas unit heater), heat lamp, radiant panel, boiler, furnace, auxiliary fans and pumps |
| Air Conditioner (AC) | Portable AC, package terminal AC, window AC, evaporative cooler, ceiling fans, central AC, evaporative cooler, attic fan, auxiliary fans and pumps |
| Domestic Water Heater | Tank (resistance or heat pump), tank less, fans on condensing hot water heater, recirculation pumps |
| Pool / Spa Heater | Pool / spa heater |
| Lighting | Fixtures hard-wired, fixtures plug-in, controls, bathroom mirror defogger |
| Refrigerator/Freezer | Refrigerator, freezer, combined refrigerator / freezer, drink / wine cooler |
| Cooker | Microwave, stove, oven, convection oven, exhaust fans with integrated lighting and controls, devices that are for heating food, e.g. toaster, toaster oven |
| Clothes Dryer | Clothes dryer |
| Clothes Washer | Clothes washer |
| Dish Washer | Dish washer |
| Electric Vehicle | Electric vehicle |
| Spa / Pool Pump | Spa / pool pump |
| Other Pump | Other pump |
| Other | Built-in and mobile vacuums, cooking and food preparation appliances not listed under Cooker, remote controls, telephones, chargers for consumer electronics, standalone exhaust fans, microwaves not used for cooking, garage door opener including integrated light, mirror defogger, humidifier, clock radio, surveillance cameras, tuner, Blue-ray / DVD / VCR, receiver, amplifier, powered speakers, radios and stereos, television, set-top box / DVR, game console, computer / accessory, other devices not elsewhere listed |

## Installation of Power Meters

We analyzed the circuit and device inventory along with the physical layout of electric panels and devices in each home to determine the least cost and most reliable plan for installing power measurement equipment and the associated equipment for wireless communication within the house and with our remote data collection systems. The plan included intentional redundancy. For example, we measured (where feasible) the main feed to each electric breaker panel and we measured each of the circuits controlled by those breakers. This allows for a comparison of the panel total use to the sum of the use on each of the breakers. Conventional true power measurement devices were used with split-core current transformers (CTs) around one leg of single phase circuits or both legs of two phase circuits (such as those serving clothes dryers). Corresponding potential transformers (PTs) were also connected to obtain the voltage for each circuit.

Figure 1 shows how we typically installed power measurement components for an electrical breaker panel. In this case, a separate electrical enclosure was mounted below the breaker panel. Sensor leads pass between it and the breaker panel, where the CTs and PTs have been installed. The new enclosure below contains the necessary multi-channel power recording devices along with the wireless transceiver that communicate one-minute recordings of electrical use to a central controller.

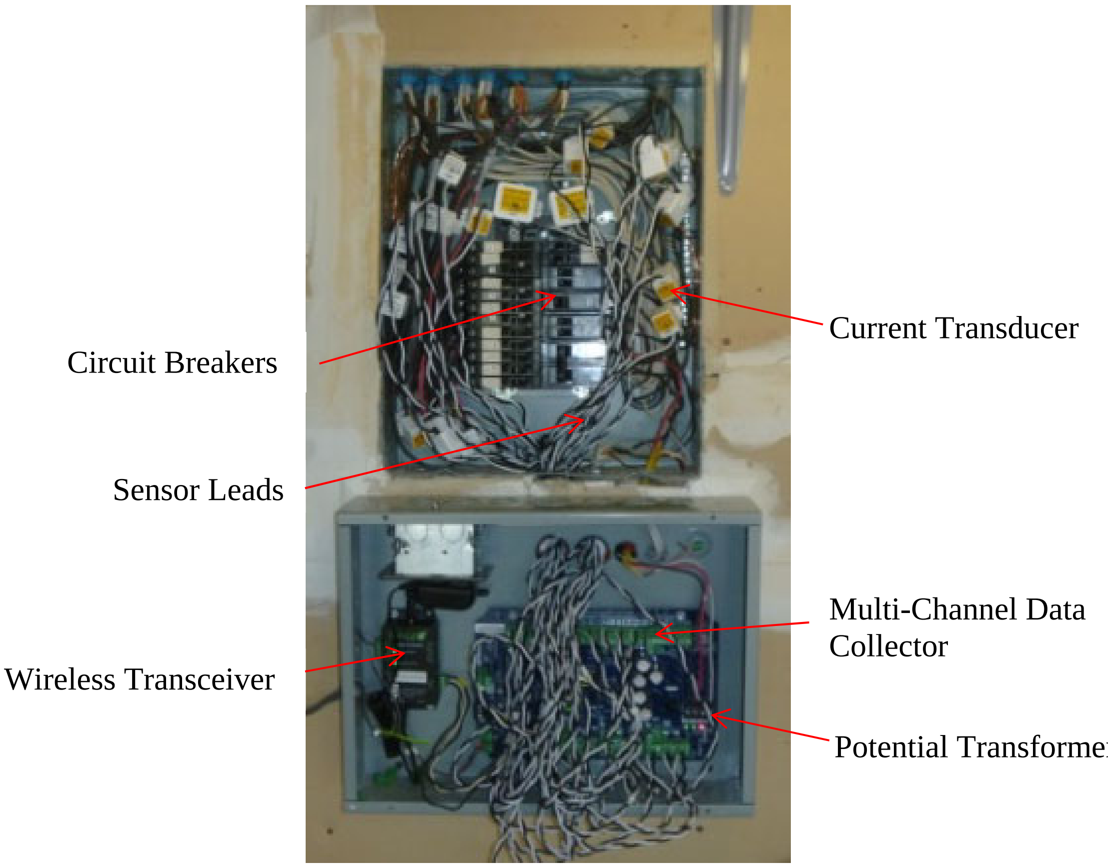


Figure 1. Typical installation of power measurement components for an electrical breaker panel.

The circuit and device inventory allowed us to identify the end use of each electric circuit. In many cases a circuit served more than one end use. A plan was developed for disaggregating each of these circuits. In some cases, we were able to install wireless plug load power measurement on devices or power strips to disaggregate the energy use into the target end uses. In cases involving circuits that serve hard-wired end uses, we used the plug load power measurement  to measure all of the non-hard-wired devices on the circuit. The hard-wired devices were the difference between power measured at the breaker and the sum of non-hard-wired plug load measurements. This "virtual" channel technique was also used to derive use for some non-hard-wired circuits.

Figure 2. Wireless plug load power measurement.

It was not possible to completely disaggregate some circuits. Any circuit that served more than two hard-wired end uses was classified based on the end use which had the largest rated power draw. These could have been separately measured but it would have required re-wiring a portion of the home, which was not feasible for this test. In some cases, more than one end use was present in a single device, e.g., an outdoor fountain or a bathroom exhaust fan that had integrated lighting. These devices would have to be disassembled in order to separately measure the end uses, which was also beyond the scope of this test.

Although it is not possible to quantify the degree of misclassification in the measured end uses, we believe that such misclassification introduces only a small error. Mixed uses were small compared to the discretely measured end uses.

## Collection of End Use Measurements

One-minute interval measurements of electric and gas end uses were obtained from the test sites for a full year, including the period used for comparison with the vendor estimates of electric end uses. Approximately 600 separate measurements, either gas or electricity use, were obtained. All measurement points within each home were wirelessly connected to a multi-protocol controller which communicated with our primary remote storage via a cellular connection. The gateway device polled each power measurement once a minute and recorded the energy used since the last polling. These recordings were pushed to our remote database once each minute.

All collected data was tested to determine whether it fell within expected ranges and for other indications of error conditions such as repeated identical values. Check sum comparisons, e.g., total energy feeding a panel compared to the sum of the energy to each of its breakers, were particularly useful in diagnosing problems with the measurement system. We also routinely looked for measurement points that failed to function.

Another important test of the data was to compare our measurements of total use to the total use measured by the PG&E meter. The comparison was made at the hourly level. We summed the one-minute readings from the PG&E meter by hour. Similarly, we summed the one-minute measurements of the energy feeding each home's breaker panels. The panels at two of the test sites did not have room to attach current transducers to the main supply circuits. For those test sites, the measured total was created by summing all of the circuits in the breaker panels.

During the early period of data collection (October and November 2014) test sites were revisited by our team to replace some malfunctioning equipment, and resolve various other data quality problems. We continued to stay in touch with each of the homeowners at least once a month following these site visits. The main purpose was to detect any changes in the home that would affect our measurements, such as moving a device from one outlet to another or plugging in a new appliance. No changes occurred during the year of measurement that required modification to the power measurements in breaker panels. However, we did work with the homeowners to adjust for changes in plug loads, by installing additional plug load power measurement for new devices, and adjustment of the end use energy equations if plug load devices were moved.

## Energy End Use in the Test Sites

The end use shares of total use measured in the six test sites is shown in Figure 3. The largest share of use is for Disaggregation Other. This end use comprises many specific devices, some of which account for a larger share of total use than some of the other end uses. For example, audio visual system, computers and accessories, set-top boxes, and televisions, all use more than Clothes Washers. After Disaggregation Other the largest end uses are Lighting, Refrigerator / Freezer and Electric Vehicle. Half the test sites had electric vehicle chargers, and the figure underscores how important this end use can be if it is present in a home. Use for the Spa / Pool Pump was nearly as large, even though only two test sites had this end use, so it is also important when present.

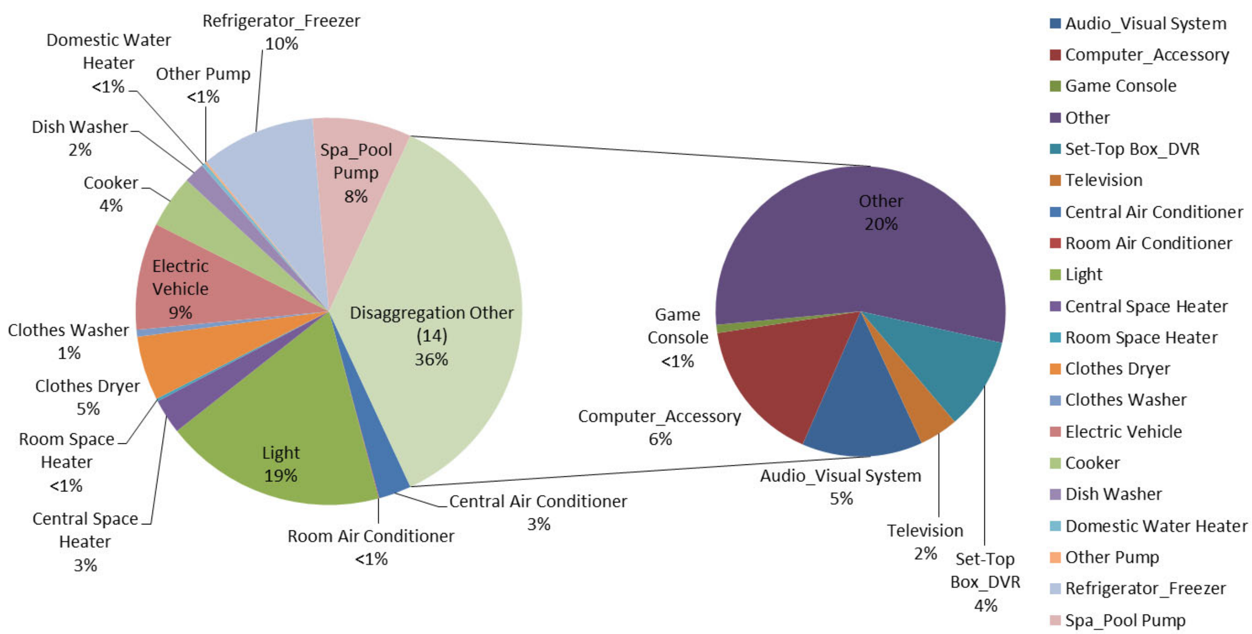


Figure 3. End use shares for all test sites (December 2014 thru April 2015).

The Disaggregation Other end use is clearly important at 35% of total use across all six test sites. Unfortunately, as shown in Figure 3, it comprises many types of devices. The largest portion of the Disaggregation Other end use is associated with devices that did not fall into any of our pre-defined device categories, shown as Other within Disaggregation Other in the figure.

Our measurements also reveal the diurnal variation for each end use, as shown in Figure 4. In this figure, the thickness of a color band is the total energy used by the test sites for that end use and hour. As shown in the figure, some end uses have very predictable and uniform energy use throughout the day, such as Refrigerator / Freezer. Most end uses vary substantially, such as Clothes Dryers or Spa / Pool Pump. Even though only two test sites have Spa / Pool Pump that end use accounts for a large share of peak use in the early morning hours.

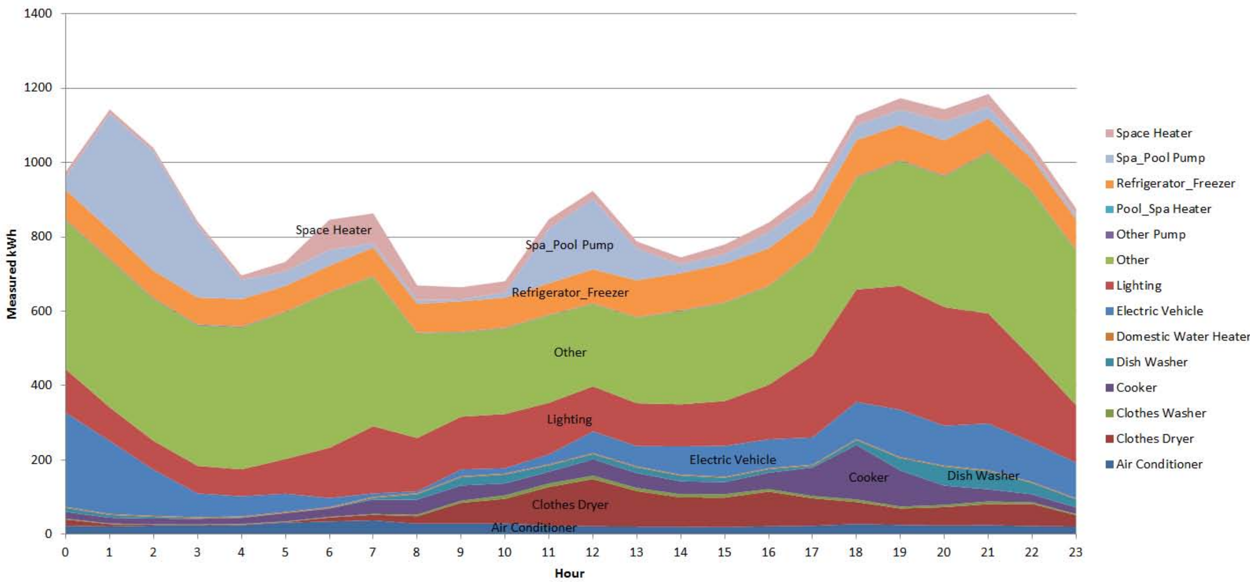


Figure 4. Average hourly load shape of end uses for all test sites (all days December 2014 thru April 2015).

## Vendor Estimates of Electric Energy End Uses

PG&E sought firms who had market-ready web based products which were capable of disaggregating total one-minute electricity usage into separate end uses for residential customers. PG&E selected three vendors for this test and compensated them for their services. Each vendor utilized proprietary algorithms to develop estimates for each of the standardized end uses defined by PG&E. Two vendors were asked to prepare these estimates for 87 homes; the third was asked to estimate end uses for 85 homes. The homes provided to each vendor overlapped, so that more than one vendor estimated end uses for some of the homes. The test sites were included among the homes sent to each vendor, but the vendors were not told which homes had end use measurement systems. The vendors delivered hourly estimates for each home's end uses. These were delivered a few days after the end of each month during the test period.

## Accuracy of Vendor End Use Estimates

We determined the accuracy of the vendors' products by comparing the vendors' estimates of electric end uses to our direct measurements in the six test sites. To ensure the vendor comparisons were based on the quality of the disaggregation and not the quality of the data, we dropped from the comparison any hour where the sum of the one-minute use provided to the vendors (as measured by the PG&E smart meter) was more than 10% different than the sum of our measured use. There are a number of reasons why the data from these two measurements did not match within 10%. The first is that the one-minute readings from the modified PG&E meters were not always continuous. There were instances where the PG&E meter use was zero for more than an hour despite the presence of devices that continuously use electrical energy. In addition, there were errors in our measurements, including omissions and invalid data. At times some of our equipment went offline and data during those periods was lost. Some pieces of equipment sometimes reported erroneous values due to software errors (which were set to zero in the dataset).

For the test period, the total use provided to the vendors was within 10% of our measured use for 65% of the hours. These hours were used in the comparison of measured use to vendor estimates, which is shown in Figure 5.

PG&E may use the data obtained in this test in evaluating the accuracy of other vendor products. Therefore, the kWh scale for the panels in Figure 5 have not been included. However, each panel uses the same scale and thus the height of each bar can be compared across panels. The number that appears above each bar is the percent of the measured end use. For example, in the Air Conditioner panel, the Blue vendor's estimated use was 30% of the measured use when we summed both estimates across all hours in the test period.

The Green vendor came closest to estimating most of the significant end uses. However, that vendor was 630% high in its estimate of the Space Heater end use. None of the test sites used electricity for their primary heat source, so our measured Space Heater end use was associated with the electric fans in the heating equipment that distribute the heat throughout the home. The Blue vendor was able to identify the largest number of end uses, although their estimates for most specific end uses were lower than what was measured.

Although, the test period was in the winter and early spring, there was some cooling and the Green vendor estimated 90% of the measured Air Conditioner use in this period, substantially more accurate than the other two vendors. In addition, the Green vendor estimated 100% of the Cooker and Spa / Pool Pump end uses. The other two vendors estimated between 50% and 70% of some end uses, but in general were further from the measured use, except for Clothes Dryers where the other two vendors were somewhat more accurate. All vendors were about as accurate for the Electric Vehicle end use, but all missed the measured use by 50% or more.

Figure 6 shows the total estimate of Disaggregation Other by test site. The vendors place much of the use in Disaggregation Other. Many of the remaining end uses were under-estimated as a result.


Figure 5. Percent of measured by end use and vendor (all test sites - December 2014 thru April 2015). All panels use the same scale.

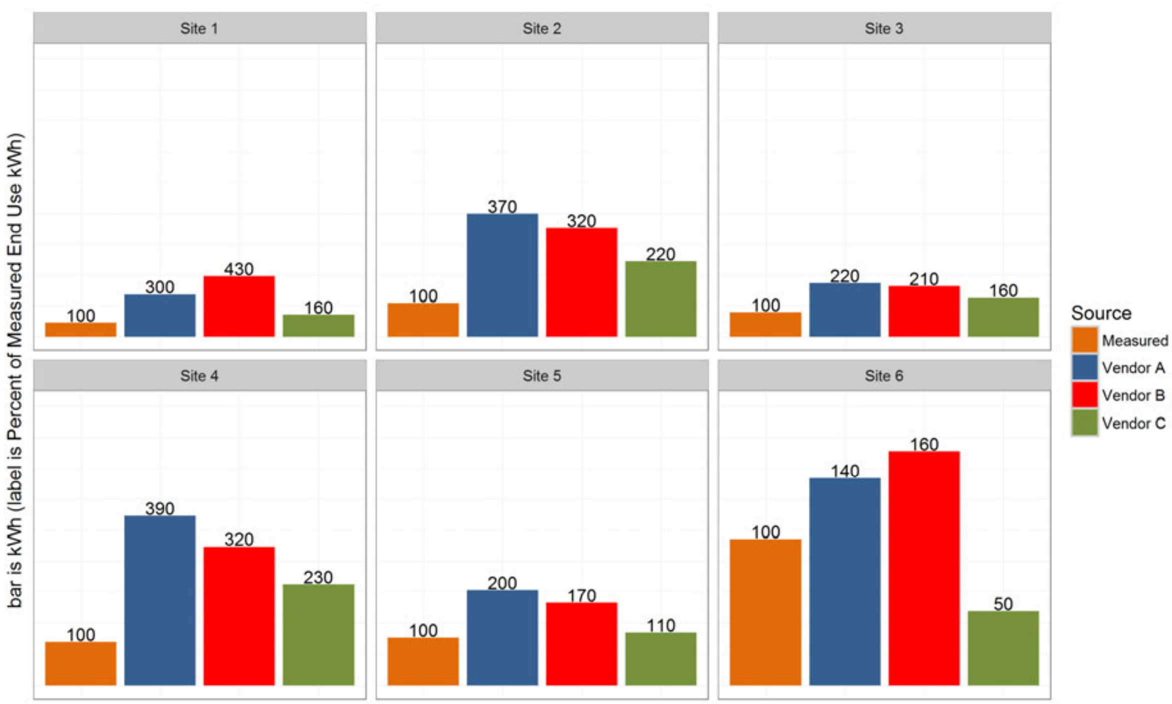


Figure 6. Percent of measured Disaggregation Other end use by test site and vendor (December 2014 thru April 2015). All panels use the same scale.

We also examined how accuracy varied across the months of the test period. As Figure 7 shows, the Green vendor estimates are between 70% and 80% of the measured Lighting end use in each of the months in the test period. However, the Green vendor's estimate for Air Conditioner (Figure 8) varies between 20% and 250% of the measured use. What appears to be an accurate estimate over the full test period is due to compensating errors at the monthly level.

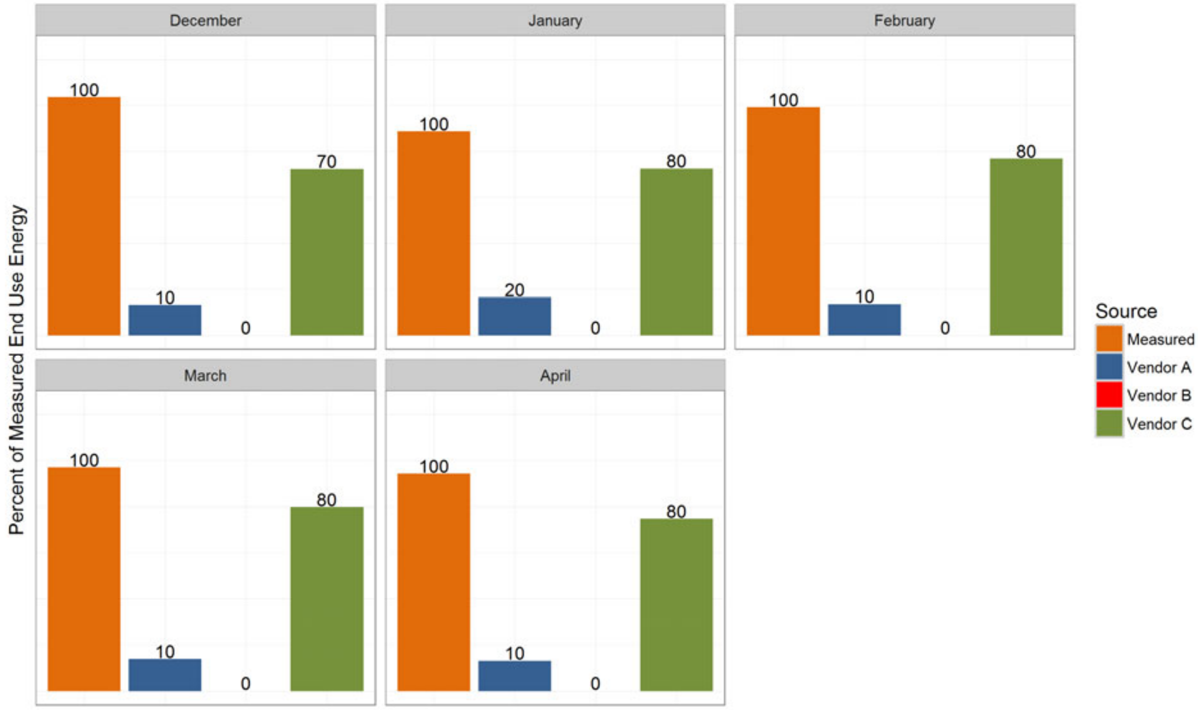


Figure 7. Percent of measured Lighting end use by month and vendor (all test sites). All panels use the same scale.

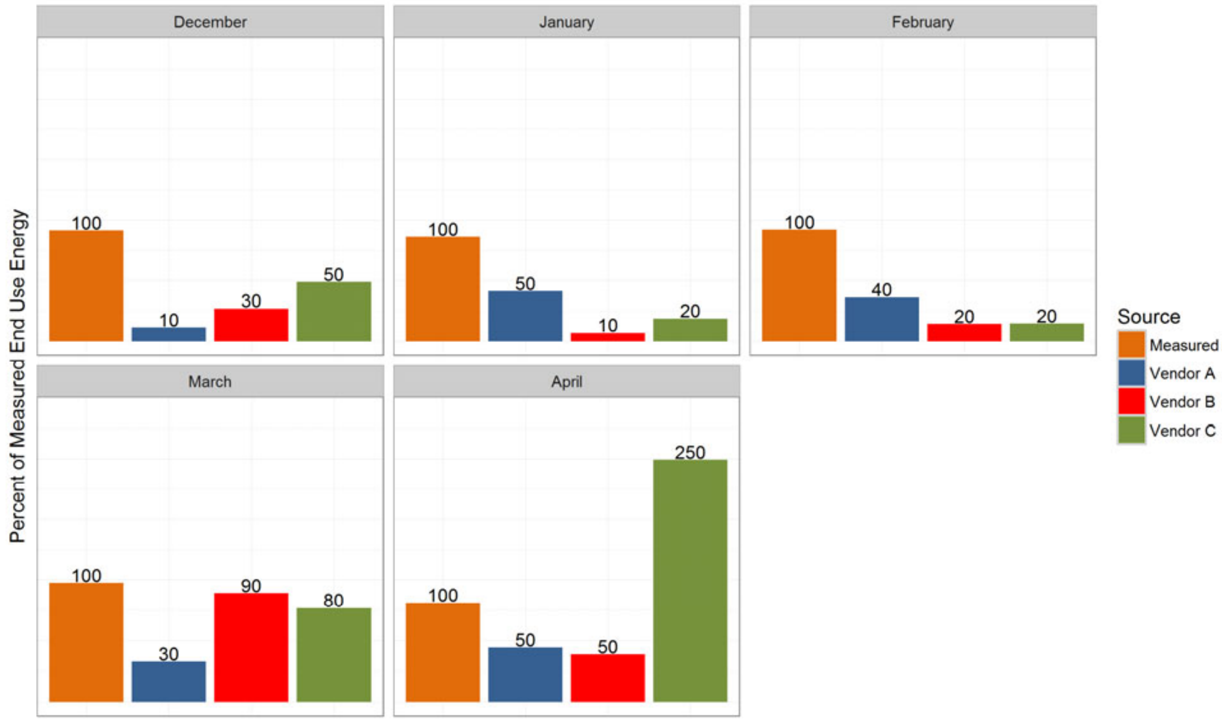


Figure 8. Percent of Air Conditioner end use by month and vendor (all test sites). All panels use the same scale.

Figure 9 further details accuracy for the Spa / Pool Pumps end use by showing separate results for each of the six test sites. Only two of these test sites have the Spa / Pool Pump end use. The Green vendor detected both of these, but also detected that end use in a third test site. The third test site has a pump for an outdoor fountain, but its use should have been assigned by the vendor to the Other Pump end use.

Figure 10 shows Electric Vehicle end use estimates by test site. None of the vendors detected this end use when it was not present, but the Red and Green vendors missed electric vehicles at Site 1 and Site 6. Figures 9 and 10 both show that vendors have room for improvement in identifying large electric end uses.

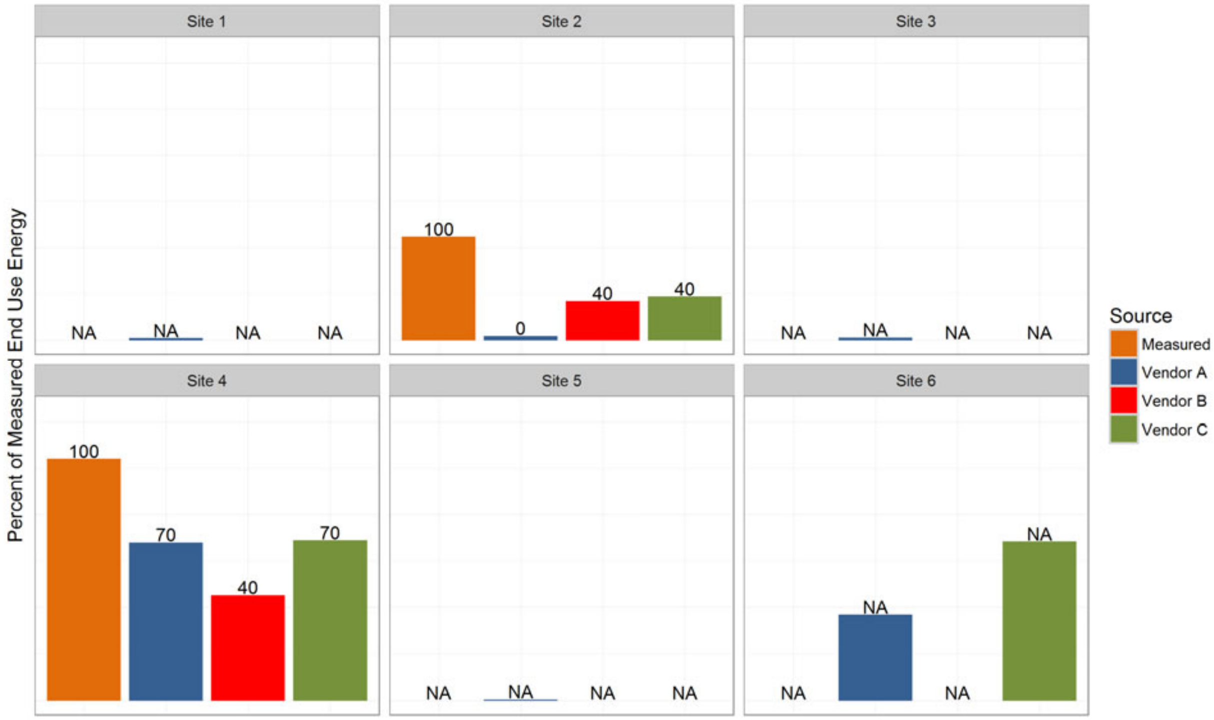


Figure 9. Percent of measured Spa / Pool Pump end use by test site and vendor (December 2014 thru April 2015). All panels use the same scale.

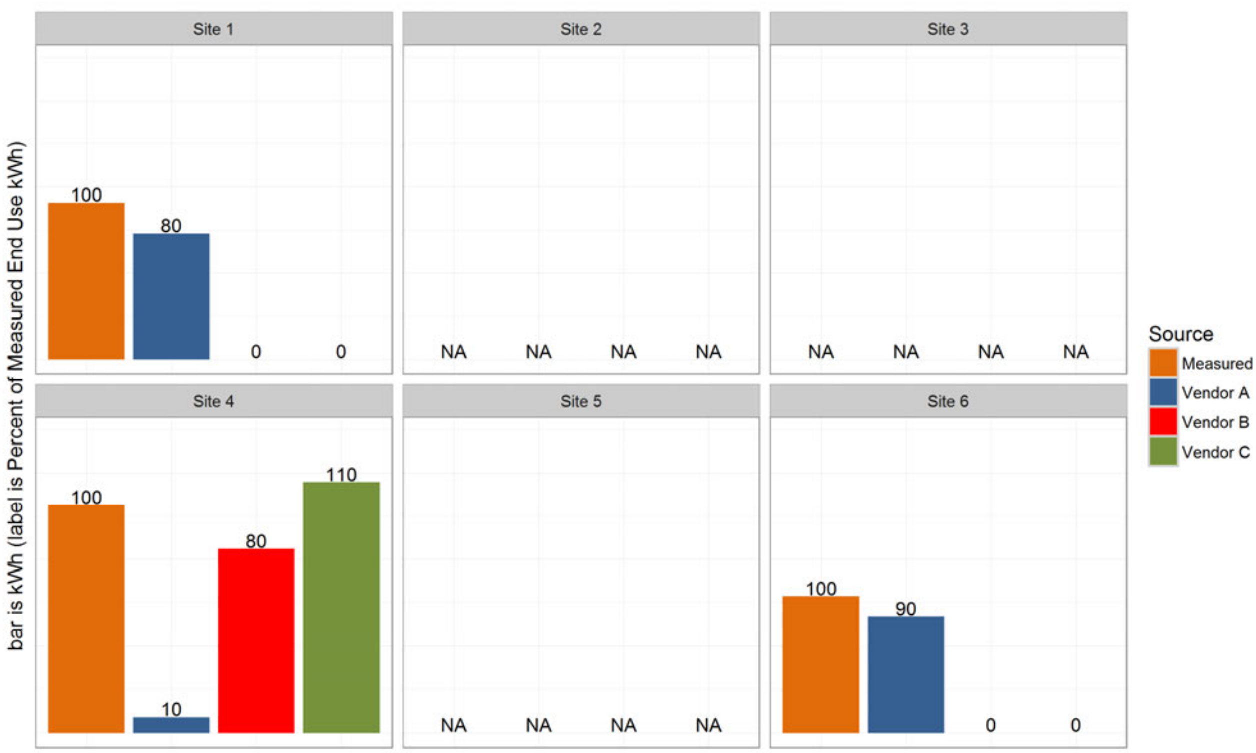


Figure 10. Percent of Electric Vehicle end use by test site and vendor (December 2014 thru April 2015). All panels use the same scale.

Figure 11 demonstrates that while some vendors reported accurate average use for lighting, the accuracy was not uniform for each test site. The Green vendor came close to estimating measured lighting use in all months but varied between 40% and 140% across the individual test sites.

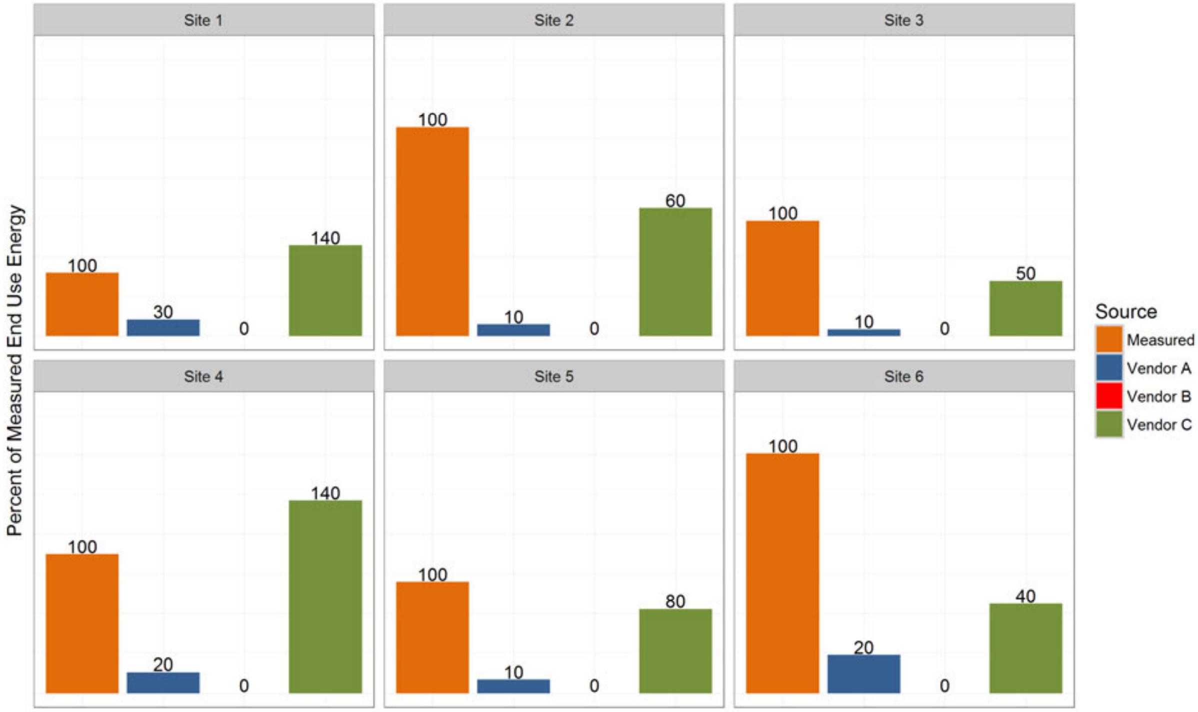


Figure 11. Percent of measured Lighting end use by test site and vendor (December 2014 thru April 2015). All panels use the same scale.

## Conclusions

We find some evidence that commercially available disaggregation products can identify some end uses from one-minute total home energy use. The Blue vendor was able to identify 12 of 13 specified end uses while the Red and Green vendors were able to identify 8 of 13 (See Figure 5). The Blue vendor did not identify Other Pump electric energy usage. The Red vendor did not identify Clothes Washer, Dishwasher, Lighting, Other Pump, or Pool/Spa Heater end uses. The Green vendor did not report Clothes Washer, Dish Washer, Domestic Water Heater, Other Pump, or Pool/Spa Heater electric energy usage.

Vendor accuracy varied for different end uses and test sites. The Blue vendor reported lighting energy as 10% to 20% of what was measured at all test sites. Blue had the greatest variability in accuracy with values ranging from 10% to 5870% of measured values. The Green vendor reported lighting energy use as 70% to 80% of energy use measured at all test sites (See Figure 6). Blue was able to identify more end uses, but did not accurately report an end use that accounts for 19% of energy used. All vendors assigned a large share of use to the Disaggregation Other end use. The Green vendor had the smallest Disaggregation Other end use. Nonetheless the Disaggregation Other end use for all vendors was typically 100% to 300% more than what was measured.

False positives of energy use are another concern. Blue and Green Vendors both identified a pool pump at site 6 where there was none (See Figure 9). Site 6 did have a fountain pump but its peak load and usage pattern are distinctly different from pool pumps. Fountain pumps run continuously, while residential pool pumps have schedules to come on once or twice per day. The Red vendor identified pool pumps at Sites 2 and 4 correctly without false positives at other test sites, although the reported energy use was 40% of directly measured use. In a similar vein, Green and Red vendors did not identify electric vehicles at two of three test sites that had electric vehicle chargers (Figure 10).

Vendor products that performed well in identification of end uses are highly inaccurate for certain end uses. This was true even for some end uses that represented a large portion of total energy consumption like Lighting. This was also true for devices that have a consistent energy demand profile like Refrigerator / Freezers, Electric Vehicles, and Pool Pumps. Vendors that had the best reporting accuracy for some end uses were more limited in how many end uses they could identify. Good accuracy in average reported energy for an end use across six test sites did not translate to good accuracy at the site level either.

There are substantial challenges to identification when there are both gas and electric end uses present. Electric vehicles compound this difficulty by adding an additional large electrical end use which is common but not always present. From our testing we conclude that at present these residential energy disaggregation products cannot identify all important end uses from smart meter one-minute data alone.