DEVELOPING APPLIANCE ENERGY USE PROFILES FOR RESIDENTIAL BUILDING ENERGY MODELING

Kristen Cetin[1], Atila Novoselac[2]
[1]Department of Civil, Architectural and Environmental Engineering, University of Texas at Austin, Austin, TX, USA

ABSTRACT

One of the largest users of electricity in the average U.S. household is appliances, which when aggregated, account for approximately 30% of electricity used in the residential sector in the United States. Building energy modelling of residential homes must accurately portray these appliance loads on a temporal scale in order to best represent today's appliance energy use, and to predict how possible future changes to their use, such as peak load shifting through "smart" appliance demand response may help reduce the increasingly stressed electric grid infrastructure. This study provide preliminary results of the analysis of disaggregated energy consumption data collected from 40 homes in Austin, TX to analyse the energy use of appliances.

INTRODUCTION

By 2030, the U.S. Energy Information Agency (EIA) estimates energy consumption in the U.S. will increase by 28%, and residential building energy consumption by 23% (US EIA 2013a). Peak electricity loads are also predicted to increase nearly 1.6 times that of the average annual consumption (US EIA 2013b). This is particularly pronounced in the hot climates such as Texas, where this peak load is estimated to increase at nearly twice this rate (ERCOT 2013), creating increasing stress on the aging electrical grid infrastructure. Energy use and peak load are similarly anticipated to increase in other countries.

With residential buildings accounting for approximately 20% of energy consumption and 36% of electricity consumption (US EIA 2013a), there is great potential to address these concerns through changes in residential building energy use patterns. The current use patterns of appliances and systems must be quantified in order to predict how appliances currently use energy, and how temporal changes in their use patterns may reduce peak loads. Home appliances, which account for 30% of annual electrical energy use in U.S. homes (US EIA 2013c), are a significant contributor to energy use, and contribute peak-energy use. However there are limited recent studies that have analized the temporal energy use of appliances.

There are several available datasets providing values for annual consumption (kWh) of appliances for a household (e.g. (US HUD 2009) (US EIA 2009)). However, how this total consumption is divided by time of year and time of day is less available (Armel et al. 2013).

A limited number of studies on temporal appliance energy use have been conducted within the U.S. The largest study to look specifically at appliance use profiles using disaggregated circuit-level data was conducted in the Pacific Northwest for 288 residences in 1989 (Pratt 1993). This multi-year study developed daily profiles for major household appliances. The results of this study are what is currently used in residential building energy modeling.

More recent studies have also looked at appliance energy use, however, most are smaller in sample size or have not monitored individual circuits of each appliance. A study of 204 homes energy consumption was conducted in in Central Florida (Parker and Mazzara 1996), however the focus was on analysis of whole-home energy use, rather than appliance-specific profiles. Saldanha et al. (2012) conducted a smaller study of home energy use of 12 homes in Canada. This study grouped all large appliance loads together, into one "non-HVAC" load rather than dividing into individual appliances. Several studies have also focused on a single appliance behavior. Hart and de Dear (2004) correlated refrigerator energy use with outdoor and indoor temperature.

As society continues to change, and thus both the appliances using energy, and the people using the appliances change, it is of interest to develop up-to-date use profiles of appliances. Today, for example, many adults work from home, about 23.4 million according to the Census Bureau, 41% more than in 1999. This may increase the fraction of daily energy use of appliances utilized during the day when residents are typically not at home. Additionally federal standards for appliances set in 1990 and revised in 1993 and 2001 have reduced energy consumption of appliances, yet the size and options available on appliances has, on average, increased. These and other factors may have an effect on appliance use, thus additional information is desired to better characterize specific appliance energy use in today's residential building stock.

Some of the most common home appliances, including refrigerators, dishwashers, clothes washers and clothes dryers, have penetration rates of 66-99% in homes in the U.S. today (US HUD 2009), and are thus chosen for use in this study. Their use depends on their characteristics, as well as household use patterns of these appliances. Previous studies have found that refrigerators consistantly consume electricity throughout the day without human intervention. User use-dependent appliances such as dishwashers, washers and dryers are only used when the owner decides to use them and thus their use depend on the household.

This research thus aims to address the need for the development of profiles of energy use to update existing assumptions on the time-of-use of appliances. This paper provides preliminary results for this analysis. The time of use of energy can provide an update input to building energy models, as well as inform utilities, manufacturers of smart appliances, and consumers about the role appliances currently play in building energy use.

METHODOLOGY

Energy Use Dataset

One year (March 1, 2012 – February 28, 2013) of energy consumption data from homes in Austin, TX, is used in this research. Energy consumption data was collected from homes using a home energy management system (HEMS), which uses "CT" (current transformer) collars attached to the homes' circuits, which monitor the individual circuit's energy use. The HEMS provides root-mean-square (RMS) of current and voltage to calculate average real power, which is saved at one-minute increments.

To ensure quality data, several checks were performed including removal of "spikes" in the data. False "spikes" occur when the HEMS is reset. These spikes were removed and assigned the value of the average of the data points before and after. Over the year studied, a total less than 0.001% of data points for each home were identified as spikes. The data was then aggregated into hourly time steps, following the methodology used for EnergyPlus (U.S. DOE 2007) and DOE-2 (LBNL 2013). Checks were missing data were also performed. If missing data was detected, these null values were not considered in the analysis.

Characteristics of Studied Appliances and Homes

40 homes of disaggregated energy use data are used. These homes were constructed within the past 10 years, and the majority of the appliances, including the refrigerators, dishwashers, clothes washers and clothes dryers were manufactured between 2007-2009.

Demographic information was collected on the studied homes and compared to that of the U.S. building stock for an understanding of the types of homes represented in the data sample. The number of occupants per home in this study (2.86) is similar to the average U.S. residence (2.6), but this dataset's homes are larger (77%) and newer, and have higher household incomes than the average U.S. household. These factors are important as they may affect energy use of the studed appliances.

Appliance circuit-level data was available for a subset of the 40 homes. 15 homes had a dedicated circuit monitored for the dishwasher, 12 for the clothes washer, 18 for the clothes dryer and 9 for the dishwasher.

Energy Use Data Aggregation

To determine the energy use patterns of appliances, three different parameters are considered. In energy simulation several different parameters are used, including an (a) normalized daily use profile of energy use, (b) multipliers based on factors such as if it is a weekday or weekend, what month of year it is, or other influencing factors, and (c) an annual energy use value. These parameters are multiplied together to obtain a 365-day, 8760-hour energy use profile for an appliance. In this research, the (b) multipliers and (c) annual energy use values are the focus. The energy use dataset is used to develop these parameters.

RESULTS

A normalized daily use profile (a) for refrigerators, washers, dryers and dishwashers have been develop ped (Cetin et al. 2014). These use profiles were found generally agree with those found by Pratt (1993) (Figure 1). In order to use the daily use profiles developed, (b) multipliers, and (c) annual energy use values are also needed.

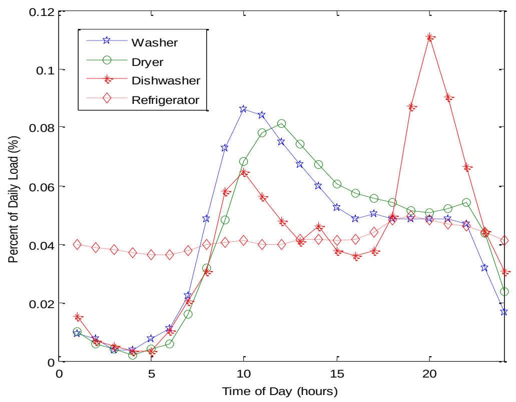


Figure 1: Normalized Daily Use Profiles (Pratt 1993)

Multipliers

If energy consumption is the same for all of a specfic type of appliance for each day throughout the year, then it would be sufficient, in representing the energy use schedule of an appliance, to only use a normalized daily use profile and an annual energy use value. Multiplying these together would thus predict the same amount of energy for each day of the year. If this energy use distribution is not the same for all days, then a multiplier is needed to change the relative magnitude of energy use so that the appliance use profile better fits the actual behavior of the applaince.

One multiplier considered in this research is that of change in energy use by month of the year. With changes in the months of the year, tempearture changes, as well as does the human behavior associated with the use of the studied appliances. To assess this change, the total energy use for each month is added together, equating to a total energy use value for that particular month. Each month's energy use value is then divided by the average energy use of monthly energy consumption of the entire year to create a set of monthly multipliers. For These multipliers would be multiplied by the normalized energy use profile in Figure 1. These multipliers are shown in Figure 2.

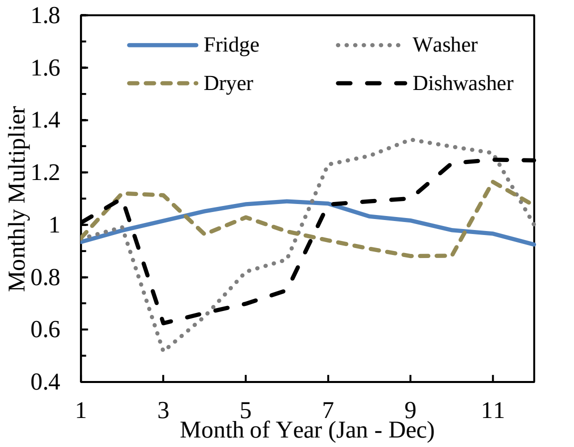


Figure 2: Monthly multipliers of energy use of large appliances representing all homes' data

Clothes washers, clothes dryers and dishwashers show decreased energy use during the spring and summer months, and higher energy use in the winter. Refrigerator energy use, however, shows increased use during the summer and lower energy use in the winter. The refrigerator will require more energy to keep food cool in the summer since it must work harder to cool the home's warmer indoor air to the constant cool tempearture inside of the refirgerator. In the winter the difference in the temperature between the inside of the refirgerator and the indoor temperature of the home would be less and thus less energy would be needed to maintain the desired refrigerator temperature. Thus it makes sense the energy use would be greater in the warm months of the year than in the winter.

Dishwasher and clothes washer energy use drops significantly in the spring and early summer months, then is higher in the mid to late summer through the beginning of the winter season. Clothes dryers use, however remains more constant throughout each of the months of the year. It is also noted that the change between months of the year is higher for these three user-dependent enegy users.

Limitations

The calculation of the monthly multipliers shown in Figure 2 can be influenced by a home that has an energy use pattern that does not follow the same trends as the other homes studied in the dataset. For example, Figure 3 shows the the monthly multipliers for each of the considered refrigerators. Most monthly multiplier profiles show an increase in energy use from February (2) to March (3), however one home's refrigerator shows a decrease during this interval. While the influence of this one profile is not signifcant, it should be noted a greater sample size would make the influence of this profile less important. This difference in monthly energy use for this particular home may also indicate there is a problem or fault with the refrigerator that should be addressed.

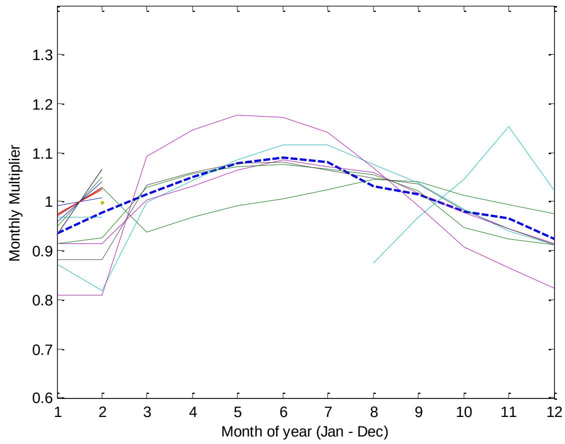


Figure 3: Refrigerator monthly multipliers for each home

Daily Energy Use

Annual energy use values are available for many different applainces, and are typically provided at the purchase of the appliance. These annual energy use values are based on an assumption of, for example in the case of a washer or dryer, a predicted number of cycles of use per year. In energy simulation, the total annual energy use value (kWh) is divded evenly between each of the 365 days, then the multiplier(s), as discussed above, are used to change the magnitude. However, it may not be the case that evenly divided the annual energy use value among each day is an accuarte portral of energy use for the year on a temporal scale. Thus this is investigated in this research.

We first look at daily energy use to better understand if daily energy use is consistant throughout the year, and how consistant it is. This is important in determining the annual energy use since annual energy use is eventually split evenly between all days of the year before being multiplied by the multipliers and normalized daily use patterns.

The hourly energy use data for each each appliance in each home is totaled into daily energy use. The mean and standard deviation, and thus the resulting coefficient of variation are calculated. In order to compare how much variation occurs across all appliances and homes, coefficient of variation is used rather than standard deviation as this provides a unitless measure of variability. Figure 4 shows, for each of the individual appliances monitored in the 40-home sample, what the average daily energy use is (x-axis), as well as its coefficient of variation (y-axis). All appliances are shown on the same plot to allow for comparison in this variation.

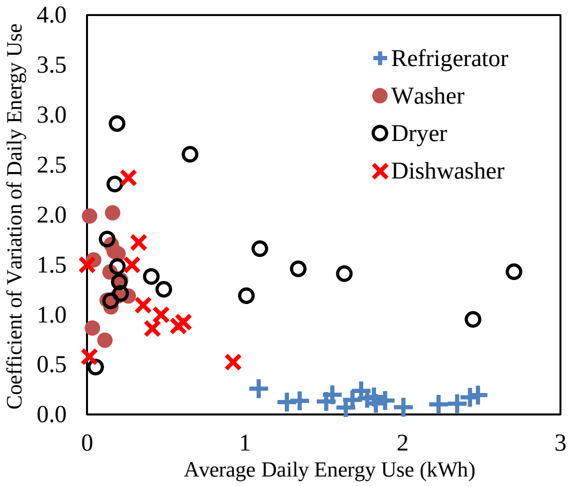


Figure 4: Average daily energy use (kWh) of all home appliances and their coefficient of variation

The consistant behavior of the refrigerators, as shown in Figure 4, is expected. Refrigerators studied in this research have a range of average daily energy use values but this value has very little variation. Since refrigerators are not highly dependent on human behavior to determine how much energy is used, this is a logical behavior.

The clothes washers, clothes dryers and dishwashers, however show singificantly more variation in daily energy use. This is particularly pronounced in the dishwashers and washers, which use a relatively low amount of daily energy used, but have a large COV. Dryers have a significantly larger range of daily energy use values. Those dryers that have the low energy use values likely are either gas dryers, a type of dryer which require only a small amount of electricity to operate the tumbler of the machine.

It makes sense that daily energy use would vary more with human-dependent appliances since users may not use the appliance every day, thus some days the energy use would effectively be zero, but other days, when perhaps two to three loads of laundry are done, the energy use would be much higher.

Base on this information, representing daily energy as an annual energy use value that is divided evenly among all days of the year makes sense, particularly for the highly consistant refrigerator energy users. With the clothes washers, dryers and the day-to-day use has much greater variability and merits greater investigation of what is causing this variation. If an additional multiplier, such as one that accounts for weekday vs weekend energy use, can be used to divide homes into two separte datasets that have less variation among this will help better match energy use data.

Annual Energy Use

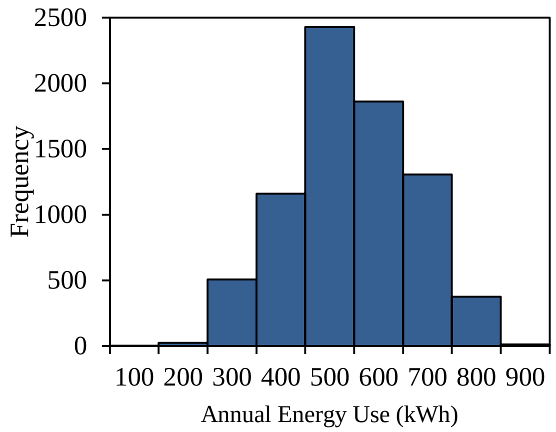
To develop annual energy use values for appliances, each circuit's energy use for each home is summed over the monitoring period to obtain an annual energy consumption value. In the case that more or less than a year worth of data was available, the total energy use over the monitoring period was normalized to equate to a 365 day monitoring period. Table 1 showes the average, median and standard deviation values of the energy use of the studied appliances.

Table 1: Annual Energy Use (kWh)

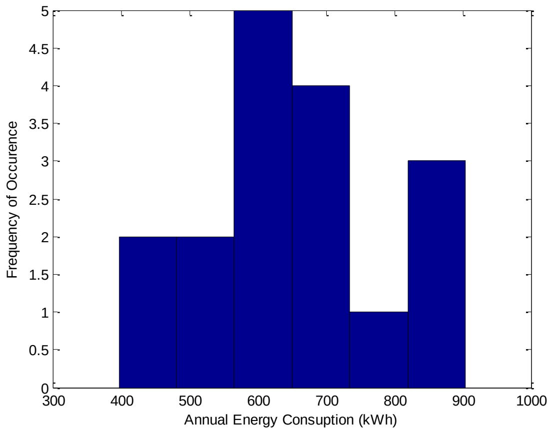
	AVERAGE (KWH)	MEDIAN (KWH)	STD. DEV. (KWH)
Refrigerator	658	648	146
Clothes Washer	51	55	26
Clothes Dryer (Elec)	477	400	300
Clothes Dryer (Gas)	60	70	20
Dishwasher	121	130	97

The average and median values are similar for refrigerators, washeres, gas dryers and dishwasher, however electric clothes dryers appear to have a harger difference and standard deviation. This is consistant with findings in Figure 4.

Comparing the annual energy use values of those provided by the California Energy Commission's Appliance Efficiency Database, the histograms show similar shapes. As an example, Figuer 5a shows the distribution of annual energy use values of refrigerators from the California Energy Commission. Figure 5b shows the histogram of this same data using the refrigerators studied in this research. The average energy use of the CEC's refrigerators is 518 kWh which is slightly less that that of the refrigerator found in this research. The CEC does not provide information on the number of each of the avaiable appliances in the database used in each home.



(a)



(b)

Figure 5. Histogram of refrigerator annual energy use of (a) all homes in the US and (b) the 40-homes in this study.

CONCLUSION

This paper has shown that using energy use data for a set of 40 homes, patterns in energy use of appliances can be developed. The following conclusions can be drawn from this research:

1) Appliance energy use varies by time of year. Refrigerators use more energy in the summer months; washers, dryers and dishwashers use less energy in the spring and early summer, and great amounts of energy in the end of the summer and fall.
2) Refrigerator daily energy use is more consistent each day than user-dependent appliances.
3) Daily energy use of user-dependent appliances varies greatly, in some cases the variation is greater than the energy use.
4) Annual energy use of appliances varies significantly even with systems manufactured in the same year in similar homes. Dryers in particular show a wide range of energy use values; some of this variation may be explained due to the fact that some dryers are gas powered.
5) Annual energy use of appliances varies more greatly across homes for user-dependent appliances (washers, dryers and dishwashers), and less in automated appliances (refrigerators).

As smart meter and other energy use data becomes increasingly available, the continuous tuning of energy modelling software will be possible. Studying use patterns and the methodologies to look at these patterns is helpful all those involved in smart metering, energy modelling or grid infrastructure.

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