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Disaggregation of Residential Electric Loads Using Smart Metered Data

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Disaggregation of Residential Electric Loads Using Smart Metered Data

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Abstract

Disaggregation of Residential Electric Loads Using Smart Metered Data

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The ability of typical utility meters and advanced meters including sub-circuit metering to disaggregate residential electric loads and determine what appliances a homeowner is using at a given time is investigated. The basics of residential electricity systems, instrumentation options, and characteristics of selected residential loads are presented. This information informs a discussion of present and future disaggregation algorithms. The conclusions highlight the importance of reactive power and current harmonics in determining power consumed and identifying modern electrical devices, and raise concerns related to the ability of typical 15 minute interval utility smart meters to disaggregate loads.

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Introduction

The continuing deployment of increasingly advanced utility and consumer residential metering systems enables interested parties to analyze residential loads with higher accuracy. Utilities and consumers are interested in the ability to know what appliances are being used at any given time for individual homes. With this information, the benefits of load control for specific devices could be predicted. Also, the energy savings achieved through a resident's participation in an energy efficiency program sponsored by an electric utility could be estimated. This data could also be used to inform regional or national predictions on equipment distribution and usage patterns.

The ability to develop algorithms that make these determinations accurately depends heavily on metering instrumentation and the load characteristics of specific appliances. First, this paper provides an overview of the electrical system in a residential home and how this system relates to general classifications of advanced metering systems currently deployed and systems expected to be deployed. Next, this paper inspects the ability of different systems to disaggregate residential loads by providing non-metering data sources and characteristics of selected appliance classes. Finally, some of the results, anticipated results, and future work on disaggregation algorithms are presented.

PECAN STREET PROJECT

The Pecan Street Project Inc. is a non-profit collaboration between Austin Energy, the Environment Defense Fund, The University of Texas at Austin, The Greater Austin Chamber of Commerce, and a number of private companies. A primary focus of this organization is the development, testing, and research associated with different consumer-based smart metering systems. Several different systems are expected to be deployed within the project's initial five-year lifespan. As of writing, one metering system is installed in the Mueller development in Austin, Texas. The metered appliance data used in this paper was retrieved from these systems.

OBJECTIVES AND METHODOLOGY

The goal of this research is to provide an a priori determination of the ability of different metering options to disaggregate residential loads. The target audience for this paper is interested parties and researchers involved in the Pecan Street Project and other smart grid deployments who are working to procure different systems, disaggregation algorithms, event detection, calibration, and other associated research and products.

Extensive background is presented concerning the definition of different appliance characteristics. Previous literature and research concerning disaggregation of loads using these characteristics is discussed.

This paper displays example data captured for selected appliance classes to provide expectations of the ability to disaggregate loads using specified instrumentation. Because these systems require additional calibration and testing, this data is not fully statistically modeled, but is discussed qualitatively and specifies future techniques that will work to assist the conclusive analysis concerning the ability to disaggregate loads using the currently deployed instrumentation. It is also hoped that the ultimate disaggregation model can be used to determine which sub-circuits may not be correctly labeled or require additional calibration.

Future analysis will be assisted by the use of utility metered data, energy audits, and additional systems capturing different data. This paper focuses on expected results and relevant knowledge and literature.

Chapter 1: The Residential System

The intricacies of electric systems in homes inform the discussion on metering, appliances, and disaggregation. This paper will document the basics of how electricity is delivered to homes, a simplified home circuit, typical configurations and effects, and the basics of residential electric loads.

DELIVERY TO RESIDENTIAL HOMES

Electricity is supplied to residential homes through a center tapped step-down transformer that splits a higher voltage into two phases of 120 Volts alternating current (AC) power operating at 60 Hertz (60 cycles per second). The center tapped neutral grounded wire enables two secondary windings that have the same voltage with one winding (or leg) that is 180 degrees out of phase with the other winding. Loads are connected in parallel to either one or both of these legs. When connected to both legs, the load is supplied 240 Volts. This is commonly referred to split-phase as opposed to double phase, as the two windings converge to a single phase for the 240 Volt line. Figures 1 and 2 illustrate the distribution to the home and to each leg, respectively.

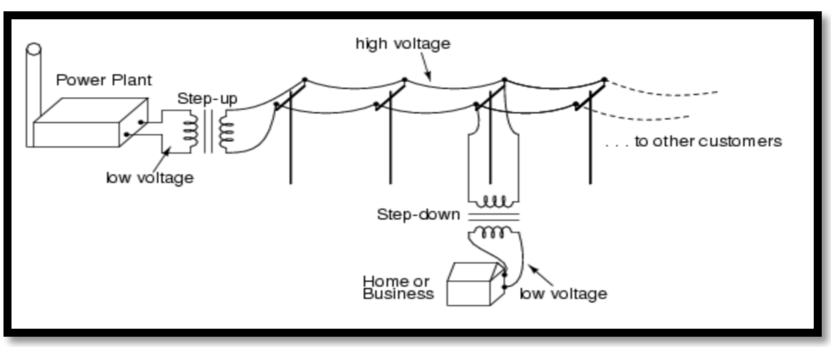
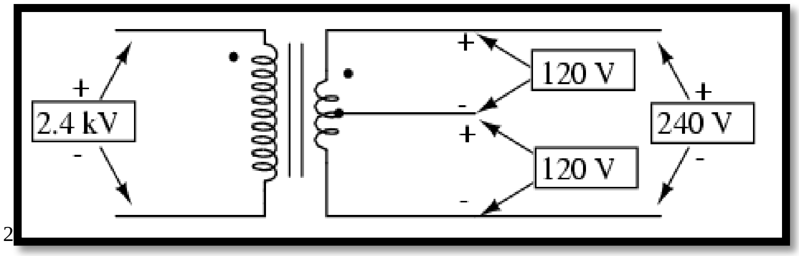


Figure 1: Distribution to Homes[1]

[1] Kuphaldt



2

Figure 2: Center-Tapped Transformer[2]

Resting on each leg and on the combined leg is a load with an equivalent impedance at any given point in time. For AC circuits:

$$Voltage\ \ Volts\ = Current\ \ Amperes\ * Impedance\ \ Ohms \tag{1.1}$$

Figure 3 shows a slightly closer look at the residential circuit, with impedance shown as 'Z'. The center wire that creates the two out of phase windings is grounded and carries the difference of the current supplied to loads when the system is 'unbalanced'.

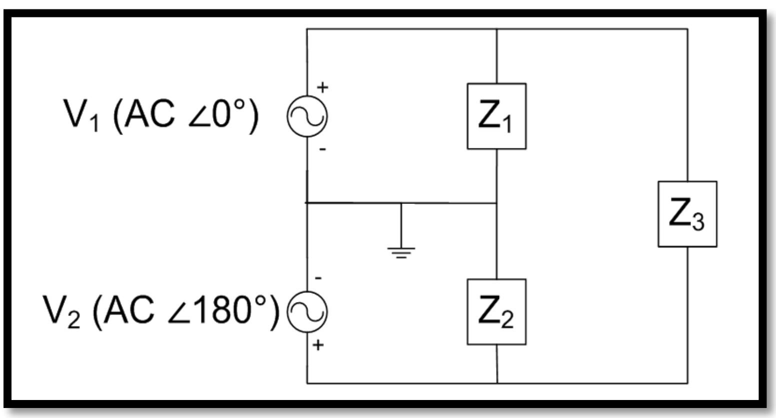


Figure 3: Simplified Residential Circuit

While V_1 and V_2 are typically stepped down from around 7200 Volts to two 120 Volt windings in the United States, Voltage supplied to the step-down transformer varies and causes the voltage delivered to each leg to vary accordingly. Austin Energy

[2] Ibid

residential voltage typically varies between 110 Volts and 125 Volts.[3] Appliances running on the lower voltage (on one leg) are typically tested at 110 Volts but may not perform properly at lower voltages. Electric utilities wishing to reduce their load, including Austin Energy in the summer, often lower the Voltage carried to transformers in order to reduce loads.

The American National Standard for Electric Power Systems and Equipment – Voltage Ratings (60 Hertz) (American National Standard Institute "ANSI" C84.1-2006) specifies an 'optimal' range between 114 Volts and 126 Volts (5% above and below nominal) for distribution systems servicing 60 Hertz AC loads and also an 'acceptable' range between 110 Volts and 127 Volts.

The 120 Volts specified by a 120 Vac (Volts Alternating Current) source actually refers to the root-mean-squared (RMS) of the supplied voltage. In the time domain, an ideal voltage supplied to a leg at 120 Vac and 60 Hz can be represented as:

$$V(time) = 120 * \sqrt{2} * \cos(2\pi * 60 * time) \tag{1.2}$$

Any function that retains its wave shape and can be represented as an oscillating cosine or sine function is termed a sinusoid. Figure 4 shows the first period of this voltage source. Here, the Peak Voltage is equal to $120 * \sqrt{2}$. Unless specified otherwise, this document refers to the RMS value of the current or voltage waveform. The $\sqrt{2}$ term is also called the 'crest factor', which is the peak value divided by the RMS value. For non-sinusoidal waveforms, which will be discussed later, the crest factor is higher.

[3] Interview with Christopher Frye, Senior Manager, Market Research & Product Development at Austin Energy, February 17, 2011.

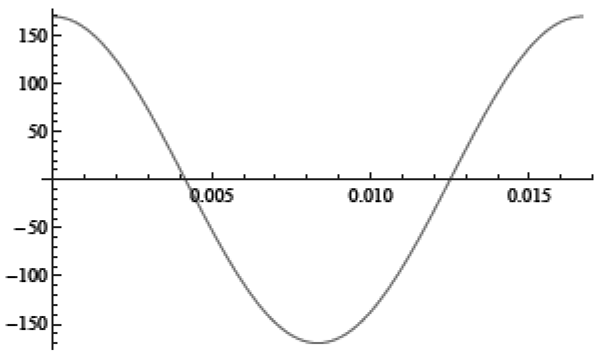


Figure 4: First Period of 120 Vac

The RMS for this function is as follows:

$$\sqrt{\frac{\int_0^{1/60}\left(120*\sqrt{2}*\cos\left(2\pi*60*t\right)\right)^2 dt)}{(\frac{1}{60}-0)}} = 120 \qquad (1.3)$$

In addition to variance in the Voltage served to residential systems, the frequency of the oscillation of this voltage can change. One reason this might change is due to the loss of a generating asset on the electric grid. For the Electric Reliability Council of Texas (ERCOT); load is actively reduced when the system-wide frequency drops below 59.3 Hz.[4] The National Electric Reliability Council requires corrective action for frequencies below 59.3 and above 60.7 Hz (Standard PRC-006-1). However, for analyzing loads in individual residential homes, variance in frequency is typically not significant. First, the aforementioned frequency values are extremes that are not typically reached, and secondly, even this extreme variation alters loads minimally.

Power factor, which varies depending on frequency and will be discussed at depth later, was modeled in SPICE under these extreme cases for a typical load and only varied between 0.795 at 59.3 Hz and 0.802 at 60.7 Hz (0.798 at 60 Hz). One other note in regards to frequency is that typical electronic appliances are rated at +/- 1% of 60 Hz and may not function correctly beyond this point. Underwriters Laboratories (UL) tests the operating range of individual appliances. This is one reason uninterruptible power

[4] Boyer

supplies are used to ensure high quality supply to advanced electronic equipment. The presence of this equipment alters the load seen on a measuring devices connected at a higher level.

Photovoltaic systems will not be covered in depth in this paper. However, when considering homes with generation capability, it is important to note that the power system changes drastically. Electricity generated from Photovoltaic systems in the home will have different power quality characteristics than the electricity supplied by the grid.

LINES LOSSES AND SUB-CIRCUITS

One simplification made to the aforementioned circuit is its handling of line losses. In reality, each line has line impedance in series with the load that causes voltage drop prior to delivery to the device load. This becomes a more complicated circuit when the common presence of a sub-panel is considered. Houses in Austin, Texas have typically zero to three sub-panels (Mueller residents have one).[5] In houses with sub-panels, not all devices are connected to the primary distribution panel. Instead, this panel sends electricity to an additional panel which has more than one appliance connected to it. Appliances requiring 120 or 240 Volts may be connected to either the main panel or a sub-panel. The impedance of the wiring therefore is different for appliances depending on their connection. Each of the wires going to devices, fixtures, or appliances is referred to as a sub-circuit.

The Voltage in a house may also vary due to voltage drops due to appliances becoming active. Some devices have a spike in current or power when they first come online before settling to their steady-state consumption, resulting in a significant and possibly characteristic “transient” response. An initial spike in current when an appliance is first turned on which may result in a sustained and characteristic voltage drop. Whether or not this transient is considered ‘significant’ depends on the metering instrumentation and what data is being collected.

[5] Interview with Chadwick Ottnat, Owner, Elite Electric, March 12, 2011.

A voltage drop on one leg may cause ‘unbalanced’ voltage where each leg carries a slightly different voltage. A change in voltage that has a very short length is termed a voltage ‘flicker’. Both of these effects are reduced for newer homes with proper wiring.[6]

In the Pecan Street Project Mueller implementation, which has homes built within the past 4 years, sub-circuits are highly differentiated. This means that electricity delivered to specific sub-circuits connected to a smaller number of devices can be captured. There are between 30 and 40 sub-circuits in each house in this development.[7] However, many older homes have sub-circuits that deliver power to partitions of the house such as the living room as opposed to having a separate line for the home entertainment system.

The differentiation of sub-circuits is significant from a power quality and appliance measurement perspective because line impedance causes voltage drops that lower the voltage ultimately delivered to loads. National Electric Code (NEC) standards require that potential voltage drops on 120 Volt AC sub-circuits may not exceed 5%. NEC also specifies voltage drop calculations for estimated loads and installed wiring. Restrictions in line impedances for specific wires in homes configured to meet NEC standards could be used to help derive a more fully formed model of the residential system, and line impedance could be tested at the time of install of a metering system. NEC standards also require a dedicated circuit for all major permanently installed appliances.

Despite variations in home wiring systems, Figure 3 on page 4 is a useful conceptual tool. At any given point in time a variable number of device loads are in parallel to one leg (Z_1 or Z_2) or both legs (Z_3). The number of appliances connected to both legs is much more static because these appliances are more expensive and rest on dedicated circuits.

[6] Warren et all

[7] Interview with Chadwick Ottnat, Owner, Elite Electric, March 12, 2011.

IMPEDANCE AND POWER FACTOR

In direct current (DC) circuits whose voltage and current sources do not oscillate, voltage and power can be expressed as follows:

$$Voltage\ \ Volts\ = Current\ \ Amperes\ * Resistance\ \ Ohms \tag{1.4}$$

$$Power\ \ Watts\ = Voltage\ \ Volts\ * Current\ \ Amperes \tag{1.5}$$

However, AC circuits can have loads that alter not only the magnitude of the current but the current waveform. Therefore, as previously discussed, Voltage is now calculated with equation 1.1 on page 4.

Whereas a resistance on a DC circuit can only alter the magnitude of the current, the impedance found on an AC circuit may shift the current waveform to lag or lead the voltage waveform. In the time domain, a load with a lagging current may look like Figure 5:

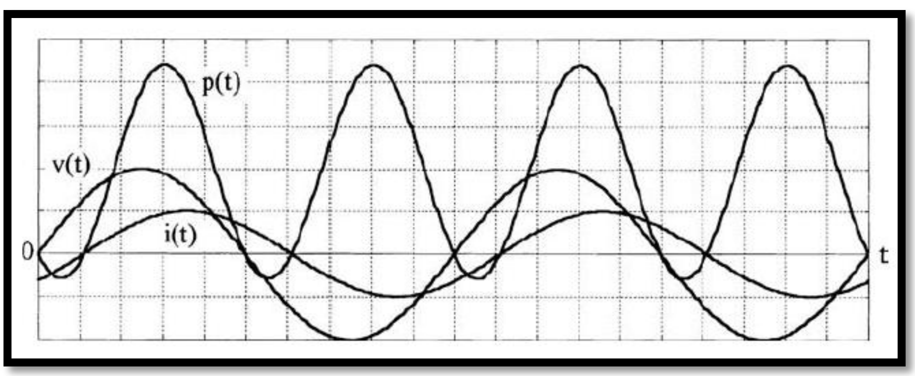


Figure 5: Load with Lagging Current[8]

The Power shown here is simply Voltage * Current at each instantaneous point in time. If you look carefully at the previous figure, you will see that due to the shift in current, instantaneous power goes below zero. If there had been no shift, positive values for voltage would be multiplied by positive values for current and negative values for voltage would be multiplied by negative values for current; resulting in a positive value for power for the entire period. The negative value for power in this example indicates

[8] Dugan et all

that a portion of power sent to the load is not being dissipated and converted to work. In the time domain, the current in this example may be represented as follows:

$$I\ time\ = Current_{RMS} * \sqrt{2} * \cos(2\pi * 60 * time\ + \Phi) \qquad (1.6)$$

The phase displacement angle, or $'\Phi'$, represents where the sinusoid begins at t = 0 and indicates how far the current waveform is shifted from the starting point. Another way to represent this is in phasor form, as shown on Figure 6:

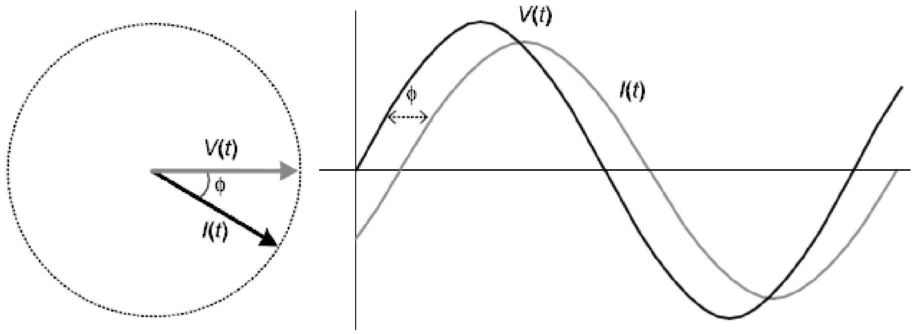


Figure 6: Phasor Representation[9]

Here, ' Φ' represents the phase angle difference between the current and voltage sinusoids. Although not indicated by the previous figure, phasor representation provides the angle as well as the magnitude, as shown here:

$$Voltage = V_{RMS}\angle 0° \qquad (1.7)$$

$$Current = I_{RMS}\angle\Phi \qquad (1.8)$$

Voltage is used as a reference, so it is set at 0°. We use RMS values for magnitudes because we are interested in the average power dissipated on the load through a given cycle, which for sinusoidal current and voltage is equal to voltage RMS multiplied by current RMS and cos(Φ).

[9] Dugan et all

This is also termed ‘Real Power’, is measured in Watts, and represents the power dissipated on the load. The multiplication of voltage and current results in a new value, termed ‘Apparent Power’ measured in Volt-Amps:

$$Real\ Power\ [Watts] = P = V_{RMS} * I_{RMS} * \cos \Phi \quad (1.9)$$

$$Apparent\ Power\ [Volt - Amps] = S = V_{RMS} * I_{RMS} \quad (1.10)$$

Figure 7 shows the ‘power triangle’ which includes a new ‘Reactive Power’ measured in Volt-Amps-Reactive and is labeled as ‘Q’:

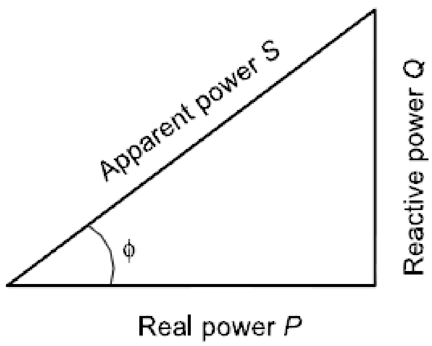


Figure 7: Power Triangle[10]

Here it is easily seen that:

$$S^2 = P^2 + Q^2 \quad (1.11)$$

$$P = S * \cos \Phi \quad (1.12)$$

$$Q = S * \sin \Phi \quad (1.13)$$

As will be discussed later, the current waveform might not be sinusoidal, so these relationships may not hold. The general relationship between Apparent Power and Real Power is:

$$Real\ Power = Apparent\ Power * Power\ Factor \quad (1.14)$$

$$0 \leq Power\ Factor \leq 1 \quad (1.15)$$

[10] Dugan et all

This is important because while almost all residential utility meters only measure and charge for real power, sub-circuit metering systems used for disaggregation may measure current only and estimate apparent power. In the case of sinusoidal voltage and current:

$$Power\ Factor = \cos(\Phi) \tag{1.16}$$

REACTANCE

Analogous to phasor form; another useful analytical representation of a sinusoid with a phase displacement angle is to place it on a complex plane, as shown in Figure 8.

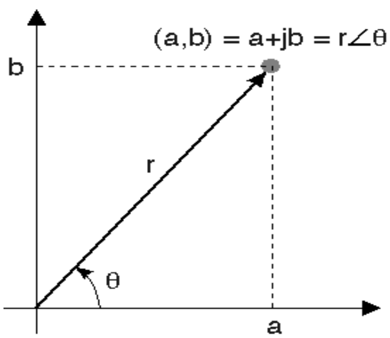


Figure 8: Complex Plane[11]

Rectangular form is shown in the preceding figure as r = a + j*b. Therefore, any particular sinusoid has a ‘real’ and ‘imaginary’ component, in the preceding diagram these are ‘a’ and ‘b’, respectively, and the magnitude of the sinusoid is ‘r’. In the case of an AC load, the magnitude is the impedance (‘Z’), the real component is termed resistance (‘R’), and the imaginary component is termed ‘Reactance’ (‘X’) – all in Ohms. The equations for impedance are similar to those previous shown for power:

$$Z^2 = R^2 + X^2 \tag{1.17}$$

$$R = Z * \cos\ \theta \tag{1.18}$$

$$X = Z * \sin\ \theta \tag{1.19}$$

[11] Johnson

Please note that in order to have a voltage waveform at 0°, the phase angle displacement of the impedance, $'\theta'$, is equal to (-1) * the phase angle displacement of the current, 'Φ', and that $\cos\ x\ = \cos(-x)$. The real power and reactive power dissipated across a particular sinusoidal impedance becomes:

$$P = V * I * \cos\ \Phi\ = V * I * \frac{R}{Z} \tag{1.20}$$

$$Q = V * I * \sin\ \Phi\ = V * I * \frac{X}{Z} \tag{1.21}$$

Reactance and Reactive Power are important terms because, like load power factor and real power, reactive power is highly differentiated among appliances.

MULTIPLE IMPEDANCES

The importance of introducing these analytical forms is that they enable the calculation of the equivalent impedances shown in Figure 3 on page 4. On each of these loads, there could be 'n' loads in parallel, and the equivalent impedance for all of these loads could be calculated:

$$\frac{1}{Z_{Total}} = \frac{1}{Z_1} + \frac{1}{Z_2} + \cdots \frac{1}{Z_n} \tag{1.22}$$

In addition, line impedances are in series with each of these circuits and could be calculated with:

$$Z_{Total} = Z_1 + Z_2 + \cdots Z_n \tag{1.23}$$

Addition and subtraction are eased by using rectangular form, and multiplication and division are eased by using polar ("phasor") form. By applying the previous equations to the equivalent impedance model of Figure 3 on page 4 and assuming sinusoidal current waveforms, we could relate the power factor of the overall house to each of the loads:

$$House\ Power\ Factor = \frac{\frac{(R_1+R_2)*R_3}{(R_1+R_2+R_3)}}{\frac{(Z_1+Z_2)*Z_3}{(Z_1+Z_2+Z_3)}} \tag{1.24}$$

This could also be represented in terms of the real power drawn from each equivalent impedance and the reactance of each impedance. It could not be represented with power factors for each load because power factor does not specify if a current waveform is lagging or leading (although most residential appliances induce lagging current). If several of the sub-circuits within each leg were captured at a house, a range of possible power factors could be determined and used as a check on the devices. Alternatively, if the power factor of the overall house is captured, as well as several sub-circuits, a range could be determined for the power factor of the un-metered sub-circuits that could be used as a test or used to predict the loads on those sub-circuits.

NON-SINUSOIDAL WAVEFORMS

As it turns out, many common residential loads do not utilize a sinusoidal current. More information about which loads do not behave in this manner will be presented in the following section on appliances. However, this is an important feature of residential systems that must be discussed generally. Non-sinusoidal waveforms are referred to as "non-linear" because a graph showing the voltage versus current for an oscillation of Voltage would not result in a linear function (a non-linear "V-I trajectory"). These loads are also often characterized as having "harmonics". Figure 9 is an example of a non-linear load – an LCD monitor.

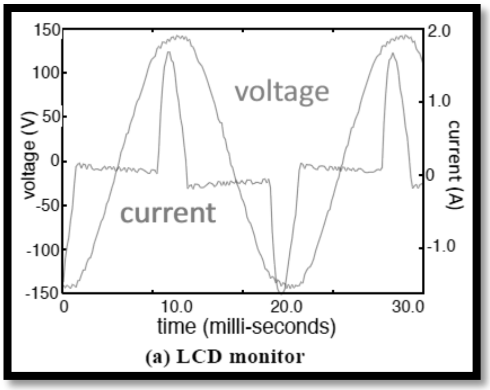


Figure 9: Non-linear Waveform Example (LCD monitor) [12]

Here, the crest factor, or ratio of maximum current over RMS current is greater than $\sqrt{2}$. It is important to note that the voltage is not perfectly sinusoidal but is close. Here, the power factor does not equal $\cos(\Phi)$ - the average power of an oscillation cannot be calculated by just using the RMS current and voltage and the phase displacement angle. The technical term for $\cos(\Phi)$ is the displacement power factor (DispPF). The proper measurement of power dissipated by these devices requires advanced processing of harmonics.

A current waveform with harmonics can be expressed as a Fourier series:

$$I(t) = \sum_{k=1}^{\infty} I_{k,Peak} * \sin(2\pi * 60 * t * k + \theta_k) \quad (1.25)$$

This paper will not focus heavily on the specific harmonics (the peak, RMS, and angles associated with specific 'k' values in this Fourier series) because instrumentation providing this information is beyond the scope of this paper. However, it is important to note that although there is some overlap among appliance classes, several appliances can be identified by the specific harmonics seen on the loads, and this is a growing area of research.

[12] Takekazu

Assuming voltage does not have harmonics (a reasonable assumption according to Grady), Real Power is now given by:[13]

$$P = V_{RMS} * \sum_{k=1}^{\infty} I_{k,RMS} * \cos \Phi_k = P_{k=1} + P_{k=2} + \cdots P_{k=\infty} \tag{1.26}$$

Total harmonic distortion (THD) is a commonly used metric for analysis of non-sinusoidal loads. THD is the ratio of the RMS value of above fundamental currents and the fundamental current at k = 1 (60 Hertz):

$$THD_I = \frac{\sqrt{\sum_{k=2}^{\infty} I_{k,RMS}^{2}}}{I_{k=1,RMS}} * 100\% \tag{1.27}$$

Using the assumption by Grady that $P \approx P_1$, power factor then becomes:[14]

$$Power\ Factor = \frac{P_{k=1}}{V_{k=1,RMS} * I_{k=1,RMS}} * \frac{1}{\sqrt{1 + \left(\frac{THD_I}{100}\right)^2}} = \cos \Phi_{k=1} * Distortion\ PF \tag{1.28}$$

$$True\ Power\ Factor = Displacement\ PF * Distortion\ PF \leq \cos \Phi_{k=1} \tag{1.29}$$

This also assumes that resistance does not change due to high frequency harmonics. This relationship illustrates that as the non-linearity increases, the true power factor (TPF) decreases, and thus a metering system that assumes linearity will incur a loss in accuracy. This relationship also shows that TPF is an indicator of the linearity of the load, if the displacement power factor is known.

[13] Grady et all
[14] Ibid

Chapter 2: Metering Options

This document will provide an overview of a few selected snapshots in metering technology. The older electro-mechanical meter, newer ‘smart’ electronic meters, and sub-circuit metering will be discussed.

UTILITY METERS

The basic metering system installed at each residential home is a single utility meter that measures the entire house load for billing purposes. These meters typically capture and transmit the real power which is typically the basis for residential rates. In regards to Figure 3 on page 4, the equivalent residential circuit is simply an equivalent resistance in parallel to both windings. Homes that generate electricity and are connected to the grid typically have two meters installed; one for measurement of power drawn from the grid, and another that measures the power sent to the grid through a generation system and the electricity consumed in the home that was generated at the home.

Electro-Mechanical Meters

Older induction and solid-state meters required monthly visual inspection to determine energy consumed (corresponding to real power). Some of these devices measure reactive power, but these are exclusively installed in commercial buildings. Utilities, including Austin Energy charge for reactive loads for entities of a certain size with a power factor below a certain value during peak load due to the increased throughput required.

The older ‘varhour’ meters installed at these commercial buildings actually perform poorly for non-linear loads and under-report reactive power during increased non-linearity. Figure 11 shows the error in power factor as a function of THD for traditional meters:

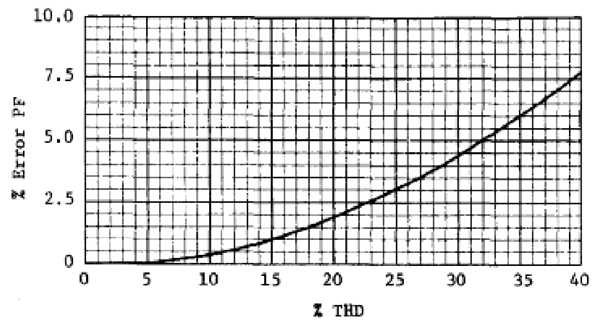


Figure 10: Power Factor Error versus THD for traditional meters[15]

Because these systems are under-reporting the reactive power under increased non-linearity, this suggests traditional meters using the same technology over-report real power, and over-charge consumers. This would be more of a factor with today's residential load which is increasingly non-linear. A factor working in the opposite direction is that electro-mechanical meters tend to slow as they age.[16]

First Electronic Meters

The next class of utilities meters was the first generation electronic meters. These meters used digital processing to more accurately determine energy consumed by residents.

First generation revenue meters were tested at three different THD levels and the results are shown on Table 1:

Table 1: Error in First Generation Electronic Meters due to Harmonics[17]

THDV	THDI	TPF	Percent overcharged
0	0	1	0.1
2.6	23.2	0.97	0.2005271
3.3	75.7	0.8	0.396356303

[15] Cox et all
[16] Evaluation of Advanced Metering System (AMS) Deployment in Texas: Report of Investigation. *Public Utility Commission of Texas*. July 30, 2011.
[17] Arseneau

4.9	88.5	0.77	0.101243853

While these meters had not yet employed perfectly accurate processing of non-linearity, this is very improved from the traditional meter. Note: this result was for three specific current and voltage waveforms; THD is listed for comparison but does not specify the exact waveform.

Contemporary Electronic Meters

Standards were introduced to ensure the accuracy of revenue meters for non-linear loads (Institute of Electrical and Electronics Engineers ‘IEEE’ Standard 1459-2000) as advanced processing was developed for the next generation of electronic meters. One report analyzed the ability for electronic meters meeting the new standard to correctly capture the current and voltage RMS at the most significant harmonics (‘k’ values used in equation 1.25 on page 15) and determined that traditional meters do not capture harmonics correctly, but current and voltage transformers used in conjunction with processing in new digital meters offer significant improvements. Results for comparison are shown in Table 2:

Table 2: Harmonics for Traditional Meters and New Electronic Meters[18]

Harmonic	Traditional Meter Error %	New Digital Meter Error %
1	0.6	0.6
3	35.4	0.6
5	55.8	0.4
7	70.7	0.2
9	82.6	0.7
11	89.5	0.6
13	96	1
15	103	0.6

[18] Gallo et all

How this translates to THD depends on the harmonics of a specific waveform. However, it provides a good comparison with other metering types. The overall conclusion of this study was that current transformers and voltage transformers used in electronic meters perform well under harmonic distortion.

The study by the Public Utility Commission of Texas (PUCT) notes that of 85,756 meters tested, 4% failed to reach the ANSI Standard C12.20-2010 revenue class "0.5" accuracy (+/- 4%) and 25% failed to reach the expected "0.1" class accuracy (+/- 0.5%). For the PUCT study, these meters were tested at light load, high load and low power factor conditions.[19] One reason sighted for missing accuracy requirements in the PUCT study were transitory – improper installation and calibration.

In addition to obtaining advanced measurement accuracy through digital processing, new electronic meters are typified by their measurement at smaller intervals and enhanced communication capabilities. Whereas the previous generation of meters had the ability to only transmit data to the utility (Automated Metering Reading, 'AMR'); these meters have a varying capability to transmit data from and to the utility (Advanced Metering Infrastructure, 'AMI') depending on the specific meter and the services purchased from the meter manufacturer. AMR systems may transmit radiofrequencies to be picked up by a vehicle drive by; while AMR and AMI systems may communicate with the utility using satellite-linked mesh networks or power line communications (PLC) to transmit data remotely.

The Edison Foundation Institute for Energy Efficiency projects 65 million 'smart' meters will be deployed by 2020, around 50% of all residential homes.[20] Figure 11 shows the geographic distribution of expected rollouts, project from September 2010:

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[19] Evaluation of Advanced Metering System (AMS) Deployment in Texas: Report of Investigation. Public Utility Commission of Texas. July 30, 2011.

[20] Utility-Scale Smart Meter Deployments, Plans & Proposals. The Edison Foundation – Institute for Electric Efficiency. September 2010. Online. Available: http://www.edisonfoundation.net/iee/issuebriefs/SmartMeter_Rollouts_0910.pdf. Accessed March 24, 2011.

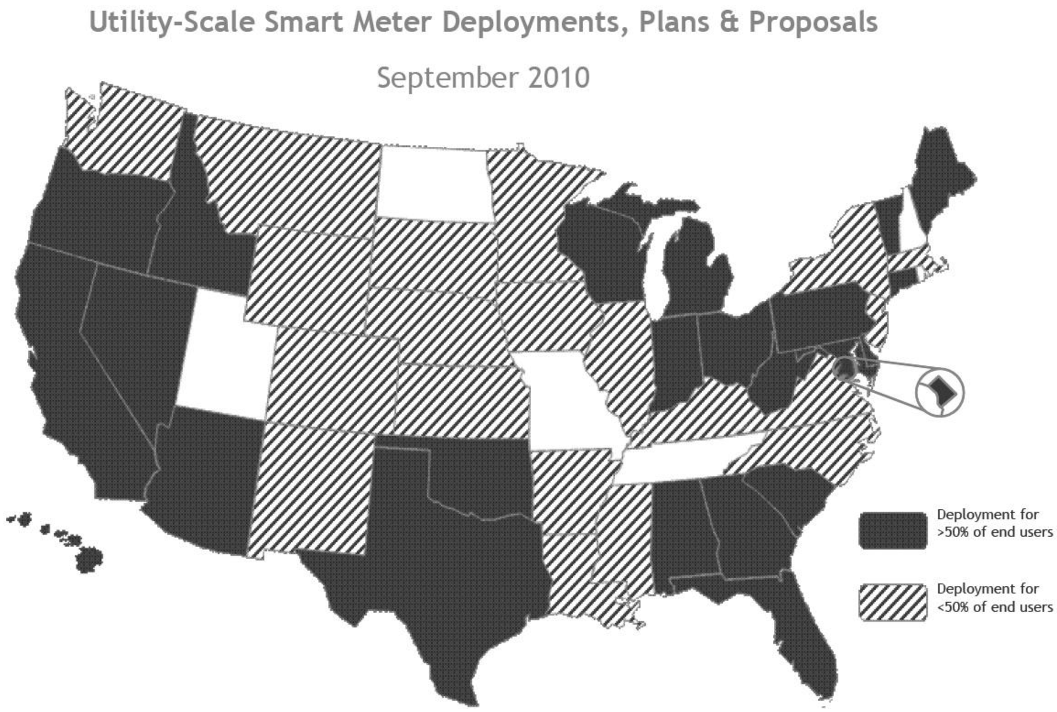

Figure 11: Projected 2020 'Smart' Meter Rollout[21]

Although the specifications vary, the vast majority of the advanced meters installed use 15 minute intervals. Also, these meters typically only capture and transmit Real Power and not power factor, reactive power, or harmonic information.[22]

Future Electronic Meters

The manufacturer of the utility meters used in Austin Energy's service area, Landis+Gyr, is currently developing advanced meters that offer additional features. Two primary features are being pursued – intervals as short as 5 seconds, and the use of disaggregation algorithms made possible with shorter intervals within the utility meters themselves.[23]

SUB-METERING

Increasingly, residents and utilities are interested in investigating loads on sub-circuits within residential homes. The instrumentation options vary but typically fall into

[21] Ibid
[22] Interview with Rob McEver, VP Regional Sales at *Landis*+Gyr, April 5, 2011.
[23] Ibid

two camps: measurement devices that capture and process current, or devices that capture and process current and voltage.

Current Measurement

Many of the sub-metering systems available to consumers measure current only. Of these systems, current transformers are typically used, which are sometimes connected to Hall Effect sensors (current to voltage transducers).

Current Transformers

Current transformers (CTs) step-down currents using a secondary winding and send the current to an impedance for direct measurement using an ammeter or voltmeter (a resistor is used for current-only measurement). A current transformer may be in a 'solid-core' or 'split-core' ("clamp-on") form factor, each type correlating to different safety and accuracy constraints, respectively.[24] Solid-core CTs, for example, displace the current waveform less and may be more suitable for instrumentation options that also measure voltage and power factor.

Accuracy standards for the United States are located within the ANSI/IEEE Standard C57.13 - IEEE Standard Requirements for Instrument Transformers. This standard specifies the maximum error, the CT class ('C' for metering CTs), and the maximum burden (Ohms used for metering CTs, Volt-Amps for relaying CTs) at the device's saturation current.[25] The international standard, IEC 60044-1 provides similar information with slightly different classes.

For a specified class, CTs have varying accuracy depending on the magnitude of the current. Table 3 illustrates this for the IEC classes.

[24] Ramboz

[25] IEEE Standard Requirements for Instrument Transformers, IEEE Std C57.13-1993.

Table 3: Accuracy for CTs, under IEC classifications[26]

Accuracy Class	+/- % of Current Ratio Error at % of rated current			
	5%	20%	100%	120%
0.1	0.4	0.2	0.1	0.1
0.2	0.75	0.35	0.2	0.2
0.5	1.5	0.75	0.5	0.5
2	3	1.5	1	1

Due to the decrease in accuracy as load decreases it is important to select CTs that are appropriately sized. At the same time, CTs must be capable of capturing the peak of a non-sinusoidal wave, or a waveform with a higher crest factor, or the value retrieved will be 'clipped'. The crest factor of a specific device is a fairly advanced metric not shown in most literature, but is known by electronics manufacturers who test devices wishing to receive Energy Star ratings and must use testing devices that do not clip current measured. A typical computer may see a crest factor between 2 and 3, where a linear load has a crest factor of 1.414.

These charts do not show how these devices perform under non-linear loads. A 0.3- C – 5 [Volt-Amps] IEEE/ANSI rated CT was tested under a variety of non-linear loads. Table 4 displays the THD of the secondary current under specified THDs for the incoming primary current delivered to a personal computer. The processing used for this is TRMS, which will be discussed in the next section.

Table 4: CT Accuracy for non-linear loads[27]

THDI(primary)	THDI(secondary	% error
6.894	10.924	1.381579
11.07	15.597	-0.12721
16.4	18.747	0.736544
19.43	20.6	1.142098

[26] Instrument Transformers— Part 1: Current Transformers, IEC 60044-1-1992.
[27] Ismail et all

This chart provides an overview of the loss in accuracy due to harmonics, but this is for a specific device and load. The author suggests loss as linearity decreases. A certified test report for the particular CT from the manufacturer could be used to develop a model that predicts the error more accurately for a specific device. Barring this, a test could be conducted using ANSI/IEEE 257.12.90, and ASNI/IEEE 37.12.91.[28,29]

Processing and Current Transducers

Much of the accuracy of these devices depends on the processing. First, a simple average, RMS, or "True RMS" value may be determined. Each of these processing options assumes symmetric current waveforms across the positive and negative portions as the negative portion of the waveform is squashed by a diode. In addition to the previously mentioned factors, a certain 'linearity error' occurs when converting this analog signal to a digital value. Please note that this does not directly refer to the linearity of the current waveform measured.

An 'encoder' processes and usually only determines the RMS, or True RMS value for a variable number of connected sub-circuits (as opposed to retrieving the peak or other measurements as well). An encoder may also measure a simple average which will increasingly be less than the RMS value, depending on the linearity of the current (simple average of the absolute value of a sinusoid = around 90% of RMS average). Some advanced meters also capture the maximum, minimum, and standard deviation of the True RMS.

The importance of the calculation method used can be shown through an example. As shown previously, the current RMS value can be multiplied by the voltage RMS and the true power factor to retrieve the average power dissipated across a load for an oscillation. The true power factor is equal to the displacement power factor times the distortion power factor. For a typical un-corrected personal computer, the displacement power factor is 0.93 and the distortion power factor is 0.645, making the true power factor 0.6. For TRMS measurement:

[28] Kennedy et all
[29] Locci et all

$$Power_{AVG} = V_{RMS} * \ I_{TRMS} * \text{Displacement PF} \tag{2.1}$$

Assuming that the processor does not incur the previously shown increased errors in calculating the TRMS value and has insignificant linearity error, the current TRMS value encapsulates the distortion power factor. For the given personal computer example; the apparent power measurement will be 7.5% higher than the real power due to the displacement power factor. However, if the current RMS value is captured instead, the apparent power calculated will be 67% higher than the real power due to both the displacement power factor and the distortion power factor.

Finally, some devices average the current. For a sinusoidal wave, $I_{RMS}/|I|_{AVG}$ is 0.9. This means that the apparent power measured will be 10% lower than the correct power factor. This may work beneficially in terms of accuracy of measuring real power because this works in the opposite direction of the power factor, but it disassociates what is measured and the appliance characteristics. For non-sinusoidal waves, the $I_{RMS}/|I|_{AVG}$ term depends on the precise I_{RMS} for specific harmonics. Unlike the crest factor, $I_{PEAK}/|I|_{RMS}$, $I_{RMS}/|I|_{AVG}$ calculation does not require the angle of displacement for each harmonic. For comparison, the ratio of the RMS current over the average current was calculated using the current RMS values of each harmonic for a specific personal computer measured in one study – the same load used the previous example. This value was estimated to be 0.73. Therefore, the 'simple average' current meter calculates an apparent power that is increasing lower than the actual apparent power as linearity decreases. In estimating load, this counterbalances some of the deviation due to power factor, but obfuscates load characteristics – current, power factor, reactive power, apparent power, and harmonics.

A current transformer is sometimes connected to a transducer which converts the AC signal on the secondary winding to a DC voltage or current using the Hall Effect. This DC value may correlate to the RMS or TRMS value of the current waveform. The connection of the transducer to a transformer isolates the system from the measuring equipment.[30] Transducers may come in two forms – ‘passive’ which require batteries or ‘active’ which draw power from the system and thus interact with the current measured to varying degrees.

For both of these metering options, processing is conducted on a digital value obtained from an analog to digital converter. The linearity incurred is typically higher for lower values, and lower for Hall Effect sensors which normalize the value measured. Another factor in current measurement accuracy is the sampling rate that the encoder uses in conjunction with the analog digital converter. This relates the number of points along an oscillation that used in the estimation of an average, RMS, or TRMS value.

The encoder may either transmit this data through radiofrequency waves to a ‘gateway’ for further transmission, or the encoder may utilize power line communications. Another factor contributing to the accuracy of sub-circuit metering depends on the successful transmission of data from encoders, which depends on building materials of the walls and location of panels inside of the house and the frequency used.

Another important feature is whether the current measurement is unidirectional or bidirectional. A current measurement device connected to the whole home phases for a house with generation and interconnection capability may be measuring the current sent back to the grid or the electricity retrieved from the grid. A unidirectional meter will be unable to know whether the system is net-generating or net-consuming. One partial way to correct for this is to utilize data retrieved from the utility meters at the grid and photovoltaic connection points. However, the data is typically only available in 15 minute intervals, and the home may switch from generating to consuming for a brief period when a cloud covers the array or a high consuming device is turned on. Because of this, for any 15 minute interval, the system may both send electricity back to the grid and utilize electricity from the grid. Another alternative is to measure all of the circuits connected to the primary panel in order to determine consumption and compare this to the generation measured on the photovoltaic circuit. This is an improved approximation that still may not capture all changes in net-generation, since a high consumption device or loss in

[30] Sasdelli et all

generation may switch the system from generating to consuming during even a 15 second interval (typical changes in cloud coverage typically resolve in around 5 seconds but may occur at any point with the 15 seconds).

Pecan Street Project Metering

In the Pecan Street Project's Mueller deployment, current measurement is conducted for each whole home 'phase' coming into the home and for 6 sub-circuits within 105 residential homes. The 'whole home phase' current measured are located prior to the connection of the any loads. This enables an estimate of the current for the entire home, by adding the currents on each 'phase'.

Current is multiplied by a manufacturer's recommended 'factor' and is multiplied by the measured voltage at the time of install to obtain an estimated average power across an aggregated interval, which is in affect a scaled estimated apparent power value. The encoders average an estimated steady-state current based on 8.333 points per each positive oscillation across each 2-4 seconds and transmit this data using a radiofrequency wave to the gateway which averages an aggregate value for each 15 seconds and transmits these aggregated values to the internet. The exact accuracy ratings of the CTs used is being investigated but the manufacturer specifies "at most 2% error." Once the data is received it is 'de-noised' – all values are subtracted by a 'noise' factor depending on the size of the current transformer. Two sizes of CTs are used, a smaller solid core for sub-circuits, and larger split-core for the whole home 'phases'.

Voltage and Current Measurement

An alternative but more expensive approach would be to measure the voltage and current waveforms. Although care must be taken to compensate for the phase shift caused by current transformers, the measurement and advanced processing of both current and voltage in power factor transducers enables a calculation of reactive power and power factor with a low error (+/- 0.5% for one device).[31] The accuracy of capturing harmonics for these devices face similar challenges as those discussed in the section on current

[31] Tutakne et all

measurement. The overall in-accuracies due to current measurement are four times more than the error due to voltage measurement.

This instrumentation could also be installed on each individual outlet with sub-circuits not serving a dedicated appliance. These could be located on smart power strips or uninterruptible power supplies. This paper however, focuses on monitoring houses that are already built and systems that do not require a large number of visible monitoring devices.

Exogenous Data Sources

In addition to data available through direct monitoring of devices, data exogenous to an individual electric monitoring system can help disaggregate loads. This data can be categorized as factors influencing loads, non-electric measurements, and appliance characteristics.

Factors Influencing Load

Weather highly influences heating and cooling loads for residential homes. Typical Meteorological Year (TMY) data is used in energy simulation programs that predict total yearly consumption and peak demand. DOE2 based simulation programs including Energy Gauge also utilize typical consumer behavior and typical residential building envelopes to predict loads.

A utility may conduct energy audits to obtain more refined values for a particular home. Energy audits could be used to obtain a statistical inference for homes without energy audits. This data could be related to data readily available through appraisal districts (the year a house is built, its size, the size of its sections, the presence of a second floor) or data available through satellite maps (precise location, orientation, shading elements) in order to provide a closer estimation of a particular home's building envelope without conducting an energy audit.

Non-Electric Measurement

Real-time monitored weather data can be used to model real consumption after the fact and forecasted weather data can inform near term consumption predictions. For homes with photovoltaic systems, measurement of solar insolation and additional meters installed on the inverter(s) informs the power generated by the panels. The set internal temperature, actual internal temperature, and internal humidity influence the air conditioning power draw significantly. The use of heating devices using natural gas influences the internal temperature which influences the operation of electric heating and cooling devices. Some devices utilizing gas also directly consume electricity.

Appliance Characteristics

Energy audits include information about sizing and presence of different appliances in a home. This information is helpful in disaggregating loads for homes with partial sub-metering.

More general data concerning appliances is available. The Department of Energy (DOE) Energy Information Agency (EIA) is the best resource for non-proprietary regional electrical end-use consumption data. EIA's 2005 'Household Electricity Report' is based on the 2001 Residential Buildings Consumption Survey (RECS) and is the most recent data that differentiates highly between appliances for different regions. It provides data specific to the top five most populated states, which includes Texas.

Several data sources are available for the entirety of the United States. The DOE – Energy Efficiency and Renewable Energy (EERE) provides differentiated estimated appliance power consumption.[32] The Department of Energy's Buildings Energy Data Book (BEDB) provides a table for the 'Operating Characteristics of Electric Appliances in the Residential Sector'. Much of the data used in this table is based off of surveys and market research conducted for the 1998 Department of Energy (DOE) report, 'Electricity Consumption by Small End Uses in Residential Buildings' and the 1998 Lawrence Berkeley National Laboratory report, 'Energy Data Sourcebook for the U.S. Residential Sector'. From these and other sources, typical Watts consumed for different operating states, average hours a particular appliance is in each operating state, and average consumption for a year for a house for particular classes of appliances are available.

[32] Estimating Appliance and Home Electronic Energy Use. Department of Energy – Energy Efficiency and Renewable Energy. 2011. Online. Available: http://www.energysavers.gov/your_home/appliances/index.cfm/mytopic=10040. Accessed February 20, 2011.

While the BEDB provides a single estimate for power for each appliance, the research in the sourced 1998 DOE report and the 2011 EERE table provides a range of real power draw.

Also, some information about the appliances at a given home can be inferred from energy efficiency programs and standards such as Energy Star. Not all devices are covered by these programs, however. Because these standards evolve over time, the age of the house informs the estimation of appliances at a particular home. The value of the home according to appraisal data could also relate to the age of appliances in the home.

A survey of specification sheets for specific devices could be trimmed to a more manageable level by using inferences made from selected energy audits and appraisal data. The energy audits being procured by the Pecan Street Project identify the exact model number for a number of selected major appliances in the home. For devices that require high currents, manufacturers typically specify the ‘amperage’ required for the device for electricians. This informs the highest possible apparent power for the device. Smaller devices such as kitchen appliances typically list the watts, or real power. However, information from a survey of selected specification sheets could be used to more fully model and predict the power characteristics of devices in a particular home. Another option, more suitable for the laboratory environment, is to directly monitor the power delivered to each sub-circuit under a set of appliance load mixes at the time of install of permanent instrumentation and use this to adjust the data this metering system receives. A ‘learning’ period where appliances are directly monitored for a set period is used in many disaggregation algorithms.

In addition to the aforementioned appliance data, many studies have been conducted that analyze the real power, reactive power, and harmonics for specific appliances and appliance classes. Data obtained through highly accurate instrumentation for specific appliances is commonly associated with studies that examine algorithms that work to disaggregate loads.

Chapter 3: Appliances

This section reviews a selected group of appliance class loads using data from direct monitoring through the Pecan Street Project, general governmental data, and the results of testing of appliances provided in disaggregation literature.

CHARACTERISTICS OVERVIEW

Residential electric appliances can be categorized into their general load characteristics. Along with the aforementioned characteristics of power factor, real and reactive power draw, and linearity: many appliances also exhibit two other characteristics: significant transient responses and multiple operating modes. An example of multiple operating modes is refrigerators' cycling. Transient responses were briefly covered in Chapter 1: Line Losses and Sub-Circuits on page 7. Each of these characteristics has varying data availability outside of direct measurement, as shown by Table 5:

Table 5: Appliance Characteristics and Data Availability

Characteristic	Data Availability
Real Power	(typical values available)
Reactive Component	(typical values available)
Significant Transient Response	(limited availability)
Multiple Operating Modes	(typical patterns available)
Linearity	(typical values, but varies)

One important note is that the reactive power consumed by certain devices, including induction motors used in air-conditioner systems, fluctuates depending on the load; generalized into the 'multiple operating modes' characteristic here.

Since many of these characteristics are not mutually exclusive, appliances typically fall into certain sets of characteristics as shown by Table 6:

Table 6: Sets of Characteristics for Appliances[33]

Set of Characteristics	Appliances
Linear, Resistive	Oven, Incandescent Lighting
Linear, w/ Reactive (Motors)	Washing Machine, Fans, Heating and Cooling
Linear, w/ Reactive and Transients (Pumps)	Refrigerator, Dishwasher
Nonlinear, w/ Reactive	Home Entertainment, Computers
Nonlinear, w/ Reactive and Large Transients	Compact Fluorescent Lighting

OVERALL CONSUMPTION

Some consideration should be given to the scale of a typical household in order to identify significant appliances. Table 7 shows the 2008 yearly aggregate average house:

Table 7: 2008 Yearly Appliance Consumption[34]

Appliance	Percentage of Load	Appliance Class	Percentage of Load
Space Heating	25.67%	Set-top box	1.69%
Other	20.19%	PCs	1.40%
Space Cooling	12.59%	Freezers	1.31%
Water Heating	10.67%	Dishwashers	1.30%
Lighting	6.07%	Furnace Fans	0.98%
Refrigeration	4.84%	Microwave	0.70%
Television	4.48%	Home Audio	0.53%
Dryers	3.95%	Computer Monitors	0.39%
Cooking	2.90%	Clothes Washers	0.34%

In Texas, for example, the cooling load would be a higher percentage, and heating would likely be less. The Energy Information Agency also projects future residential

[33] Adapted from Akbar et all
[34] Annual Energy Outlook 2008. Department of Energy - Energy Information Administration. 2009.

electric load. They project relative increases in energy consumed by devices with reactive loads and non-linear loads[35]

SELECTED APPLIANCES

By looking at the largest loads in residential devices, the Pecan Street Project targeted specific sub-circuits to meter within its metering system in Mueller. Out of the thirty different sub-circuits measured, this document will focus on the top seven appliances identified by Pecan Street Project that correlate with high load devices, as shown by Table 8:

Table 8: Selected Pecan Street Project Captured Sub-circuits

Sub-Circuit	**Voltage**	**Captured**
Air Conditioner	H	102
Clothes Dryer	H	40
Dishwasher	L	62
Home Entertainment	L	44
Home Office	L	38
Microwave oven	L	94
Refrigerator	L	98

This table also states whether or not the particular sub-circuit is on both legs ('H') or on a single leg ('L'). The houses in this sample do not have electric heating or electric water heating. Although these circuits are highly differentiated, they do not necessarily correspond with an individual appliance. The 'Home Entertainment' circuit may, for example, contain several appliances (TV, set-top box, audio equipment). After discussing induction motors used in several of these appliance classes, this paper will discuss the load characteristics of each of the sub-circuit, in the order presented on Table 8 with the inclusion of power supplies prior to the discussion of the home entertainment circuit.

[35] Ibid

Single Phase Induction Motors

Since a large number of residential appliances utilize induction motors, the general electrical characteristics of these devices should be investigated. As loads increase, the power factor increases. Different induction motors may utilize different specialized circuitry to alter the power factor, but the general curve of the power for a non-calibrated induction motor is shown in Figure 12:

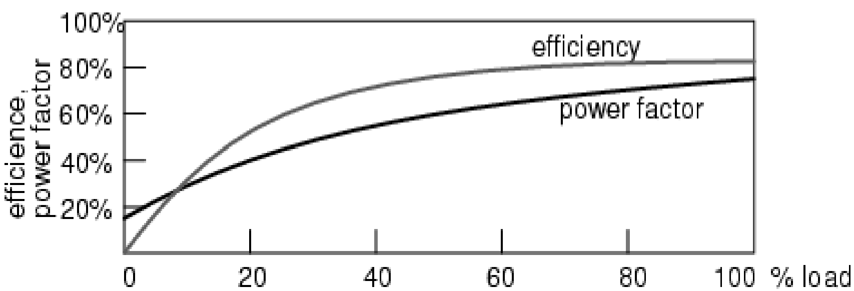

Figure 12: Un-corrected Power Factor Variation for Induction Motors[36]

This general curve is important to note, but may not apply to the specific device due to advanced power factor correction circuitry and because the motor is only part of the power draw on a device. Further modeling could be employed based on specification sheets in order to correctly model variations in power factor due to variations in load for specific appliance class. Alternatively, if power factor were measured on a sub-set of houses with similar devices, this data could be applied to homes without the full metering system.

The linearity of induction motors also varies with the load. Because of this, the THD value is not sufficient in describing the linearity. The IEEE Standard 519 specifies a Total Demand Distortion (TDD) which is the THD at a specified load. Typical equipment utilizing induction motors have low THD at rated loads compared to advanced electronic equipment, and therefore have been generally characterized as linear loads in Table 6 on page 32.

For reference however, variable speed heat pumps fed by induction motors used in advanced equipment that have improved efficiency have a significantly higher TDD.

[36] Kuphaldt et all

Newer models of heat pumps have been tested by the Electric Power Engineering Centre (EPEC) at the University of Canterbury. For visual inspection, here are their results for a selection of heat pumps:

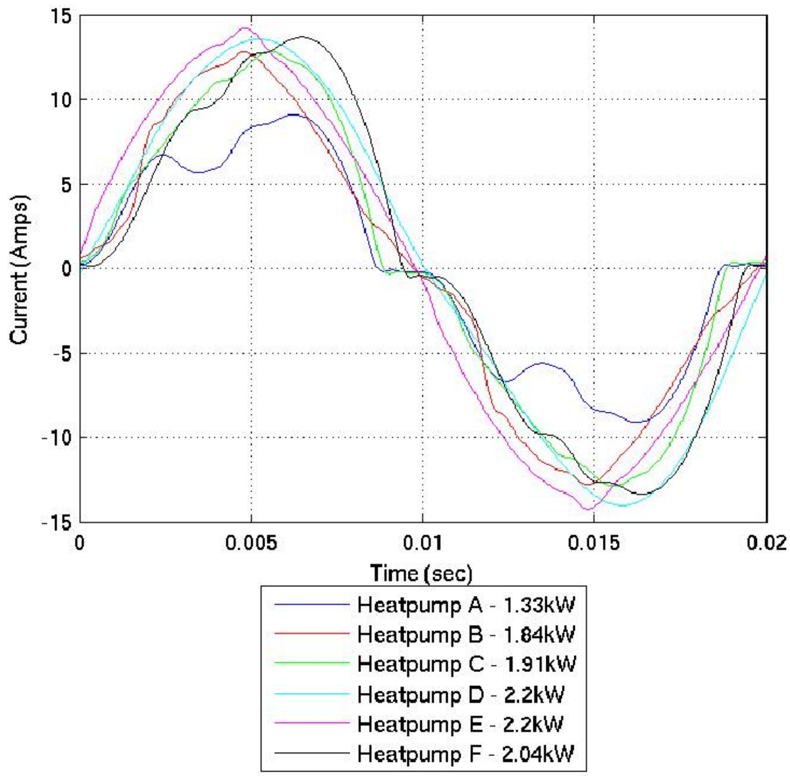

Figure 13: Current Waveform for a variety of Heat Pumps[37]

Heatpump 'D' is a traditional non-variable heat pump and induces a perfectly sinusoidal current waveform. The linearity of the other devices increases as the Wattage increases, and current THD varies between 8% and 63%.

Induction motors also have large transients. When a large generator comes online, such as a capacitor-start induction motor, the motor may draw 6 to 10 times its steady-state current for a variable period. In addition, a voltage sag may occur that decreases the voltage by around 20% for 2-3 seconds.[38]

A metering system could be implemented that measures the current and voltage at the circuit on a very granular level that saves these peak values or the standard deviation

[37] Hardie et all
[38] Dugan et all

of the current or voltage across an aggregated interval. This data could then be transmitted to a disaggregation algorithm that first learns these characteristics and then uses them to determine appliance events going forward.

Air-Conditioners

Much of the research on modeling loads has focused on Air-Conditioning. Energy simulation programs typically model the hourly (eQuest, Energy Gauge) using typical weather patterns, building envelope information, and aggregated equipment patterns and consumer behavior to determine yearly total and peak load.

Correct identification of Air-Conditioning loads is important from a disaggregation perspective because many systems have a single-point utility meter that measures the whole home, and sub-circuit monitoring may not capture every circuit. Many algorithm techniques control for this load in order to predict remaining load.

The significance of the Air-Conditioning (AC) load can be shown graphically. A typical home in Texas was identified by an energy efficiency consulting firm, and modeled for Austin, Texas using Energy Gauge. Figure 14 shows the load on a cool day without Air-Conditioning.

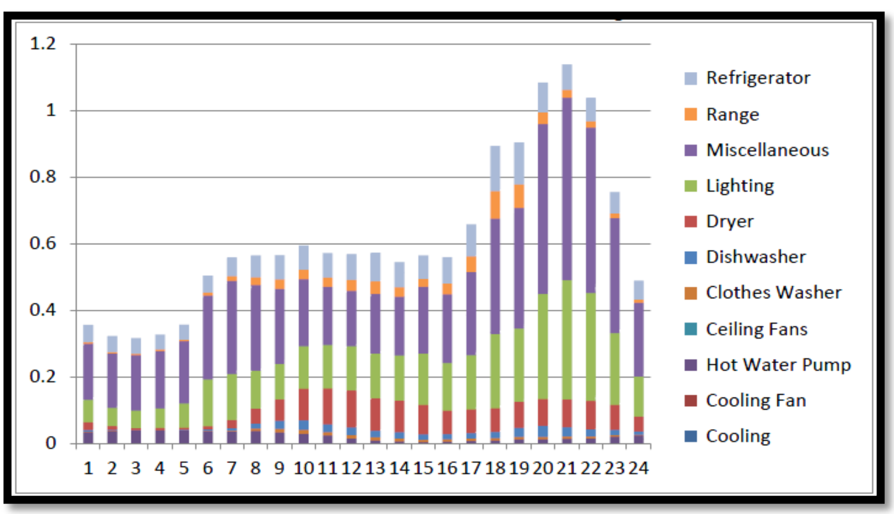

Figure 14: Simulated House Load on December 21st (kWh versus Hour)

Contrast this to June 21st, on Figure 15, where the overall consumption is much higher and Air-Conditioning takes up a large portion of the load:

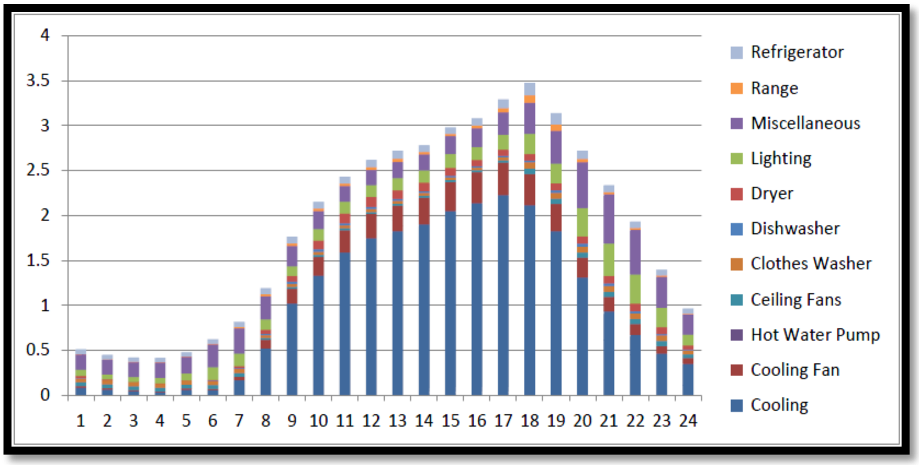

Figure 15: Simulated House Load on June 21st (kWh versus Hour)

These graphs are also illustrative of the inherit limitations in energy simulation programs based off of DOE2.1 to disaggregate smaller load profiles. The usage patterns, or ‘schedules’ for non AC loads are designed to predict overall yearly consumption and peak consumption. Not much variation is shown, for example, among different 15 minute intervals for refrigerator consumption.

However, a post-facto simulation of the building with known weather data can pin-point information about the building envelope (lag and magnitude of heat flows) as well as specifics about the air-conditioning device. Figure 16 shows a plot of the outdoor ambient temperature with the predicted energy consumption for air conditioner units with different efficiency ratings:

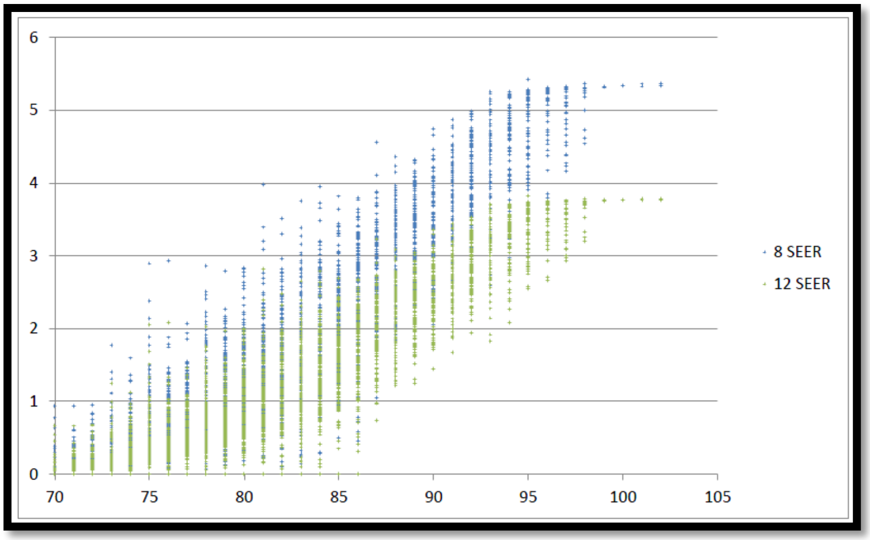

Figure 16: AC Consumption for SEER 8 and 12 (kWh versus outdoor temp)

While there is significant overlap, this suggests that simply having a metering system with hourly data could provide in-depth information about the air conditioning unit at a house. Delays in energy flows due to building envelopes typically resolve in one hour. Hourly metering should enable a utility to infer the type of air conditioning system used (central air, split-system, window units, ductless mini-split) and the efficiency of the unit.

Air Conditioner Efficiency

The efficiency of particular AC systems is a significant piece of information in disaggregating whole home loads. The Seasonal Energy Efficiency Ratio (SEER) [Btu/Wh] is an estimate for the yearly efficiency of an AC system. By knowing the size of the unit [Btu/hour] and the real power drawn [Watts], and the total operating hours, the total annual consumption can be estimated. However, a SEER value is scaled based on outdoor weather patterns in selected cities around the country, so this value may not reflect the efficiency perfectly. This Air Conditioning, Heating and Refrigeration Institute (ASHRAE) standard - Air Conditioning and Refrigeration Institute Standard 'ARI' 210/240 - was developed to incorporate some information about the changes in efficiency of a unit in relation to changing load.

AC units' efficiency is also rated at a specific rated load, as assigned by ASHRAE, to determine a rated Energy Efficiency Ratio (EER) [Btu/Wh]. An overall SEER value can be converted to an estimated EER using the formula:[39]

$$EER = -0.02 * SEER^2 + 1.12 * SEER \tag{3.1}$$

While a SEER value simulates typical changes in efficiency for units, an Integrated Part Load Value (IPLV) (ARI 550/590) uses measured efficiencies at 100%, 75%, 50%, and 25% load and typical seasonal variations across selected cities to get a more accurate measure of efficiency. A Non-Standard Part Load Value (NPLV) can be developed that uses the same measured efficiencies used in IPLV for input location-specific weather data to identify an even more accurate figure.

At any specific load, by knowing the heat flow and the electricity consumed, you could obtain an EER value for a specified time interval. If the EER value at a specified load is known, heat flow could be obtained if the energy consumed for that interval is known. According to ASHRAE, 3.41214 British Thermal Unit (Btu) per hour is equivalent to one Watt. The maximum efficiency of an AC unit is limited by the second law of thermodynamics, which when applied to the Carnot cycle for an AC unit, specifies that (for cooling):

$$EER \quad \frac{Btu}{Watt*hour} \leq 3.41214 * \frac{Temperature_{Indoor}}{Temperature_{Outdoor} - Temperature_{Indoor}} \tag{3.2}$$

The right side of this equation corresponds to:

$$\frac{3.41214\,\frac{Btu}{hour}}{Watts} * Coefficient\ of\ Performance = 3.41214 * \frac{Heat\ [Btu]}{Work\ [Btu]} \tag{3.3}$$

Therefore, at any given time, you can measure the Coefficient of Performance and compare to maximum potential values readily. One other value used for AC systems is kW/ton. A "cooling ton", also identified as a "ton of refrigeration", is the amount of heat

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[39] Building America House Simulation Protocols. Department of Energy – Energy Efficiency and Renewable Energy – Building Technologies Program. October 2010. Online. Available: http://www.nrel.gov/docs/fy11osti/49246.pdf. Accessed March 10, 2011.

(transported thermal energy) needed to freeze one short ton of H_20 at 32° Fahrenheit across 24 hours. One cooling ton requires 12,000 Btu/hour.

A problem with analyzing the system using only efficiency ratings is that the unit might not be sized properly. Correct sizing of the AC unit requires sufficient analysis of the local climate, building envelope, and occupancy patterns. Manual J, "Residential Load Calculation," published by the Air Conditioning Contractors of America (ACCA) has a recommended procedure for sizing of AC equipment. Advanced energy audits could infer both the real power and expected efficiency of the unit, but also whether or not the unit is properly sized; a condition which may obfuscate the actual AC load in a utility metering system that does not directly capture the AC sub-circuit.

Air-Conditioner Data

Another way to look at air-conditioning load is possible through the Pecan Street Project's metering. Figure 17 shows the portion of the load that was on the air conditioning circuit (electricity consumed by the compressor) on Monday April 11th, 2011, for a particular house. In order to illustrate the usefulness in typical 15 minute smart meters in determining AC loads, Figure 17 is aggregated to 15 minute intervals:

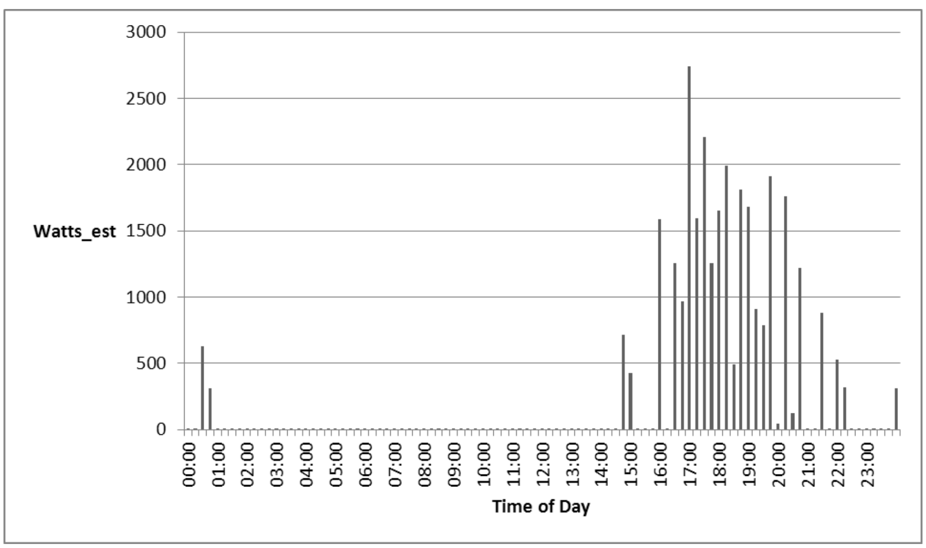

Figure 17: Pecan Street Project, Air-Conditioner, 15min

Here you can clearly see when the resident came home and turned on appliances and reduced the internal set temperature. The magnitude and length of this load shape appears to translate relatively well for the aggregated data. However, 15 minute aggregation shifts the data into bins which do not necessarily correlate to the actual active mode length. Additional data such as energy audits and consumer behavior statistics are likely necessary but disaggregation appears possible. This data could also be viewed in 15 second intervals. Figure 18 shows this:

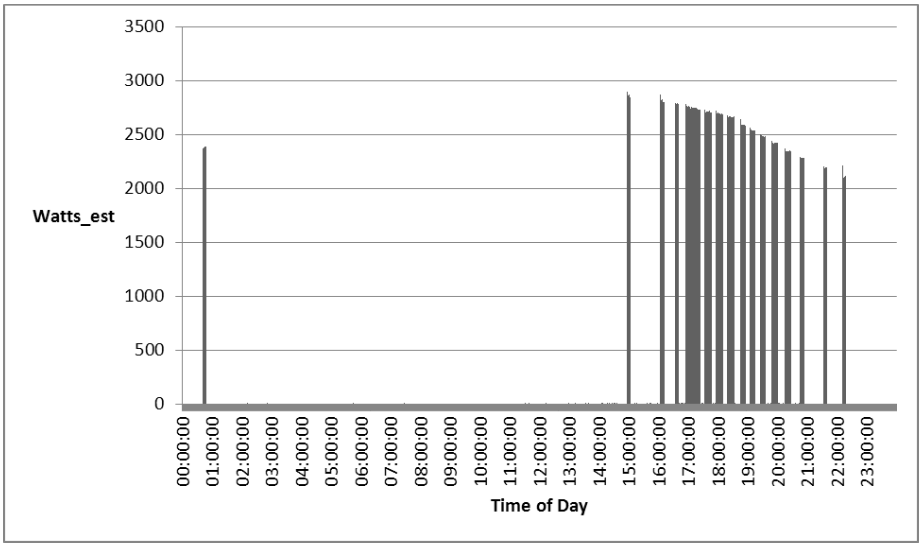

Figure 18: Pecan Street Project, Air-Conditioner, 15sec

The 15 second data defines the length the AC unit is on during each active mode. It appears that the 15 second data is sufficiently significant for use in disaggregation algorithms placed on utility meters that measure total consumption at a similarly reduced interval. The use of the estimated real power values begs the question of what is the power factor for air conditioning systems.

As suggested by Table 6 on page 32, air conditioners are by large linear loads with a reactive component. Also, AC compressors use inductive motors which generally have varying reactive power requirements.

An air conditioner study was conducted by Electric Power Research Institute (EPRI) to examine ACs.[40] Included in this analysis was an examination of reactive load for 17 compressor Air Conditioner systems (as opposed to heat pumps). The units tested had a variation in SEER rating and are relatively new models using some power factor

[40] Gaikwad et all

correction. These units were tested at three different outdoor ambient temperatures. They determined that in steady state, 80-87% of real power is consumed by the compressor motor, 10-12% by the indoor fan, and 3-5% by the outdoor fan.[41]

They also concluded that the steady state reactive power does not alter much as temperature changes; so the power factor does increase as load increases. Figure 19 shows this in more detail, with each vertical line representing an AC system:

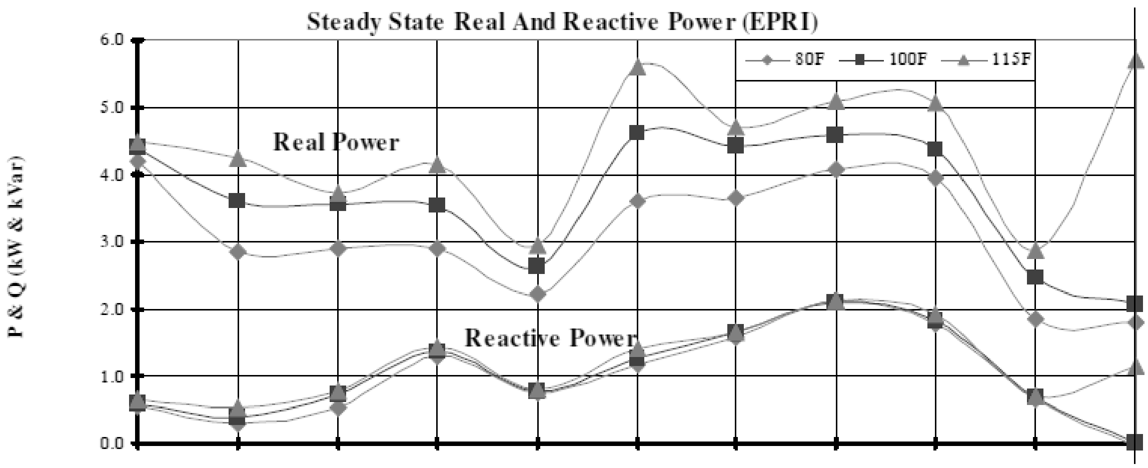

Figure 19: Measured Real and Reactive Power for different AC systems[42]

However, it appears to fluctuate much less than the un-corrected curve shown on Figure 12 on page 34. The second worst case AC system tested by EPRI had a power factor between 0.95 and 0.98 as temperature changed as shown by the seventh vertical line on the chart. The lowest measured power factor for all seventeen AC systems was measured at around 0.81 (not shown on Figure 19). The overall conclusion indicates that the power factor only drops significantly under very low load conditions. Figure 19 also suggests that the reactive power requirement for different units is fairly unique, and a measuring system that can capture or estimate the reactive component of the AC system, would be useful in identifying the AC model and inferring additional information about its characteristics by pulling data from a pre-determined or learned database of different AC systems.

[41] Ibid
[42] Ibid

A final, but important consideration for air-conditioning loads is that they are influenced by a number of factors that are endogenous to the residential electric load. Many major appliance types generate sensible and latent heat that must be compensated by the air-conditioning system. A variable that would be endogenous to a model of the overall residential system would be consumer behavior, because not only do persons inside a house maintain an internal set temperature, they release heat and alter radiative energy flows within the house. Occupancy could be inferred from the non-AC load.

Electric Clothes Dryers

DOE states that 67.2 million homes had electric clothes dryers according to the 2005 RECS.[43] This corresponds to 60.4% of homes in the United States. DOE estimates that these units are active for around 359 cycles a year, contributing around 1,000 kWh for homes with electric clothes dryers. With a typical cycle set at one hour, this would mean that these units dissipate 2780 Watts when active.[44]

The length of these cycles is highly variable, so an estimation of power cannot be correctly made with this data. Like air-conditioning systems, there are many different types of systems (spin, condenser, heat pump, and others). Unlike air-conditioners, electric dryer efficiency does not vary significantly (power versus heating required) and are not covered by energy efficiency standards. One older 1984 study directly monitored electric clothes dryers and determined that in their active mode, they consumed between 430 and 1240 Watts (much lower than previously shown), with a power factor between 0.89 and 0.97 respectively.[45] Unlike AC units, electric dryers have discrete operating modes. A brief survey of Maytag electric dryers reveals models that use 720 to 5000 Watts, but this value depends on the mode of operation and size of the unit, not on the heating required.

[43] 2005 Residential Energy Consumption Survey. Department of Energy – Energy Information Agency. Online. Available: http://www.eia.gov/emeu/recs/contents.html. Accessed March 16, 2011.

[44] Residential Sector Energy Consumption - Operating Characteristics of Electric Appliances in the Residential Sector. Department of Energy – Buildings Energy Data Book. Online. Available: http://buildingsdatabook.eren.doe.gov/TableView.aspx?table=2.1.16. Accessed March 1, 2011.

[45] Levins

Depending on the type of equipment, electric dryers increase the internal ambient air and alter humidity. From a single house load disaggregation perspective, the best way to disentangle this contribution to the load is to have a learning period that analyzes heating and cooling loads for similar internal and outdoor conditions with and without electric drying loads. Also, at the point of install of an advanced metering system, an energy audit could reveal the number and type of electric dryers at the home. Alternatively, ASHRAE – Fundamentals does provide typical sensible and latent heat information for commercial appliances which could potentially be scaled to residential units. Energy simulation programs incorporate these heat flows.

For one home being measured at the 15 second interval, a dryer completed two cycles:

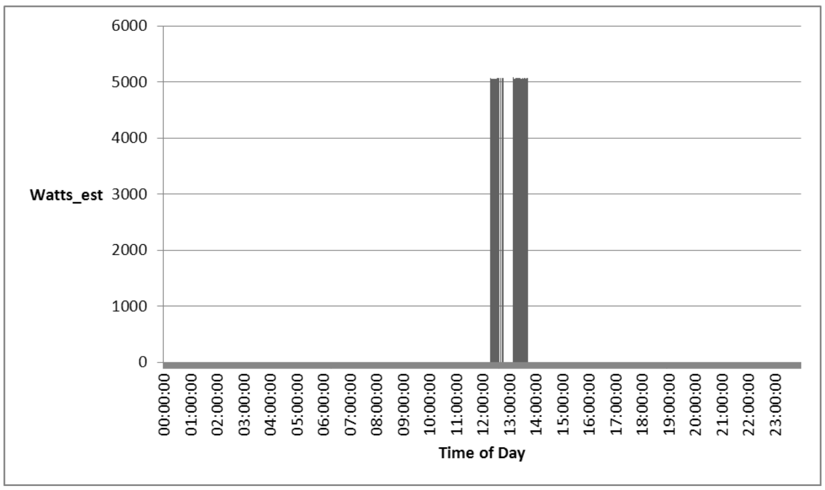

Figure 20: Pecan Street Project, Electric Clothes Dryer, 15sec

This indicates that the current did not incur any significant transient response at the 15sec level, and stayed fairly stable throughout the cycle. The estimated Watts is around 5000, which is in the upper range of possible values. This dryer could be in its high heating mode, or there could be multiple dryers used simultaneously.

We could also view this from the typical electric utility meter perspective, at 15 minute intervals:

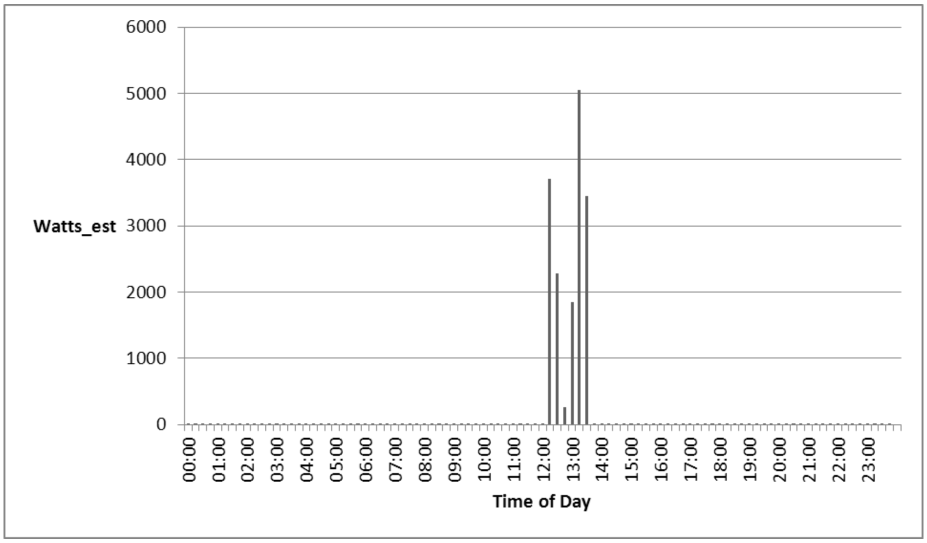

Figure 21: Pecan Street Project, Electric Clothes Dryer, 15min

Because this data is aggregated by 15 minute intervals, the general load shape of this device is lost unless a cycle corresponds perfectly with a 15 minute interval. However, as with AC, the length and magnitude may be sufficient for disaggregation models that utilize energy audit data, if other devices are not present with similar magnitude and duration.

Dishwashers

Dishwashers are similar to air-conditioning units in that they utilize induction motors. However, dishwashers vary from typical AC units that use compressors because they use motors to drive heat pumps. Also, their load shape curve provides more transient responses that are significant at larger intervals. Another difference between dishwashers and the previously discussed appliance classes is that residential dishwasher units are typically connected to 120 Volts as opposed to 240 Volts.

Dishwashers are also available in variable speed versions. However, their reactive power and linearity have been shown to be very low in measurement and modeling. This is likely because the heating mechanism is essentially a purely resistive element, unlike air conditioning systems, but similar to typical dryers.[46] Figure 22 shows a very slightly lagging current waveform for a tested and modeled dishwasher:

[46] Gondim et all

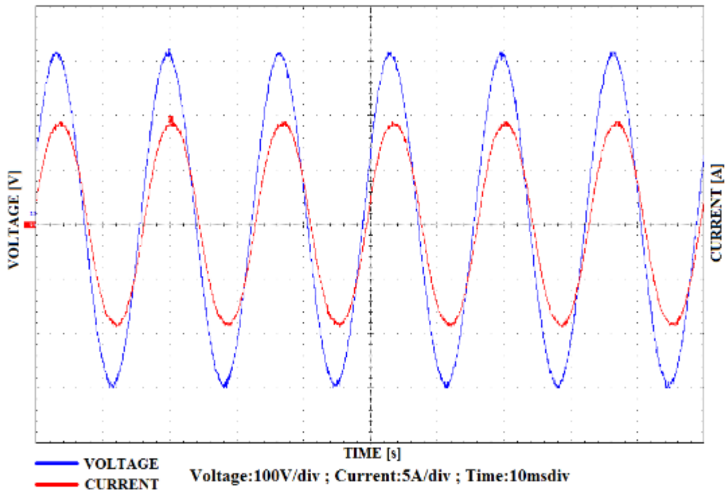

Figure 22: Dishwasher Waveforms

This study also states that dishwashers typically do not require a significant starting current, so unlike devices with large induction motors using capacitors, they do not cause a large initial voltage drop.

The 1998 DOE survey on dishwashers suggests that typical dishwashers dissipate 1200 to 1400 Watts.[47] The BEDB data suggests that these devices are typically active for 365 hours a year with an estimated of 120 kWh per year to drive the motor.[48] Unlike electric dryers, Energy Star does provide some information and standards for the real power draw of dishwasher through its Energy Factor metric, which is a measure of the cycles per kWh. DOE tracks the age of appliances, which could be translated into expected real power consumed based on appraisal data (age and value of the house) or energy audits. Figure 23 shows an example dishwasher power draw:

[47] Little

[48] Residential Sector Energy Consumption - Operating Characteristics of Electric Appliances in the Residential Sector. Department of Energy – Buildings Energy Data Book. Online. Available: http://buildingsdatabook.eren.doe.gov/TableView.aspx?table=2.1.16. Accessed March 1, 2011

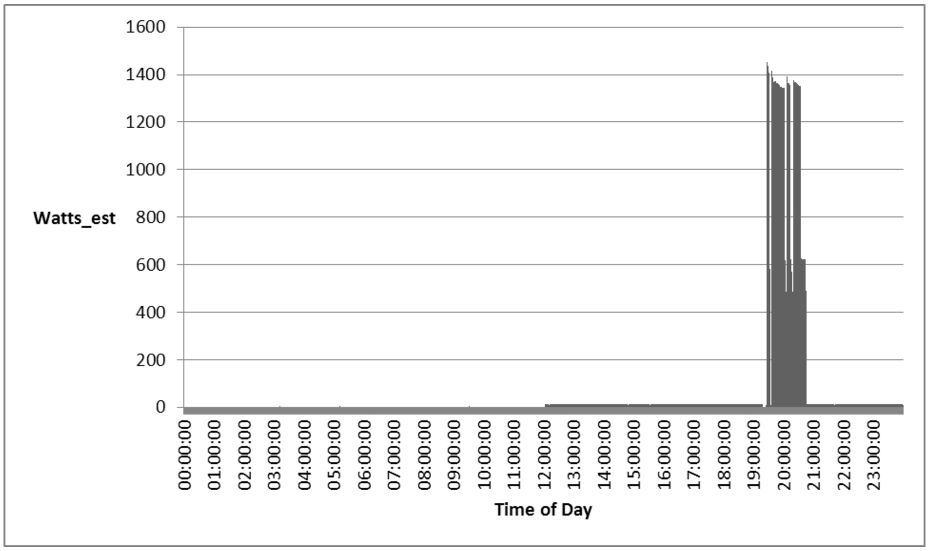

Figure 23: Pecan Street Project, Dishwasher 1, 15sec

It is clear that this signature could be learned by a disaggregation algorithm. The slight downward slope and changes in operating mode are very distinctive. Figure 25 shows it aggregated to 15 minutes:

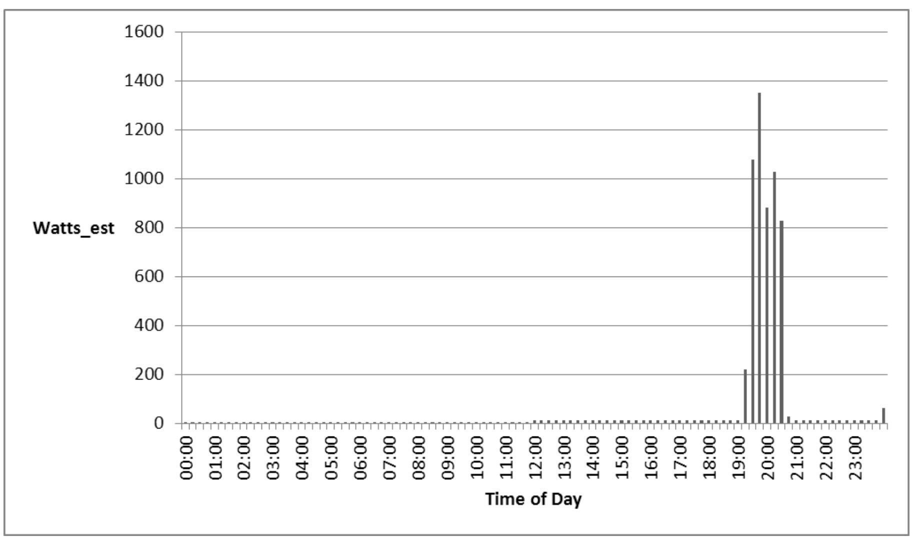

Figure 24: Pecan Street Project, Dishwasher 1, 15min

Statistical analysis would be required to confidently state whether the load profile of dishwashers is sufficient in disaggregation techniques that use a single 15 minute utility meter to infer when dishwasher loads are present. For comparison, here is the other dishwasher reading for the same selected day for a different house:

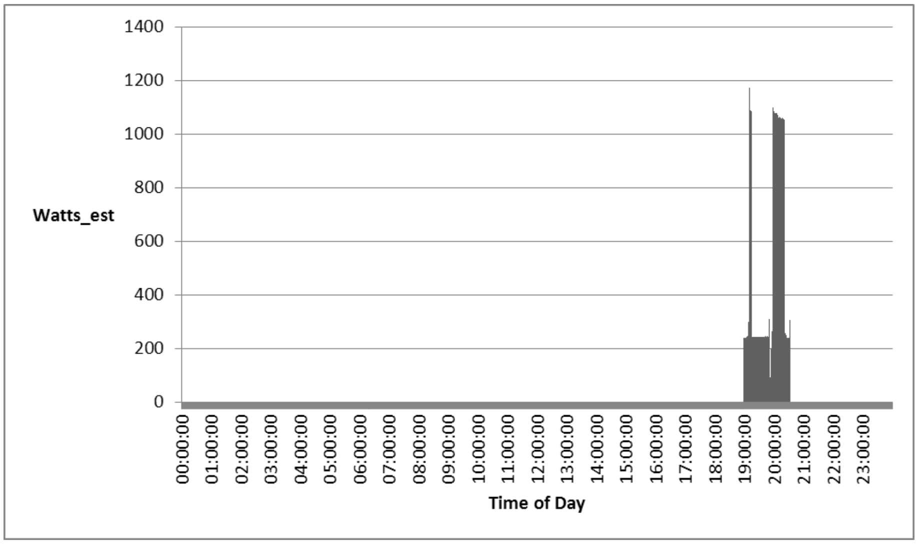

Figure 25: Pecan Street Project, Dishwasher, 15sec

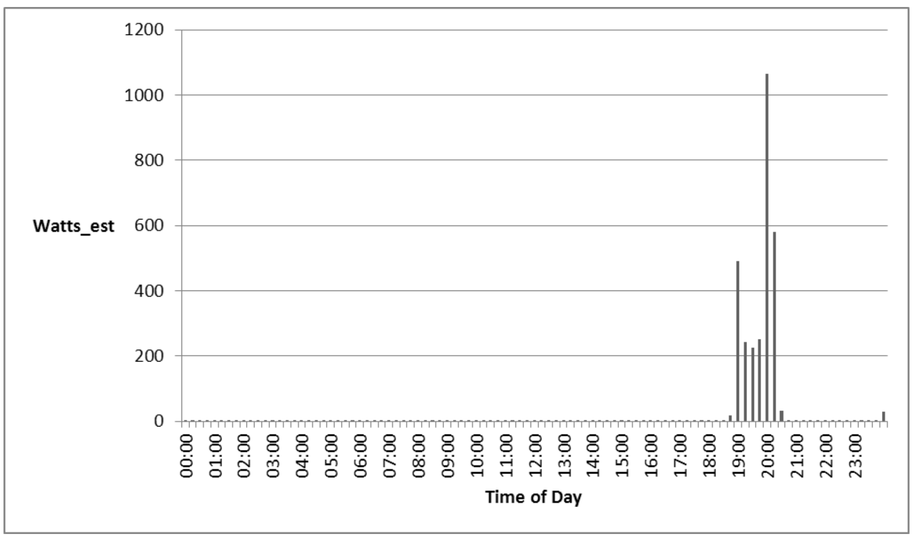

Figure 26: Pecan Street Project, Dishwasher 2, 15min

Further analysis is required, but based on these two dishwashers, it appears that a single point 15 second meter may be able to identify the dishwasher during its downward sloping periods, and that a 15 meter hides this information and shifts the data into different 15 minute ‘bins’ much like with clothes dryers and many other appliances. The ability to disaggregate this load may depend on the number of appliances that draw a similar peak, when the dishwasher is used, the learning method employed, and energy audit data.

Power Supplies

Before discussing the home entertainment and home office sub-circuits, Uninterruptible Power Supplies (UPS) should be covered, as they are most likely to be located on one or both of these sub-circuits. UPSs provide continuous high quality power to devices that are more dependent on power quality. The Computer and Business Equipment Manufacturers' Association (CBEMA) curve was developed for computers to specify the allowable magnitude and length of different changes in power supplied to electronic equipment. Essentially a UPS device adds stored DC energy to rectified input power supply, and sends this through an inverter and filter for a critical load to provide high power quality for critical applications.

Older UPS devices use a capacitor based inverter optimized for a 0.7 to 0.9 lagging load. In this case, the UPS itself has a leading power factor, and the overall power factor is closer to 1. However, newer devices vary significantly in their design. Standards in the European Union limiting non-linearity have led to devices that are optimized for higher power factors and alternative designs are being pursued to minimize power loss due to this constraint. Newer non-corrected switch-mode power supplies (SMPSs) have negligible displacement power factor (neither lagging nor leading) and have an estimated distortion power factor of 0.7.[49] Energy Star is currently reviewing product certification requirements for UPSs. Energy Star does provide guidelines for external power supplies, deferring to international standards that analyze the minimum efficiency of the units and require the power factor to be above 0.9 for devices with an input power above 100 Watts.[50]

It becomes increasingly difficult to disaggregate loads seen on a higher level sub-circuit that have UPSs because of the variance in UPS design and their effect on the overall current measured. If it is important to perfectly disaggregate loads at this level,

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[49] Leading Power Factors. Emerson Network Power. Chloride. Online. Available: http://www.chloridepower.com/Documents/Unprotected-downloads/Techpoints/English-UK/Leading-power-factors-and-UPS-systems.pdf. Accessed April 5, 2011.

[50] International Efficiency Marking Protocol for External Power Supplies. Energy Star. 2011. Online. Available: http://www.energystar.gov/ia/partners/prod_development/revisions/downloads/International_Efficiency_Marking_Protocol.pdf. Accessed April 5, 2011.

one option is to install smart power supplies that directly monitor the loads attached to the device. Another approach is to analyze changes in load characteristics as opposed to absolute values using a learning period.

Home Entertainment Equipment

The Home Entertainment circuit is very different than the previous sub-circuits discussed so far. It could encompass a wide array of devices and these devices are typically non-linear. It also typically has a lower load that is active for a longer period of the day.

While these devices are a growing portion of the load, energy simulation typically groups this and other advanced electronics together as miscellaneous equipment (Energy Gauge and eQuest). Statistical analysis is used to group these devices together in single point disaggregation methods using consumer behavior data. However, as the load share of these devices increases and as these devices are typically used at peak hours, there is growing interest in monitoring these devices for load management, customer services, and power quality analysis. It is interesting to note that in the European Union, many devices are constricted by standards restricting current harmonics (IEC 61000-3-12). Only in the 2001 RECS was data collected by EIA for appliance classes outside of the traditional categories: Space Heating, Space Cooling, Water Heating, Refrigeration, Cooking, Clothes Dryers, Freezers, and Lighting.

The first obvious equipment that can be expected to be located on a home entertainment circuit is a television. California has set requirements for power draws from televisions, dependent on the screen size, and also requires power factor be above 0.9. This requirement may infiltrate devices marketed to the entirety of the United States. Other likely devices on this sub-circuit are audio equipment, video content players, and set-top boxes.

As with other appliances discussed, this paper does not intend to be an exhaustive description of every possible type of appliance, but intends to share an overview that indicates the challenges and possibilities for the disaggregation of loads. This is especially true for home entertainment equipment, as the different possible configurations are very high. This paper will focus on televisions and stereos, and very briefly discuss video content players and set-top boxes, in that order.

Televisions

Televisions contribute a significant portion of the yearly load, as shown by Table 7 on page 32. The 1998 study found a typical Wattage to be 250 for color TVs with 4 Watts standby.[51] Energy Star rates TVs. More differentiated typical real power consumed for different set is provided by the BEDB:

Table 9: Typical Real Power, Televisions[52]

Type	Watts	Hours Active	kWh/year
Analog, <40"	86	1,095	184
Analog, >40"	156	1,825	312
Digital, ED/HD TV, <40"	150	1,095	301
Digital, ED/HD TV, >40"	234	1,825	455

An increasing number of studies have examined the harmonics of television sets as their share of the load has increased. An older 1993 power quality study found that among 8 households, televisions had a THD_I between 25 and 142, and a THDV between 5 and 6.6.[53] This corresponds nicely with Grady's assumption of insignificant voltage harmonics. A more recent study found a THD_I of 79 for an 80 Watt television. This THD value corresponds to an estimated 0.785 distortion power factor and displacement power factor of 0.85. Table 10 is a consolidation of the results of more recent studies:

[51] Little

[52] Residential Sector Energy Consumption - Operating Characteristics of Electric Appliances in the Residential Sector. Department of Energy – Buildings Energy Data Book. Online. Available: http://buildingsdatabook.eren.doe.gov/TableView.aspx?table=2.1.16. Accessed March 1, 2011.

[53] Warren et all

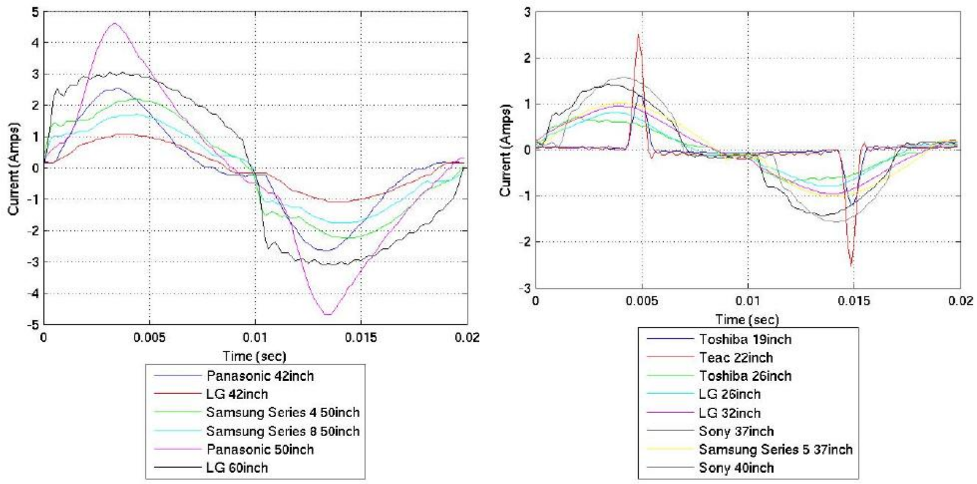
Table 10: Measured Television Power and Harmonics

Source	Type	disppf	tpf	Watts	VAR
Singh	-	0.978	0.5367	68.02	125.49
Grady	-	0.988	0.629	-	-
Patidar	-	0.85	0.67*	80	89.36*
Ghorbani	-	0.90*	0.52	50	79
Takekazu	CRT	-	0.62	41	66
Takekazu	LCD	-	0.72	44.1	60.8
Takekazu	LCD	-	0.96	136.1	141

The values shown with an asterisk in this and following tables are estimated using equation 1.28 on page 16.

An important characteristic for televisions when analyzing the load on a particular leg is that these loads have a leading current waveform, i.e. are largely capacitive as opposed to inductive. The ‘VAR’ recorded in the tables in this document is the absolute of the reactive power drawn by the devices, as most studies did not explicitly state whether the displacement was lagging or leading. The average true power factor for these measured instances is 0.665, which is significantly lower than the displacement power factor average, 0.939.

The EPEC study analyzed 14 different modern television sets and organized them by type – Plasma and LCD TVs:



Plasma TVs LCD TVs

Figure 27: Plasma and LCD TV current waveforms[54]

There is much more variation in the current harmonics for the Plasma TVs; the two smallest and non-linear LCD TVs were connected to an external power adapter. This significant variation adds complexity for disaggregation techniques that do not have direct access to these current waveforms or information about the TV installed. However, this differentiation could be useful within metering instrumentation that can analyze the harmonics to a sufficient degree.

Stereos

Stereos are also a significant load. Here is a set of typical values:

Table 11: Typical Real Power, Stereos[55]

	Active [W]	Idle [W]	Off [W]	Active [hr]	Idle [hr]	Off [hr]	kWh/year
Stereo Systems	33	30	3	1,510	1,810	5,440	119

[54] Hardie et all

[55] Residential Sector Energy Consumption - Operating Characteristics of Electric Appliances in the Residential Sector. Department of Energy – Buildings Energy Data Book. Online. Available: http://buildingsdatabook.eren.doe.gov/TableView.aspx?table=2.1.16. Accessed March 1, 2011.

The 1993 Power Quality survey found THD_V to vary between 3.5 and 4.1% and THD_I to vary between 40 and 102%, corresponding to estimated distortion power factor between 0.93 and 0.70.[56] This also matches Grady's assumption of negligible voltage harmonics. The displacement factor is small for this device class, as it is nearly in phase and many advanced devices cannot be easily characterized as lagging or leading.[57] The more recent EPEC study looked at 8 different audio equipment devices:

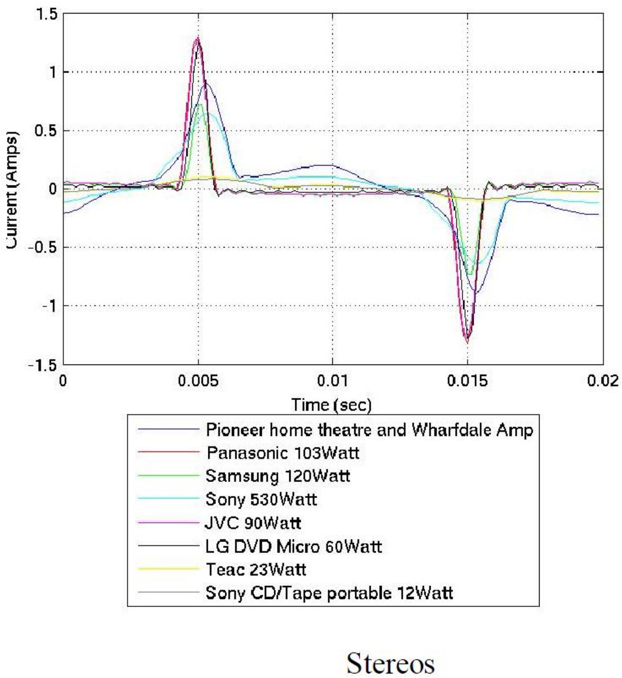


Figure 28: Current Harmonics for Audio Equipment

As shown here, stereos are more consistently non-linear and have more consistently characteristic harmonics. As with other devices not using induction motors, the linearity and power factor remain mainly consistent throughout a specified operating mode. As an example of the variation in operating mode variation, the Jabalpur Engineering College study tested a specific stereo under cassette and radio playing operating modes:

[56] Warren et all
[57] Ibid

Table 12: Stereo Harmonics Variation depending on Operating Mode[58]

	disppf	tpf	Watts	VAR
stereo system cassette playing	0.868	0.774	5.86	4.79
stereo system radio	0.926	0.787	7.78	5.66

Other Home Entertainment Equipment

Other typical home entertainment equipment includes set-top boxes and video-playing devices. This section discusses these three devices briefly. Set-top boxes, which are used to connect televisions to external signals, are covered by the 2008 DOE report:

Table 13: Typical Real Power, Set-Top Box[59]

	Active [W]	Idle [W]	Off [W]	Active [hr]	Idle [hr]	Off [hr]	kWh/year
Set-top Boxes	20	0	20	6,450	0	2,310	178

Many other small electronics equipment such as the gateways used in consumer metering systems, cable boxes, and others, likely match this characteristic – a small load that is plugged in for the majority of the year. Energy Star has finalized its certification for Set-top Boxes, a certification process that will begin in September of 2011.[60] Within their requirements they specify the type of metering system that is appropriate for devices with low power draw and high non-linearity. They require these devices have a limited stand-by power draw.

[58] Singh et all
[59] Residential Sector Energy Consumption - Operating Characteristics of Electric Appliances in the Residential Sector. Department of Energy – Buildings Energy Data Book. Online. Available: http://buildingsdatabook.eren.doe.gov/TableView.aspx?table=2.1.16. Accessed March 1, 2011.
[60] Program Requirements for Set-top Boxes. Energy Star. 2011. Online. Available: http://www.energystar.gov/ia/partners/product_specs/program_reqs/archive/STB_Program_Requirements_V1.0.pdf. Accessed April 17, 2011.

A final example of a device likely located on the home entertainment circuit is a video playing device. Video playing devices are covered by the 2008 DOE report and the Japanese appliance recognition study:

Table 14: Typical Real Power, Video-Playing Device[61]

Active [W]	Idle [W]	Off [W]	Active [hr]	Idle [hr]	Off [hr]	kWh/year
17	13	3	170	5,150	3,430	78

Table 15: Video-Playing Device Power and Power Factor[62]

Watts	VAR	tpf
17.4	25.3	0.68

These devices, like stereos and set-top boxes are typified by relatively low real power draw, and static low power factor and high non-linearity.

With the discussion of the devices on the home entertainment circuit considered, the overall circuit can be evaluated:

[61] Residential Sector Energy Consumption - Operating Characteristics of Electric Appliances in the Residential Sector. Department of Energy – Buildings Energy Data Book. Online. Available: http://buildingsdatabook.eren.doe.gov/TableView.aspx?table=2.1.16. Accessed March 1, 2011.
[62] Takekazu et all

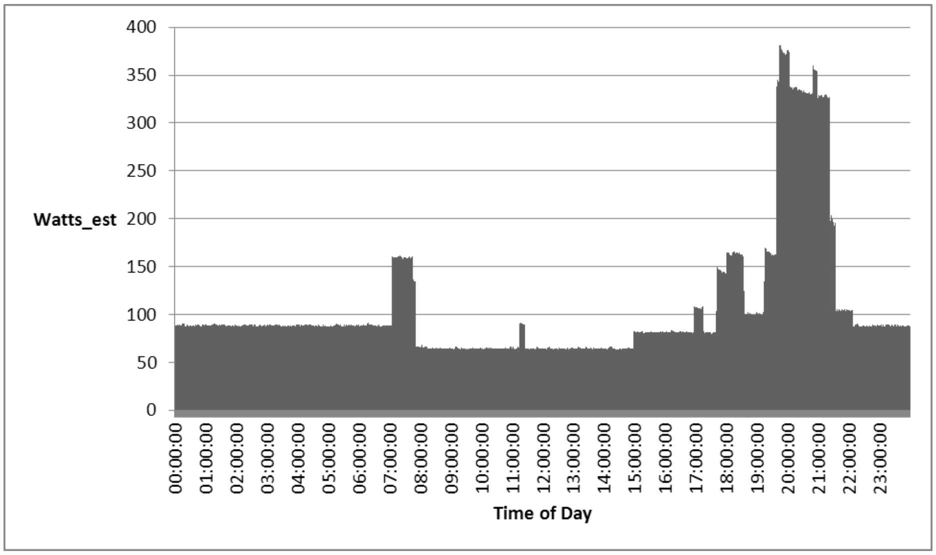


Figure 29: Pecan Street Project, Home Entertainment, 15sec

It appears that many devices on this circuit are active throughout the day. The slight variation seen when the circuit is flat-lined could be due to changes in reactive power, voltage delivered, or errors due to linearity. It is also not clear whether the slight curvature seen for specific appliances (shown by the jumps in estimated Watts) is due to changes in real power drawn or other factors. However, overall, most the devices appear to have a characteristic power drawn that could be disaggregated from the overall sub-circuit if the exact devices where known for this house. However, these devices are inexpensive and technology changes more rapidly for small electronic equipment, so data collection for this would be costly compared to the savings of controlling these loads or purchasing more efficient appliances.

The disaggregation for an overall home could be designed to disaggregate the aggregate home entertainment load. In this regard, the load profile for this overall circuit is fairly unique compared to the loads discussed thus far. A relationship between inferred residents' presence in the home and these loads is likely. However, from a utility metered disaggregation point of view, these loads are very small, and it may be difficult to differentiate between shifting of other appliances into 15 minute bins and loads associated with home entertainment as opposed to other appliances. Here is what the load looks like when aggregated:

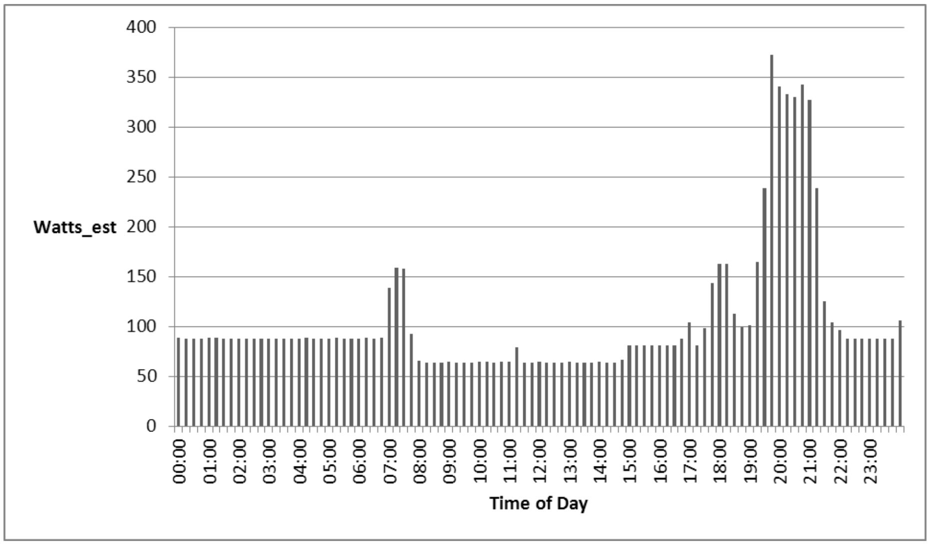


Figure 30: Pecan Street Project, Home Entertainment, 15min

The load actually fits into 15 minute bins very nicely. This could due to the typical active operating range of these devices being over 15 minutes, and the relatively static power factor and non-linearity. However, the magnitude of this low power draw is likely not characteristic.

Home Office Equipment

Similar in many ways to the home entertainment circuit, is the home office circuit. This circuit is also typified by devices with a low static power factor, high static non-linearity, and multiple devices with multiple operating modes. A UPS or external power supply may be used to deliver power to these devices. The 2008 DOE report provides some overall information:

Table 16: Typical Real Power, Office Equipment[63]

Device	Active [W]	Idle [W]	Off [W]	Active [hr]	Idle [hr]	Off [hr]	kWh/year
Desktop Computer	75	4	2	2,990	330	5,440	237
Laptop	25	2	2	2,368	935	5,457	72
Desktop Monitor	42	1	1	1,865	875	6,020	85

A number of research studies have resulted in the following measurements:

Table 17: Typical Office Equipment, Power and Power Factor

Source	Type	disppf	tpf	Watts	VAR
Singh	PC	0.999	0.809	119.98	148.22
Singh	PC	0.974	0.8344	107.37	195.12
Grady	PC and printer	0.999	0.58	-	-
Ghorbani	Monitor	0.93*	0.56	20	27
Ghorbani	PC	0.96*	0.62	90	118
Ghorbani	Printer	0.44*	0.43	40	34
Ghorbani	Laptop	0.94*	0.5	26	44
Takekazu	PC	-	0.64	23.6	36.6

Similar to other advanced electronic equipment, the displacement power factor is near unity for most devices. However, the true power factor, which incorporates the non-

[63] Residential Sector Energy Consumption - Operating Characteristics of Electric Appliances in the Residential Sector. Department of Energy – Buildings Energy Data Book. Online. Available: http://buildingsdatabook.eren.doe.gov/TableView.aspx?table=2.1.16. Accessed March 1, 2011.

linearity of the devices, is significantly lower and variable among devices. As with home entertainment equipment, these devices may have a leading displacement power factor.[64]

Energy Star provides guidelines for personal computers which detail how the efficiency changes as load changes. For the higher level view provided in this document, efficiency changes in advanced electronics are considered insignificant, in comparison with larger loads. However, Energy Star is a good source for information about the demand from different classes of advanced electronic equipment, and indicates the variability of the linearity and power factor among devices. In order to be approved for Energy Star 5.0 for computers, the internal power supply must have power factor correction that reaches at least 0.9 power factor for a specified rated output.[65]

Here is an example home office circuit as measured through the Pecan Street Project:

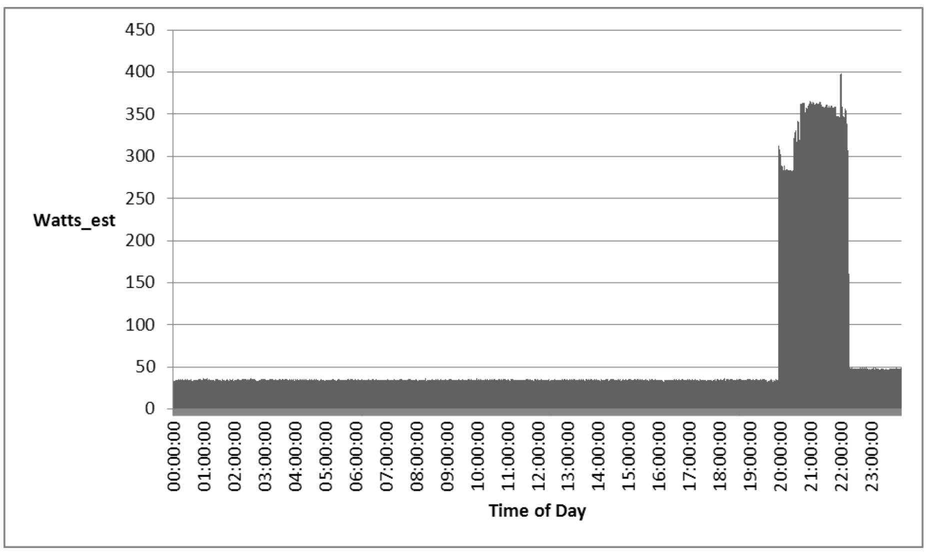


Figure 31: Pecan Street Project, Home Office, 15sec

[64] Grady et all

[65] Version 5.0 System Implementation. Energy Star. Online. Available: http://www.energystar.gov/ia/partners/product_specs/program_reqs/Computers_Intel_Whitepaper_Spec5.pdf. Accessed April 16, 2011.

Here it is aggregated to 15 minutes:

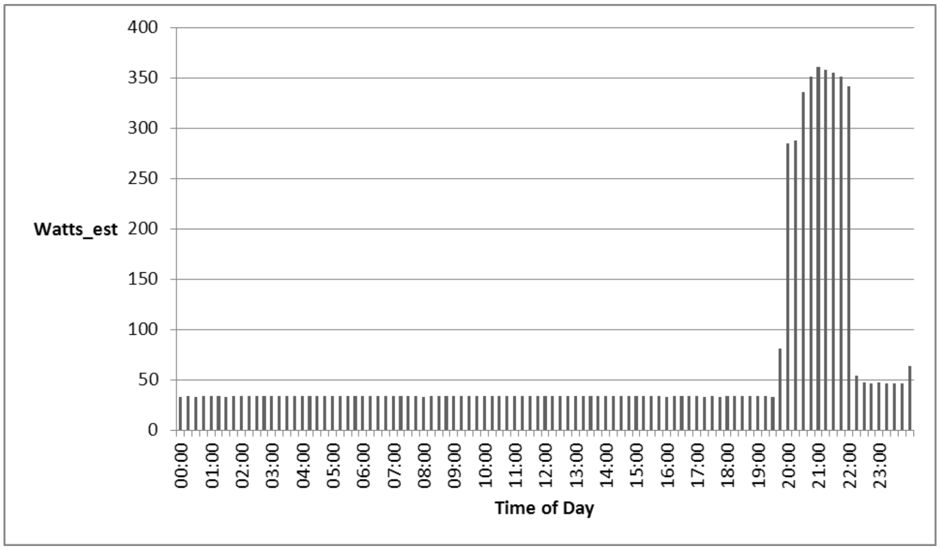


Figure 32: Pecan Street Project, Home Office, 15min

Much of the discussion for the home entertainment circuit applies here. While this load aggregates nicely, the question in regards to the utility meter is whether this small bump as seen on the whole house could be distinguished from other loads. Based on how the load is shifted into 15 minute bins for major appliances due to their variations in cycles and load, it's unlikely. A utility meter that measures the whole house at a quicker interval may fair better.

Microwave Ovens

Microwaves are an example of a load with high power factor, high linearity, and high demand for a short duration. The DOE 2008 report states these as typical values:

Table 18: Typical Real Power, Microwave[66]

Active	Idle	Off	Active	Off	(kWh/year)
1,500	0	3	70	8,690	131

[66] Residential Sector Energy Consumption - Operating Characteristics of Electric Appliances in the Residential Sector. Department of Energy – Buildings Energy Data Book. Online. Available: http://buildingsdatabook.eren.doe.gov/TableView.aspx?table=2.1.16. Accessed March 1, 2011.

Here are the results of the studies:

Table 19: Microwave Oven Power and Power Factor

Source	disppf	tpf	Watts	VAR
Grady	0.998	0.982	-	-
Ghorbani	0.93*	0.9	1350	609
Takekazu	-	0.95	1032.7	1078.9
Takekazu	-	0.97	733.1	750.7

Here is an example microwave oven as measured through the Pecan Street Project:

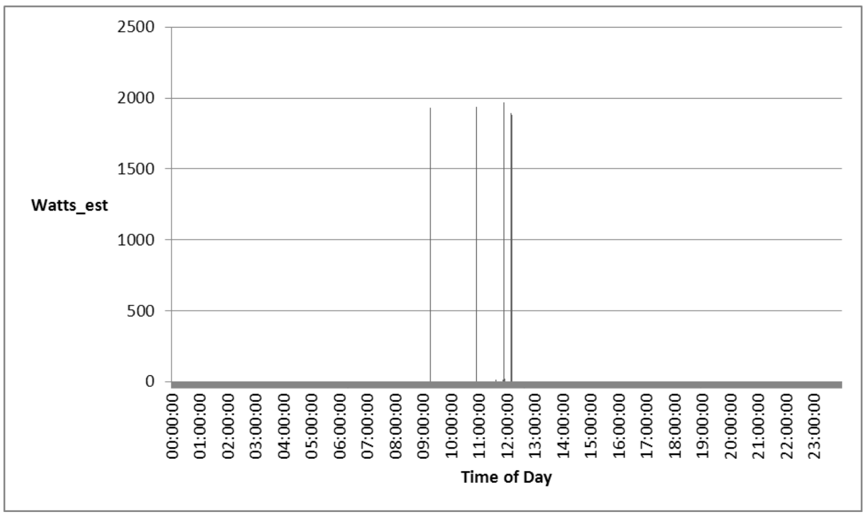


Figure 33: Pecan Street Project, Microwave Oven, 15sec

Microwave ovens have a very high power draw for a short interval. Older microwave ovens may turn off and on when cooking at a slower rate. It is important to note how quickly the demand changes. In the example shown, the estimated Watts goes from 738.75 to 1930 Watts from 9:14:30 to 9:14:45. Here, successful transmittal of packets containing the average current across each 15 second interval is significant in determining the total consumption for this appliance.

Here is the load aggregated to the typical utility smart meter interval:

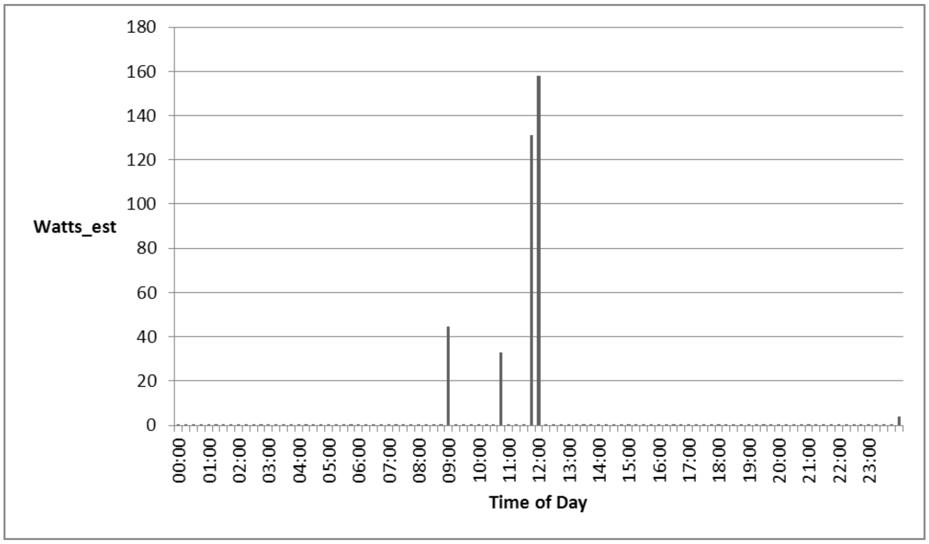


Figure 34: Pecan Street Project, Microwave Oven, 15min

Here the load shown is the average across each 15 minute interval. Because microwave ovens are switched on for much lower periods than this, the power shown on this chart is much lower. Also, the short length that the microwave is turned on prevents the characteristically brief but large demand to be seen by the utility meter. Advanced algorithms are required to fully state whether a bump seen due to a microwave oven could be identified by the system. However, compared to the variations in previous loads this seems unlikely.

Refrigerators

Refrigerators work very similarly to AC systems. They typically use an induction motor to power a compressor. They also contribute to the internal temperature and humidity (typical values available through ASHRAE). As such, they can be expected to have low non-linearity (except for devices with variable speed motors), and a slightly variable power factor depending on the correction used in the device. Energy Star provides specifications for refrigerators.[67] While the DOE report does not provide typical values, here are the results for a few tested refrigerators:

[67] http://www.energystar.gov/index.cfm?fuseaction=find_a_product.showProductGroup&pgw_code=RF

Table 20: Refrigerator Power and Power Factor

Source	disppf	tpf	Watts	VAR
Grady	0.875	0.867	-	-
Ghorbani	0.81	0.8	105	74
Takekazu	-	0.72	98	134
Takekazu	-	0.78	101.4	129

Because the devices tested were largely linear, the displacement power factor makes up most of the power factor. Refrigerators also have a few characteristics due to their operating modes. Refrigerators typically cycle between an active mode with a high load and then cycle off and consume very little power. When these devices are cycled on, they can exhibit significant transient responses as seen on 15 second intervals, due to the increased current needed to initialize the motor. Here is a refrigerator as seen by the Pecan Street Project:

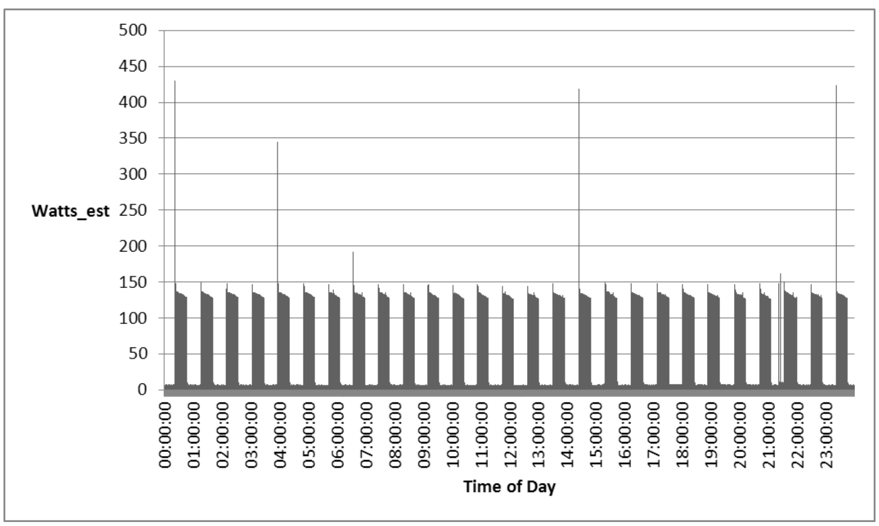


Figure 35: Pecan Street Project, Refrigerator, 15sec

The refrigerator load is clearly significantly characteristic on this interval. Slight transients are seen each time the device goes active, while a few cycles exhibit very large transients. Here is a refrigerator when aggregated to 15 minutes:

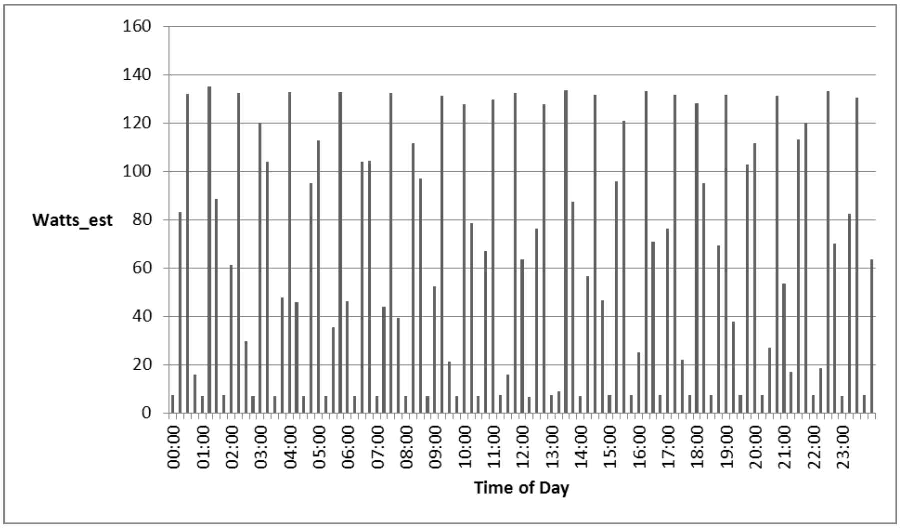


Figure 36: Pecan Street Project, Refrigerator, 15min

The exact timing of the operating modes is not clear, but the maximum value seen across the intervals is fairly consistent and matches the actual load well. The curve across a cycle appears to be fairly consistent, depending on the cycling length in regards to the interval. However, disaggregating this load from other loads with similar 15 minute values will depend on algorithms that statistically predict and estimate this curve.

Other Devices

Many other common residential appliances have not been discussed in this paper. At least one of 13 other appliance types is measured by the Pecan Street Project. Of the appliance types not measured, fans and lighting are the most significant. Compact Fluorescent Lighting (CFLs) constitute a significant portion of lighting loads and are highly non-linear, compared to incandescent light bulbs that draw purely resistive loads, and are the focus of much research and have high data availability. Fans are also typically highly non-linear and have sufficiently characteristic harmonics which can be utilized in systems capturing detailed waveform data.

Chapter 4: Disaggregation Techniques

Disaggregation techniques typically fall into two categories: systems using sub-metering which directly monitor specific loads, and modeling using single-point utility meters or alternative single-point meters. The Pecan Street Project is in a unique position to combine and evaluate each of these efforts and assist the development of future single-point algorithms. This section discusses sub-circuit disaggregation and then single-point disaggregation.

SUB-CIRCUIT DISAGGREGATION

Given the accuracy considerations presented in the section on Sub-Metering on page 21, sub-circuit instrumentation offer an alternative to disaggregation algorithms and enable the direct capture of load information. For dedicated circuits, no disaggregation algorithms are necessary, although the principles of these methods could be used to develop a calibration procedure. However, for circuits with multiple appliances, such as the home entertainment circuit, home office circuit, and each 'phase', disaggregation algorithms are necessary to determine what is residing on circuit at a particular time. Additionally, sub-circuit monitoring solutions are limited by the number of devices that can be directly monitored; a disaggregation algorithm would be necessary to determine the timing of identification of additional loads.

Like utility meters, typical sub-metering systems do not include disaggregation algorithms out of the box. Instead, they focus on accurately capturing the power drawn by specific measured devices. However, the data collected through sub-metering could inform an overall disaggregation algorithm used on the house. This data could also inform algorithms used on houses without sub-metering, and work to create clusters that could decrease the necessity of training periods.

SINGLE-POINT DISAGGREGATION

There is a long history of development of models that attempt to predict appliance consumption in specific buildings. For the purposes of this paper, models that utilize "bottom-up" approaches will be discussed, as opposed to purely statistical predictive models. Single-point techniques are termed "non-intrusive" as they do not require direct monitoring of specific appliances and loads. Despite being classified as non-intrusive, most of these techniques require a variable length intrusive "training" period, where each appliance is directly monitored and each load profile is learned before being input into a model that utilizes event detection going forward.[68] Within the classification of single-point systems, there are systems that utilize advanced meters and revenue grade utility meters, which will be discussed in that order.

Using Advanced Meters

Disaggregation methods that use advanced meters are capable of capitalizing on many of the characteristics discussed in the section on appliances. Throughout the 'training' period, when the appliance being used is known, characteristics of the overall and individual load are captured and 'clustered'. Because of the variance among different appliances, very few techniques attempt to input pre-determined clusters and rely solely on historical data.[69]

If the system captures a few of the previously discussed load characteristics, clustering could be created on the real versus reactive power plane and the current harmonics versus real power plane. The next two figures show possible results:

[68] Zeifman, M.; Roth, K.; , "Nonintrusive appliance load monitoring: Review and outlook," Consumer Electronics, IEEE Transactions on , vol.57, no.1, pp.76-84, February 2011.
[69] Ibid

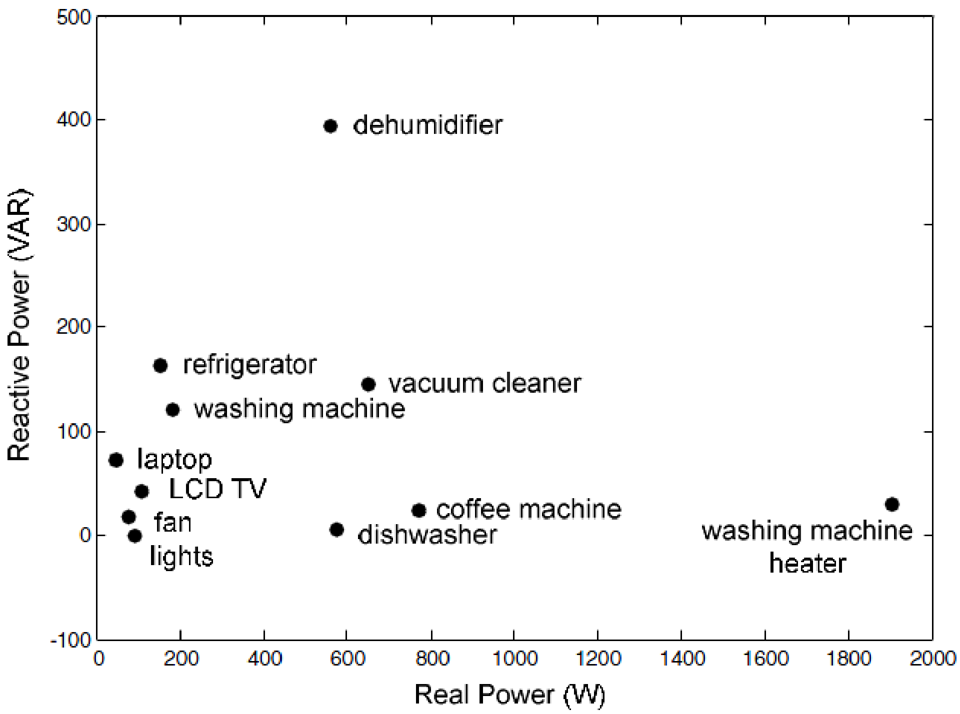


Figure 37: Reactive Power versus Real Power[70]

Here single points are shown for different appliances when those loads are the only load in the house. However, metering would provide a ‘cluster’ of points for different groups of loads. Additional significant dimensions to this data vary depend on the device in question but most importantly, the operating mode of the device. Figure 40 indicates the clustering possible if THD is measured:

[70] Du, Y.; Du L.; et al; , "A review of identification and monitoring methods for electric loads in commercial and residential buildings," Energy Conversion Congress and Exposition (ECCE), 2010 IEEE , vol., no., pp.4527-4533, 12-16 Sept. 2010.

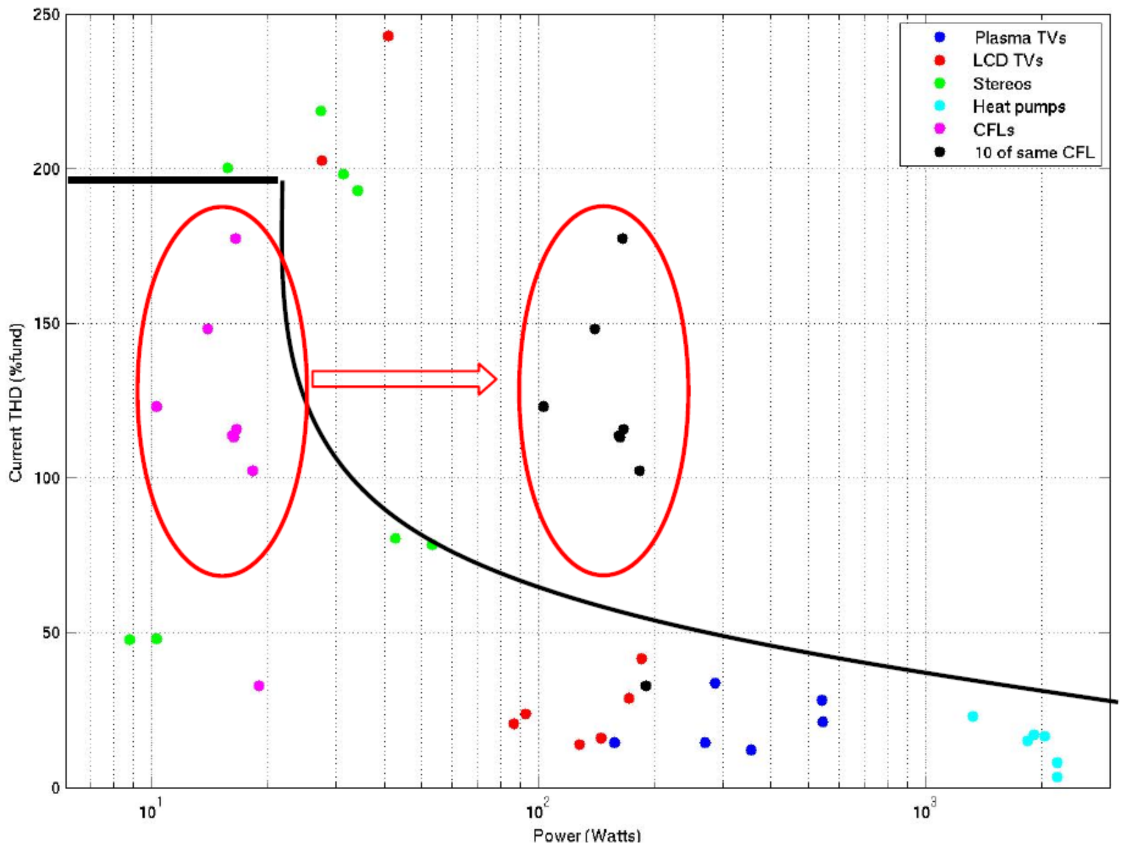


Figure 38: Current THD versus Log Scaled Real Power[71]

The analysis shown here is for a number of devices across several different possible home configurations. Again, this data is for when the selected loads are the only loads in the house. It is generally shown that THD decreases as real power increases, and that different specific devices do have slightly different values. CFLs are displayed twice to indicate that in a given house, there will typically be more than one of these devices installed (10 is used here).

Figure 37 indicates that capturing the reactive power is not only important for determining the actual power dissipated, it is indicative of the total load on the system. Absolute values of THD for the whole home may not be as characteristic in this determination as they depend heavily on the specific devices installed and the wiring of the house. For an individual house however, changes in harmonics could be indicative of

[71] Hardie et all

the load if training periods are utilized. Also, THD can be important in determining what devices are located on a sub-circuit with multiple sockets, as opposed to dedicated circuits.

A thorough description of the efforts made by researchers and specific techniques is available through Michael Zeifman's "Nonintrusive Appliance Load Monitoring: Review and Outlook" and the "Disaggregated End-Use Energy Sensing for the Smart Grid" article in the January-March 2011 issue of 'Pervasive Computing'.[72] In addition to the electrical characteristics of loads, an alternative approach is to sense electro-magnet interference (EMI) given off the increasing number of devices with switch-mode power supplies (SMPSs). Two significant drawbacks to this method are that not all devices utilize SMPS, and the EMI signals can be altered by nearby homes, equipment, and equipment turnover. More discussion of the advantages and drawbacks of this technique can be found in the aforementioned literature.

An exhaustive description of the capabilities, requirements, and results for a selection single-point implementations is shown on Table 21, as provided in the Persuasive Computing article:

[72] Disaggregated End-Use Energy Sensing for the Smart Grid. Pervasive Computing. January-March 2011. Online. Available: http://www.cs.washington.edu/homes/sidhant/docs/ElectriSense_Journal.pdf. Accessed April 20, 2011.

Table 21: Disaggregation Results for Advanced Single-Point Systems[73]

Extractable features / Comparison criteria	Real/ reactive power (watts vs. VARs)	Apparent power from $\lvert I_{AC} \rvert$	Harmonics of $\lvert I_{AC} \rvert$	Startup of I_{AC}	$\lvert V_{AC} \rvert$	Transient voltage noise signature	Continuous voltage noise signature
Sensing hardware	Smart meters capable of medium-rate sampling	Current clamps or inductive sensors	Current clamps or ammeters	Current clamps or ammeters	Voltmeter	High-sampling-rate voltmeter	Medium-sampling-rate voltmeter
Disaggregation level	Device category	Large load category	Large load category	Large load category	Large load startup detection	Individual devices with mechanical switches	Individual devices utilizing SMPS, or other electronic load controls
Example devices that can be disaggregated	Fans, motors, HVAC systems, forced air heaters	Stove, dryer, electric heaters	Fans, dryers, compressors	CFLs, motors	Motor appliances, dryers, electric heaters	Any switched load	Continuously switched devices: CFLs, TVs, DVD players, charging units
Algorithm	Clustering of watts and VARs	Step change in magnitude	Magnitude of harmonics	Pattern matching of startup transients	Magnitude	Pattern matching on transient pulses	Pattern matching on features of resonant frequency
Installation	Breaker or meter: inline ammeter with voltmeter	Breaker or meter: inline ammeter, or affixed outside	Breaker or meter: in line, or affixed outside	Breaker or meter: in line, or affixed outside	Plug-in anywhere	Plug-in anywhere	Plug-in anywhere
Ease of physical installation excluding calibration	Very difficult	Current clamps: difficult; inductive sensors: easy	Difficult	Difficult	Very easy	Very easy	Very easy
Ease of calibration	Very easy	Difficult	Difficult	Easy	Very difficult	Easy	Very easy
Cost (including cost of installation)	Very high	Low	Medium	Medium	Very low	Very high	High
Advantages	Automatic categorization of certain loads, works well for appliances	Simple, enables central database of signatures, reduces per-home calibration	Discriminates among devices with similar current draw	Discriminates among devices with similar current draw and startup	Simplicity and cost	Nearly every device has observable signature, independent of load characteristics	Stable signatures among homes and devices, independent of load characteristics
Limitations	I and V must be sampled synchronously, few devices with diverse power factor	Few devices with diverse power draws	Limited to large inductive loads that distort AC line, loads must be synchronous to 60 Hz	Limited to loads with diverse, long duration startup characteristics like motors and some CFLs	Few devices affect VAC line, susceptible to line variations	Requires per-home calibration, requires fast sampling (1–100 MHz)	Requires medium sampling rate (50–500 kHz)

[73] Ibid

Using Utility Meters

Systems that employ several of the previous features are cost-prohibitive in terms of equipment and employ intrusive initial learning periods. Therefore single-point systems for residential homes are more likely to utilize utility meters. Here we will discuss methods using existing utility meters and meters that can be reasonably expected to be deployed in the medium term.

Existing Utility Meters

While many utilities including Oncor are developing algorithms that attempt to disaggregate loads based on utility smart meters, many of these algorithms are currently being developed and are proprietary. In addition to the algorithms themselves being proprietary, they rely on proprietary equipment load profile statistics. For reference, the firm contracted by Oncor to develop their model states that they are capable of predicting major appliances such as heating and cooling, odd high consumptive appliances such as Jacuzzis, and a limited number of other major appliances.[74] Similar comments were made by a company that develops algorithms for different types of systems that is currently working with Pecan Street Project data to investigate disaggregation methods for the Pecan Street Project metering system.[75]

These techniques also typically rely on the results of utility surveys which include equipment saturation and consumer behavior metrics.[76] One such study utilized proprietary databases formed from such surveys to assign changes in load to specific appliances surveyed. Weather information is often appropriated for these algorithms. The results cited were that the “rule-based algorithm” could determine load profiles for major heating and cooling appliances.

Another study went a step further and was capable of assigning different aggregated loads to “housework, personal hygiene, cooking, and leisure time.”[77] This

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[74] Interview with Wayne Willis, VP of Sales & Marketing, Detectent. Janurary 14, 2011

[75] Interview with Luke Fishback, Owner, PlotWatt. April 1, 2011.

[76] Powers, J.T.; Margossian, B.; Smith, B.A.; , "Using a rule-based algorithm to disaggregate end-use load profiles from premise-level data," Computer Applications in Power, IEEE , vol.4, no.2, pp.42-47, Apr 1991.

[77] Capasso, A.; Grattieri, W.; Lamedica, R.; Prudenzi, A.; , "A bottom-up approach to residential load modeling," Power Systems, IEEE Transactions on , vol.9, no.2, pp.957-964, May 1994.

technique relied significantly on behavioral surveys and estimations; one significant factor was household income.

The two previous algorithms should not be expected to produce disaggregation for specific electronics equipment or information about the efficiency of equipment that does not constitute the majority of the load during its active mode. As shown throughout the section on appliances, these techniques are significantly limited by capturing 15 minute data. Figure 36 shows a house on the 15 minute interval:

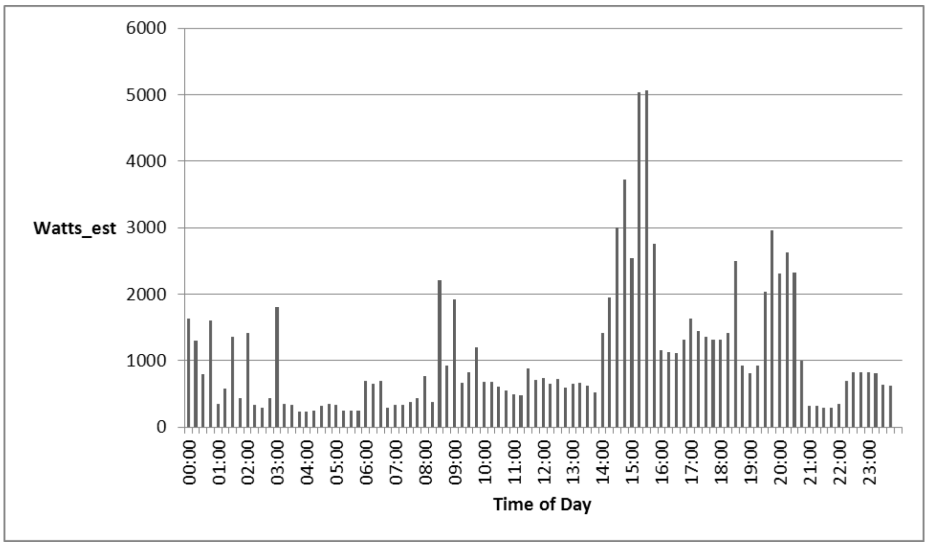

Figure 39: Pecan Street Project, Whole House, 15min

A rule based algorithm that assigns loads based on event detection based on statistical inferences will make some correct predictions to be sure, but many of the appliance's real power is not characteristic on this interval. Here is the same house viewed on a 15 second interval:

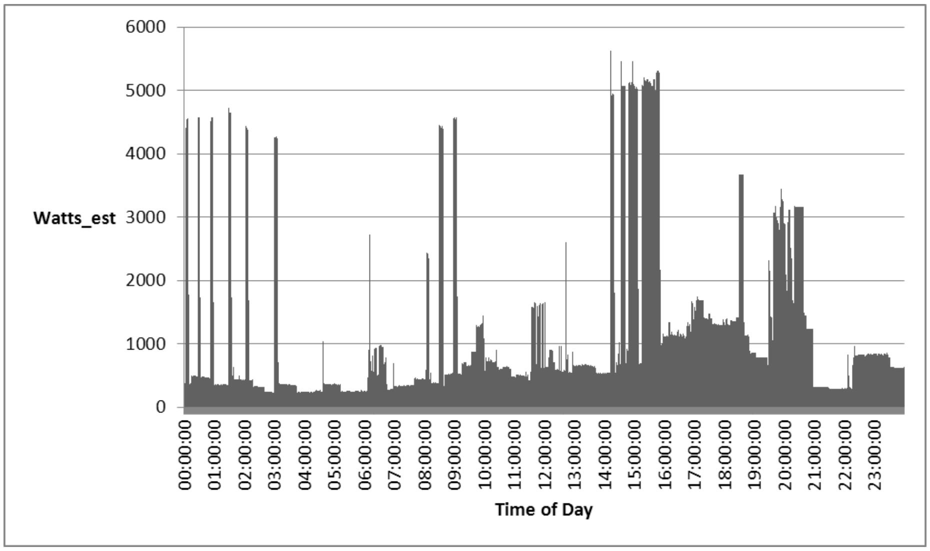

Figure 40: Pecan Street Project, Whole House, 15sec

Here more events can be detected, which is cited as the most important feature of these methods. For example, the refrigerator active mode can be visually identified.

Future Utility Meters

This brings us to the discussion of methods for future utility meters. As discussed in the section on meters, future utility meters may capture the real power at a lower interval. Although these algorithms are still under development, and are typically proprietary, there is a growing amount of literature on algorithms suitable for this instrumentation. One method was designed for systems where an optical sensor was attached to existing utility meters to estimate changes in load every second. This method relies heavily on historical data and requires no training period.[78] The specific algorithm used is currently a genetic algorithm that predicts events, but this is cited as possibly an incorrect procedure. The accuracy of this type of technique could be improved by utilizing energy audit data and the statistics used in aforementioned methods.

[78] M. Baranski, J. Voss, “Detecting Patterns of Appliances from Total Load Data Using a Dynamic Programming Approach,”Fourth IEEE International Conference on Data Mining (ICDM’04), 2004.

Conclusions and Future Work

This paper serves as an a priori investigation into the abilities of different metering systems to correctly capture the real power dissipated on loads and disaggregate loads into their constituent parts. Different appliance characteristics, most notably reactive power and current waveform linearity, are shown to be significant factors in both of these goals. These characteristics have been discussed for chosen appliance classes and the ability to group and differentiate among appliance classes has been discussed. Concerns have been raised for the ability to disaggregate loads using 15 minute single-point real power measuring utility meters.

This research indicates several things that could be investigated further through the Pecan Street Project. Comparisons between sub-metering and single-point meters and enhancements for disaggregation and related consumer products could be researched.

Recently, the Pecan Street Project began capturing Austin Energy utility metered data. Additionally, the status of meters in the Mueller deployment has recently begun being captured. Finally, energy audit results have begun to be recorded. After the additional work in conducted to decipher the precise meaning of each labeled sub-circuit is completed and additional calibration is conducted, the expected ranges of power factor and linearity could be used in conjunction with packets lost and timing optimization to match Pecan Street Project values with Austin Energy values.

The Pecan Street Project could use the sub-circuit readings to disaggregate the total load in two ways. First, an algorithm could be developed that does not require matching with Austin Energy and uses raw values from the current measuring system. In conjunction with energy audits, this routine could work to identify the non-metered appliances on each house. The second option is to de-scale the raw data into estimated apparent power and make approximations of the total power factor of the house and the power factor of measured appliances by comparing with utility data. As shown in this paper, the remaining power factor will be highly illustrative of the remaining load. Both of these algorithms could be used together to estimate remaining loads and identify meters not optimally calibrated.

When the Pecan Street Project data is sufficiently matched with Austin Energy, more informed research into the relative abilities of single-point metering and sub-circuit monitoring can be completed. Going forward, the Pecan Street Project will be deploying several different systems inside and outside of Mueller. The homes dispersed outside of Muller will provide a wider range of residential income levels, size of home, and year built, which may be useful in appliance distribution studies. Every incremental new system deployed will enhance the calibration of each other system and provide additional sources of appliance load profiles for researchers interested in developing disaggregation algorithms.

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