Is Your Refrigerator Running?
Energy Use and Load Shapes for Major Household Appliances

Ben Larson, Robert Davis and Jeffrey Uslan, Ecotope Inc.

ABSTRACT

Household appliances represent a significant fraction of the non-space conditioning, non-water heating load in residential settings. Knowing how much energy they use and when they draw power is essential to estimating the potential for energy savings and load mitigation. This paper presents the appliance findings from the results of a comprehensive, residential, energy use measurement study of one hundred houses in the Pacific Northwest. The paper describes how much energy is currently being used by refrigerators, freezers, clothes washers, clothes dryers, dishwashers and cooking ranges as metered in the households. Further, it presents time-of-use information in the form of load shapes. The load shapes are critical to understanding how new appliance designs can integrate into a smarter grid and demand response (DR) programs, while interacting with home owners in novel ways. The shapes are becoming increasingly crucial to informing the national standard settings process as time-of-use becomes as important as annual energy savings.

Introduction

As part of the Residential Baseline Stock Assessment Metering (RBSA Metering) project, Ecotope, a Seattle-based energy efficiency research, design, and consulting company, metered appliance energy use in 104 houses in the Pacific Northwest (NEEA 2011). Sponsored by the Northwest Energy Efficiency Alliance (NEEA), the study is a subsidiary of the larger regional survey, the Residential Building Stock Assessment (Baylon 2012). The houses studied were selected randomly from the population of houses in Washington, Oregon, Idaho, and western Montana (see Figure 1). A combination of random digit dialing (RDD) and utility phone lists were used to create a sample frame from which houses were recruited in to the study. The sampling was stratified only on geography and not on occupancy, house size, utility usage, etc.

RSBA Metering has lasted in excess of two years monitoring energy use at five minute intervals. The study directly measured most energy end uses in houses. These end uses included space heating, space cooling, water heating, lighting, large appliances (often referred to as white goods), consumer electronics, and other miscellaneous loads. The paper summarizes findings from the first year of data on appliances, consisting of refrigerators, freezers, clothes washers, clothes dryers, dishwasher and cooking ranges.

The appliance electricity usage was measured with one of two devices. The first measured appliances that were on independent circuits at the electrical panel like the dryer and range. It reported with 10 Watt resolution and an accuracy of 0.2%. The second device was deployed to measure 120V appliances plugged in to wall outlets such as refrigerators and freezers. The device reported with 0.1 W resolution and accuracy of 1.5%. The five minute logging interval was selected to strike a balance between achieving enough time resolution and bounding the data handling tasks of a multi-year study. The resolution was fine enough to distinctly observe the major appliance energy use events such as automatic defrost in freezers, dryer heating element cycling, and dishwasher heating element use. The five-minute scale is too long, however, to observe certain events like lamps turning on inside a refrigerator when the door is opened. Those events, however, are counted in the energy use because the data logged is the average power over the five minute interval.

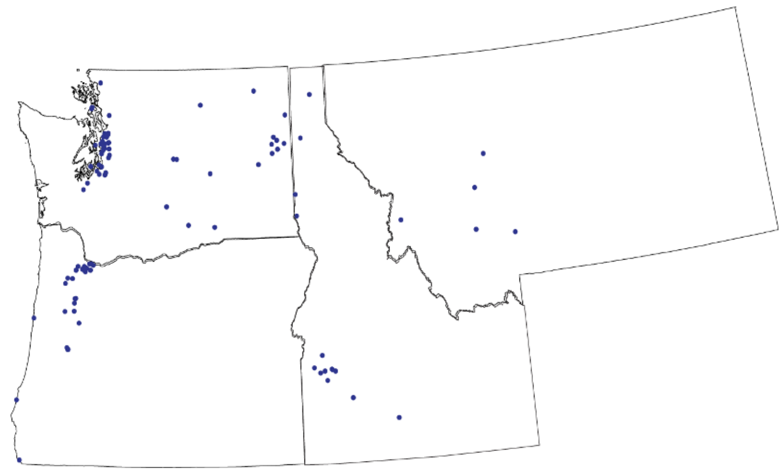

Figure 1. Location of metered sites across the Pacific Northwest.

Although the exact saturations differ, appliances are found in various combinations in every house across the country. The appliances represent a significant fraction of the non-space conditioning, non-water heating load in residential settings. Indeed, the RBSA Metering study showed the typical mix of electric appliances in houses across the Northwest use 2,300 kWh/yr. The study excluded metering the small fraction of cooking equipment and dryers fueled with natural gas. All appliances are important both in terms of their contribution to overall household electricity use and as potential conservation measures. Accordingly, most of the appliances are already subject to federal-level, minimum energy performance standards. All are important in the characterization of the non-heating/cooling, non-DHW, and non-lighting usage in the home.

In addition to the total amount of electricity consumed by an appliance, its time-of-use is important to power planners seeking to balance supply resources with demand. The five-minute interval measurements show how devices operate at the sub-hourly time scale. Further, the energy uses are aggregated at hourly, daily, and monthly intervals to show large-scale patterns in appliance usage. Those patterns show how devices depend on environmental variables, like air temperature, and on occupant behavior.

Understanding time-of-use information can contribute to the further setting and updating of national standards. For instance, to give credit in a standards setting process for shifting a dishwasher load, it's first necessary to know when those loads appear and if it is useful to shift them. Further, measuring existing load shapes sheds light on how to best integrate appliances in to a smarter grid. In the case of refrigerators and freezers, the data demonstrate automatic defrost events could be scheduled to occur at off-peak hours. For dishwashers, the load shapes suggest simple delay timers may be effective in shifting load for demand response applications from peak periods to off peak times. With laundry equipment, the shapes suggest shifting energy may be more challenging due to the machines more constant, repeated use during waking hours.

Overall Appliance Energy Use

The study metered nearly all electric appliances in a house except when data loggers failed to provide usable information. Table 1 shows the appliances found on site at all of the 104 metered sites, those which were metered, and those that provided viable data for inclusion in the analysis. Largely, sites proved non-viable because of data logger failure to record or report the energy use. As Table 1 shows, nearly every clothes washer, clothes dryer, freezer, and refrigerator was metered. A smaller percentage of dishwashers, often due to wiring challenges, were metered. The number of cooking ranges found onsite includes both electric- and gas-fueled ranges. Nearly every electric range was metered.

Table 1. Metered appliance count

Appliance	Number of appliances		
	On site	Metered	Viable data
Clothes Washer	103	102	97
Clothes Dryer	103	99	93
Dishwasher	93	64	58
Freezer	60	52	46
Range (Electric or Gas)	103	71	63
Refrigerator	133	131	120

The nomenclature used throughout this paper bears mention. "Freezer" refers to stand-alone appliances whose purpose is to freeze food. "Refrigerator" refers to the typical refrigerator-freezer combination (either side-by-side or stacked vertically). "Electric Range" includes energy used both on the range top and for the oven. For any given site, there is at most one of each appliance except for refrigerators. In the cases where a house had more than one refrigerator, we designated the refrigerator in the kitchen or pantry area as primary and additional refrigerators as secondary. The secondary refrigerators were most commonly located in garages.

Table 2 places the individual appliances in context relative to one another by summarizing the annual electricity use of each. The biggest user, well ahead of any other, is the dryer. The next biggest contributors are the refrigerators and freezers; after that come electric range, dishwasher, and clothes washer. All error bounds (EB) reported in the paper are for the 90% confidence level. To provide further context, Table 3 summarizes the average house characteristics information across all sites.

Table 2. Major appliance yearly usage (averages)

Appliance	Annual kWh		n
	Mean	EB	
Clothes Washer	55.0	5.2	97
Clothes Dryer	724.9	54.6	93
Dishwasher	238.7	36.8	58
Freezer	608.8	59.9	46
Electric Range	313.9	34.7	63
Primary Refrigerator	604.4	24.8	99
Secondary Refrigerator	600.0	109.7	21

Table 3. House characteristics

Characteristic	Value
Occupant count	2.71
Bedroom count	3.13
Floor area (ft^2)	2,145

Refrigerators

Residential refrigerators and freezers have undergone three federally mandated efficiency upgrades, one each in 1990, 1993, and 2001 (BTO 2013a). Figure 2 shows the expected downward trend in annual energy use implied by the ever more stringent standards. The figure plots energy for both primary and secondary refrigerators while the regression fit is conducted only on the primary refrigerators. Although site-to-site variation is high, the slope of the fitted line at -13.5 kWh/yr, suggests, in a 20-year time period, refrigerator energy use has decreased 270 kWh on average.

The classification of primary and secondary refrigerators is of importance regarding the ambient temperature surrounding the equipment. Although we can reasonably assume the temperature in living spaces is similar across houses, the temperature in secondary locations, such as garages, varies more widely and, in the Northwest, is annually lower on average than the living space. A substantially different average ambient temperature will lead to different energy use of a refrigerator. Without a large enough sample size of secondary refrigerators to control for these temperature variations, we conducted all the comparisons on primary refrigerators only.

Other factors influence the annual electricity usage, such as occupant cooking habits and kitchen temperature, but even with all these considered, we see a downward trend in the averages, indicating that the standards have been largely effective in reducing energy consumption. The results also indicate that, to the extent older equipment is still being used, there is potential for significant savings through utility-based programs.

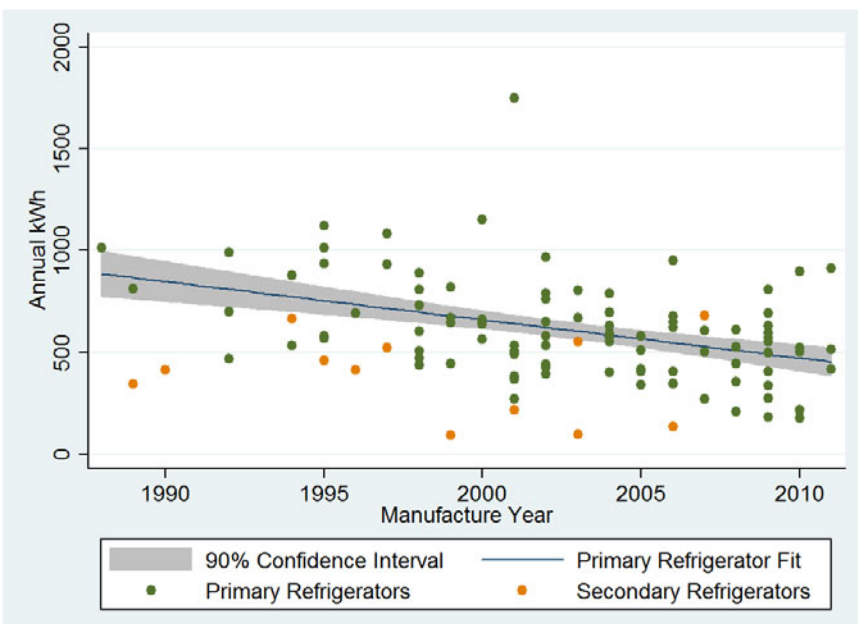

Figure 2. Annual refrigerator energy use by year of manufacture.

Within a day, the average hourly refrigerator power draw exhibits slight variations (Figure 3). As expected, the usage decreases in the night-time hours, given that the space containing the refrigerator likely reaches its daily minimum and door opening events are curtailed. The usage peak in the evening is due, in large part, to occupants placing warm food items in the refrigerator. An investigation of the average energy use by day of week shows a flat line with no dependence on weekdays or weekends.

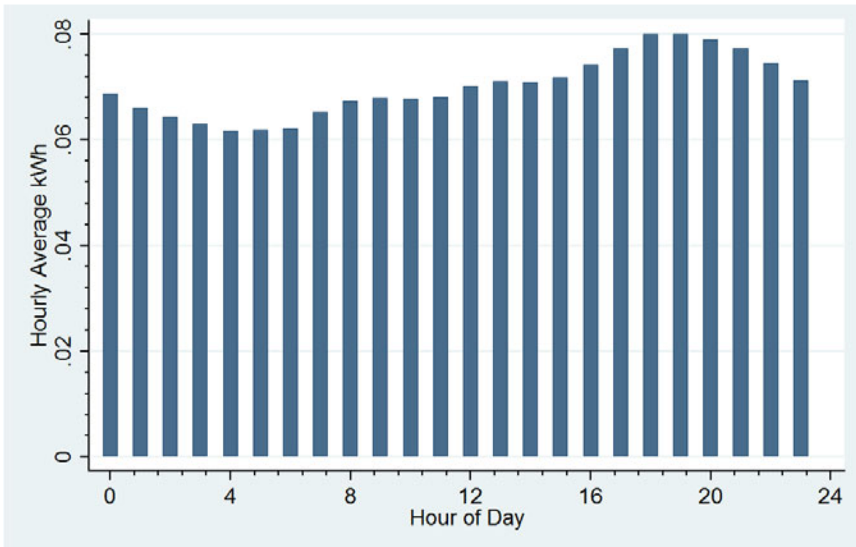

Figure3. Primary refrigerator hourly load shape for 103 units.

Metering energy use at a five-minute time scale reveals load patterns to demand response programs. For example, Figure 4 shows the power measurements of two refrigerators, each in a different house, for two days in the summer. Both are located in kitchens and have a volume of 20 ft^3. Refrigerator A was manufactured in 1995, while B was in 2006. Although both refrigerators show a typical cyclic behavior from the compressor, a demand response opportunity lies in the defrost control. Both pieces of equipment have automatic defrost, which is indicated by the spike in power to 800 W (in blue) and 425 W (in red). They defrost as needed but do not repeat at any obvious frequency. Post-defrost, both compressors run for a longer period of time, presumably to reduce the interior temperatures after the defrost cycle. A simple control could be conceived to restrict the times when the defrost cycle occurs to off-peak hours, thereby reducing peak demand from both the defrost and the recovery event. The control could receive a signal from the utility to prevent defrost, or a timer on the refrigerator itself could schedule defrost to occur only in the overnight hours.

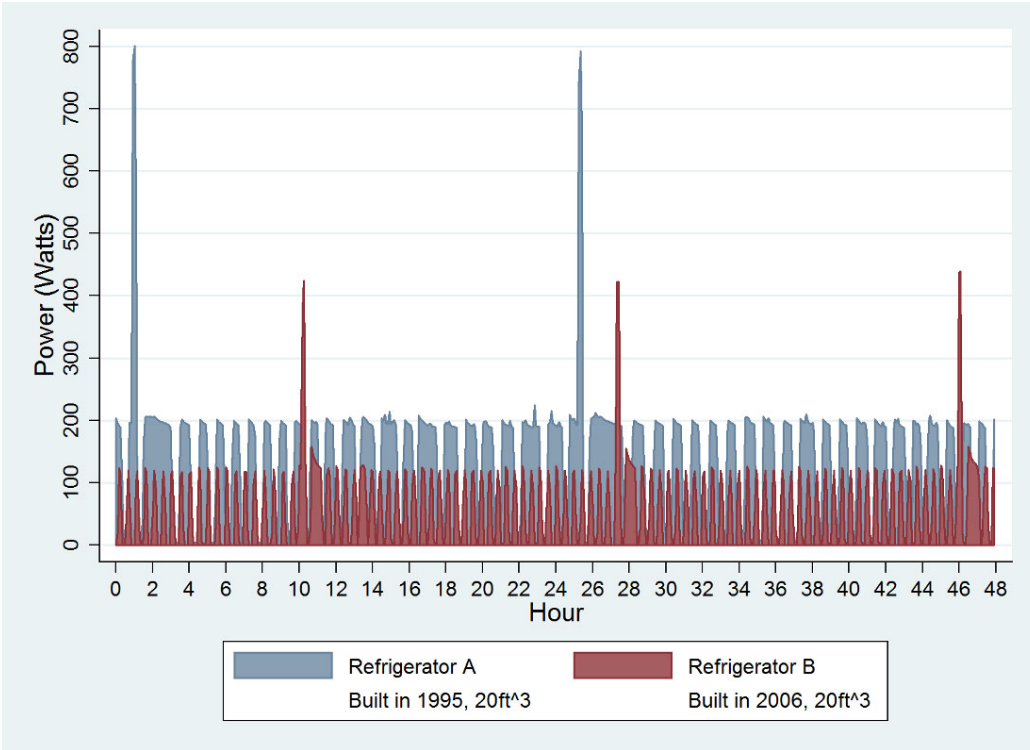

Figure 4. Detailed typical refrigerator power patterns. Two days beginning midnight 7 July 2012.

Monthly energy profiles most clearly show the dependence of energy on ambient temperature. Figure 5 shows the energy use for primary refrigerators inside conditioned space. Usage in August averages 1.9 kWh/day versus 1.5 kWh/day in January. Many houses have mechanical cooling, but interior temperatures are overall higher in summer. Refrigerators in garages or basements, subject to larger temperature swings, show a different annual profile. With appliances, refrigerators are only second to freezers in variation of energy use throughout the year. Most other appliances have the same energy use month-to-month regardless of season.

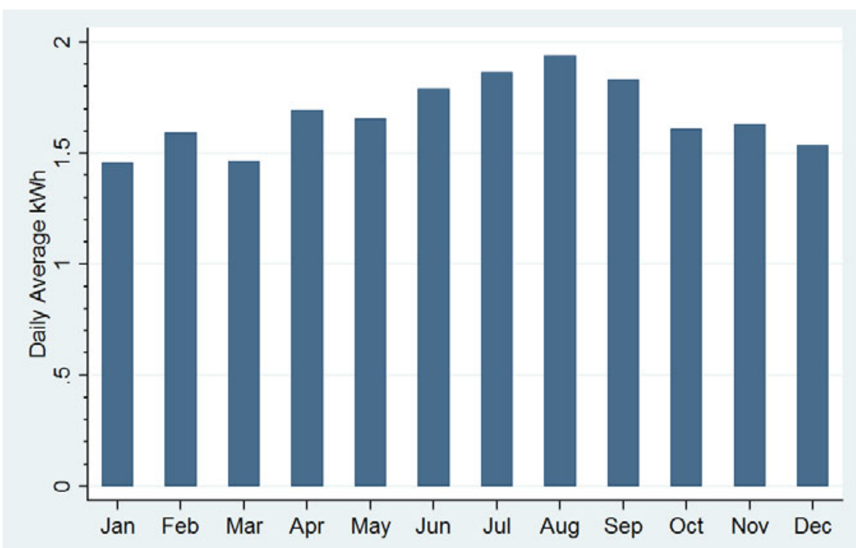

Figure5. Primary refrigerator monthly load shape. Based on 103 units.

Freezers

There are far fewer stand-alone freezers than refrigerator/freezer combinations. The freezers in the study were predominantly found in unconditioned spaces like the garage. The trend in annual freezer usage is similar to the refrigerator/freezer combination, with older equipment using, in some cases, more than 1,000 kWh/yr (see Table 4). Newer equipment uses half of that. Further, Table 5 shows upright freezers use more energy annually than chest freezers. The number of cases is small, but the vintages are evenly distributed across both types and the pattern is clear. The continued persistence of extremely old (pre 1990) equipment indicates there is potential to save electricity by replacing these with newer models. Additionally, the observed energy use difference between upright and chest freezers indicates another area of conservation potential. Moreover, as with refrigerators, “smart” defrost controls could shift the events to off-peak times.

Table 4. Freezer annual energy use by vintage

Manufacture Date Bin	Freezer annual kWh by vintage		
	Mean	EB	n
Pre 1989	1,047.1	144.2	6
1990-1999	534.3	206.9	5
2000-2009	556.2	176.7	9
Post 2009	526.3	158.5	5

Table 5. Freezer annual energy use by type

Type	Freezer annual kWh		
	Mean	EB	n
Chest	460.8	95.8	13
Upright	780.9	102.1	19

Dishwashers

The annual machine energy (defined as electricity consumed by the device but not by that embodied in the hot water it uses) of dishwashers does not follow the same pattern as refrigerators and freezers. Figure 6 demonstrates there is no persistent trend in energy usage for dishwashers over three rounds of federal standards upgrades in 1988, 1994, and 2010 (BTO 2013b). The observation is not surprising, given the standards have mainly focused on the amount of hot water used in dishwashers, which is not captured by measuring the machine electrical consumption. Further, the study did not collect extensive information on wash cycle type, which could be important to understanding the energy trends if the occupants opt to use additional heat from a dishwasher’s resistive elements. Cycle type, combined with a water flow meter, would provide nearly full insight into dishwasher operation in a future study.

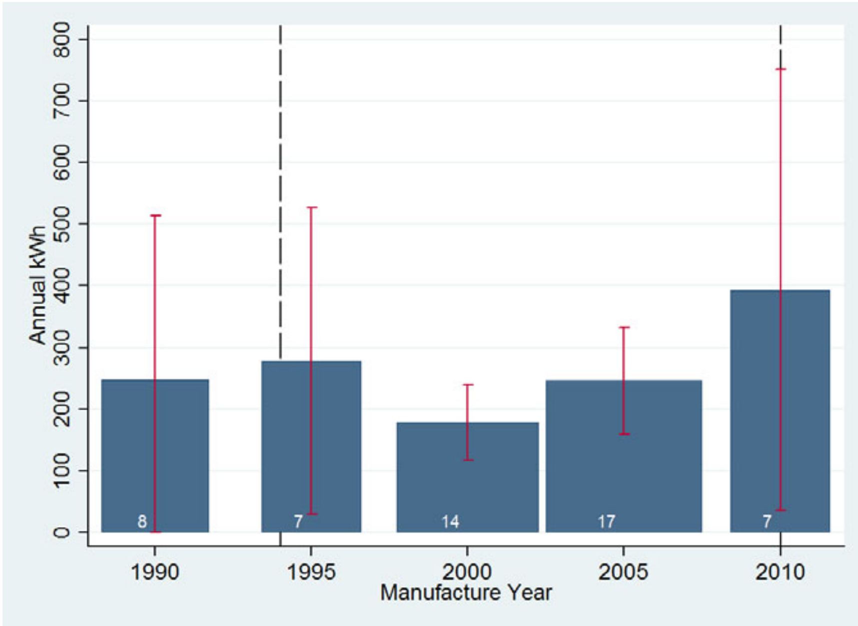

Figure 6. Annual dishwasher energy use. Federal standard implementation years marked as dashed lines. Red lines show the 90% confidence interval about the mean. Bar widths are proportional to the number of cases in each age bin. White number at bottom shows exact count.

The investigation of dishwasher energy use dependence on the number of occupants showed no trend. A linear regression showed that energy use holds steady irrespective of the occupant count. If anything, single-occupant households use less dishwashing energy than two or more occupant households. However, in the larger households, energy use may even decrease slightly per person as occupant count increases. Further study is needed to determine the degree to which the number of people drives energy use.

Unlike refrigerators and freezers, which are devices operating on a thermostat, the dishwasher runs in direct response to occupant action. The result is a large variation of energy use within a day. Figure 7 shows both the weekday and weekend days. The energy use is highest during waking hours. Modern dishwashers often come with timers to delay the start of the cycle, however, the study did not differentiate between dishwashers with and without timers. As the feature becomes more common, the load shape may shift. Moreover, timed, or smart grid-enabled dishwashers could move the peaks away from the morning (coincident with winter heating) and early evening (coincident with summer cooling) to reduce overlap with utility grid peaks. Such a control could be directed to run the dishwasher in the next eight to twelve hours, whenever the best for the grid, without inconvenience the occupant. Importantly, only by continuing to observe load shape data will it be possible to know if the prevalence of dishwasher timers will shift the energy use in to the night or if further market intervention by a demand response program will have the opportunity to do so.

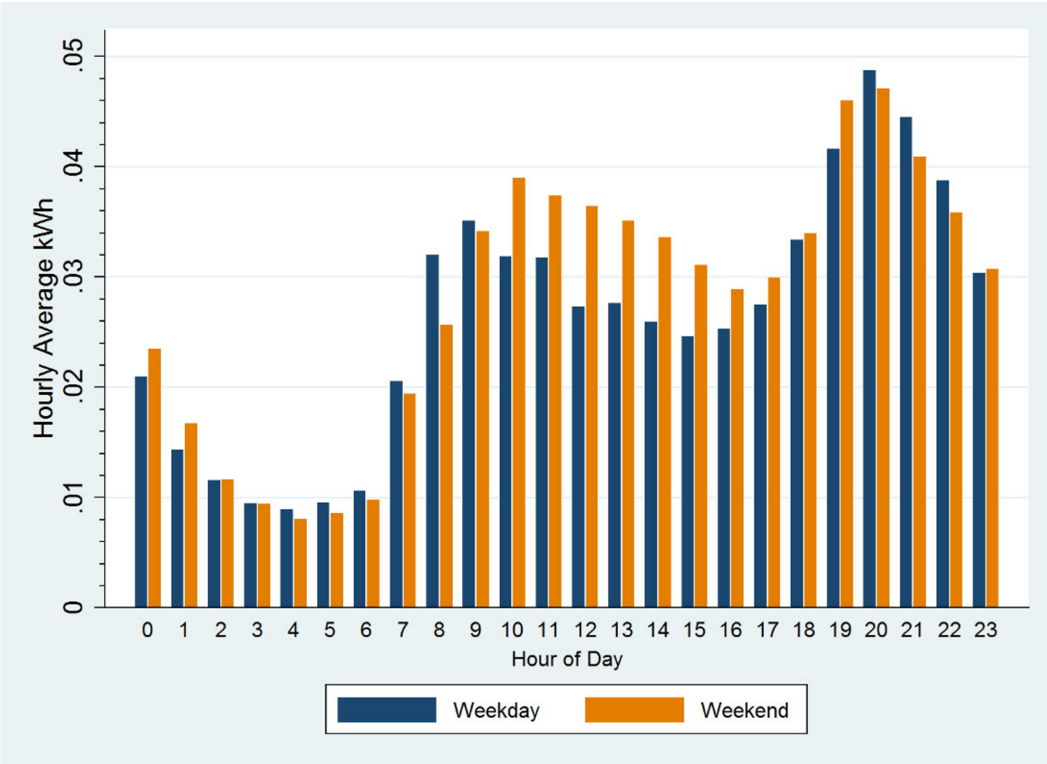

Figure 7. Dishwasher weekday and weekend hourly load shape.

Laundry Equipment

The final major appliance category we examined was laundry equipment. Nearly every site has a washer and dryer. There are fewer than five natural gas dryers in this set of houses, and their usage was not metered. Dryer usage is much more significant than washer usage, with an average annual consumption of 725 kWh versus 55 kWh for washers.

With only one round of federal standards, effective in 1994 (BTO 2013c), the study showed no measurable change in dryer energy use by year of manufacture. Fundamentally, the consistency among vintages is unsurprising given that current dryer technology is to use a resistance heating element to evaporate water from the clothes. The determinant of consumption is how much water is in each load going in to the dryer. Indeed, the clothes washer has the most impact on that factor.

The annual use depends on the number of loads dried, which in turn depends on the number of occupants in the house. Figure 8 plots the annual energy use versus number of occupants and includes a regression line fit through the origin. The fit shows energy use of 250 kWh/yr per person. We forced the fit through the origin because a dryer in a house with no occupants uses no energy. The graph shows considerable variation in energy use for a given occupant count, but there is still an upward trend with more occupants. No other appliance energy use shows as much dependence on the number of occupants as does a dryer.

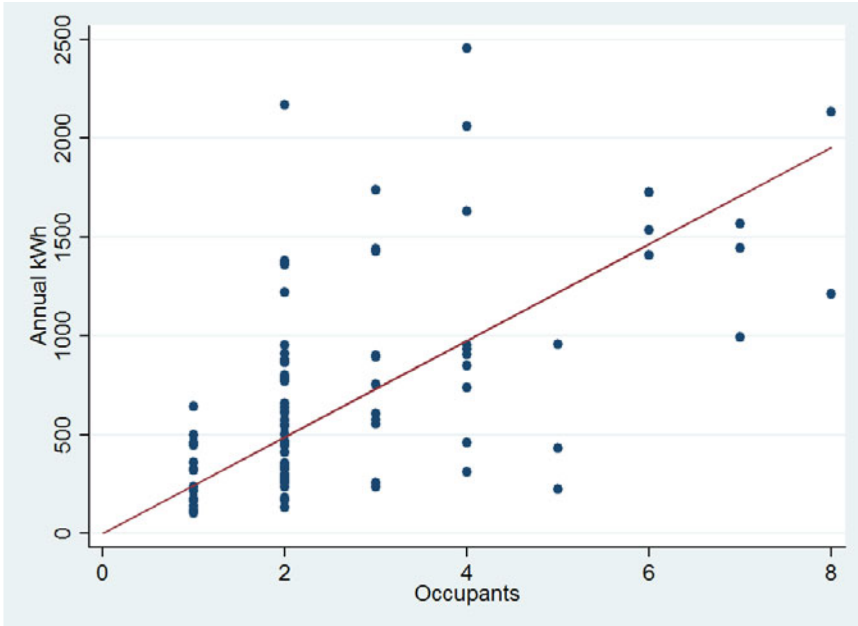

Figure 8. Clothes dryer annual energy use versus occupant count.

Direct clothes washer energy use (exclusive of the embodied energy in the hot water supplied to the machine) is an order of magnitude less than that of dryers. As in the case of dishwashers, a substantial part of the federal efficiency standard targets overall water usage (BTO 2013d). Those savings are realized directly at the water heater and indirectly at the clothes washer. Table 6 shows that horizontal axis washers use less energy than vertical axis washers, although both are relatively small compared to dryers. An analysis of the clothes washer energy use by vintage showed no meaningful change in machine energy use over time.

Table 6. Clothes washer annual energy use by type

Axis type	Clothes washer annual kWh		
	Mean	EB	n
Horizontal	48.3	5.8	39
Vertical (with agitator)	64.1	8.8	50

Load shapes for laundry equipment are shown in Figures 9 and 10. Much like dishwashers, laundry equipment runs when directed by occupants giving rise to a large variation in energy use over the course of a day. Figure 9 displays the laundry equipment usage patterns during the average weekend day. As expected, clothes washer energy use is a tiny fraction of dryer energy use. The peak power draw is during the middle of the day. Not visible on the graph, because of scale differences, the clothes washer usage peaks before the dryer. In fact, as expected, the metering data indicated that usage of the washer always precedes the dryer.

Figure 10 confirms that more laundry is done on weekends than weekdays. The clothes washer shape for day-of-week is nearly identical (but at a lower magnitude) to the dryer. Of all the appliances in the house, laundry equipment shows the greatest variation between weekday and weekend. Most other appliance loads are flat across the week.

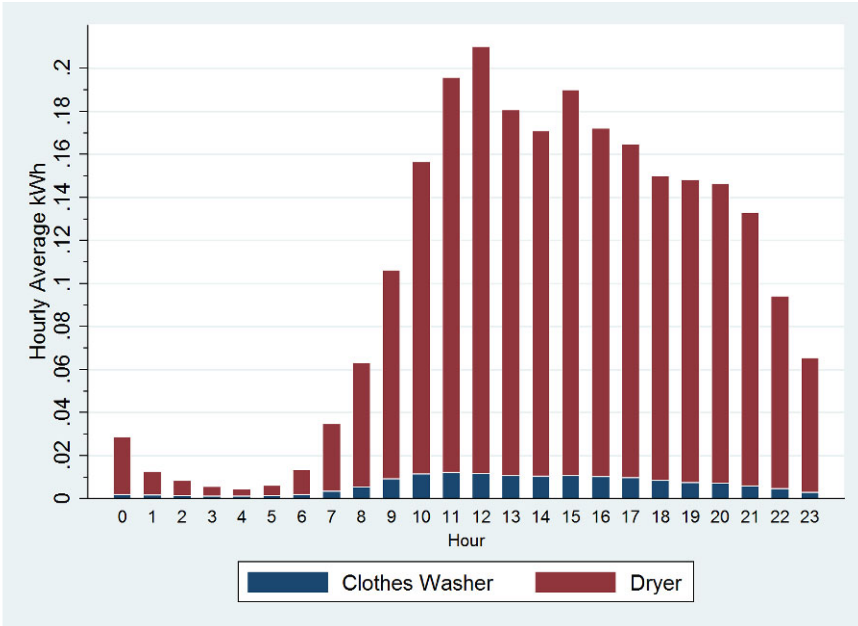

Figure 9. Laundry weekend hourly load shape.

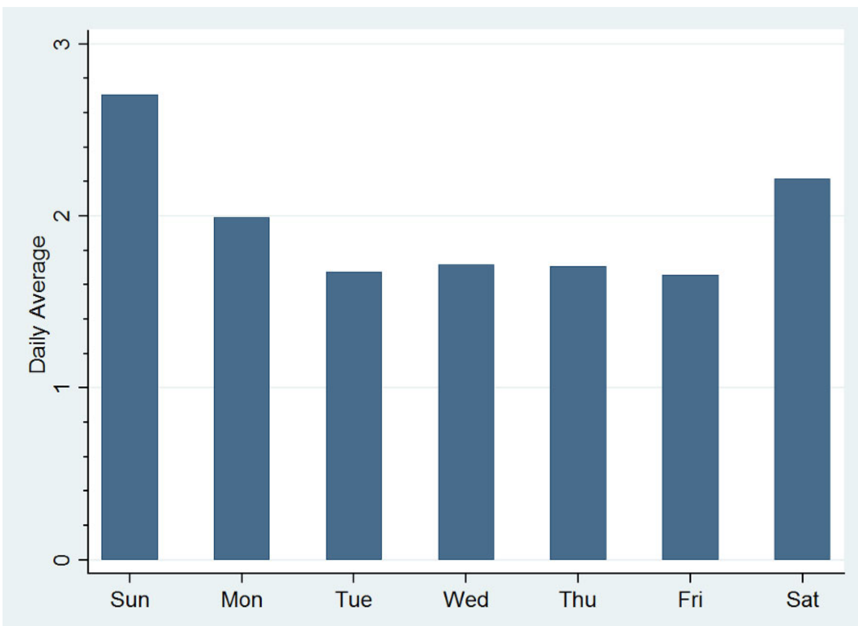

Figure 10. Dryer weekly load shape.

Conclusions

RBSA Metering monitored appliance energy use in over 100 houses in the Pacific Northwest. To the extent that occupant behavior and appliance vintages are similar across the country, the data are applicable outside the region. The metered data showed the measured energy of dryers, refrigerators, and freezers constitute the majority of appliance energy usage in a given house. The graphs of energy use by year manufactured show federal standards have been particularly effective in reducing refrigerator energy use. The time-of-use information provides insight in to how the equipment operates on a five minute timescale. The fine-resolution data reveal how smart grid-enabled appliances could operate to offset peak power draws. Moreover, the load shapes at daily, weekly, and monthly scales clearly show how occupant behavior influences certain appliances while ambient conditions are more important for others. Knowing when and how much energy appliances use is critical to taming the electric load beast.

References

Baylon, D., P. Storm, K. Geraghty, and R. Davis. September 2012. *2011 Residential Building Stock Assessment: Single-Family Characteristics and Energy Use*. http://neea.org/docs/default-source/reports/residential-building-stock-assessment-single-family-characteristics-and-energy-use.pdf?sfvrsn=12

BTO (Department of Energy Building Technologies Office). 2013a. "Residential Refrigerators and Freezers." http://www1.eere.energy.gov/buildings/appliance_standards/product.aspx/productid/43

BTO (Department of Energy Building Technologies Office). 2013b. "Residential Dishwashers." http://www1.eere.energy.gov/buildings/appliance_standards/product.aspx/productid/67

BTO (Department of Energy Building Technologies Office). 2013c. "Residential Dryers." http://www1.eere.energy.gov/buildings/appliance_standards/product.aspx/productid/36

BTO (Department of Energy Building Technologies Office). 2013d. "Residential Clothes Washers." http://www1.eere.energy.gov/buildings/appliance_standards/product.aspx/productid/39

NEEA (Northwest Energy Efficiency Alliance). 2011. *Residential Test Bed*. http://neea.org/initiatives/emerging-technology/residential-test-bed