NON-INTRUSIVE ENERGY USE EFFICIENCY INDEX

FOR ASSESSING ENERGY EFFICIENCY OF A HOME

A Thesis

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In Partial Fulfillment

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Master of Science

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by

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Non-Intrusive Energy Use Efficiency Index for Assessing Energy Efficiency of a Home

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Abstract

The cost of energy is always on the rise. With improvements, homeowners can diminish the amount of energy their house consumes. Many homeowners want to take advantage of the lowered monthly costs that come with energy efficient appliances. Additionally, home buyers may desire a way to compare the energy efficiency of one home to another. Much of the energy efficiency of a home depends on the structure, rather than the appliances contained therein. We introduce a Non-intrusive Energy Use Efficiency Index (NEU-EI) to provide a benchmark in assessing the efficiency of a building, to the potential benefit of homeowners, contractors, and others.

1. Introduction

Energy efficiency is currently a topic of widespread interest. The goal of energy efficiency is to use energy in an optimum manner to achieve the same service that could have been achieved using a common, less efficient manner [1]. Many homeowners want to take advantage of the lowered monthly costs that come with energy efficient appliances. Others look to reduce their energy consumption in order to reduce their impact on the environment. Depending on the inefficient appliance and the new efficient appliance, the amount of time it takes for it to pay for itself may be minimal; therefore, replacing the appliance would be financially sensible. Utilizing thermally efficient insulation (including windows and doors) and reducing the amount of air leakage between rooms and between the inside of the building and its exterior will also help out the overall energy efficiency of the building. Most homeowners are interested in improving the overall efficiency of their house to reduce costs as well as to reduce their energy usage. A monitor for energy consumption would be helpful for homeowners interested in their overall energy efficiency. For a new home, the benefit would be that the homeowner could start with a baseline of efficiency and then watch for variations in the pattern that would indicate the home had an energy problem that needed to be identified and fixed. For a retrofit application, the homeowner would use the baseline to set the priorities of fixing any energy inefficiencies until it could get to an "energy efficient" status quo and then watch for patterns that would indicate deviations that needed to be addressed.

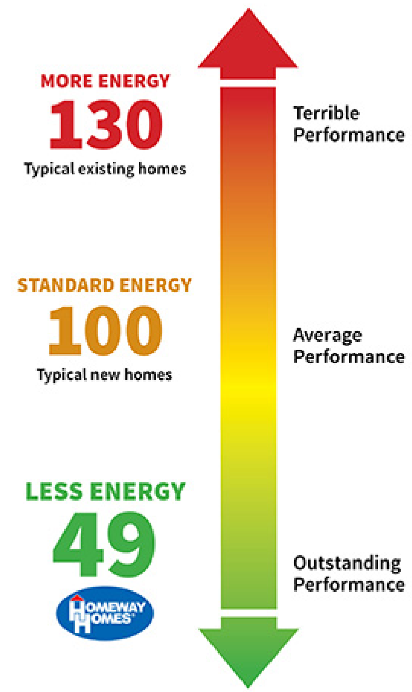

Figure 1 Graphic representation of the HERS index graphic shows the grading scaled used by RESNET [21]

One way that a homeowner could evaluate the energy efficiency of their home is to use the Home Energy Rating System (HERS) index. Introduced in 2006 by the not-for-profit corporation Residential Energy Services Network (RESNET), the HERS index is a nationally recognized standard setting index used to classify the energy efficiency industry in the United States. The Department of Energy, the Department of Housing and Urban Development, and Environmental Protection Agency all recognize the HERS index. The tests for the HERS index include a blower door test, duct leakage tester, checking for existing and potential combustion safety problems and infrared cameras to determine any hot spots showing weak areas for insulation. These tests and tools are used to determine the amount and location of air leaks in the building envelope, the amount of leakage from HVAC distribution ducts, the effectiveness of insulation inside walls and ceilings and any existing or potential combustion safety issues. Included in the calculations are the floors over unconditioned spaces (like garages), attics, foundations and crawlspaces, windows and doors, vents and ductwork, the water heating system and thermostats. Then they enter the data calculated from each category into the RESNET system. RESNET will then give the house a HERS score and also a cost/benefit analysis for making improvements to the house. These improvements only pertain to the structure of the building, along with the HVAC system for the building. Any other appliances are not measured or monitored.

The HERS index is based on a baseline model of a comparable house that is given a score of 100. Then the homeowner's house is compared to this baseline model and given their score. If a house is given a score of 70 then it is considered 30% more efficient than the baseline, but if it is given a score of 130 then it 30% less efficient than the baseline. The baseline home is a model of the same size and shape of the actual home [2].

Potential home owners have two options when it comes to energy efficient housing: building a home from the ground up utilizing energy efficient building design and appliances, or buying a prebuilt home and making appropriate alterations to improve energy efficiencies. When building a new home, the homeowner or the builder has the ability to make the house an Energy Star rated house or a Leadership in Energy and Environmental Design (LEED) certified house. Energy Star is a program created by the United States Environmental Protection Agency that incentivizes companies to create energy efficient devices. A home that is Energy Star certified has been designed and built to standards that exceed normal homes on the market. For the home to be certified it has to be designed using RESNET-accredited software to determine the target rating of a house the homeowner wants to build. Then the software is used again to configure the preferred measures to reach and exceed the target rating. Once the house is built using the preferred measures, an inspector is called out to the site to verify that all the necessary procedures have been followed to establish certification. When a device meets the Energy Star qualification, it receives their stamp of approval. This stamp of approval tells the customer that the device they are looking at can save them money on electricity. LEED certified houses are buildings that are built or remodeled with a strict set of expectations set forth by the United States Green Building Council (USGBC). The expectations cover many areas of the home and how the home was built or remodeled, including how far away the material was sourced, what chemicals were used to create the home, and where any waste was disposed. Both of these systems cover efficiencies for lighting, heating and cooling, and even water protection. Both programs provide the homeowner with guidelines to help become more energy efficient, but the majority of homeowners need help in deciding what appliances, renovations and usage patterns need to happen in order to help the home become more energy efficient.

While most people aren't in a position to build a new home, they can still take advantage of the options to improve the energy efficiency of an existing home. One option is to have their home tested and rated on the HERS index. The HERS index was created to classify home efficiency based on a "reference home" created to model the home in question [2]. Another option would be to replace appliances within the home with energy efficient ones. This option allows the homeowner to pick and choose what appliances they think may need to be replaced. Their decisions will not always be accurate. If the homeowner had a way to establish the power usage of appliances in their home, they could calculate which appliances are costing them the most money and using an excessive amount of energy. Once the amount of power consumed by the appliance is determined, the homeowner can compare their appliance to a new one to figure out how much the efficiency difference is. The amount difference can then be multiplied by the service provider's price per kilowatt hour (¢/kWh). The calculated cost will then help determine if purchasing a new appliance is cost effective, meaning that the appliance will save the homeowner enough money quickly enough for the purchase to be considered a good replacement, or would only benefit the overall efficiency of the home. This way the homeowner could determine what they would like to do based off of facts and not assumptions.

The homeowner could replace appliances within the home in order to help reduce their house's overall energy consumption. If the homeowner had access to a database with information of the energy efficiencies of newer versions of appliances, as well as the current energy efficiency of their in home appliances, they could make an informed decision on replacing appliances Without a list of data, the homeowner could choose the appliances they believe are the most necessary to replace. Their assumption would be based upon what appliances they believe are using more energy than it should, appliances that have newer more efficient replacements available, and the price of the replacement appliance. If the homeowner had a tool to inform them of what energy the appliances are actually using, this could help them figure out which appliances to replace and in what order. On a larger scale, the homeowner could calculate the heating/cooling efficiency of their house. It is easier to establish the heating/cooling of a house that is just built with new appliances, but as a house gets older, air leaks can occur, making the HVAC system work harder. Over time appliances will become less efficient than when they were new. This is also exacerbated by the always increasing efficiencies of new appliances and insulation; while not making the house worse, it does increase the gap of energy efficiencies versus the new appliances.

If one was to take into account the specifications of their HVAC system, their windows (how many and the efficiency of them), and the insulation used within the house, they could figure out what their hypothetical energy efficiency would be in the house. This may not, however, reflect actual energy efficiency as there may be unforeseen variables and unknown circumstances such as leaks, insulation degradation, or geologic shifts. As a house ages, structural imperfections appear. They appear in the form of inadequate insulation and leaks. Blown-in cellulose was a common form of insulation during the 1970's due to the oil embargoes causing other forms of insulation to be hard to get or expensive. The main drawback with this type of insulation is that air moves easily through the low-density material [3] [4]. Fiberglass is another type of popular insulation material. If installed incorrectly, it can be a poor insulator. When compared to blown-in cellulose, fiberglass has a lower overall thermal efficiency, and the thermal resistance (R-value) is smaller [5]. R-value is the difference in temperature across an insulator divided by the Heat Flux Density (the amount of heat transferred over a unit time and unit area). A material with a higher R-value works better as an insulator than one with a lower value. Unfortunately, after a house has already been built, there are not many areas where insulation can be added/changed. The locations that can be modified are limited to unfinished areas such as attics, garages and basements.

Even a well-insulated house can succumb to leaks. Leaks can occur around windows, doors and anywhere that materials change direction or type. Nature can also play a part when dealing with the creation of the structural imperfections. Constant weather changes (temperature, humidity, etc.) and geologic shifts are just some examples of these natural forces [4]. When addressing the problems of air leaks in a house, it is common to think about replacing doors and windows. The biggest culprits, however, are in the attic and basement of the house. A common area for leaks in the basement can be found along the top of the basement wall. This area is prone to developing leaks where the concrete wall meets with the wood frame of the house. Changes in temperature and humidity affect concrete and wood differently. An example of this is as humidity increases wood will swell more than concrete. Wood however, does not swell evenly, and a previous flat spot can now be uneven, creating gaps with the concrete. The outside air can seep in through the gaps or even let conditioned air out. There are other areas in a house that are prone to leaks, such as the attic hatch, plumbing vents, open soffits, recessed lights, furnace ducts, and the basement rim joists [6]. If a homeowner has an established energy efficient HVAC installed in their house, a simple to use tool could inform homeowners to energy inefficiencies within the home. It would not be able to tell them where exactly, but if their system is rated at a certain efficiency and is relatively new, then the homeowner would know that there has to be somewhere that the house is wasting energy. This could be through inadequate insulation/windows or air gaps that have been caused be geologic shifts or breakdown of sealants such as caulking around windows.

Monitoring the loads within a house or building would inform the owner what devices are using the majority of the energy in the structure. If the owner learns that the amount of energy consumed by their refrigerator is less than the amount of energy a new refrigerator would use, they would be encouraged to purchase a new one in order to reduce the total amount of energy their house consumes. They could also approximate when the new appliance would pay for itself.

A recently developed method for tracking energy use is called Non-Intrusive Load Monitoring (NILM). NILM is the method of monitoring power usage without having multiple sensors installed throughout the building. Using a sensor installed at the meter or inside the panelboard, NILM is able to decipher the power usage signatures of the devices within the building. Being able to calculate what devices are consuming electricity within the home makes NILM a remarkable method for keeping tabs on the efficiency of a home. Since it is installed either at the meter base or inside the electrical panel, it does not get in the way of normal everyday tasks. NILM can inform a homeowner of devices or appliances that are running when they are not supposed to be running, or they are running longer than they are supposed to. This will help the homeowner make decisions on what devices/appliances need to be checked or maintained in order make the house more energy efficient. Since the device is installed at the meter base or inside the panelboard, it can easily be installed in an already built home or during construction of a new home.

2. Background

Home appliances can be divided into two main categories, linear loads and nonlinear loads. Linear loads have no irregular harmonics in their current signature. The load impedance remains the same even as the voltage increases. This shows that they follow Ohm's Law (voltage applied equals the current in the system multiplied by the resistance in the system). Due to these characteristics, they can be easily plotted in a simple graph [7]. Linear loads are considered to be more conventional appliances/devices. Examples of linear loads are fans, motors and heaters.

Appliances/devices that have nonlinear loads utilize power electronic devices. Power electronics refers to the application of solid-state electronics to control and convert electric power. These appliances are considered nonlinear because when sinusoidal voltage is applied, the current signature produced is nonlinear, therefore, it is problematic to distinguish on a standard graph [7]. Nonlinear loads are made up entirely of devices created since the early 1990's. Examples of appliances/devices that have a nonlinear load are computers, fax machines, printers, newer refrigerators, televisions and electronic lighting ballasts.

The types of appliances found within the home can be broken down into smaller categories which include resistive appliances, pump operated appliances, motor driven appliances, electronically fed appliances, electronic power control appliances as well as fluorescent lighting. Some devices/appliances may have many functions that allow them to be in two or more categories. Resistive appliances comprise of the largest number of household appliances. Some of the characteristics of resistive appliances include no reactive power, no harmonic current signature and short transient. Examples of resistive appliances would be heating appliances such as cookers, ovens, the heating elements of dishwashers and washing machines, and incandescent lighting. Pump operated appliances are made up of appliances that use electric motors to run a pump. These appliances have a considerable amount of reactive power, a long transient upon startup, and odd numbered harmonic current signature. Examples include dishwashers, washing machine pumps and refrigerators and freezers. Motor driven appliances are made up of devices that are operated with a motor. They are similar to pump operated appliances, but are different due to their transients switching less. Examples of motor driven appliances include appliances such as the motor that spins the drum of a washing machine, kitchen mixers, and ceiling fans. Electronically fed appliances are low consumption appliances. Their transient has a very high amplitude and high harmonic current signature. Examples of such appliances are computers and televisions. Electronic power control appliances are increasing in popularity. Their characteristics vary depending on the power level they operate at. They include halogen lights and some vacuum cleaners. Fluorescent lighting has a two-step transient, high third harmonic current signature and considerable current-voltage phase shift [7]. NILM monitors are constantly working to decipher these types of loads.

NILM is still a relatively new method for tracking power consumption of individual devices or appliances. With NILM there is only one device that monitors all of the devices and appliances within the house. By comparing the current and voltage waveforms of the total load, NILM monitors estimates the number and the kind of individual loads that are turned on. This is done by a single monitor installed on the meter base or in the panelboard. Every appliance has its own power signal when it starts up and continues to run. This monitor deciphers the power signals

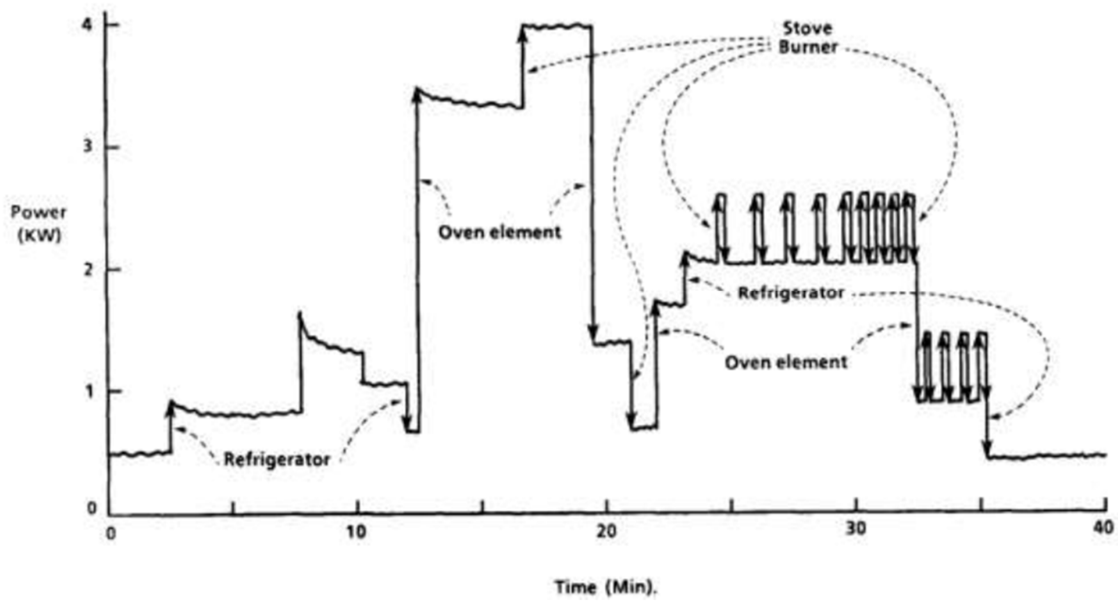

Figure 2: Power versus time graph during which different appliances turned on and off [8].

received and matches up the data with previously calculated waveforms for various devices/appliances [8].

The idea of NILM was first conceived by George Hart of the Department of Electrical Engineering. He and his research team discovered while looking at load

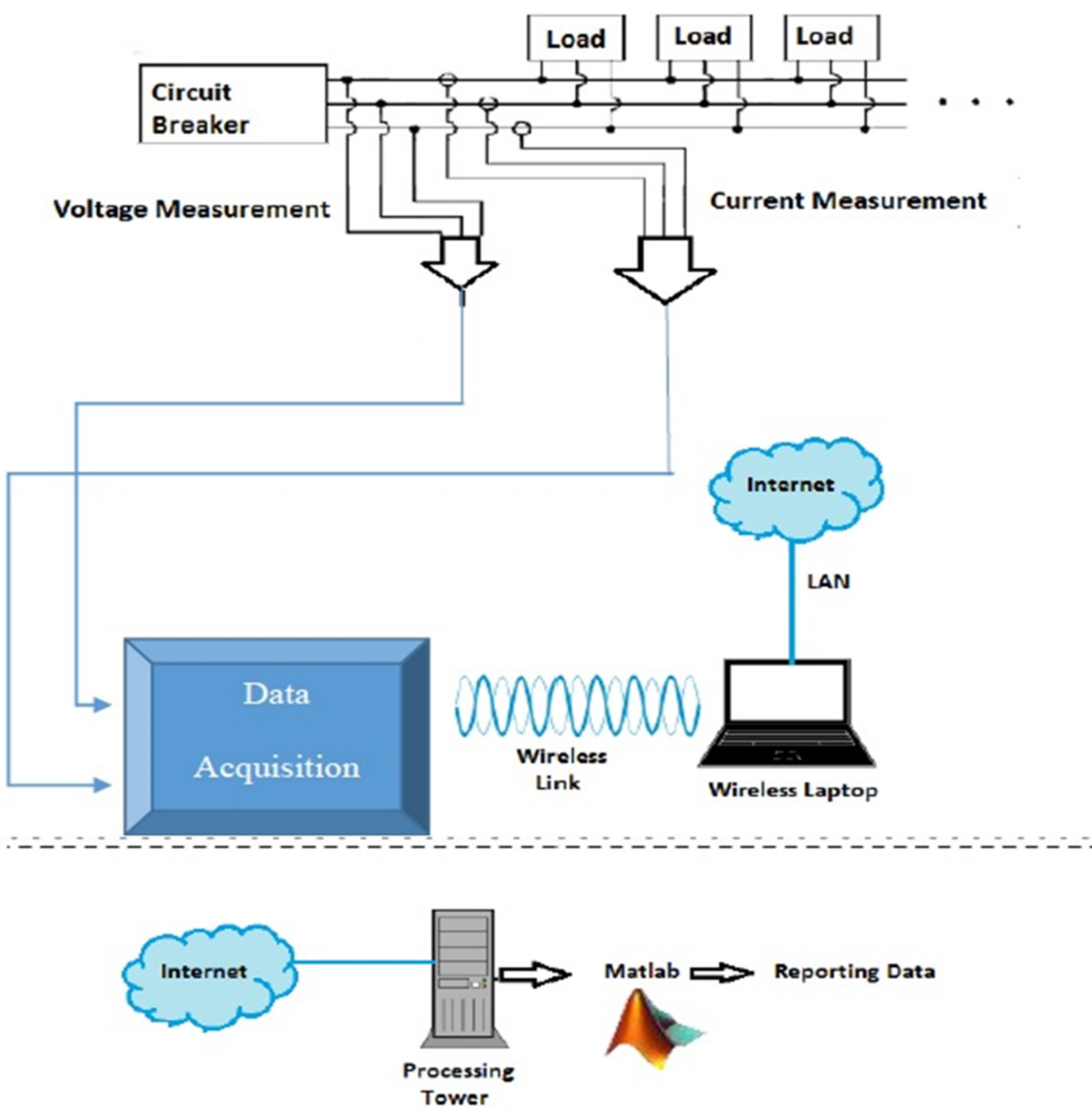

Figure 3: Block diagram of a prototype NILM system [18]

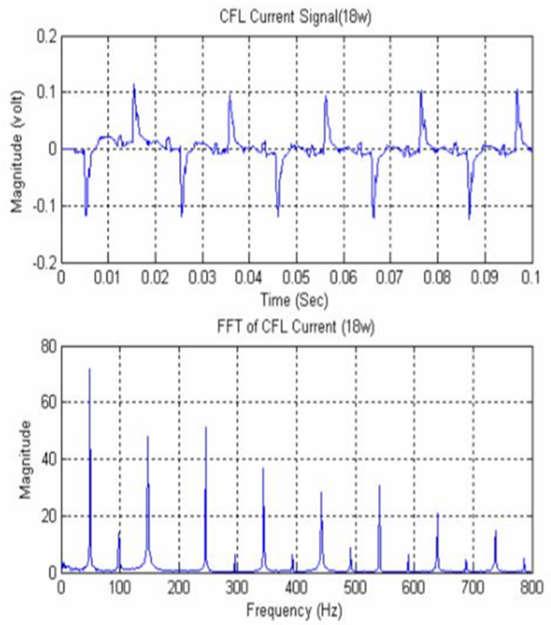

Figure 4: Compact fluorescent lamp current signal plot in time and frequency domain [7]

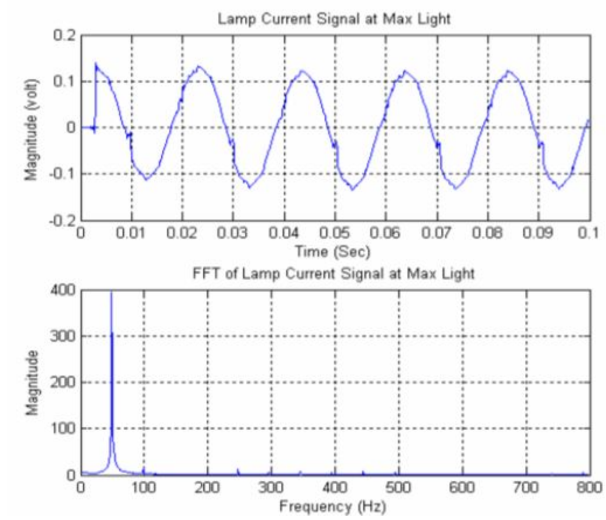

Figure 5: Lamp dimmer current signal plot in time and frequency domain when light is at full light [7]

data for a photovoltaic study that they were able to visually detect on/off events for major appliances in the home [8]. Events are discrete on/off occurrences that typically cause a change from one (nearly constant) state to another. In these instances, they are the measurements of electrical power. Recorded events with equal magnitudes and opposite signs are combined together to determine operating cycles and power consumption of each individual device [7].

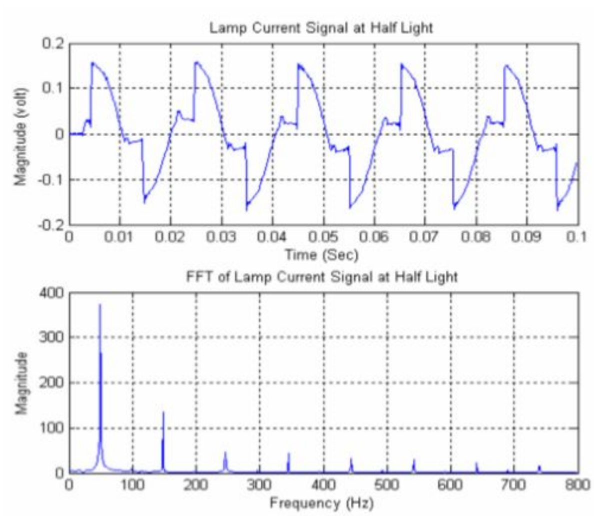

Figure 6: Lamp dimmer current signal plot in time and frequency domain when light is at half light [7].

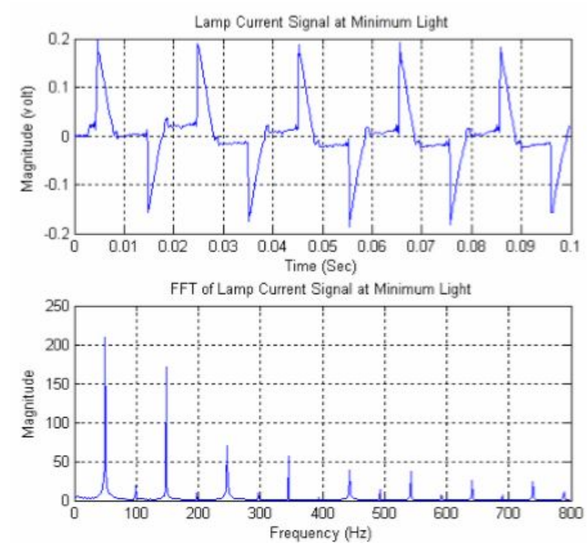

Figure 7: Lamp dimmer current signal plot in time and frequency domain when light is at minimum light [7].

There are some issues with deciphering certain types of devices. The increase in popularity of electronically fed appliances has led to an increase in confusion of the entire scope of power consumption of the house. Electronically fed appliances/devices utilize electronic power inverters which produce harmonics

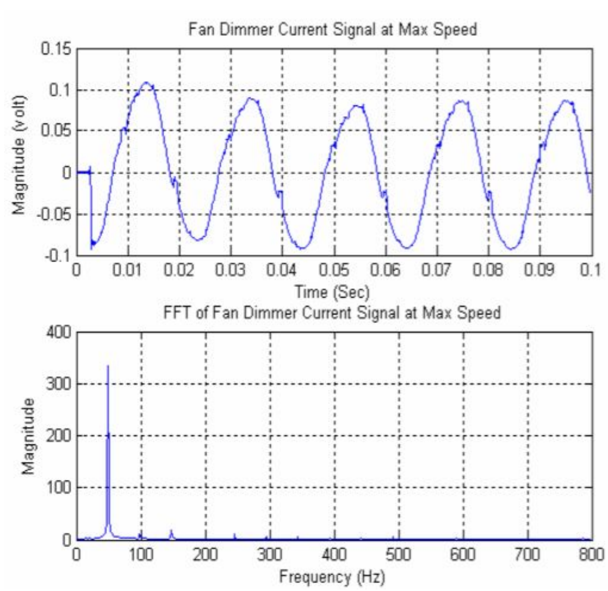

Figure 8: Fan dimmer current signal plot in time and frequency domain when fan is at maximum speed [7].

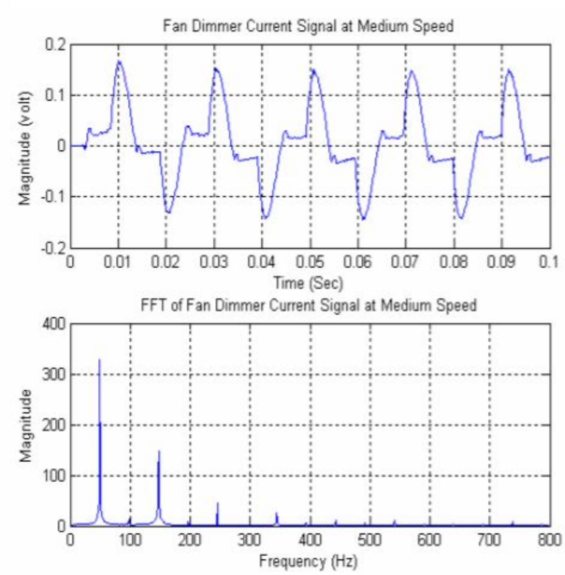

Figure 9: Fan dimmer current signal plot in time and frequency domain when fan is at medium speed [7].

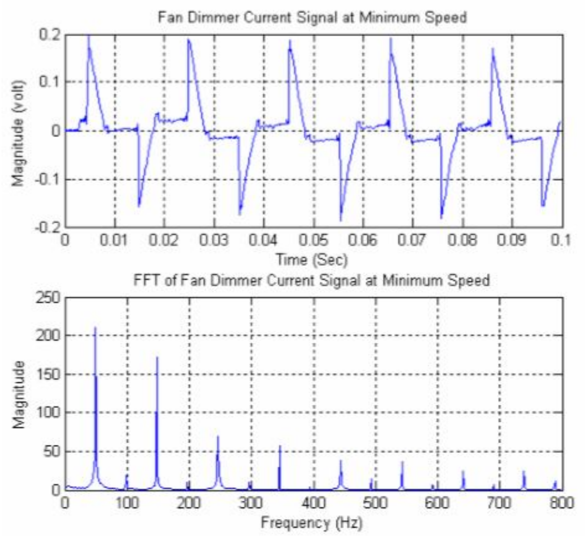

Figure 10: Fan dimmer current signal plot in time and frequency domain when fan is at minimum speed [7].

in the current waveform. In order to regulate the power, they use varying width pulses, which make it hard for any NILM system to distinguish which appliance/device has turned on or off. The width of the pulses is determined by the voltage and current. The electronic power inverter detects when the voltage fluctuates and increase or decrease the current pulse width accordingly. Likewise when it detects fluctuations in the current, it will adjust the voltage pulse width accordingly. Due to this, these devices are considered nonlinear as they are constantly changing positions on the ∆P-∆Q plane that is looked at for much of the NILM process [7].

Mahmood Akbar and Dr. Zubair Ahmad Khan of the Electrical Engineering Department from the University of Engineering & Technology in Lahore, Pakistan, worked with NILM to decipher these nonlinear devices. They developed an algorithm using the fast Fourier transform (FFT) for each event. Using devices that produce a nonlinear ∆P-∆Q plane, compact fluorescent lightbulbs (CFL) and dimmer switches connected to both light fixture and fan, they constructed a procedure to identify each device and help separate them from similar devices. They saw that the FFT for the CFL over a time span of 0.1 seconds was different from the dimmer switch during the same span of time (Figure 4). They also saw that the dimmer switch provided different results depending on what it was connected to. When connected to a light it produced greater harmonics than when connected to the fan (Figures 5, 6 and 7). They also discovered that when connected to the fan, the dimmer setup consumes greater reactive power than when connected to the light (Figures 8, 9, 10). When comparing dimmer setups, they made sure to compare in similar positions and used the same dimmer for both setups. They compared the FFT of the incremental current signal and the FFT of the signatures for the entire house during that timeframe [7].

Another group of people who have developed some work in the area of NILM is Nipun Batra and Amarjeet Singh from IIIT Delhi along with Kamin Whitehouse of the University of Virginia. Their work in “energy disaggregation” (NILM) proved that it can provide actionable feedback, which could lead to substantial energy savings. They evaluated 58 refrigerators in separate homes in order to figure out if their technique was viable. Their technique consisted of several different steps: finding baseline duty percentage, finding defrost energy, finding usage energy and finding baseline energy.

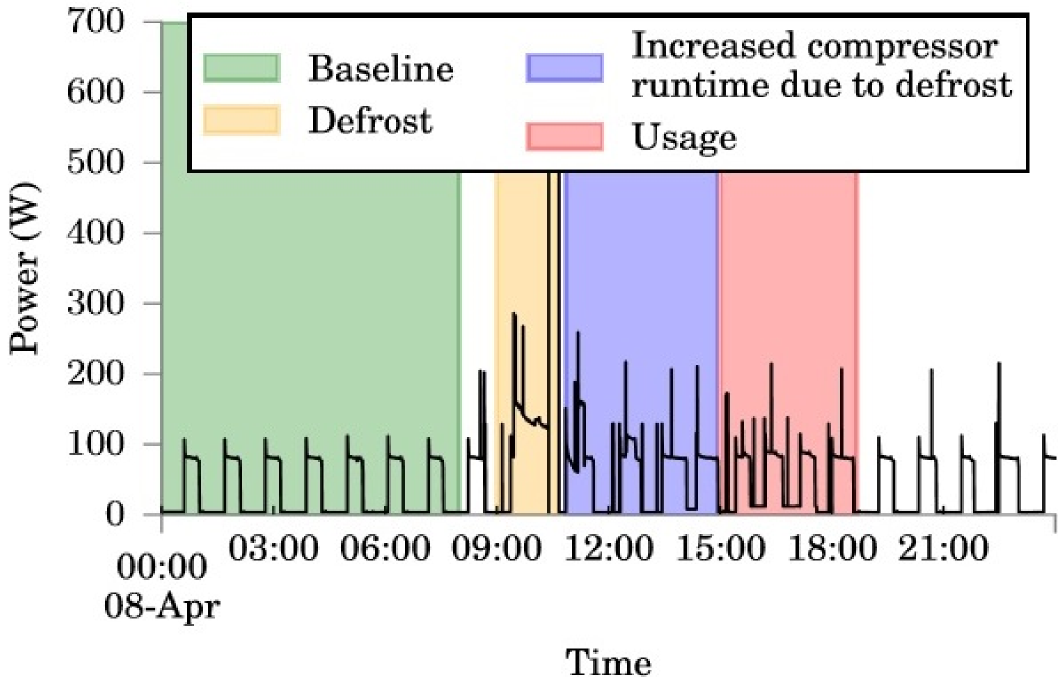

Figure 11: Break down of example refrigerator power consumption generated by Batra, Singh and Whitehouse [9].

For finding baseline energy, Batra and Singh, along with Whitehouse evaluated the times the refrigerator compressor was on and the times it was off. They decided the duty percentage was the starting point. In order to find this, they took the time the compressor was on and divided that time by the sum of the time on and the time off. They evaluated the refrigerator overnight during 1:00 am and 5:00 am to avoid any times when the refrigerator could be in excess use. Then they used the median of the duty percentage in order to reduce any outlying values.

Defrost energy is made up of two parts, the energy consumed while the refrigerator is in defrost mode and the additional energy needed by the compressor to regulate the temperature inside the refrigerator during the compressor cycle that follows the defrost mode. The energy consumed while the refrigerator is in defrost mode is easily evaluated. The additional energy consumed is obtained by the added duty percentage divided by the baseline of the compressor cycles that follow the defrost mode.

In order to find the usage energy, Batra, Singh and Whitehouse had to first find usage cycles. Usage cycles are considered to be the refrigerator cycles that are altered by actual refrigerator use. Then they had to remove all defrost cycles and the compressor cycle that follows each defrost cycle. Once those were removed, they looked for cycles that were higher than the baseline duty percentage. Finally they came up with a formula that involved the multiplication of several varying values. These values include the energy the refrigerator compressor uses, the sum of the duration of when the compressor is on and off, and the difference of the duty percentage minus the baseline duty percentage.

The final step in the procedure that Batra, Singh and Whitehouse created was to find the baseline energy. In order to find the baseline energy, they had to exclude all of the values that were affected by defrost and usage. This allowed them to compare the refrigerators of the different homes and to come up with the data they were after.

Using all of these steps, they were able to determine several values. They were able to decipher that the defrost cycle affects the next 3 compressor cycles. They also were able to determine that the percent higher than normal duty cycle ranged from 11-16%, which gave an energy usage error of less than 2%. This technique that they came up with allowed them to classify the refrigerators with 84% accuracy [9].

NILM is still a new area of research. Since George Hart and his research team first discovered that they were able to read certain patterns in the power waveform, new ideas and technology advancements are constantly being developed. The methods of deciphering the wave patterns and determining what device/appliance are continuously being improved and streamlined.

3. Sense Technology

One of the first commercial NILM monitors on the market is the Sense home energy monitor. This monitor is able to tell the difference in power consumption of most devices/appliances in the home. It knows that the current going through a fluorescent light bulb has sharp peaks and valleys whereas the current going through an incandescent light bulb has a smooth sinusoidal path. It uses a technique in which the algorithms are able to detect the electrical signature of each device and use that information to analyze the amount of power each device consumes as a part of the entire home's power usage profile [10]. It is also able to distinguish between two similar items, such as two refrigerators. Even though the two refrigerators may be of the same make and model (and therefore have the same current signature), it is unlikely that they are synchronized exactly, which would allow the monitor to distinguish between the two. The proximity of the device/appliance also helps the Sense monitor to distinguish between similar items. If there are two fans of exact make and model in a house, but one is wired in such a way that it is closer to the breaker panel than the other, it will have the same current signature as the other fan, but it will have a higher amplitude due to the strength of the signal.

The Sense monitor does everything outside of the panel wirelessly. The homeowner has to have wireless internet to which the monitor can connect. The homeowner also has to download the Sense app to their phone. Once it is downloaded, the app has to connect to the monitor and be activated. Once the monitor is activated, it will start to “learn” the homeowner’s house. The data is then transmitted to the homeowner’s smartphone and can be accessed with the app. With this data, the homeowner is able to monitor their power usage patterns within the house [10].

The Sense module is a plug and play module. Once the homeowner gets it started, it starts to “learn” the homeowner’s house. This can take a while as the number of devices in a house can be numerous. The learning is done without any intervention by the homeowner. While it is running, the module is taking 4 million recordings per second. With this high sampling rate, the data received provides information about the appliances within the home. When this information builds up over time, the Sense module is able to create a detailed library of device signatures, which helps the module to decipher the power signals. The learning process is hands off, so the module can observe the normal everyday occurrences of devices in the house under standard operating contexts. Many devices do not have just an on or off setting, but also operate at stages in between. A standard dishwasher can be on but have different motions going. The motor could be running, or it could be in rinse, drain or standby modes. The Sense module is programmed to realize certain patterns out of the box; for instance, it can take advantage of the fact that clothes dryers typically run after the clothes washer has stopped. Also, microwaves are normally run in increments of 30 seconds [11].

The makers of the Sense module are interested in anomaly detection. This is the detection of abnormal events that occur after a baseline has been established. Anomaly detection can help inform the homeowner of the change in habits of devices/appliances in the home. This information can help the homeowner decide if the object in question needs to be repaired or even replaced. This will lead to energy/cost savings and possibly prevent harmful events such as fire or gas leaks. If a refrigerator starts to malfunction, the appliance will defrost more frequently than normal. This will lead to extra energy being wasted while performing the extra defrosts and the following cool down in order to keep things cool.

HVAC units that are malfunctioning can use excess energy while running and can lead to homeowner discomfort. Gas furnaces can also show malfunctions. Even though gas furnaces are not fully electric, there are still several mechanisms that use electricity which can be detected. Gas furnaces have spark igniters, blower motors and inducer motors, motors that operate the inducer fan which help pull the heat from the furnace. If any of these have shorter run times or if the spark igniter is not sparking correctly, this can be detected by the module. If the spark igniter runs more than necessary before the blower motor starts, this can inform the homeowner that there could be an issue that could lead to a major problem, such as a gas leak.

4. Sense Evaluation

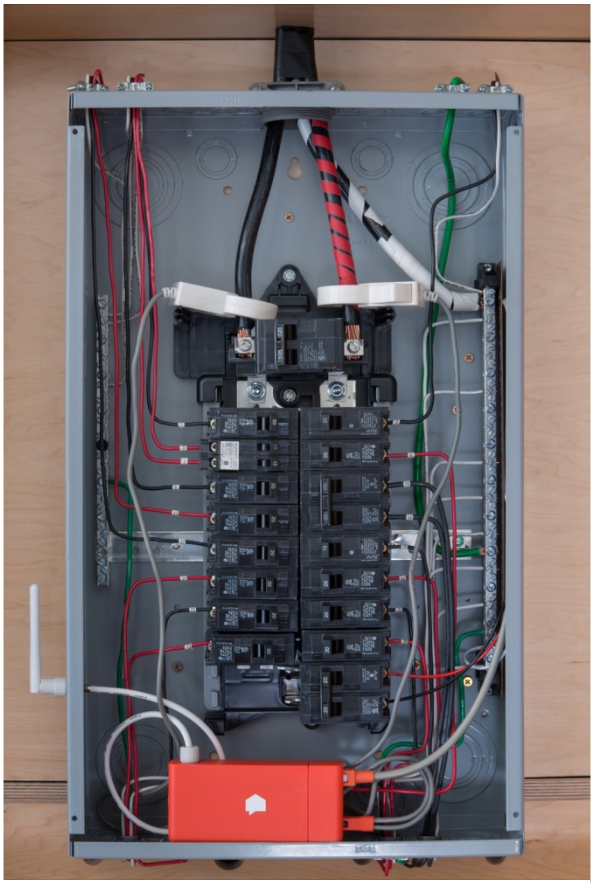

Figure 12: The Sense unit, shown installed in a conventional electric service panel [20].

The Sense device has been a breakthrough monitor for NILM technology. While it can inform the homeowner of many different things, there are additional things that are needed in order for a system that would notify the homeowner of ways to make their home more energy efficient. In order to make accurate comparisons, the homeowner would need to be able to see how much energy is used for a complete billing cycle. Currently, the Sense device only allows for daily breakdowns of power usage per device. It also is not able to distinguish when an appliance may be considered running but may be between cycles.

The setup for the evaluation of the Sense monitor is as follows: The monitor was setup in a two story house, with around 2,100 square feet and 8 foot ceilings. The house has a furnace that utilizes natural gas from the local utility company and also has a water heater that runs on the same natural gas. The monitor is installed into the breaker panel by using two current loops attached to the mains of the panel and also a connection to a 2 pole 30 amp circuit breaker per the manufacturer's requirement for minimal power. The monitor's wireless adapter is plugged in on one side and then it is installed through a knockout in the panel side. The monitor itself rests on the bottom of the panel and is hidden behind the panel cover.

In order for this evaluation to work, a way of accessing the data was needed. The only way possible was to go back day by day and record in Microsoft Excel

	December	January	February	March	April	May
Ameren	796	659	657	650	689	1162
Sense	798.9	657.8	577	651	366.8	355.6
	June	July	August	September	October	November
Ameren	1745	1713	1494	1375	769	702
Sense	1717.5	1769.1	1503.7	1396.5	777	694.4

Table 1: Power consumption, in kWh, collected from Ameren billing statements and from Sense

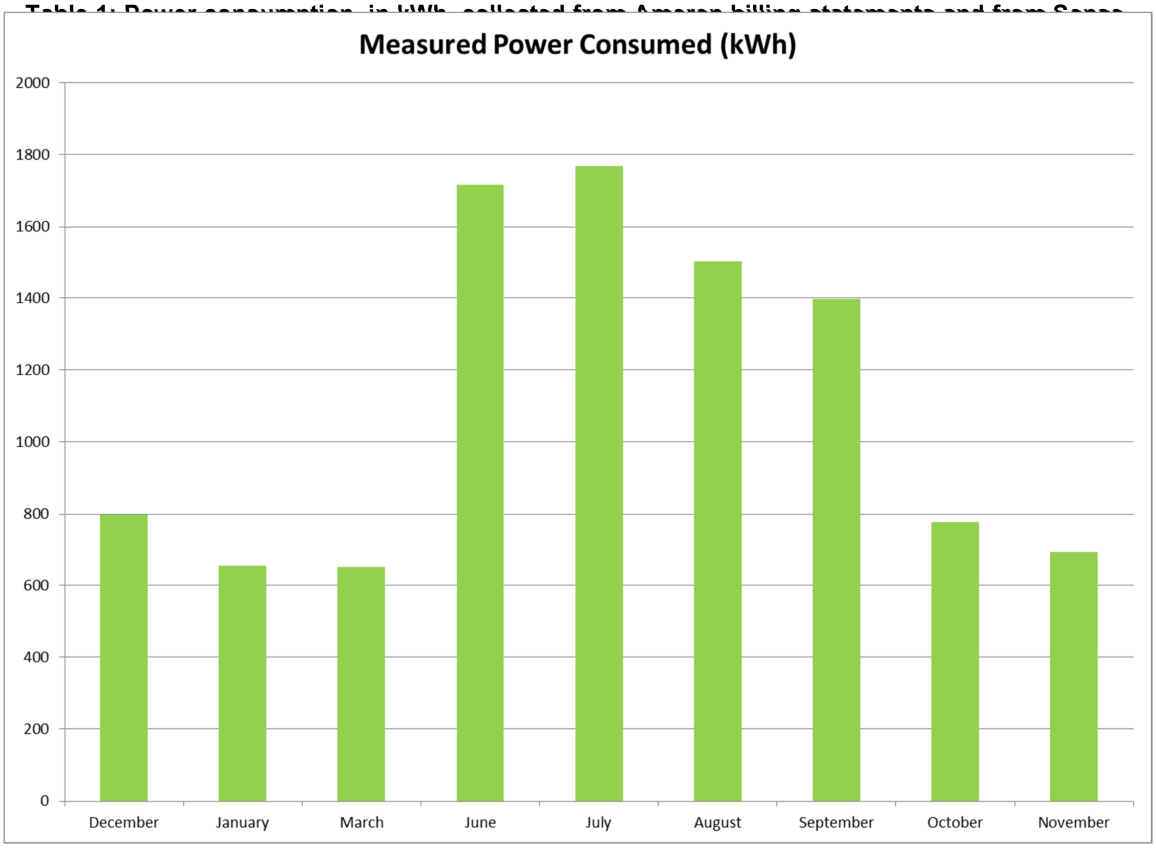

Figure 13: Power consumption, in kWh, as recorded from Sense monitor.

the data for each day. To evaluate the accuracy of the monitor, the data from the electric provider, Ameren, was then acquired. Ameren has the follow regulations set forth by the Federal Energy Regulatory Commission (FERC), and is also regulated in Missouri by the Missouri Public Service Commission (MPSC). The billing cycle for Ameren starts on the 21st of each month, therefore the data for each month collected from the Sense device was evaluated from the 21st of the month previous (Table 1). The data for each month was then graphed in order to give a visual representation of each month's power consumption (Figure 13). The Ameren data was also graphed for similar reasons (Figure 14). Then the two sets of data were compared to show how accurate the Sense device is (Figure 15).

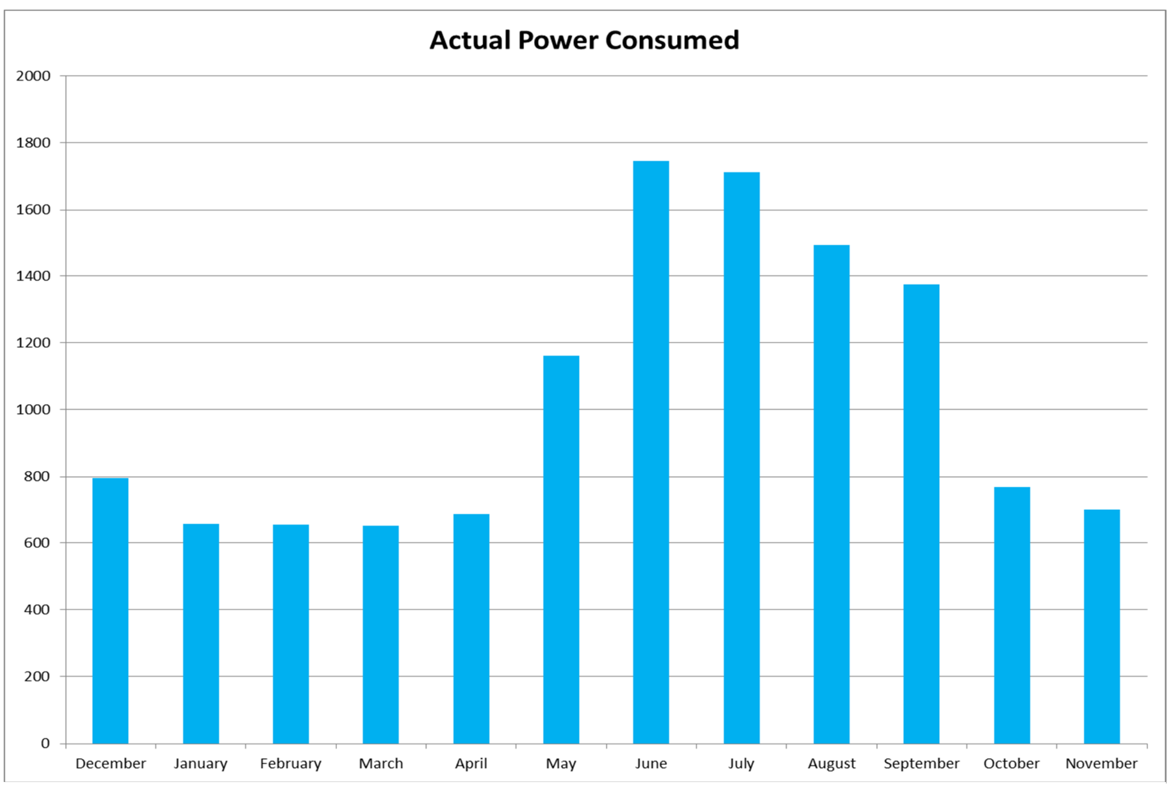

Figure 14: Actual power, in kWh, consumed as reported by Ameren

Table 2 illustrates the percent error for of the data collected from the Sense monitor compared to the data that Ameren reported. For accuracy sake the months of February, April and May were intentionally left out due to insufficient data

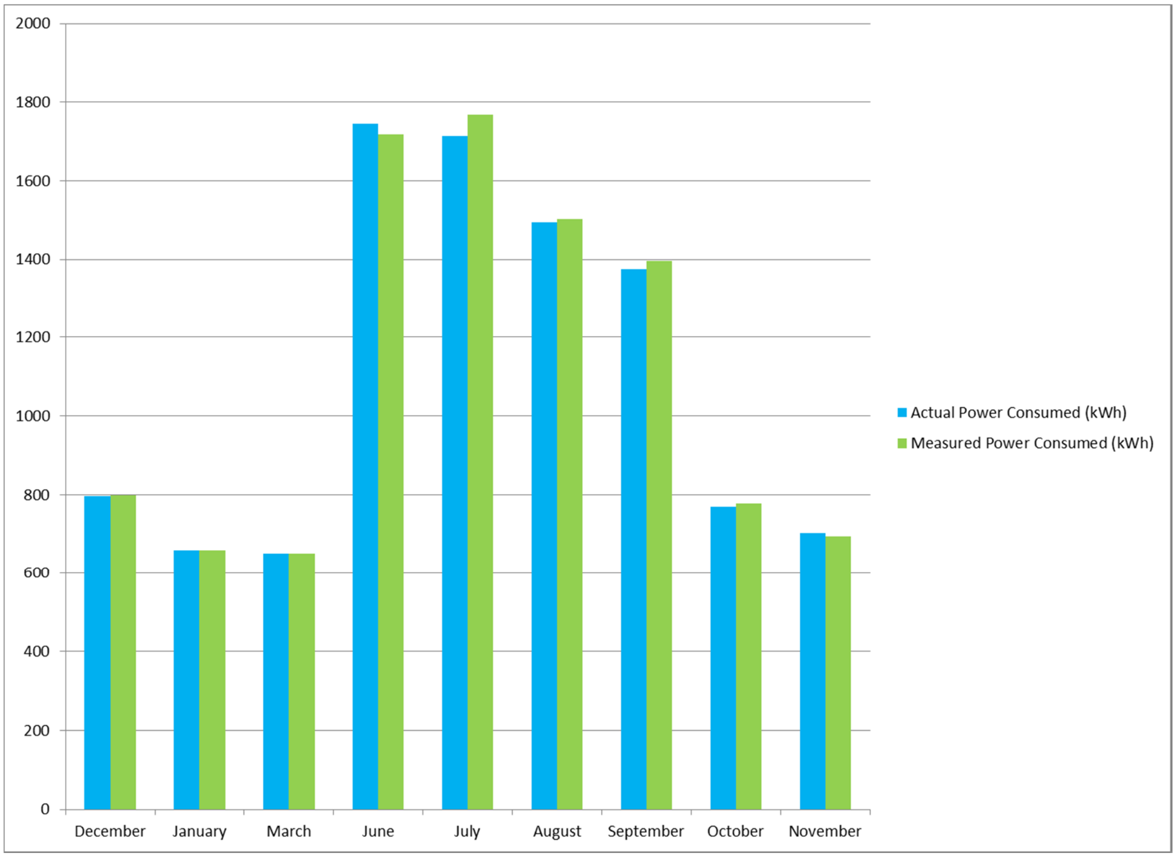

Figure 15: Data collected from Ameren (Actual Power Consumed) and from Sense monitor (Measured Power Consumed), illustrated side by side for comparison.

collected from the Sense monitor. For an unknown reason there were several days during those months when the device did not record any data. During the months of June and November, the Sense monitor measured less than what Ameren reported. For the months of January and March the Sense device was marginally off from

Percent	December	January	March	June
Error	0.36%	0.18%	0.15%	1.58%
July	August	September	October	November
3.27%	0.65%	1.56%	1.04%	1.08%

Table 2: The percent difference in data collected from the Sense monitor measured against data received from Ameren

what Ameren reported. For the remaining months, the Sense device measured higher than the Ameren data. The inconsistencies in the measured data when compared to the actual data from Ameren show that, while there is at most a 3.27% difference, the Sense device still has room for improvement when it comes to its measurements (Table 2).

From there, the data from the Sense monitor was examined for what devices were the main power consumers for each month. Due to the way the Sense app is set up to break down the usage per device, the method of data retrieval was changed to actual month usage, instead of adjusted to match the billing cycle for Ameren. In an attempt to simplify the amount of categories, all devices that used less than 1% of the total kWh used during the month were

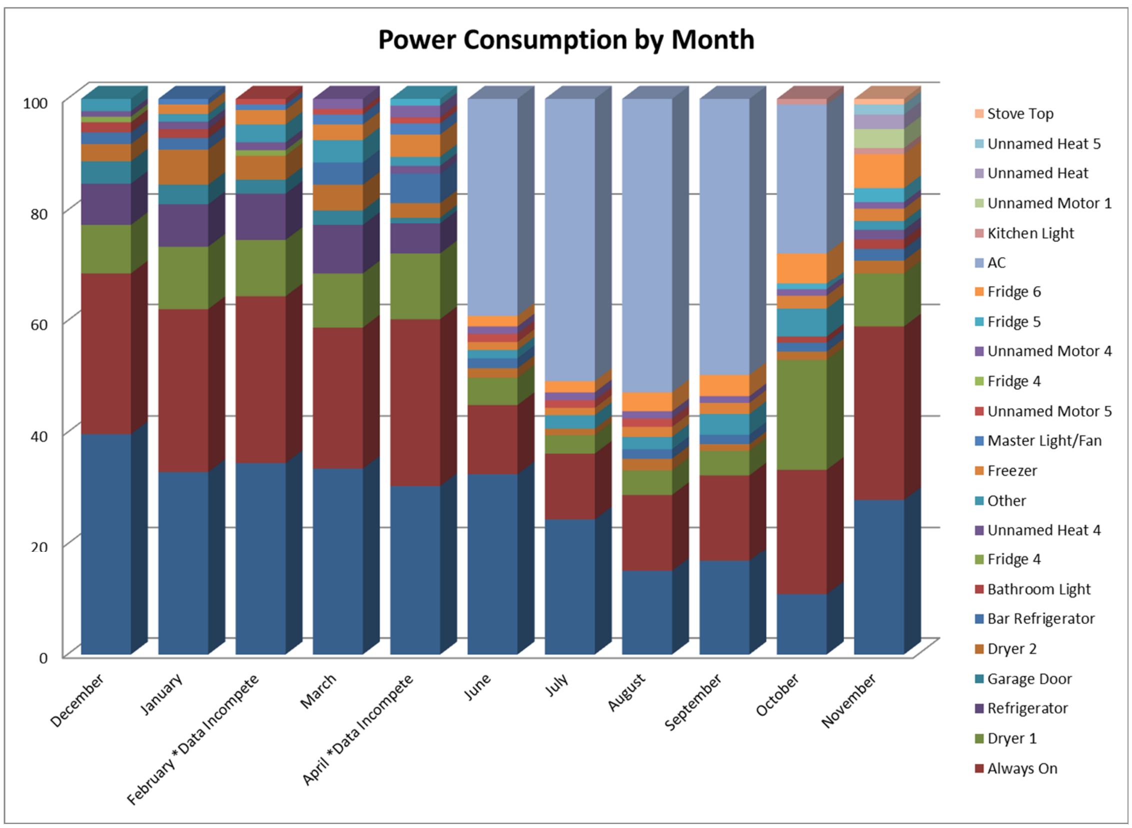

Figure 16: Chart showing power consumption by month of the different appliances/device that the Sense monitor learned. December 2016 through November 2017.

combined into the same category of Other. For ease of descriptions two other categories are listed: Always On and Unknown. The Unknown category consists of the devices/appliances in the house that the Sense device has not learned [sic] what they are. The Always On category consists of devices that take too much power to turn back on after they have been completely shut off. These devices are powered down to a standby mode. Some of these devices consist of televisions, computers, and video game stations. Other devices are ones that are continually draw power even while not in use. Examples of this type would be cell phone chargers, alarm clocks, and coffee pots. The months of February and April are included with the footnote showing the data is incomplete as a significant number of days are missing due to internet issues. The month of May is excluded since most of the days during that month were missing data.

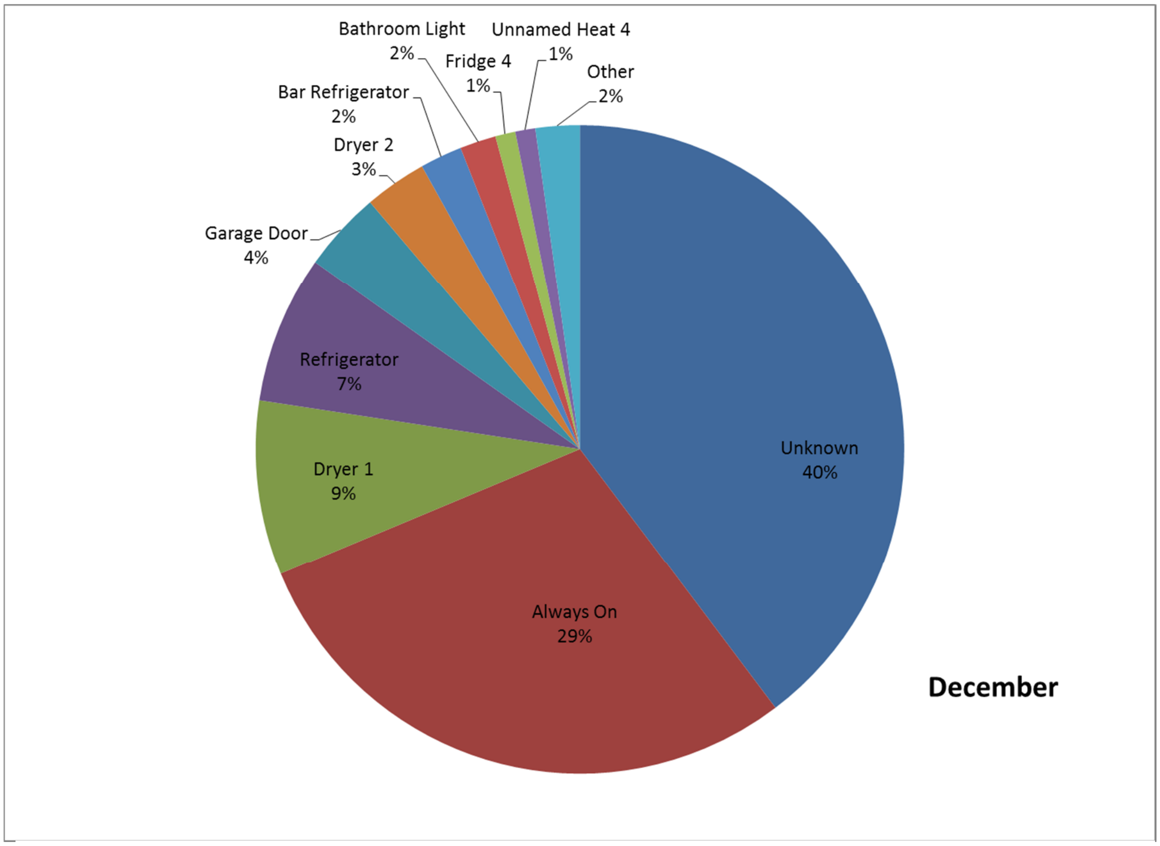

Figure 17: Pie chart showing the power consumption of different categories/devices in relation to percentages of the rest for the month of December 2016. Total kWh for the month, 692.5 kWh.

During the month of December 2016, the Sense device was still learning the house it was installed in (Figure 17). Due to this, the largest category is the Unknown category with 39.7% of the kWh used during the month. The second largest category is that of the Always On devices with 29% of the kWh used during the month. The devices that consumed the third (8.7%) and fourth (7.4%) largest amount of energy used are Dryer 1 and Refrigerator respectively. The rest of the devices as shown by the graph are Garage Door, Dryer 2, Bar Refrigerator, Bathroom Light, Fridge 4, Unnamed Heat 4, and Other.

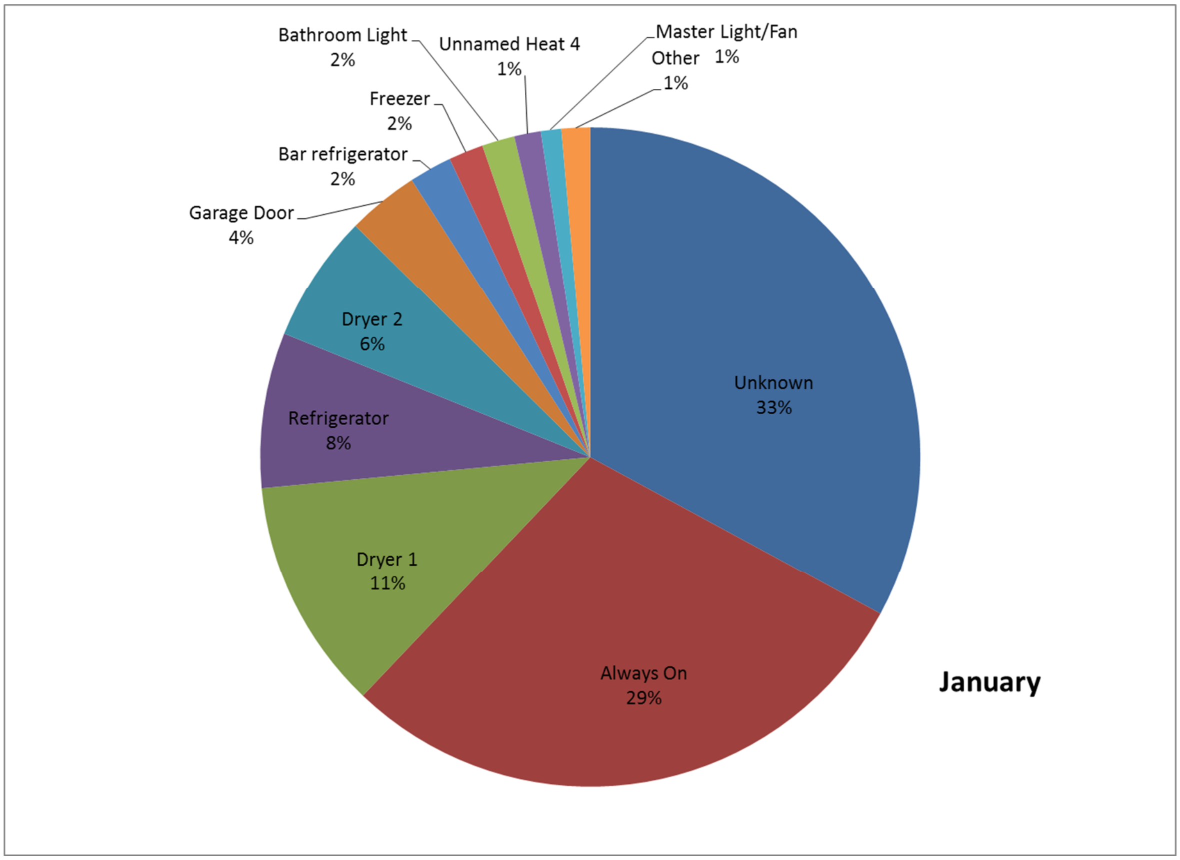

Figure 18: Pie chart showing the power consumption of different categories/devices in relation to percentages of the rest for the month of January 2017. Total kWh for the month, 722.2 kWh.

During the month of January 2017, the Sense device had learned more devices within the home (Figure 18). The largest consumer is still the Unknown category (32.9%) followed by the Always On category (29.2%). The Unknown category has shrunk, which makes sense as there has been more elapsed time for the Sense device to decipher more devices/appliances within the house. Dryer 1 (11.4%) and Refrigerator (7.6%) are still the third and fourth appliances. The remaining devices read similar to the previous month, but this time there is the addition of Freezer (1.7%), Unnamed Heat 4 (1.3%), and Master Light/Fan (1%).

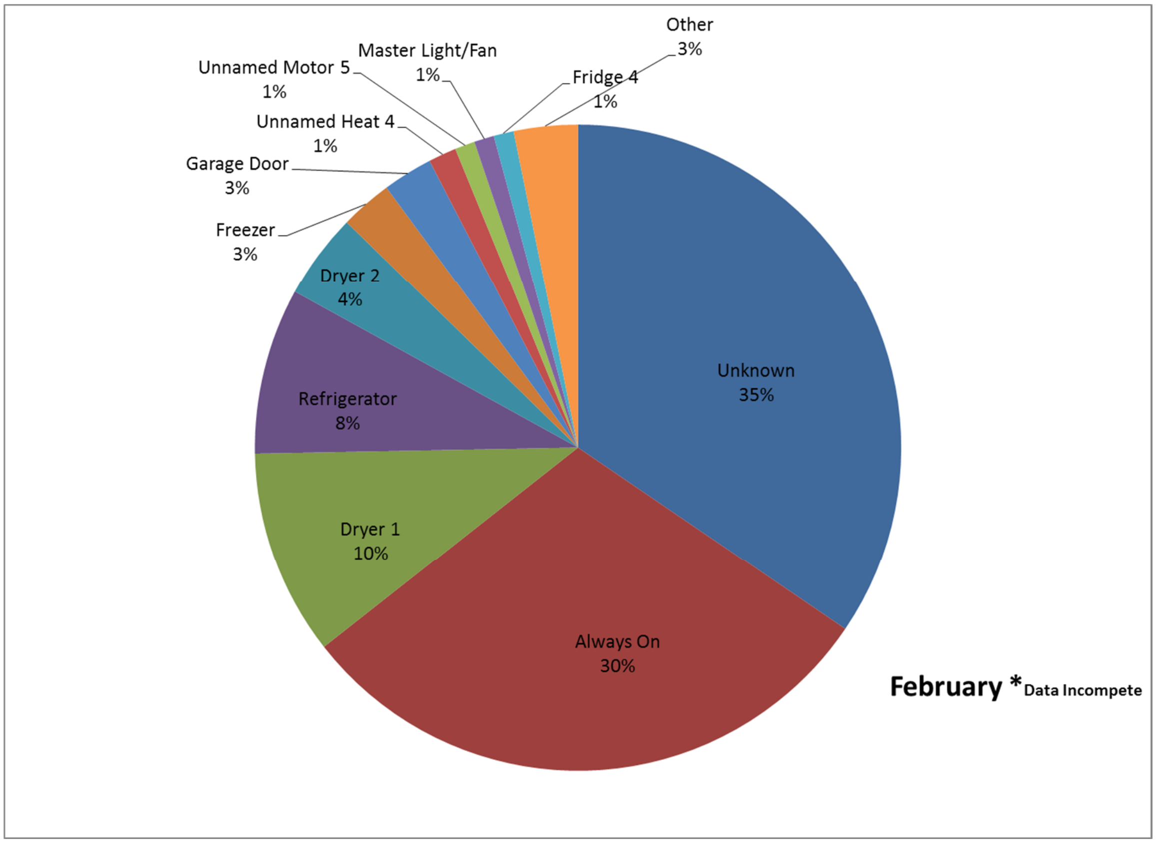

Figure 19: Pie chart showing the power consumption of different categories/devices in relation to percentages of the rest for the month of February 2017. Total kWh for the month, 612.1 kwh.

During the month of February 2017, the house the Sense device was installed in had internet issues and was unable to collect data during those days (Figure 19). The categories of Unknown (34.5%), Always On (29.9%), Dryer 1 (10.3%), and Refrigerator (8.3%) remain in the same order as the previous months. Unknown did increase in percentage, but this could be explained by decreased usage of other devices or due to the missing days. In comparison, Always On did remain at the same percentage from the previous month. The remaining devices were Dryer 2 (4.3%), Freezer (2.6%), Garage Door (2.5%), and Unnamed Heat 4 (1.4%). Unnamed Motor 5, Master Light/Fan and Fridge 4 are all tied at 1%.

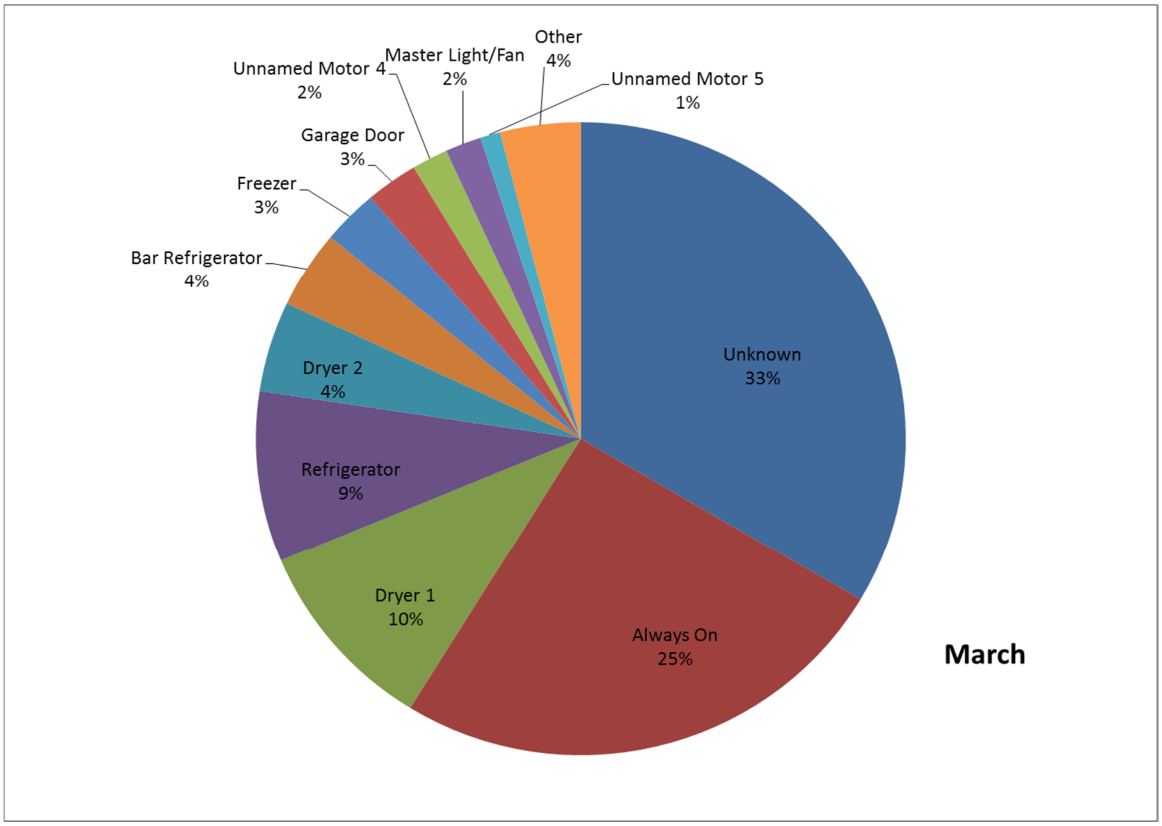

Figure 20: Pie chart showing the power consumption of different categories/devices in relation to percentages of the rest for the month of March 2017. Total kWh for the month, 631.3 kWh.

The month of March saw little change from the previous months at the top of the list (Figure 20). Unknown (33.5%), Always On (25.3%), Dryer 1 (9.9%) and Refrigerator (8.7%) in that order are still measured to be the largest energy consumers per month. The Sense monitor has found more devices, but it shows inaccuracies of what they are. There is only one dryer in the house it was installed in, yet it shows that Dryer 2 was the 5th largest consumer of electricity for the month. Instead of it being a dryer, it must be a device that has heating elements and motor similar to a dryer.

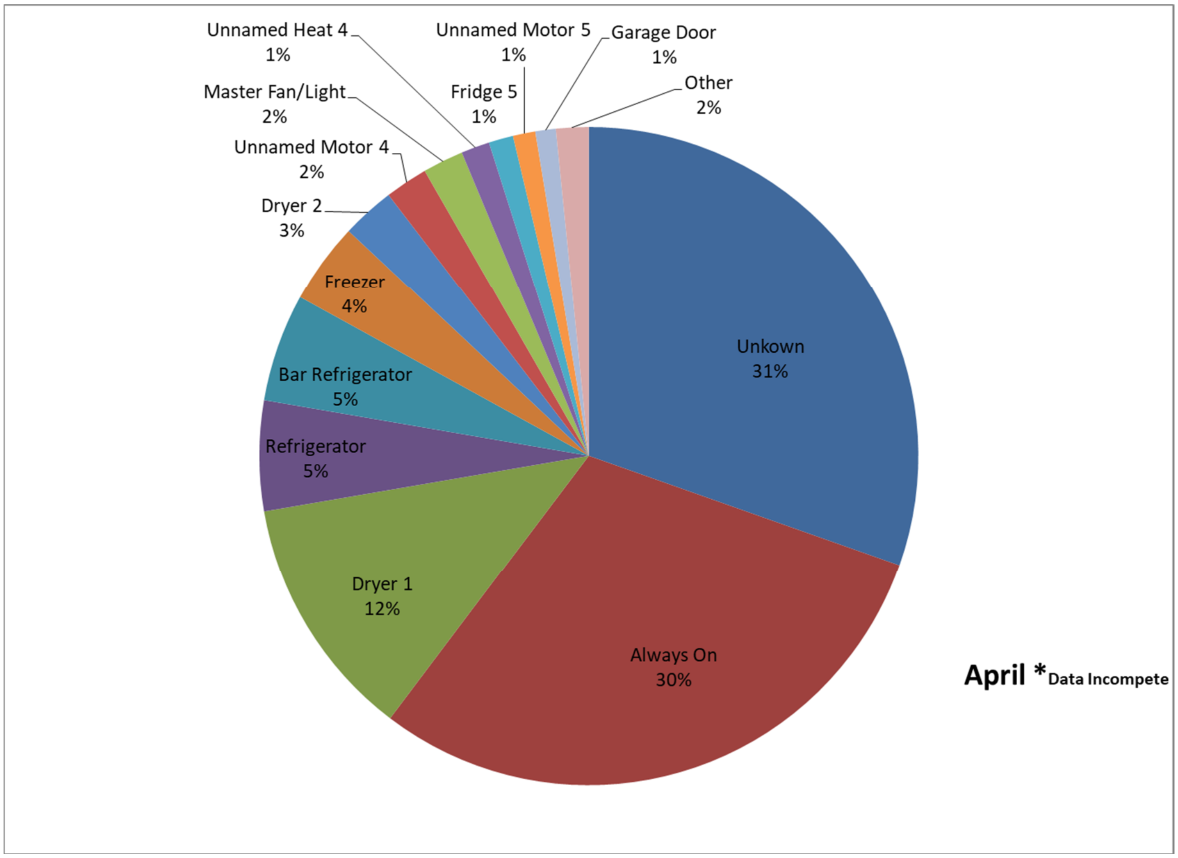

Figure 21: Pie chart showing the power consumption of different categories/devices in relation to percentages of the rest for the month of April 2017. Total kWh for the month, 615.9 kWh.

The month of April has incomplete data due to days with internet outage, but it was able to be collected for over half of the month (Figure 21).The data collected shows the continuation of the Unknown (31%) and Always On (30%) categories using the majority of the energy in the home. These two are still followed by Dryer 1 (12%) and Refrigerator (5%). Bar Refrigerator (5%) is followed by Freezer (4%) and Dryer 2 (3%). Unnamed Motor 4 and Master Fan/Light are tied at 2%. The remaining devices are all at 1%. There is little change during this month when compared to the previous months, even with the incomplete data.

The month of June was the first time the Unknown category was not the highest consumer (Figure 22). During this month, outside temperatures were warm

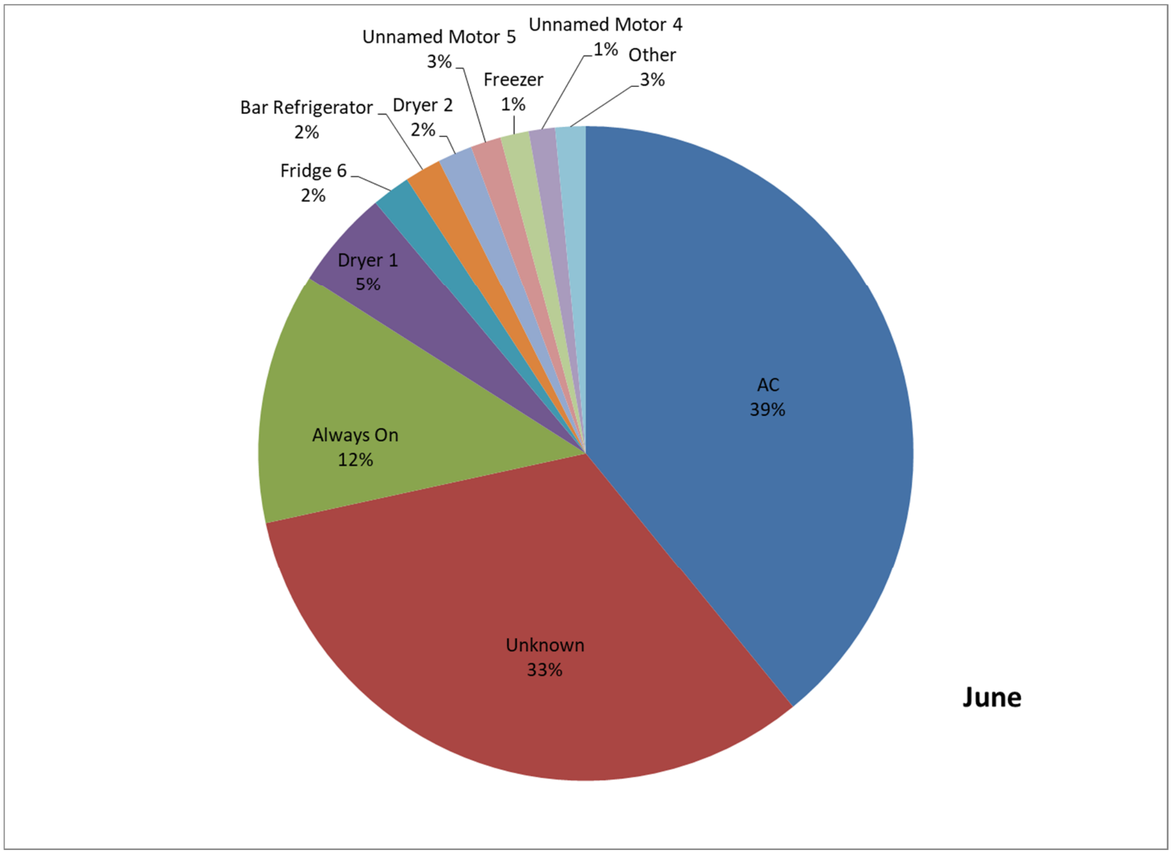

Figure 22: Pie chart showing the power consumption of different categories/devices in relation to percentages of the rest for the month of June 2017. Total kWh for the month, 1392.3 kWh.

enough for the necessity of the air conditioner (AC). It consumed 39% of the energy for the month. Unknown used 33% of the energy, while Always On used only 12%. This smaller amount for Always On could be from an increase in the total amount of energy used for the month and could also be due to an increase in the amount of devices the Sense Monitor has learned. Dryer 1 is next at 5%, while Unnamed Motor 5 came in at 3%. Fridge 6, Bar Refrigerator, and Dryer 2 are tied at 2% of the total for the month. The remainder is Freezer (1%), Unnamed Motor 4 (1%), and Other (3%). One item that stands out is the addition of Fridge 6. In the house there are only two refrigerators and two freezers. During this month the Sense device had forgotten the category of Refrigerator.

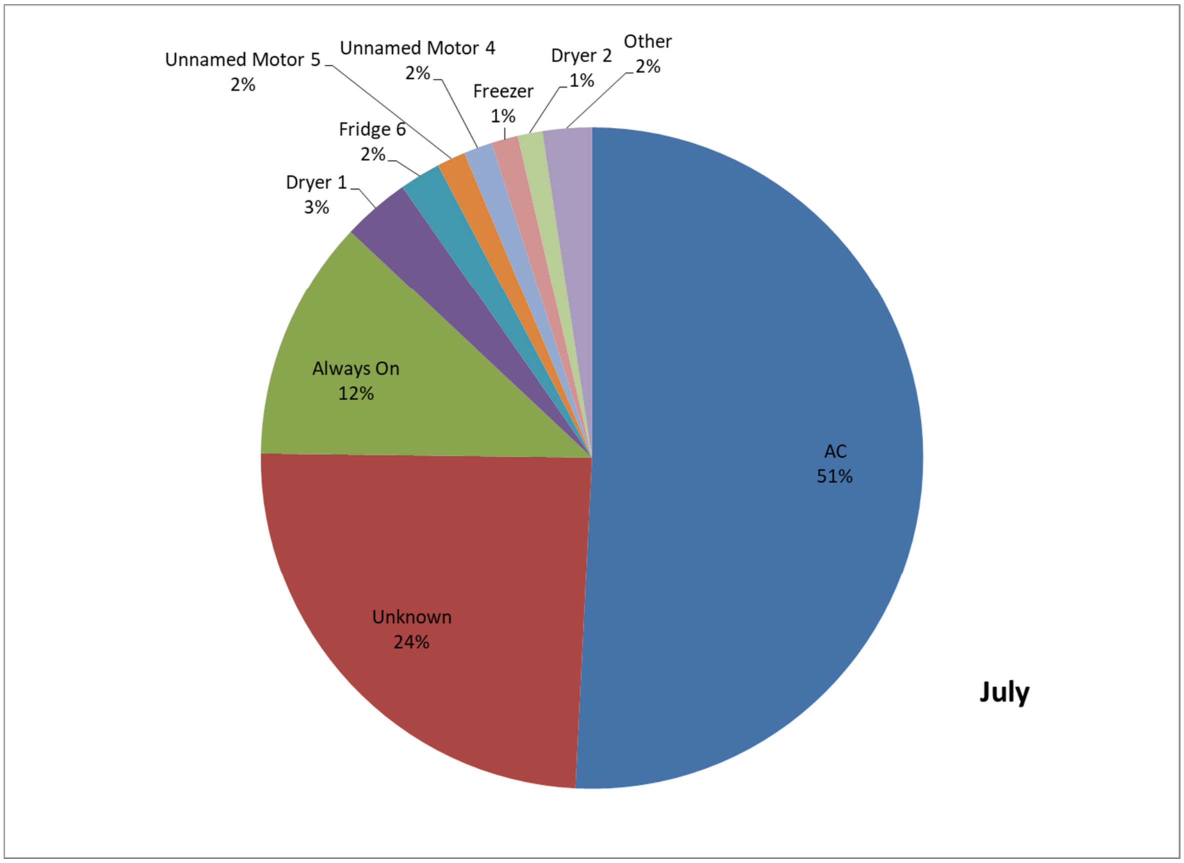

Figure 23: Pie chart showing the power consumption of different categories/devices in relation to percentages of the rest for the month of July 2017. Total kWh for the month, 2003.1 kWh.

The month of July was the first time a single category consumed more than half of the total energy used during a month (Figure 23). AC used 51% of the energy used for the month. This would be due to high outside temperatures during summer. Unknown comes in at 24% and Always On at 12%. These two have been consecutively in this order, showing that even after 7 months there still are a number of things this device has not learned. Next is Dryer 1 with 3%, followed by Fridge 6, Unnamed Motor 5, and Unnamed Motor 4 all at 2%. Freezer and Dryer 2 used 1% of the total energy used for the month. The remaining devices/appliances in the category Other used 2%.

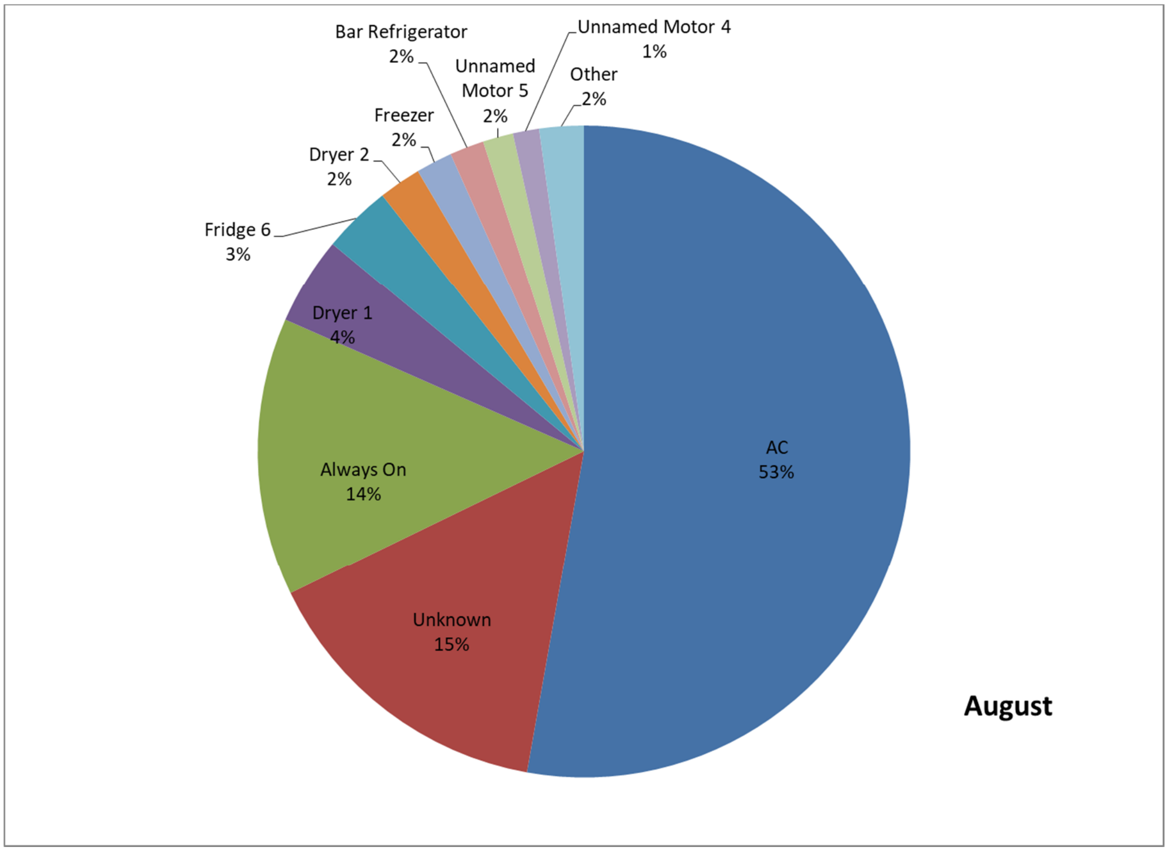

Figure 24: Pie chart showing the power consumption of different categories/devices in relation to percentages of the rest for the month of August 2017. Total kWh for month, 1513.0 kWh.

During the month of August, the largest percentage of energy consumed by one category for a month was measured (Figure 24). AC was measured to consume 53% of the total energy for the month. With that the Unknown category percentage going down considerably (15%) and the Always On category percentage staying around the same value (14%), it could be described that the Sense device started to identify more appliance/devices within the house. Dryer 1 (4%) and Fridge 6 (3%) are still next in line followed by Dryer 2, Freezer, Bar Refrigerator, and Unnamed Motor 5 at 2%. Unnamed Motor 4 was measured at 1% of the total energy consumption and the final percentage (2%) is made up of everything else in the house (Other).

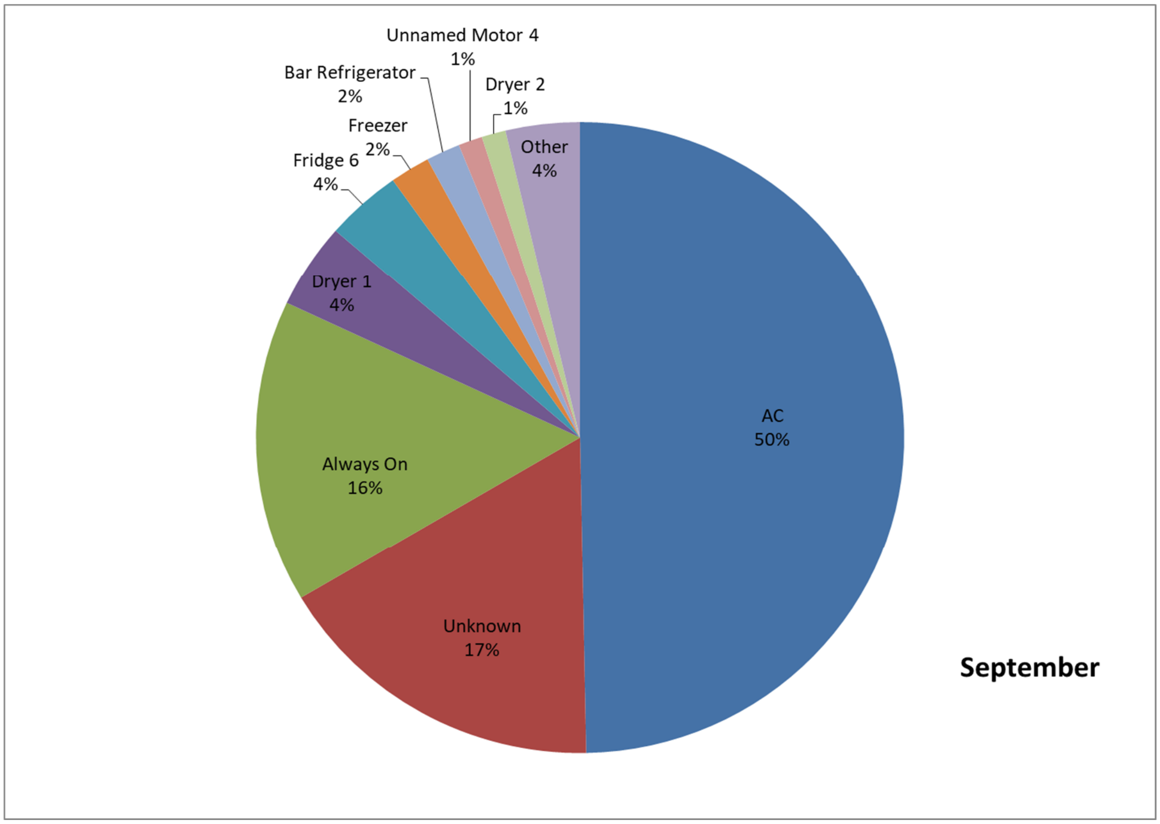

Figure 25: Pie chart showing the power consumption of different categories/devices in relation to percentages of the rest for the month of September 2017. Total kWh for the month, 1449.8 kWh.

The month of September had no real change in the order of the categories (Figure 25). AC used 50% of the total energy consumed for this month, while Unknown used 17% and Always On consumed 16%. These are again followed by Dryer 1 and Fridge 6, both consumed 4% of the energy used during the month. Freezer and Bar Refrigerator both used 2%, and Unnamed Motor 4 and Dryer 2 consumed 1%. The remaining, Other, used 4% of the total energy for the month.

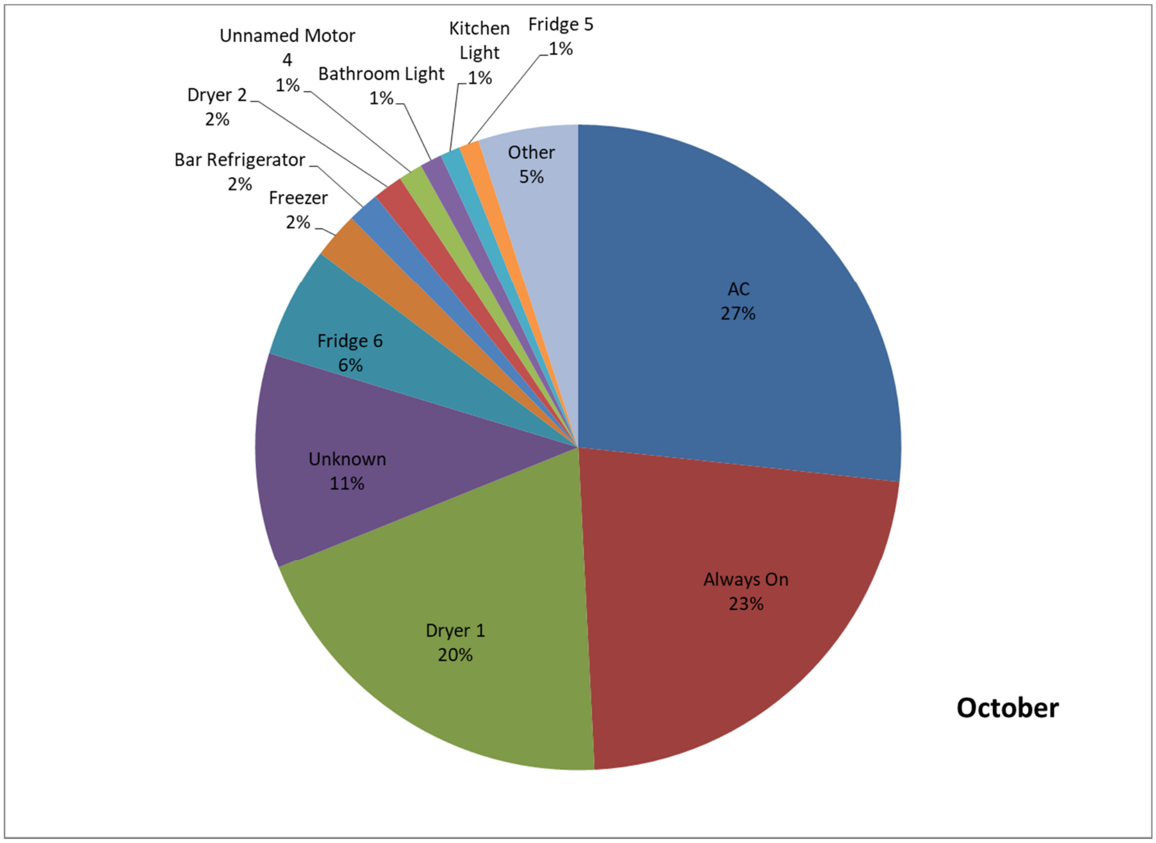

Figure 26: Pie chart showing the power consumption of different categories/devices in relation to percentages of the rest for the month of October 2017. Total kWh for the month, 1002.8 kWh.

The month of October saw some change over the previous months (Figure 26). Due to lower outside temperature, the Air Conditioner was not needed as much as previous months to cool the house. This led to AC still having the largest percentage of energy consumed, but only at 27% of the total energy used for the month. Always On (23%) was the second largest category for the month. Dryer 1 (20%) used more than Unknown (11%) for the first time during the evaluation of the Sense monitor. Fridge 6 was measured to use 6% of total energy consumption for the month. These categories are followed by Freezer, Bar Refrigerator, and Dryer 2 at 2% of the total energy consumed each. Unnamed Motor 4, Bathroom Light, Kitchen Light and Fridge 5 all used 1% each, and the remaining 5% was consumed by devices in the Other category.

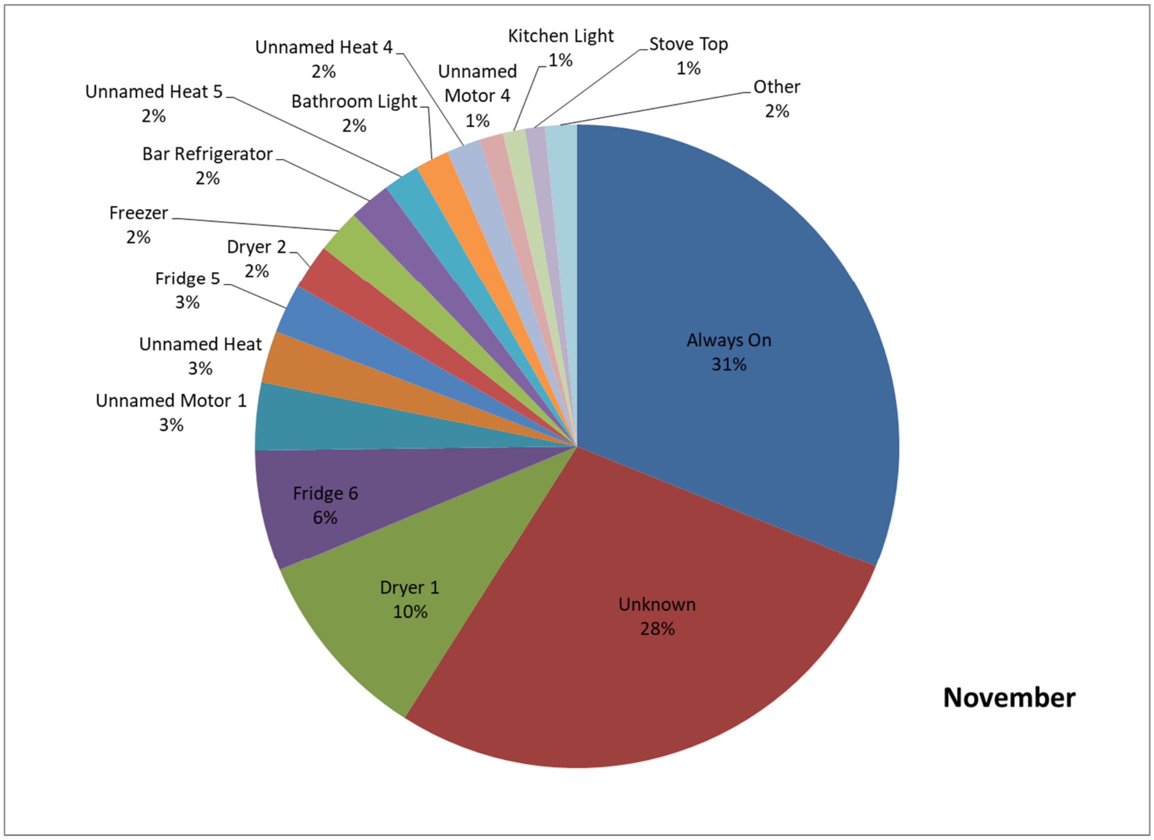

Figure 27: Pie chart showing the power consumption of different categories/devices in relation to percentages of the rest for the month of November 2017. Total kWh for the month, 674.9 kWh.

For the final month of the evaluation of the Sense monitor, November showed the largest amount of devices/categories that consumed 1% or more of the total energy (Figure 27). Always On (31%) consumed the most energy for the month and was followed by Unknown (28%). Dryer 1 and Fridge 6 are the next largest consumers of energy at 10% and 6% respectively. There are three devices that each consumed 3% of the total energy for the month, Unnamed Motor 1, Unnamed Heat, and Fridge 5. They are followed by Dryer 2, Freezer, Bar Refrigerator, Unnamed Heat 5, Bathroom Light, and Unnamed Heat 4. Each of these devices/categories used 2% of the total energy for the month. Unnamed Motor 4, Kitchen Light, and Stove Top each used 1% of the total energy of the month. The remaining 2% falls into the Other category.

After comparing the accuracy of the Sense monitor with the measurements from Ameren and looking at the breakdown of the monthly energy consumption per device, many issues were found. One issue would be the difficulty to gather or export the information from the monitor to Microsoft Excel or another spreadsheet program. Having this capability would allow the homeowner to have a readout of the current energy consumption and the possibility to compare with previous months and years. Having the data readily available per device could show the homeowner if a device is consuming too much energy since they would be able to see the data from previous times. If the device could send weekly and monthly readouts and summary reports to the homeowner, they may not need to export the data. The app already has the ability to email or send a push message to the homeowner's phone, it would not be much of a stretch to have it do the summary reports as well.

If the homeowner has purchased the Sense device as a way of keeping track of appliances and devices that may not be functioning properly, it still has room to improve. The device does not have a setting to inform the homeowner when a device has been consuming more energy than usual. An example of how this ability could be useful would be if it could inform the homeowner that their refrigerator has been consuming more energy than usual. An advance form of this ability would be for the Sense device to notify the homeowner if it believes the refrigerator door has been left open in order for them to be reminded to close it. It would also be able to inform the homeowner of possible security issues. If the garage door opener was only turned on once to open the garage door and the device does not see a second instance where the garage door opener would be closing the garage door, it could then inform the homeowner that the garage door may be left open. Another example would be if the HVAC system has been running for an extended period of time or has been running more frequently it would be able to inform the homeowner that a door or window may have been left open. With this knowledge, the homeowner could feel more confident in the safety of their home, whether they are present or not.

Another issues for the Sense device is the length of time it takes for the device to learn the house. It does not automatically know what devices are running in the house. It takes a few weeks to begin to understand the patterns in the house and decipher what may be running. The monitor starts with one category, Unknown, and soon after has one called Always On. The Always On is the catch-all for items that are constantly drawing power even if the homeowner believes them to be turned off. The monitor has currently been installed in the house for 15 months and new devices/appliances are still appearing, which uncovered another issue. Some of these new devices that have been found are ones that it had previously known. Refrigerator Light is an example of when this happened. It was one of the first items learned by the Sense Monitor and designated Unknown Light 1. It was figured out that the light in question belonged to the light inside the refrigerator and then named Refrigerator Light. It was then rediscovered in September as Unknown Light 4 and was found to be the light inside the refrigerator. The Sense app was verified to see when the previous iteration of the refrigerator light had last ran, only to find the app said it had been off for 5 months.

It is not currently understood as to why they are viewed as a new devices and the previous found versions are no longer valid devices, which is to say that they no longer are able to produce data. Another form of the inaccuracy of the monitor is the detection of more of one type of device/appliance than there is in the house. An example of this happening is Dryer 1 and Dryer 2. In the house of installation there is only one dryer and it has been determined to be Dryer 1. It is currently unknown what device/appliance is Dryer 2.

There is also an issue of accuracy for each newly found device. One issue with accuracy is device/appliance run time. As many appliances have different cycles or multi-functions, the Sense device is unable to understand that even though a certain motor has stopped running the device may have heating coils that may have turned on. An example of an appliance with this setup would be a dishwasher. Another accuracy issue is the initial description of newly found device. When it finds a new device it tells the homeowner what it believes the device is. Then the homeowner can set up to be notified when this device turns on in order to help find out what the device actually is. If it believes the device is a light or something controllable as such, the homeowner is able to turn on the lights one by one and see if the device pops up as being turned on. Some of the initial descriptions are vague, Unnamed Motor and Unnamed Heat are examples of initial descriptions that do not give the homeowner much in terms of clues as to what the device/appliance could be. If the homeowner is able figure out what the device is and where it is located, they are able to label where the device is located in the house and even input make and model of the device. This information is simply for the homeowner's use and not for use by anyone else.

Though there are many shortcomings with the Sense device, it still has great potential. It was able to successfully determine the type of device (light, heat, motor, etc.) on the devices it learned. The installation of the Sense monitor was very simple and the setup of the app was straightforward. The app itself is easy to navigate. It has the ability to send push notifications to notify the homeowner when a certain device or appliance has turned on. The Sense device's overall accuracy of the power consumption was just off of the actual amount measured by Ameren. The month with the largest difference was July, with only 3.5% off of the Ameren measured amount.

5. Conclusion

In order for the Sense device to be considered reliable, the accuracy of its measurements (what device is on and if there are multiple functions for the device) would need to be improved and then certified by a third party. Ameren is regulated by FERC (and by the MPSC in Missouri), and in order to maintain confidence in the data, the Sense monitor needs to be regulated by an outside party to insure accuracy of its measurements.

The Sense monitor still has many aspects that need to be developed if it wants to a worthy addition to many homes. Decreasing the time it takes to learn devices/appliances within the home and then retaining them are two areas where the Sense monitor can improve. Enabling the Sense monitor to notify the homeowner when a device/appliance may need to be replaced due to using more energy than what may be normal would help add inherent value to the purchase of the monitor, as would allowing the homeowner to export data into a spreadsheet in order to keep record of previous data. Allowing for easier dissemination of the data that the monitor collects would help inform the homeowner of instances when abnormal events happen (refrigerator door or garage door being left open).

If the Sense monitor is able to improve on its faults, it can become a useful tool to a homeowner. It would be able to inform them of ways they could decrease their homes overall energy consumption. It would also inform the homeowner of potential security risks. It would have the ability to potentially detect if windows or doors were left open by examining the habits of certain devices within the home.

In its current status, the Sense monitor is not a miracle device. It utilizes the NILM phenomenon that George Hart and his researchers discovered to decipher what devices/appliances are running within a building. It has potential to be a useful instrument, and with possible updates to the app for the device many of these faults, if not all, can be overcome. If this happens then the Sense monitor will be a valuable tool for decreasing the energy consumption of a house.

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