April 28, 2014
REPORT #E14-283

Residential Building Stock Assessment: Metering Study

Prepared by:
Ecotope Inc.
4056 9th Avenue NE
Seattle, WA 98105

Northwest Energy Efficiency Alliance
PHONE
503-688-5400
FAX
503-688-5447
EMAIL
info@neea.org

Authored and Analyzed By:

Ben Larson, Lucinda Gilman, Robert Davis, Michael Logsdon, Jeffrey Uslan, Ben Hannas, David Baylon, Poppy Storm, Virginia Mugford, and Nick Kvaltine all of Ecotope, Inc.

Acknowledgements:

Ecotope would like to thank David Kresta and Anu Teja, Northwest Energy Efficiency Alliance (NEEA) project managers, for coordinating the Residential Building Stock Assessment Metering (RBSA Metering) advisory group and providing support and direction to this research. We appreciate the contributions of the RBSA Metering advisory group to the design and implementation of the study. We also appreciate the contributions of Bonneville Power Administration (BPA), the Pacific Northwest National Laboratory (PNNL) and Avista Utilities to the research.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Glossary of Acronyms and Abbreviations

AC	air conditioning
ACH	air changes per hour
ACH50	air changes per hour at 50 Pascals of pressure
AFUE	annual fuel utilization efficiency
aMW	average megawatts
ANOVA	analysis of variance
ASHP	air source heat pump
BPA	Bonneville Power Administration
Btu	British thermal unit
Btu/hr	British thermal unit per hour
CDD	cooling degree days
CFL	compact fluorescent lamp
COP	coefficient of performance
Council	Northwest Power and Conservation Council
CPU	central processing unit
CRT	cathode ray tube
CSV	comma-separated value
CV	coefficient of variation
DHW	domestic hot water
DOE	Department of Energy
DVD	digital video disc
DVR	digital video recorder
EB	error bound
ELCAP	End-Use Load and Consumer Assessment Program
ER	electric resistance
ft	feet
HDD	heating degree days
HP	heat pump
HSPF	Heating Seasonal Performance Factor
HVAC	heating, ventilation, and air conditioning
ID	identification
IDT	indoor temperature
IOU	investor-owned utility
kVA	apparent power
kVAR	reactive power
kW	kilowatt
kWh	kilowatt hours
kWh/day	kilowatt hours per day
kWh/yr	kilowatt hours per year
LCD	liquid crystal display
LED	light-emitting diode
LPD	lighting power density
MMBtu	one million British thermal units

n	number of observations
NEEA	Northwest Energy Efficiency Alliance
ODT	outdoor temperature
Pa	Pascals
PNNL	Pacific Northwest National Laboratory
PTAC	packaged terminal air conditioner
PTCS	Performance Tested Comfort Systems
QC	quality control
RDD	random digit dial
RBSA	Residential Building Stock Assessment
RMS	root mean square
SF	Single-Family
sq.ft.	square feet
TMY3	Typical Meteorological Year (based mostly on 1976-2005)
UA	The sum of the thermal transfer coefficient (U in Btu/hr°Fft^2) times the area (A) of the components of the building, not including infiltration.
VAC	volts alternating current
VBDD	variable base degree day
VLT	vapor line temperature (for heat pump monitoring)
VPN	virtual private network
W	Watts
W/sq.ft.	Watts per square foot

Executive Summary

Residential Building Stock Assessment – Metering (RBSA Metering) is a project of unusually large scope in a region already uncommonly committed to large-scale primary research. Its goals are broad: update a swath of load shapes for the first time in twenty-five years, assess the major determinants of residential energy use, and identify opportunities for energy savings for programs across the region. The project lays the foundation for updating the Northwest's approach to subjects including load forecasting, wind integration, capacity planning, demand response, the smart grid, and energy efficiency. All these topics benefit from, if not require, the direct time-of-use measurements of energy use that this project delivers.

RBSA Metering, currently in its second year, is a whole-house metering study covering most energy end uses in 101 homes in the Pacific Northwest. The study is sponsored by the Northwest Energy Efficiency Alliance (NEEA) and conducted by Ecotope, Inc. As energy efficiency is a primary energy resource in the Northwest, the information generated by RBSA Metering is an essential element in developing efficiency resources that can meet the region's future energy requirements. The results will guide future energy planning efforts and provide a solid base for assessing energy savings in residential programs throughout the Northwest.

The report on the RBSA Metering project is as much a window in to the analytical possibilities created by the RBSA Metering dataset as it is a stand-alone document. The dataset, to be delivered shortly after the report, is a rich trove of energy and energy-related measurements at over one hundred houses spanning more than a year. Aggregated at fifteen-minute intervals, the data not only show total energy use but the time the use occurred for all the devices monitored. Given the breadth and depth of the dataset, the analytical possibilities are nearly boundless and are likely to provide material for long-term future investigations. Acknowledging that not nearly every avenue of inquiry could be followed, this report is an exposition of the more significant findings. Most importantly, it serves as an example of the kinds of analyses that are possible.

1.1. Background

For more than thirty years, the Northwest has relied heavily on increased efficiency to reduce demand for energy (especially electricity). This effort has resulted in substantial reduction in the growth of energy demand and obviated the need to expand or build additional power plants across the region. A critical input to this process is the predictability of the savings from efficiency measures. The best practice to estimate savings of efficiency measures requires knowing the "base case" efficiency and energy use so that savings take account of current use patterns and efficiency levels. Savings for energy efficiency programs are calculated from this base to establish the goals and accomplishments of efficiency programs.

RBSA Metering was intended to expand and update previous studies. Regional planners will be able to revise the detailed load shape information developed during the End-Use Load and Consumer Assessment Program (ELCAP) study (1988-1992). The ELCAP study did not address important end-use issues that are relevant today. Indeed, some of the end-uses present today did not exist at that time, especially in the consumer electronics sector. Furthermore, the data collected in the ELCAP did not include the impacts of several rounds of federal appliance, heating, and lighting standards that have had a profound impact on the design and efficiency of numerous residential products and heating ventilation and air conditioning (HVAC) equipment.

RBSA Metering is a subsidiary of a larger regional survey, the Residential Building Stock Assessment (RBSA).[1] The RBSA was designed as an audit-based characterization of the residential sector that takes into account the diverse climates, building practices, and fuel choices across the region. The RBSA includes both the principal characteristics of the houses (size, insulation level, and heating systems) and the principal characteristics of the occupants. Finally, the large sample allows the benchmarking of energy use with the region's residences in sufficient detail to assess the progress on improved energy efficiency over the next several years.

1.2. Methodology

1.2.1. Sample design

The RBSA Metering sample was designed to represent single family houses across the Northwest as best as possible within project budget constraints. The relatively high costs of detailed, multi-year, residential metering limited the number of sites available to the sample. Working within the sample size, the design worked to optimize the location and variety of sites according to the following goals:

- Locate the metering group within the context of the RBSA study so the more intensive, but narrower, metering study can inform the results of the wider RBSA onsite surveys.
- Provide a representative picture of energy end uses.
- Provide a representative balance of heating system types (including heat pumps).

Ecotope developed three sampling regions: Puget Sound, western Oregon, and an eastern region composed of eastern Washington, Idaho and western Montana. The number of sites within each region is shown in Table ES1.

Table ES1. Distribution of RBSA Metering Homes

Region	Distribution of Houses RBSA Metering Study
	Number of Observations (n)
Puget Sound	36
Western Oregon	30
Eastern Washington	16
Idaho	14
Western Montana	5
Total	101

[1] For information on the RBSA study, reports, and databases, see http://neea.org/resource-center/regional-data-resources/residential-building-stock-assessment.

1.2.2. Metering

The final metering plan included three parallel platforms. The first was centered at the house electrical panel and includes direct measurement of the whole house service drop plus major loads such as heating systems, water heaters, and clothes dryers. The second platform is based on a network of plug measurement nodes to pick up items such as appliances and consumer electronics; this platform includes both wired and wireless elements. Third, lighting fixture on-time is measured with stand-alone data loggers. This platform is the only one requiring on-site visits to retrieve the logged data.

The metering platform is not limited to electrical loads but also measures consumption of gas-fired devices. Data from all end uses except lighting are uploaded to Ecotope's servers daily. The target loads for monitoring are:

- Whole house service
- Heating (both electric and gas) and cooling
- Hot water (both electric and gas)
- White goods / appliance: refrigerator, freezer, clothes washer, clothes dryer
- Consumer electronics: TV, TV accessories and Computer, computer accessories
- Lighting
- Other large loads: hot tubs, well pumps, sump pumps, electric cars, etc.)
- Outdoor and indoor temperature

1.2.3. Analytic Methodology

After a quality control and data vetting process, Ecotope performed several analyses on the dataset to produce the information in the report. The most basic totaled the energy use of each device on hourly, daily, monthly, and yearly periods. These summaries formed the basis of the energy end use findings. Further effort was made to produce weather normalized estimates for the heating and cooling uses. Additionally, in the appliance, consumer electronics, and lighting categories, we used the RBSA surveyed saturation of various devices to estimate the current energy use of these categories for the typical house across the Northwest.

Given the fine time-scale of the measurements, considerable effort was made to analyze and prepare time-of-use load shapes. Investigation at all time-scales is critical because different end uses vary at hourly, daily, weekly, and monthly intervals. For example, lights are used more at certain hours of the day than others; clothes washers run more on weekends than weekdays, and water heating energy changes by month. Ecotope created load shapes for weekdays and weekends, for days of the week, and for months of the year.

1.3. Findings

1.3.1. Water Heating

The project investigated the energy use of both gas and electric tank water heaters. In all, forty-nine electric tank sites showed an average energy use of 3,030 kWh/yr with approximately 2.2

people per site. Gas water heating tanks used 148 therms/yr for 3.0 occupants. The results compare favorably with previous regional water heater studies and suggest water heating energy has decreased slightly in the past two decades. For gas water heaters, the project used a novel measurement technique using the flue temperature to estimate the actual flow of natural gas. The method delivered usable data from 80% of all gas sites metered.

In both the electric and gas cases, the fifteen-minute sampling interval allows for the creation of detailed load shapes. The data show the expected morning peaks, weekday/weekend variation, and seasonal variation. Overall, the energy use varies ±20% seasonally – a large swing that is second only to space heating energy use changes. The comparison of the daily load shapes the earlier ELCAP study show that the DHW use patterns have changed enough to affect the shape of the savings whenever conservation measures are implemented.

1.3.2. Heating and Cooling

Heating systems in the study included, in order of prevalence, gas forced air furnaces, air source heat pumps, baseboard zonal electric heaters, electric forced air furnaces, ductless heat pumps, dual fuel heat pumps, one gas boiler, one gas heating stove, and one ground source heat pump. The focus of the analysis is on system types that can be summarized together in order to make generalizations about them. They included forced air furnaces (both gas and electric), heat pumps, and electric resistance heaters. On the cooling side, the central, forced-air systems (air conditioners and air source heat pumps) were analyzed together. No zonal cooling systems were included.

Energy use for space heating and cooling was analyzed using variable-base degree day regression in order to translate the metered usage during the year of record into a generalized, normal weather year. While simultaneously allowing for generalization, normalized weather analysis requires strict constraints on the data which limit the number of metered sites available to summarize. Specifically, the only eligible sites are those with entirely metered utility fuel. Houses with supplemental heat (such as wood and propane) are excluded. Table ES2 shows the heating energy use index (EUI) – weather normalized and floor area normalized energy use) for the main system types. Cooling energy use, when present, is typically only 5-10% compared to the heating usage for the year. For central cooling systems the average energy used is 0.4 ± 0.07 kWh/sqft-yr (1.34 ± 0.24 kBtu/sqft-yr).

Table ES2. TMY3 EUI (kBtu/sqft-yr) by Heating System Type (Abridged)

Heating	TMY3 EUI by Heating System Type		
	Mean	EB	N
Baseboard Electric Resistance	17.74	3.33	6
Electric Forced Air Furnace	23.37	4.12	7
Gas Forced Air Furnace	29.41	2.31	43
Heat Pump (Heating Use Only)	10.55	1.94	10

Across all systems, there is a large variation in the magnitude of usage by site, but similarities in the time patterns of use. As expected, heating systems peak in December and January and have minimal use during the summer months. For central heating systems (forced air furnaces and central heat pumps) there is a large peak demand around 7:00 or 8:00 am, and a second smaller peak late in the afternoon/early evening. Baseboard electric resistance heaters have much less variation through the day with only a modest increase in use in the wake-up hours of the morning. On the cooling side, the central systems only have a single peak late in the afternoon.

Heat pumps are more complex both in their function and in analyzing their energy use. Air source heat pumps are the most common type of heat pumps metered and are the focus of the analysis. A combination of occupant behavior and thermostat functionality (both indoor thermostat and lockout thermostat, if installed) contributed to a wide variation in energy use, on top of poorly functioning heat pumps. Only half of the air source heat pumps meet the house heating load solely with the compressor at 30°F outdoor temperature; sizing heat pumps correctly for optimum energy use in a heating-dominated climate is still a challenge. Table ES2 shows the electric resistance sites used more than twice the energy per year than heat pumps, even with poorly configured heat pumps using more electric resistance heat than desired.

1.3.3. Major Appliances

The project achieved a near-census in metering appliances (also known as white goods). The average house in the Northwest, with saturations determined by the RBSA survey, uses 2,300 kWh/yr to run its electric appliances. The dryer, refrigerators, and freezers comprise 78% of the electric appliance energy. Table ES3 shows annual use averages for metered appliances.

Table ES3. Major Appliance Yearly Usage (Averages)

End Use	Annual kWh		
	All Regions Mean	EB	n
Clothes Washer	55.0	5.2	97
Dryer	724.9	54.6	93
Dish Washer	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

In addition to the overall energy use, the data, when grouped in to categories by year of manufacture, show the impact of improved federal standards. The standards have had the most significant effect on the efficiency of refrigerators and freezers. The refrigerator load shape has remained substantially the same since the ELCAP study although the daily total energy use has dropped in magnitude by over 50%. Clothes washer and dryer load shapes show the strongest difference between weekday and weekend use patterns.

1.3.4. Consumer Electronics

Two broad categories of devices were metered – televisions and television accessories, and computers and computer accessories. Computers were the biggest energy users, followed by set-top box/DVR combinations and televisions (Table ES4).

Table ES4. Consumer Electronics Energy Use

End Use	Annual kWh		
	Mean	EB	n
Set-Top Box	160.5	17.5	23
Set-Top Box and DVR	253.0	26.0	13
CPU	331.7	43.9	49
Computer	210.0	34.7	56
Computer Accessories	143.3	41.0	60
DVD	23.7	8.3	26
DVR	224.3	22.5	18
Game Consoles	90.5	15.3	39
Monitor	144.7	39.5	21
Stereo	85.8	40.0	8
Television	210.2	16.6	145

Televisions, computers and set-top boxes offer significant opportunities for savings. Television savings are based on getting users to turn their televisions off when unused; the amount of achievable savings will require more research. Computer savings focus on changing power management strategies; research by Bensch et al. (2010) indicates users are willing to change power settings to reduce energy use. Set-top box savings are achievable only by working with a consortium of manufacturers, software companies and cable providers to change the way these devices work when idle.

1.3.5. Lighting

The fundamental quantities describing residential lighting energy use are remarkably small in number. They include the average daily on-time of a lamp and the total installed wattage in a house. RBSA Metering measured both quantities. A complete audit of lighting in the house reported the number and type of fixtures, lamps, and wattage. The lighting loggers, deployed on a select number of fixtures, recorded the lamp on-time. The audit and logger data combine to produce a measurement of energy use. When applied to the full population of RBSA single family houses, the average lamp on-time is estimated to be 1.8 hrs/day. The average LPD was 1.42 W/ft^2. Referencing the average RBSA floor area, the average house in the Northwest currently uses 1900 kWh/yr for lighting.

In addition to the average on-time, the lighting loggers also revealed how lighting use changes as the amount of daylight changes. Use in July was only 1.3 hrs/day while in December it was 2.3 hrs/day.

1.3.6. Whole-House Energy Use

The 41 electric-only sites used 20,650 kWh/yr. The 57 gas-primary heat sites used 663 therms/yr and 9,541 kWh/yr. The combination of direct measurement and reasoned inference succeeded in identifying 85%-88% of all site energy used across the houses. For the electric-only sites, 38% of the total site energy is used for heating, 4% for cooling, and 15% is used for water heating. For non-space conditioning, non-water heating purposes the data report usage of 7802 kWh/yr across all sites. Of that total, 25% is used for appliances, 25% for lighting, 10% for the metered consumer electronics and 10% for known “other” loads not fitting neatly in to any previous category. The remaining 2,500 kWh/yr was unmetered. Some of the unmetered electricity is surely used by more consumer electronics and likely also space heaters.

The energy distributions within the houses clearly demonstrate where the biggest end uses are and where conservation efforts can be focused to obtain the largest gains. Across all sites, the distributions show the two largest end uses remain space and water heating. Appliances and lighting are the next largest end use categories. Consumer electronics and other miscellaneous loads are a diverse yet relatively small fraction of total household energy use.

1.3.7. Highlighted Findings

Although the report outcomes are vast, several findings highlight the relevance of the data to meeting project objectives and regional need. The study shows cooling energy remains a fraction (one tenth) of the energy used for heating. Gas load shapes provide new information on when gas is used demonstrating although gas furnaces and water heaters are similar to their electric resistance counterparts, they have higher peaks. Electric resistance DHW and refrigerator data reveal load shapes both different and similar from the older ELCAP study highlighting the risk of making grid decisions with dated information. Further the DHW and refrigerator data reveal how each device could act in a demand response capability or interact with the smart grid. The breadth and depth of the lighting study is the first of its kind for the Northwest suggesting average fixture on-time per house is 1.8 hrs/day. Previously, to estimate lighting energy efficiency improvements, the region had to reference on-times from small studies within the Northwest or use studies from different geographic regions. Finally, the detailed study of ducted air-source heat pumps demonstrates there are still significant opportunities for efficiency improvements along the lines suggested by previous research (Baylon 2005).

1. Introduction

This report summarizes key findings from the Residential Building Stock Assessment Metering (RBSA Metering) study, primarily sponsored by the Northwest Energy Efficiency Alliance (NEEA) with additional funding from Bonneville Power Administration (BPA), Pacific Northwest National Laboratory (PNNL) and Avista Utilities. NEEA is a non-profit organization working to maximize energy efficiency to meet future energy needs in the Northwest. NEEA is supported by, and works in collaboration with, BPA, Energy Trust of Oregon, and more than 100 Northwest utilities on behalf of more than 12 million energy consumers.[2]

RBSA Metering is an intensive, whole-house energy use study designed to meter energy end uses in single-family houses across the Northwest including Idaho, Montana, Oregon, and Washington. The study measures the energy use of heating and cooling systems, domestic hot water (DHW), appliances, consumer electronic plug loads (televisions, computers, etc.), and lighting in over 100 houses. The study will update regional knowledge about the drivers of residential energy use, allowing planners to assess conservation opportunities and to plan for future loads and resource acquisition. This study is intended to provide the region with a granular assessment (15 minute resolution) of energy use in the residential sector. Although the study focuses primarily on electric loads, gas space and water heat were also measured.

RBSA Metering was designed as an adjunct to the RBSA home characteristics study.[3] The broader RBSA provides a regional representative characterization of the residential sector using a large, region-wide phone survey to establish a geographically stratified sample frame from which the samples for the onsite survey of single-family, manufactured, and multifamily residences were drawn. In order to leverage the comprehensive nature of the RBSA sample design and sample frame, Ecotope developed a nested sample and survey methodology for the RBSA Metering study. This sample was linked to the larger onsite survey sample and in turn to the regional sample frame.

Ecotope designed a metering plan to deliver both the detailed time-sensitive load for each of the channels measured and an aggregate energy use number that can be compared to the billing analysis of the entire RBSA single-family sample. RBSA Metering sites received the full RBSA onsite survey and are included in the RBSA dataset. Both the basic and metered RBSA site surveys included an extensive participant interview addressing energy use behaviors and household purchasing decisions.

RBSA Metering was intended to expand and update previous studies. Regional planners will be able to revise the detailed load shape information developed during the End-Use Load and

---

[2] For information on NEEA, see www.neea.org. For information on BPA, see www.bpa.gov. For information on PNNL, see www.pnl.gov. For information on Avista, see www.avista.com.

[3] For information on the RBSA study, reports, and databases, see http://neea.org/resource-center/regional-data-resources/residential-building-stock-assessment.

Consumer Assessment Program (ELCAP) study.[4] The ELCAP study did not address many important end-use issues that are relevant today. Indeed, some of the end uses present today did not exist at the time of that study, especially in the consumer electronics sector. Furthermore, the data collected in ELCAP did not include the impacts of several rounds of federal appliance, heating, and lighting standards that have had a profound impact on the design and efficiency of numerous residential products and heating, ventilation, and air conditioning (HVAC) equipment.

The current study, as originally planned, would collect data for two years. For its first year, the study was strictly a metering study of existing conditions. In the latter part of the second year, the study is also being used as a test bed for new technologies of interest to the region. Data used in this report are taken from the first year of record, from April 2012-March 2013.

The study takes advantage of advances in metering technology and a significant amount of research and development. All end uses except lighting are networked together and submit data daily to Ecotope's servers. This data reporting system can be replicated in future large-scale studies.

1.1. Background

Since 1980, the Northwest has relied upon energy efficiency in *all* sectors to provide load stability and to cost-effectively meet future electricity generation requirements. This process has focused on a regional planning effort led by the Northwest Power and Conservation Council (the Council). The Council is an extra-governmental body established by Congress in 1980 and appointed by the governors of the four Northwest states.[5] The Council has developed a series of regional power plans and energy efficiency goals to meet the region's expanding economies and power needs. In effect, the Council's mandate was to use demand-side efficiency measures as a primary resource for meeting future load growth in the Northwest. The next regional power plan (the 7th Power Plan)[6] will be completed in 2015.

A key piece of preparing each Plan is baseline information on the state of the residential building stock, including building characteristics and energy use patterns. RBSA Metering specifically provides the latter in great detail which can be linked to the former with the RBSA database. Periodic evaluations by the Council and others have concluded conservation programs have succeeded in delivering an accumulated savings of 5300 average megawatts (aMW)[7] over the past thirty years (Council, 2012). To continue accumulating savings, program planners across

---

[4] The ELCAP study ran from 1988 to 1992 and resulted in multiple reports and a dataset (see http://rtf.nwcouncil.org/ELCAP/), which are still in use today.#!#See section 1.2 for a further description of the study.

[5] For information about the Northwest Power and Conservation Council, see http://www.nwcouncil.org/about/

[6] For information on the 7th Power Plan, see http://www.nwcouncil.org/energy/powerplan/7/home

[7] An average megawatt (aMW) is the amount of electricity produced by the continuous generation of one megawatt over a period of one year (8,760 hours).

the region need reliable baseline information about energy, as it is currently used in houses, to identify potential energy savings and build strategies for reliable residential program delivery.

The changed pattern of consumption generated by energy efficiency measures must be well understood to characterize the impact of energy efficiency. Utilities must provide voltage support across every hour of the day including peak times. Traditionally, the region has used its hydroelectric facilities to respond to short-term transient changes in load. This approach is effective as long as the total amount of capacity requirements are well within the overall capacity of the hydroelectric system. As regional loads grow and as new resources come online that are more intermittent, such as wind, the hydroelectric system becomes more constrained. As a result, detailed load shapes that describe aggregate end-use patterns in all sectors become important to managing both peak load demands and intermittent power sources. Detailed metering is necessary to understand both the timing and the management opportunities among the loads served by utilities for their customers. Furthermore, the value of energy efficiency must be modified to include how the load shapes of the individual components are changed, either for better or for worse, by the introduction of energy efficiency technologies.

1.2. Previous Studies

Several important studies have occurred in the Northwest in the last twenty-five years in support of these goals. The most ambitious of these studies was ELCAP, which began in the mid-1980s and continued through the early 1990s.[8] ELCAP included a set of residential and commercial sites and attempted to measure the major electrical end uses plus the entire electrical service load to the house. Many reports have been published on the ELCAP research; one that focuses on residential results is Pratt et al. (1989). Most of the demand load shapes from this study are still in use by the Council, utilities and consultants in both this region and nationally. Several smaller studies have focused primarily on space heating, heat pumps, and electric hot water tank usage (e.g., Roos and Baylon (1993)), but these studies have not been broad enough in scope to capture other uses such as branch circuit appliances or lighting. No definitive regional lighting studies have been conducted, although some preparatory work was done in the late 1980s, and the Tacoma City Light study (Tribwell and Lerman (1996)) provided some useful insights. More recent lighting studies done elsewhere in the United States (such as KEMA (2010)) have benefited from a large sample size and improved dataloggers.

In the last five years, increasing interest in specific loads, such as consumer electronics, has coincided with the availability of more powerful (and cheaper) measurement platforms. Researchers such as Brown et al. (2006) and Bensch et al. (2010) have had success in measuring usage of appliances such as televisions and computers and have identified various types of control strategies that influence both time of use and accumulated usage.

Few studies have measured natural gas use in the Northwest on a large number of houses or produced natural gas load shapes. Pigg and Cautley (2010) address residential gas hot water

[8] The ELCAP database is available at http://rtf.nwcouncil.org/ELCAP/.

heating usage in considerable detail, and the intent in RBSA Metering is to offer as much insight into gas load shapes as the study design would support.

1.3. Study Limitations

Budgetary constraints reduced the current RBSA Metering sample size. At the request of NEEA, the sample for the first phase of the RBSA Metering study was not designed to be a complete regional sample covering all RBSA regions and housing types. The metered sample covered five of the seven sampling regions within Idaho, Montana, Oregon, and Washington. The areas were selected to cover a range of climates and state populations. To achieve statistical significance, the three eastern regions were combined in one. For end uses not immediately related to heating systems, (e.g. water heating, appliances, lighting, electronics) the metering sample can be expected to characterize the regional population. For the heating end uses, 101 sites are not enough to create regional generalizations across all climates. Depending on system type, initial generalization is possible, however, more sites are needed to deal with the large variation in heating and cooling energy between houses and improve the confidence in the generalizations.

The initial installations took a full day; most of them took place during the work week. Thus, the invasive nature of the metering installation likely represented a greater inconvenience for working people than for retired people, since they had to take a day off of work. A potential selection bias existed for people who can easily be at home during the day. A participation incentive was used to address this issue, but it could not completely eliminate a potential bias. At the request of project sponsors, neither employment status nor household income level were collected so assessing this particular bias is problematic. However, Ecotope implemented statistical tests (analysis of variance [ANOVA], Chi-squared) which did not identify a significant difference between the metering sample and the regional RBSA single-family sample. The variables explored in the tests included, but were not limited to house floor area, house occupancy count, TV count, refrigerator count, lamp count, HVAC type, and fuel type. Refer to sections 2.1, 3.1, and Appendix 5 to compare the metering sample and the overall single-family RBSA sample.

Participants were committed to the study. No participants dropped out because of the inconvenience the equipment represented. However, a total of 11 participants dropped out during the first year and a half due to external circumstances – death or sale of house. The metered data from these sites are still usable, but do not span the full period.

The plug load meters, because they are in the finished area of the house, are susceptible to disturbances by occupants. Every attempt was made to install them as unobtrusively as possible; however, occupants do occasionally unplug them and relocate end uses. Ecotope believes most of this was caught during the data quality control (QC) phase, when end-use energy signatures were compared and outliers identified. Major appliance loads (metered at the electrical panel) are much less susceptible to this issue. Occupants were also given a log book, where they were encouraged to record changes in usage (such as replacement of a heating system or refrigerator). Some occupants called Ecotope when they made a major change.

Metering lighting fixtures posed significant challenges. An average of 20 lighting loggers was deployed on individual fixtures in each house. The loggers measured the on-time of the fixtures by sensing illumination. Due to budget constraints and attrition, only 35% of all fixtures were typically measured across all houses, so an inventory of the non-metered fixtures was also conducted so overall lighting usage could be calculated. The calculation and analysis combined the known wattage of fixtures and the room type in which the fixture was located with the on-time measured by the lighting logger. An over-arching goal for the project was to measure and individually identify as much of the energy use in a house as possible. Towards that end, the datalogging installation protocol called for measuring the most-used fixtures in a given room. Because the goal was to measure energy, if the occupant reported they had a floor lamp in a far living room corner that they claimed was rarely used, it did little good to deploy one of the limited lighting loggers on it. Although that approach was useful to measure as much energy as possible, it has proved problematic in estimating the on-times of the unmetered fixtures. If the most-used fixtures were metered, it stands to reason that the unmetered fixtures were on less per day. Thus, the extrapolated on-times could be over-estimating use.

2. Methodology

The RBSA Metering sample was designed to represent single family houses across the Northwest as best as possible within project budget constraints. It was also designed to be linked to the characteristics details collected on the overall RBSA sample so the metering results can be expanded to larger populations.

Ecotope designed the overall data collection to subdivide the overall house service consumption into its principal end uses at each house. The metering platform is designed to measure or infer 90% of the electrical energy use on site: major electric loads are metered at the electric panel, persistent plug loads are metered where the plug in to outlets, and the lighting load was metered using a lighting logger that provided the on-time at the fixture level.

Gas usage was measured at the furnace and water heater using indirect methods. The meters monitored the status of the burner (on or off), and the amount of gas used was calibrated at the initial site visit. The gas consumption of the appliance could then be inferred from the measured duty cycle. Because there was no gas flow metering device, the site-wide gas consumption could not be measured or inferred if other gas-fired appliances such as stoves or dryers were present.

2.1. Sample Design

The RBSA Metering sample was designed to nest within the overall RBSA sample stratification. The nested sampling strategy allows the metering results to be expanded to the larger populations of the RBSA sample (for additional detail, see Baylon et al., 2012).

2.1.1. Sampling Goals

The constraints on a sample of this type are largely set by the overall budget. The cost of the metering is relatively high. Thus judicious sampling is required to cover the end uses, appliances, and space heating variations inherent in the single-family sector. Among these constraints are the need to create electric load shapes for a variety of end uses that have not been studied in detail for more than 20 years. As a result, the selection process focused on a few significant heating characteristics. These included a sample encompassing the colder climates in western Montana, and a small oversample of heat pumps especially in the maritime climates of Puget Sound and western Oregon. Even with these constraints, the overall integrity of the sampling process was maintained as much as possible to ensure the final results could still be generalized.

The sampling approach for detailed metering of the residential sector has several challenges. First, although the sector itself is relatively homogeneous in building characteristics, individual occupant behavior and demographics are quite variable. Second, there are geographic variations in both occupant behavior and building characteristics. The building characteristics variations are brought on by historical variation in codes and standards between states and different customary practices in different geographic areas. When coupled with the region's need to assess energy efficiency opportunities in consumer products such as televisions and appliances, the challenges dictate relatively large samples are required approaching. Ecotope's own estimates and other studies suggest 300-550 sites are required (KEMA 2012).

The relatively high costs of detailed, multi-year, residential metering limited the amount of sites available to the sample. Working within the small sampling size, the sample worked to optimize the location and variety of sites according to the following goals:

- Locate the metering group within the context of the RBSA study so the more intensive, but narrower, metering study can inform the results of the wider RBSA onsite surveys.
- Provide a representative picture of energy end uses.
- Provide a representative balance of heating system types (including heat pumps).

2.1.2. Sampling Methodology

The metering study stratification was based on the seven RBSA sampling cells:

- Puget Sound, Washington
- Western Washington (outside Puget Sound)
- Western Oregon
- Eastern Washington
- Eastern Oregon
- Idaho
- Western Montana

The primary metering sample design objective was to represent as many of these cells as possible within the metering budget. To achieve these goals, Ecotope designed the metering sample to focus resources on areas with large populations as well as areas with diverse climates. The two most populous areas in Washington and Oregon were sampled separately, and approximately one-third of the sample was drawn from three of the RBSA's four eastern sampling cells. This sampling approach resulted in the following RBSA Metering strata:

- Puget Sound
- Western Oregon
- Eastern Washington, Idaho, and western Montana

Puget Sound includes the seven counties around the Sound: King, Snohomish, Pierce, Kitsap, Thurston, Island, and Skagit. Western Oregon includes the coast to the Willamette Valley. Eastern Washington extends from Wenatchee and Yakima to the Idaho border. In Idaho, the region includes the panhandle and the Snake River plain. In Montana, the region covers the western part of the state from the Idaho border to Bozeman and Helena. This larger eastern region has significant climate variation, but many other variables may be more consistent among these areas that are essentially rural with several large population centers.

The minimum statistical criteria were set at 80/20. These criteria allow substantial variation while still allowing some variables to be reported that have a wide confidence interval. Setting these criteria as a minimum ensures that most data points could be useful in establishing a generalized picture of the region's residential customer energy use. For the individual sampling areas, the coefficient of variation (CV) was set at 0.85, which means the ratio of the standard deviation to the mean of any one metered result could be as high as 85% and still meet the minimum statistical criteria.

A secondary goal of the metering sample design was to provide representative coverage of heating fuels. To address this goal, the initial metered site recruiting effort was random and focused on the minimum sample size required to meet the statistical criteria (approximately 25 sites per cell). Once the minimum sample size was achieved, the remaining sites were drawn from participants in the overall RBSA to ensure a more even split between electric- and gas-heated houses. In practice, the sites drawn through random recruitment used more gas heat (as that is the most common residential heating fuel). In the three sampling strata recruitment shifted to electrically-heated houses when the threshold of 25 sites was reached.

In spite of the potential bias associated with meeting the secondary goal, a review of the comparable characteristics of the RBSA Metering sample and the larger RBSA single-family survey results revealed few categories exhibiting statistically significant differences at the 90/10 level. Interestingly, there were no differences at the 80/20 level for which the sample design criteria were initially set. Pushing the level to 90/10, as is reported throughout the report (not the 80/20 level), shows generally good agreement between both samples suggesting it is indeed possible to link between RBSA Metering energy use and the RBSA saturations.

Ecotope performed analysis of variance (ANOVA) and Chi-square tests on a wide range of variables to determine whether the RBSA Metering population is representative of the RBSA population and, by extension, the region at large. ANOVA compares the distributions of numeric variables and determine whether they come from the same population. More technically, the test determines whether two distributions have the same mean value. Chi-square tests determine whether two samples come from the same population, but pertain only to categorical variables.

To determine statistical significance, Ecotope selected the commonly used p-value level of 0.05. If the ANOVA or Chi-square test returns a value less than 0.05, there is said to be a selection bias between the RBSA Metering sites and the RBSA population. Ecotope investigated many variables with ANOVA including house floor area, house occupancy count, TV count, refrigerator count, and lamp count. The smallest p-value in the tests was 0.13 demonstrating there is no selection bias. Further, the Chi-square tests, for categorical data, including fuel type and HVAC system type, for both the region as a whole and within the sampling cells, showed p-values ranging from 0.2 to 0.7. Numerous other variables, not listed here, were also tested and known showed results suggesting a significant selection bias.

2.1.3. Sample Frame

The sample frame for RBSA Metering was derived from the sample frame for the larger RBSA effort. To develop the RBSA sample frame, a large phone survey was conducted to identify and later recruit a random sample of sites through the region. The basic phone survey was conducted using purchased phone lists with random digit dial (RDD) as well as other randomized customer lists provided by local utilities. This survey was conducted in 2011 and resulted in a total of 8,190 survey responses, distributed through seven sampling areas throughout the region. Out of this overall RBSA sample frame, about 800 houses were selected at random to be recruited into the RBSA Metering sample. All of these houses were contacted as potential participants. Ultimately, 71 sites were recruited from this list.

The remaining metered sites were recruited from residences that had been audited for the RBSA onsite survey. This process used random selection from this list; however, given the difficulties of recruiting, almost all the audited sites in the RBSA sampling areas were contacted and asked to participate.

2.1.4. Sample Distribution

Sites are distributed throughout the geographic regions in the sample design. Within each region, the distribution is random. As expected, there are clusters of sites in the densely populated metropolitan areas of Seattle/Tacoma, Portland, Boise, and Spokane. Figure 1 shows the final site distribution.

Figure 1. Final Distribution of RBSA Metering Sites

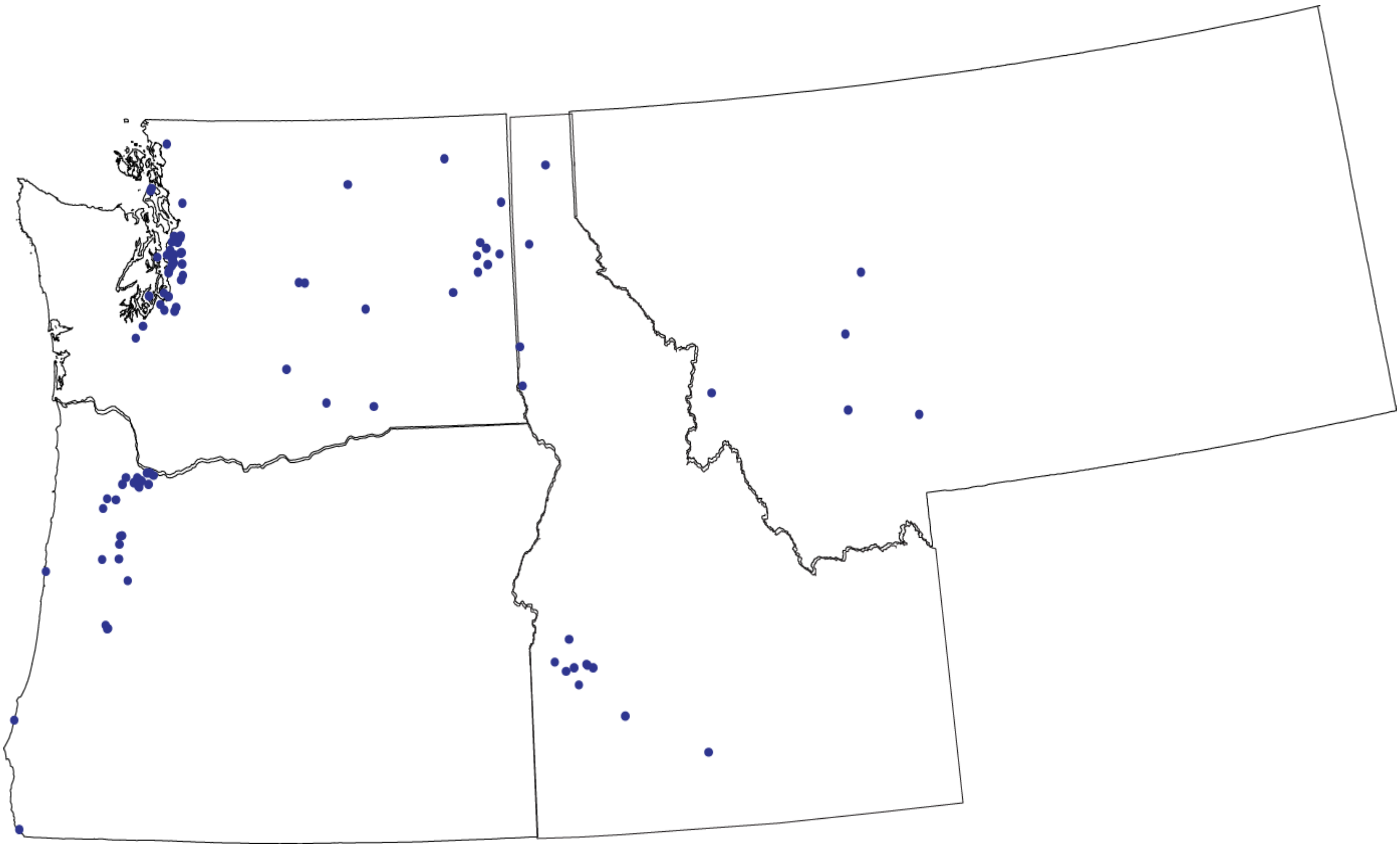


Table 5 shows the distribution of sites recruited randomly as opposed to sites recruited from among RBSA participants in the various regions. Sites were recruited from among RBSA participants to maintain a representative balance of heating fuels. The heating fuel distribution is shown in Table 6.

Table 5. Geographic Distribution of RBSA Metering Sites

Region	Geographic Distribution of Sites in RBSA Metering Study		
	Random Recruiting	Recruiting from RBSA Site Surveys	Total
Puget Sound	27	9	36
Western Oregon	25	5	30
Eastern Washington	10	6	16
Idaho	6	8	14
Western Montana	3	2	5
All Regions	71	30	101

Table 6. Primary Heat Source Distribution of RBSA Metering Sites

Primary Fuel		Primary Fuel of House by Region RBSA Metering			
		Electric	Heat Pump	Gas	All Fuels
Puget Sound	**N**	9	5	22	36
Western Oregon	**N**	7	7	16	30
Eastern Region	**N**	10	6	19	35
All Regions	**N**	26	18	57	101

Unlike the main RBSA, RBSA Metering had no targets for investor-owned utility (IOU) versus public utility site distribution. Ultimately, 57 sites were metered in IOU territories and 44 were metered in public utility territories. Table 7 shows the initial distribution of IOU versus public sites across the regions.

Table 7. Site Distribution by Utility Type

Region	Utility Ownership Type Distribution of Houses RBSA Metering Study		
	IOU	Public	Total
Puget Sound	16	20	36
Western Oregon	20	10	30
Eastern Washington	5	11	16
Idaho	13	1	14
Western Montana	3	2	5
All Regions	58	44	101

2.1.5. Sample Weighting

This section considers the weighting requirements and implications for the RBSA Metering sample. The sites sampled for RBSA Metering were selected from five of the seven geographic regions included in the broader RBSA single-family house characteristics study. Table 8 shows the five geographic cells and the corresponding populations of single-family households. Within each of these regions, the sites were randomly selected (except that quotas were set for the primary heating system). Using the known number of households in each cell, Ecotope generated a probability weight associated with each site within each cell, also shown in Table 8. These probability weights equal the number of sites in the general population represented by a single metered site. Note that the total count in Table 8 is 104 and not the 101 original sites due to three sites being added as other sites dropped out of the study.

Table 8. Sampling Populations and (Probability) Weights for the Metered Sample

Geographic Cell	Sampling Populations and Probability Weights of Houses RBSA Metering Study			
	Reference	Households	Probability Weight	Total
Puget Sound (WA)	PS	1,278,211	34,546	37
Western Oregon (OR)	WOR	1,005,334	33,511	30
Eastern Washington (WA)	EWA	453,626	26,684	17
Idaho (ID)	ID	524,022	34,935	15
Montana (MT)	MT	288,127	57,625	5
All Cells (ALL)	ALL	4,023,937	34,128	104

When eastern Washington, Idaho, and Montana are considered as a single group (the eastern region), the probability weights across the three RBSA Metering sampling strata are nearly identical. This alignment indicates the proportion of houses metered in each stratum was nearly the same. When the weights are nearly identical, calculating a weighted and unweighted mean results in a nearly identical value. Consequently, as expected and demonstrated in section 2.1.2, ANOVA tests showed no difference across the strata; hence, Ecotope uses no form of weighting in this report for RBSA Metering information. All the results, unless specifically noted, are reported as simple means. Likewise, the error bounds are also calculated in the same unweighted manner. Characteristics for the overall RBSA study are reported using their population weighted values so the reader can compare the RBSA Metering sample to the Pacific Northwest population at large.

2.2. Metering Specification

2.2.1. Overview

To align with the region's keen interest in careful energy planning, this project had to construct a durable metering plan that would be adaptable to a range of housing sizes and energy use loads. The plan had to be able to measure as many individual loads in the house as possible (both at the electrical panel and elsewhere), had to be secure, and had to allow for remote monitoring and retrieval of data. Because sites are spread out over several thousand square miles and include fairly remote locations, there also had to be careful consideration of cellular communication service.

The final metering plan included three parallel platforms. The first was centered at the house electrical panel and includes direct measurement of the whole house service drop plus major loads such as heating systems, water heaters, and clothes dryers. The second platform is based on a network of branch circuit measurement nodes to pick up items such as appliances and consumer electronics; this platform includes both wired and wireless elements. Third, lighting fixture on-time is measured with stand-alone data loggers. This platform is the only one requiring on-site visits to retrieve the logged data.

The metering platform in this study is not limited to measurement of electrical loads but also tracks consumption of gas-fired appliances (with a focus on gas furnaces and water heaters). Very little detailed information has been available in the region on residential natural gas load shapes, especially in relation to a physical survey of the site and related usage influences. Therefore this work will improve understanding of the major end uses in natural gas houses. Measuring gas usage can be challenging (Pigg and Cautley, 2010) but the approaches used in this study (current-sensing relays and thermocouples, plus one-time gas meter clocking and combustion efficiency measurement) have allowed a reasonable, safe estimation of time of use and accumulated consumption.

2.2.2. Metering System Architecture

Data from most end uses are uploaded to Ecotope's servers once per day. These data include the heating, hot water, appliances, and plug loads. The exception is lighting loggers, which are not networked and are periodically downloaded manually. The combined platforms collect nearly 600,000 data points per day across the three platforms. Uploaded data are checked nightly using automated routines (described in Appendix 4). See Appendix 3 for an overview of system security.

2.2.3. End Uses Measured

The target loads for monitoring are:

- Whole house service
- Heating and cooling
- Hot water
- White goods / appliance: refrigerator, freezer, clothes washer, clothes dryer
- Consumer electronics: TV, TV accessories and Computer, computer accessories
- Lighting
- Other large loads: hot tubs, well pumps, sump pumps, electric cars, etc.)
- Outdoor and indoor temperature

Appendix 2 lists the types of equipment that are monitored in this study and the equipment used to monitor them. Ecotope excluded small loads such as toasters, hair dryers, electric toothbrushes, and microwaves because they do not represent a large power draw and their performance is not considered a significant interest for the region nor amenable to improvement.

For equipment metered at the panel, accumulated true root mean square (RMS) energy and five-minute snapshots of true power (kW), apparent power (kVA), reactive power (kVAR), and voltage are measured using current transformers and power meters. The whole house load is metered using the sum of two measurements, each 120 volts alternating current (VAC) to neutral, for both sides of the panel. All other loads are single phase.

For gas equipment, cumulative use and use per logging period are tracked using sensors installed on the equipment. The meter/logger equipment for dedicated circuits measures instantaneous values each logging period. The WattsUp.NET plug-load meter logs accumulated true RMS energy and instantaneous snapshots of true power and power factor every five minutes. These data are logged every five minutes with the exception of indoor temperature, where hourly data provide sufficient resolution to assess energy use and load shapes.

Lighting is logged with time-stamped on/off events that are later merged into the main dataset. The lighting loggers were installed directly on or near fixtures; in some cases, a small, flexible fiber-optic wand was used to improve measurement resolution. The logger itself was self-contained and battery powered so that the status of the remaining metering system had no effect on the status or data collection of the instrument. Each instrument could store up to 18 months of data, which was manually downloaded on an annual basis.

2.2.4. Selection Strategy

HVAC equipment, water heaters, and appliances on dedicated circuits were metered at all sites.

The budget allowed for an average of 8.6 plug meters per site and as many appliances and plug loads as possible were metered. Refrigerators and clothes washers (where not on dedicated circuits) were metered with the plug load meters.

Consumer electronic plug loads were selected using the following priority:

- The primary television. The initial determination of "primary" was made through discussions with the occupants. Subsequently, using the metered data, Ecotope assigned primary televisions as the ones with the most annual on time.
- The set-top device associated with the primary television
- The primary home office including a computer and as many peripherals as possible, measured with one WattsUp meter
- Remaining WattsUp meters were used to meter additional miscellaneous plug loads in the following priority:
    - Room air conditioning (AC) if the equipment was present when the installers were at the site
    - Freezer
    - Additional refrigerator
    - Additional TV(s)
    - Space heater

Lights are collected into switch groups and room types. At the most basic level, a "switch group" consists of all the lamps on a single control. For example, a free-standing lamp with a built-in switch would be one switch group; three ceiling lights on one switch would be another switch group.

In March 2013, a full lighting audit was performed that compiled the lighting characteristics in each room of each site. This audit collected data on fixture type, lamp type, switch type, bulb type, and wattage for each fixture in the house and classed them into switch groups. This method allowed us to calculate energy use of metered lights, as well as the total lighting power in each room.

To select which lights to meter, the installer queried the occupant about their overall lighting use patterns especially in the most complex rooms (e.g. living rooms with switchable task lights). With this input, the installer rank-ordered the lights in the house based on how much they were used and selected the top 80% for logging. Unoccupied rooms and lightly-used areas were often avoided even when they represented a large fraction of the total lighting power. By prioritizing the metering in this way, the plan was to observe the largest possible amount of lighting energy with the smallest amount of loggers. Observing the most lighting energy would minimize the overall unknown energy in the house.

2.3. Metering Process

2.3.1. Recruiting

In October 2011, Ecotope began recruiting participants from the list of phone survey participants. Participants were offered incentives of $500 to $700 to participate in the study: $200 to $300 at the start and $150 to $200 per year thereafter. Three recruiters worked afternoons, evenings, and weekends to contact potential participants.

The success rate for recruiting from the phone survey list was approximately 10% to 12%. The major barriers to participation were the large commitment involved and credibility. Issues of credibility arose because people often did not recall participating in the phone survey (which by this point might have occurred four to six months prior) and had trouble believing that someone was calling to offer them $500 to $700 out of the blue. Recruiting calls were also lengthy (20 minutes or longer) because we needed to provide a significant amount of background to the study. Multiple calls were required for many participants because the participant needed time to consider the study or discuss it with a partner.

In early November 2011, as the target number of randomly sampled houses in each region was reached, Ecotope began recruiting from the database of participants who had already participated in the main RBSA. This doubled the recruiting success rate immediately, to a range of 20% to 25%, and reduced the length and number of recruiting calls. Credibility was no longer as much of an issue, because participants understood the general background of the study and had already had one positive experience with a NEEA study. They still correctly recognized that the study represented a major commitment on their part. Table 5 above shows the distribution of houses recruited randomly as opposed to houses recruited from among RBSA participants in the various regions.

2.3.2. Field Work

Installations began on October 5, 2011, and finished on December 29, 2011. The three installation teams each consisted of a team lead, an instrumentation technician, a surveyor, and an electrician. One team covered the Puget Sound region, one covered western Oregon, and one covered the eastern sites. Installations generally took six to eight hours. Appendix 3 shows some pictures from installations.

Significant effort went into research and development of the metering systems prior to the installations; experience gained during installations led to additional improvements in systems and methods. Improvements were propagated to earlier installations during lighting logger data download visits as needed. Best efforts were made to meter all significant loads, but inevitably some fraction of the load went unmetered at every house.

A second round of visits took place in March 2012 to collect data from lighting loggers and to perform a round of repairs. Some sites had wireless connectivity issues with the plug load meters, and some sites had wired meters that were misconfigured. Due to the volume of repairs performed in these visits, the first metering year ran until the end of the first quarter of 2013 (Q1 2013). Repairs have continued since then; a second round of lighting logger downloads took place in March 2013.

2.3.3. Field Work Quality Management

Considerable prototyping work occurred in Ecotope's field labs in advance of installations to ensure high-quality work from the first installation onward. All field technicians attended a four-day training with both class and field segments to ensure their familiarity with the equipment and the standards of the project. A detailed manual was developed as both a training aid and field guide. Ecotope's technical director attended one of the first installations of each field team to observe and give feedback. Ecotope solicited feedback from the field teams and propagated their suggestions to others. This feedback loop led to rapid improvements in field procedures.

2.4. Data Management and Data Quality

Data quality management started before installations began. The field technician training familiarized the technicians with not only the technical requirements of the project, but also the data collection standards and methods. The field manual included extensive guidance on the paperwork associated with the project.

Given the large amount of equipment involved in this project – there are, on average, 35 end uses metered per site, requiring 50 or more pieces of equipment – Ecotope developed two parallel systems for tracking inventory. The first was a computerized system. Sensors were tracked with an automated inventory system that collected sensor identification (ID), location, and end-use information. Sensor IDs were scanned in by barcode; location and end-use information were selected from pick lists. This reduced the opportunity for typographic errors in the all-important data fields that were later fed into the sensor database. Standardized forms were also developed that collected sensor ID, location, and end-use information. These functioned as paper backups to the computerized inventory system.

A complex system was developed to monitor and manage data flow and to check quality at every step. A more detailed discussion of data quality procedures is provided in Appendix 4.

2.5. Analytic Methods

2.5.1. Water Heating

Both electricity and natural gas are used to heat water. The RBSA Metering project measured the energy use of both electric and gas water heaters. By design, the study observed only tank water heaters and not the instantaneous, or on-demand, variety. The distribution of gas and electric DHW tanks appears in Table 9.

Table 9. Water Heater Fuel Type: Metered Sites

Region	Number of Tanks Metered		
	Electric	Gas	Total
Puget Sound	19	18	37
Western Oregon	19	11	30
Eastern Region	21	16	37
Total	59	45	104

Electric water heater energy use was metered directly. A current transformer was attached to the hot water circuit in the panel and, through simultaneous measurement of electrical panel voltage, true RMS energy of the tank was measured and logged. In the study, the electric tanks were predominantly 50 gallons in size.

Gas tanks have a burner underneath the tank and a flue in the center of the tank for combustion exhaust. Gas tanks in the study typically had burner output capacities of 40,000 British thermal units per hour (Btu/hr) and stored either 40 or 50 gallons of water. Metering gas DHW tanks is more complex than metering their electric counterparts. The metering specification did not include an overall gas flow measurement (due to the cost of such a meter), so burner on-time was measured indirectly with a thermocouple placed in the water heater flue. Another approach, which would have employed an electronic switch attached to the tank gas valve, was judged too risky since there was concern the switch would be vulnerable to damage (thereby risking a gas leak).

The thermocouple strategy proved problematic but ultimately workable. Fundamentally, the thermocouple and accompanying electronics report a voltage proportional to temperature inside the flue. As such, there is a delay in registering a temperature change during the fire-up period followed by an elongated cooling-off period. Ecotope developed an algorithm to reliably determine the on-time despite these challenges. Some of the sites, however, added further complications to overcome. These sites showed seasonal variation in thermocouple measurements, essentially moving the “on” and “off” states with time. Ecotope developed an adaptable algorithm to capture moving states to provide reliable on-time measurements of the gas DHW tanks. Once the on-time was known, the energy used was calculated with information obtained from clocking the gas utility meter while onsite.

Because water heating energy varies throughout the year, Ecotope required a full year’s worth of continuous data for each site to be included in analysis in the report. After scrubbing the data, sites were excluded for the following reasons:

- Thermocouple inference algorithm proved inadequate at: 1 gas tank site
- Metering period short of full year due to occupants leaving study: 3 electric and 3 gas sites
- Missing significant data within year of record: 5 electric and 2 gas sites
- Datalogging problems: 1 electric and 3 gas sites
- Heat pump water heater installed during study: 2 electric sites

Overall, the list shows that more than 80% of sites produced useable data for a continuous year. Some additional post-processing could be conducted on the sites with data missing within the time period to impute energy use depending on the desired analysis. This report considers continuous, year-long data only. The heat pump water heater sites were excluded from the analysis because there were only two sites. Those data are still available in the dataset. Table 10 gives the final accounting of sites used in the DHW analysis.

Table 10. Water Heater Fuel Type: Usable Sites

Region	Number of Tanks with Usable Data		
	Electric	Gas	Total
Puget Sound	16	13	29
Western Oregon	15	10	25
Eastern Region	18	10	28
Total	49	33	82

2.5.2. Space Heating and Cooling

Space heating and cooling present a unique analytical challenge. The weather in any given year may not be representative of long-term "normal" weather patterns. Consequently, it is not possible to directly generalize heating and cooling energy consumption from a given year to a typical year. To generalize, it is necessary to create a model of heating behavior from the observed weather and then apply the model to typical weather.

The acute weather dependence of heating and cooling also restricts the granularity with which one can forecast usage, as the most convenient model for a single heating system – degree day regression – only works down to the scale of daily data. An hourly generalization would better inform utility grid concerns, but the level of difficulty and subtlety of forecasting at that time span was deemed beyond the scope of this analysis. Instead of a generalized forecast, the report presents example hourly load shapes of the measured usage during the months of July and January. Although not weather normalized (that is, the data are reported for July 2012 and January 2013 and not adjusted to typical year conditions), those shapes can still be used to understand the time of use within a day.

2.5.2.1. Weather Normalization

Ideally, the heating data (and cooling, when present) exhibit a signature dependent on the outdoor temperature for a given house. That relationship governs how the heating (cooling) system responds to normal weather conditions. To produce weather-normalized and generalizable findings, Ecotope opted to conduct a variable-base degree day regression (VBDD) for all heating and cooling system types. This regression technique determines how linear the relationship between outdoor temperature and space conditioning energy is for a given building (Fels 1986, Geraghty 2009, and Larson 2013). The outputs of the method can be used to predict heating and cooling energy in any climate and weather year on a daily basis.

The VBDD technique is more commonly applied to building utility billing data. In RBSA Metering, Ecotope applies the technique to the daily metered heating (or cooling) energy and average daily measured outdoor temperature. Unlike with billing analysis, the underlying data is known to be heating (or cooling) energy only, so the usual problems of disaggregating non-heating, seasonally-varying loads like DHW and lighting is circumvented. As a result, the modeled estimates from metered heating or cooling are far better than those from total bills alone.

The goal of the VBDD analysis is to establish a clear, linear relationship between outdoor temperature and measured energy use. We employed an iterative review process to examine the outputs for goodness of fit between the energy usage and outdoor temperature, both with heating and cooling. Houses with irregular occupancy (whether through intermittent or widely varying occupancy), erratic control settings, malfunctioning equipment, or other causes obscure that relationship. Simply rescaling observed energy usage by the ratio of typical degree days to observed degree days without any in-depth review of the data opens up the possibility of producing misleading analytic findings. Therefore, the analysis of RBSA Metering site heating and cooling usage relied on detailed graphical study of each site’s heating and cooling data.

In some cases, the graphical study showed the relationship was strong and reliable. Those sites provide the most useful information. In other cases, this effort was less successful and we could not assert a strong or reliable relationship between outdoor temperature and heating energy usage. Where we knew there was additional, metered electric heating, for example from plug-in space heaters, we included this usage in the actual kilowatt hour consumption in heating. Taking that step always improved the fit. At the time of the report the analysis was restricted to examining only sites with a single fuel type on site (either gas or electric).

In this analysis, the data are normalized to Typical Meteorological Year (TMY3) weather for a given weather station (NSRDB 2008). The TMY3 dataset consists of hourly observations, so applying the weather normalization parameters results in an estimated energy use for every hour of the year. While this produces a reasonable estimate of the yearly energy use and monthly energy use, there is less confidence in looking at results on a daily or hourly basis because occupant behavior differences during different times of the day and different days of the week are not accounted for in the weather normalization model, and time-lag effects of the building components are also not accounted for.

2.5.2.2. Heating and Cooling Data Quality

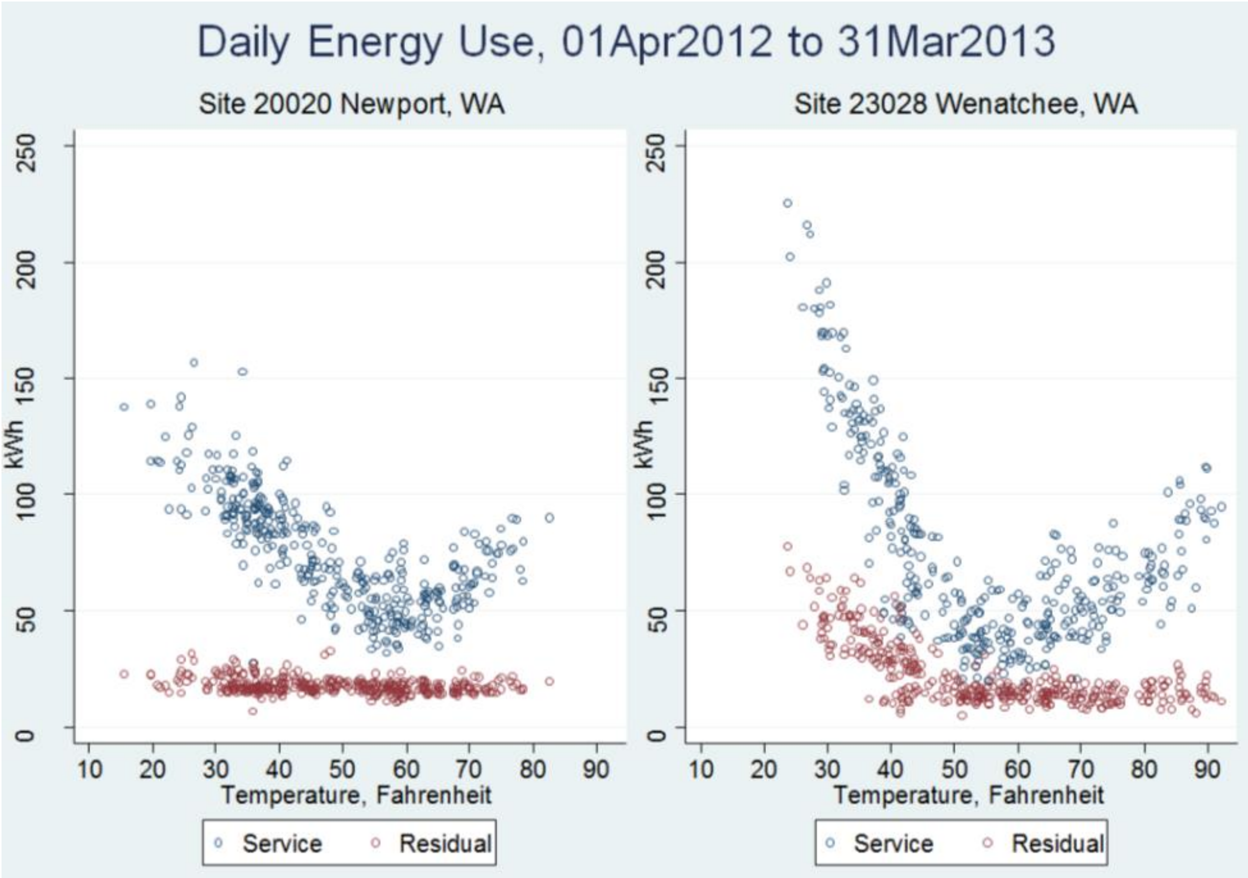
Data quality was, as always, a point of concern and focus of resources. The rigorous procedure for vetting data involved an analyst generating a series of graphics for each site and hand-examining these graphics. The graphics consisted of a time series plot of daily heating and cooling data for the year of record (April 1, 2012, though March 31, 2013); a scatter plot of all daily heating and cooling related end uses against average daily outdoor temperature; a scatter plot of daily measured whole-house electricity usage (service drop) and residual (unmetered load) against average daily outdoor temperature; a degree-day regression plot showing calculated heating slope and balance point, and calculated cooling slope and balance point (if applicable). For the purpose of the detailed analysis, sites were deemed usable if

1. The entirety of the heating (or cooling) load was successfully metered throughout the heating (or cooling) season for the year of record.
2. The heating system consisted of a single fuel type, although the site could have more than one system as in the case of zonal resistance heaters (portable or fixed) augmenting the electric furnace or heat pump.
3. System usage responded approximately linearly with respect to degree days.
4. The residual, unmetered load did not show a strong relationship with outdoor temperature. Ecotope excluded sites in which the unmetered load showed an obvious seasonal dependence, reflecting a situation where the meters did not observe this usage directly.

The measurement plan called for metering all of the heating and cooling systems in a house. In some houses, with gas furnaces for example, monitoring the furnace use is all that is required. In other houses, with multiple heating systems, more sensors are needed. The field technicians asked the occupants about their heating habits in order to monitor all the heating use. Still, it was obvious not all heating or cooling was metered at all sites. The most common cause was the occupant using plug-in space heaters to supplement their heating needs. The portable space heaters were usually not independently metered. Likewise, for cooling, occupants sometimes used window air conditioners. They placed these only seasonally in the windows. The project scope did not include a revisit to the sites in the summer to capture this energy use so it was missed.

Figure 2 shows the daily average energy use at two sites and illustrates how criterion 4 above was employed. Site 20020 shows both heating and cooling signatures. Further, the residual load (defined as the total measured service minus all known individual loads) is flat. In contrast, the residual load at site 23028 shows a distinct uptick starting at 45°F outdoor temperature. All of the water heating, lighting, and appliance loads, which can vary seasonally, are subtracted from the total. Therefore, a large, remaining residual load that is correlated with outdoor temperature is fully indicative of unmetered heating energy use.

Figure 2. Residual, Non-Metered Heating Load Example



The data quality criteria were set for the following reasons. First, it does little good to report an undefined subset of the space conditioning load. Second, developing tools to generalize heating usage for a multiple-fuel-source house was determined beyond the scope of this analysis. Ideally, the energy from all fuel types would be converted to common units, and a two-stage model would both forecast total usage and also the composition of that usage vis-à-vis fuel source. It is possible the analysis could eventually perform this aggregation but currently it does not. Finally, to generalize based on linearity with degree days, the underlying relationship must be at least approximately linear with degree days. Otherwise, the generalization makes no sense.

Table 11 shows the type of heating system and heating climate zone for each site in the study. There is clearly a diversity of system types and climate zones. There is a preponderance of gas furnace systems which is expected given their prevalence in the overall population.

Table 11. Heating System Type across Metered Sites

Heating Equipment	Site Count by Heating Climate Zone			
	1	2	3	Total
Baseboard	7	6	0	13
Boiler	1	0	1	2
DHP	3	0	0	3
Electric FAF	7	1	0	8
GSHP	1	0	0	1
Gas FAF	44	7	3	54
Gas Heat Stove	1	1	0	2
Heat Pump	16	2	1	19
Heat Pump Dual Fuel	2	0	0	2
Total	82	17	5	104

Table 12 shows the distribution of heating system types after the rigorous QC process was applied to the data. Problems that caused sites to be disqualified from the main analysis included

- being installed too late to observe the heating season for the year of record (2),
- decommissioned too early to observe the heating season (4),
- the presence of unmetered heat sources (5),
- a badly non-linear relationship between heating energy and degree days often caused by irregular occupant behavior (5),
- multiple heating fuel sources (6),
- bad or missing data from sensor malfunctions that resisted repair attempts (9), and
- malfunctioning heating equipment (specific to heat pumps) (4).

Table 12. Heating System Type – Useable Sites

Heating Equipment	Site Count by Heating Climate Zone			
	1	2	3	Total
Baseboard	4	2	0	6
Boiler	1	0	0	1
DHP	1	0	0	1
Electric FAF	6	1	0	7
Gas FAF	34	6	3	43
Gas Heat Stove	0	1	0	1
Heat Pump	9	1	0	10
Total	55	11	3	69

The criteria for inclusion in the general analysis were strict and specific. Many of the sites that were eventually excluded still provided useful metered data, but we could not always account for all the heating energy apparently used on site. Further expansion of analytical techniques will allow for more sites and sites with multiple fuel sources. Additionally, even though some of the data did not meet the full criteria for continuous, annual collection, it can still be used to answer other questions which do not require generalizable models of heating energy use.

2.5.2.3. Heat Pump Methods

Heat pumps deserve special mention in both the methods and, later, in the findings. Air source heat pumps (ASHPs) are a complicated part of the Pacific Northwest residential space heating and cooling mix. Over the past twenty years, significant efforts have been expended to both study and incentivize efficient heat pumps and installation procedures (Baylon et al. 2005, Reichmuth et al. 2005). The most recent, ongoing effort is the Performance Tested Comfort Systems (PTCS) program which is underwritten by Bonneville Power Administration and administered by regional utilities. This program requires installers to set outdoor lockout controls to limit use of electric resistance heat, test a system for proper airflow across the indoor coil, and check refrigerant charge. Residential customers are offered incentives for installations of air source heat pumps that meet the specifications (Regional Technical Forum 2007).

In RBSA Metering, there were twenty-five sites which used some type of heat pump for providing comfort in the house (Table 11). Most of the sites were traditional, ducted, air-source heat pumps, but three used ductless heat pumps; two were dual fuel systems, meaning they were an air-source heat pump with a fossil fuel furnace backup; and one is a ground source heat pump.

Most of the focus of the analysis is on the standard air-source ducted heat pumps because they form the bulk of the heat pump system category. Furthermore, most of the analysis and findings focus on the heating side. In most Northwest climates, heating is the only significant use of the heat pump. Even in climates with some amount of cooling, the cooling loads are typically one-tenth of the heating load. (See Figure 18, page 55, in the results section for a clear illustration.)

2.5.2.4. Heat Pump Specific Examples: Heating and Cooling Analysis with VBDD

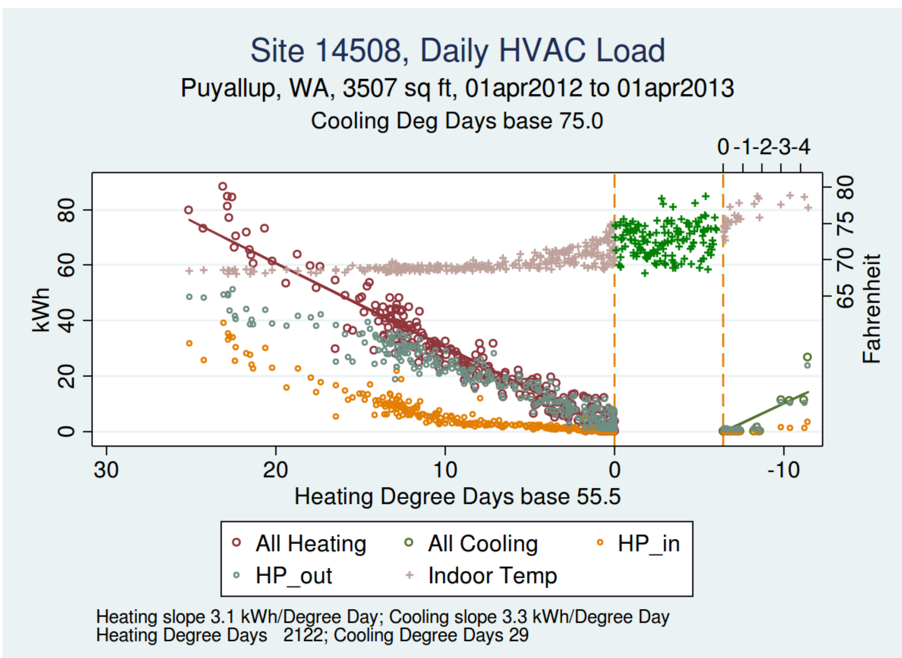
This section demonstrates how the detailed analysis is conducted for heat pumps. Heat pumps are generally the most complicated heating systems to analyze. Therefore, parts of the same methods are employed for the other heating systems.

There are a number of variables that affect overall energy usage in heating and cooling, including the heat loss rate of the house and its relationship to the nominal capacity of the heat pump; the condition of the ducts as expressed by both leakage fraction or value and surface area of the ducts that were located in unheated buffer spaces; and also, of course, the location of the site, as indicated by the climate zone. At the less well-behaved sites, we have information about problems that were identified at installation or later, including failed compressors, low refrigerant levels or other issues. The data show fairly clearly in most cases where additional problems occurred, such as compressor malfunction, and so these have to be considered in overall heat pump performance over the course of various heating and cooling seasons.

Figure 3 depicts the annual behavior for the official year of record of a 5 ton air source heat pump in the south Puget Sound region. The graphic is information-rich. Electricity consumption is plotted on the left vertical axis and indoor temperature is plotted on the right vertical axis. The average daily outdoor temperatures are shown on both the upper and lower horizontal axes as values relative to the house's balance points. In heating, the balance point is the outdoor temperature below which the heating system must turn on to maintain the desired indoor temperature. In cooling, the balance point is the outdoor temperature above which the cooling system must turn on to maintain the desired indoor temperature. Electricity usage by the heat pump's outdoor unit is shown by red circles and usage by the indoor unit (air handler and electric resistance elements) is shown by orange circles. The "All Heating" label in the legend also means this site uses some 120 VAC plug-in heaters; this usage is included in the overall heating energy usage.

The lines on the graph are outputs from the VBDD regression showing the "best-fit" relationship of either space heating (left portion of the graph) or space cooling (right portion of the graph) to outdoor temperature. The VBDD method calculates a base heating degree temperature; below this outdoor temperature, the house needs heat from the heat pump to stay at a comfortable temperature. If the house is relatively well-insulated, has more internal heat gains, or more direct solar heat gains, the balance point will be lower than for the same size house in the same location with less insulation and/or internal gains.

Figure 3. Seasonal Heat Pump Performance



HP_in: Heat pump indoor unit (including electric resistance)
HP_out: Heat pump outdoor unit

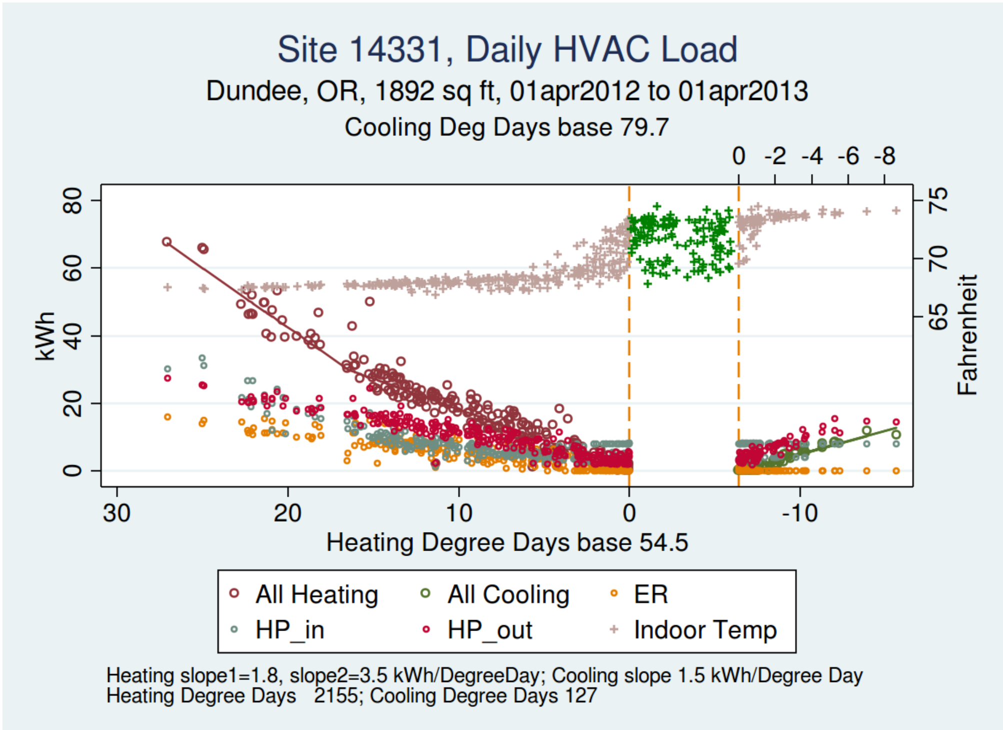
At site 14508, most of the heating is provided by the vapor compression cycle but at colder temperatures (HDD in the low 20s, or around 30-35° F), one notes the "HP_in" usage does lever upward, indicating some electric resistance element operation. This system employed an outdoor temperature lockout on the electric resistance elements. Indoor temperature during the heating season (indicated by crosses) is maintained at about 70° F. Once the heating load goes to zero (that is, there are no heating degree days), we can see the interior temperature float (green crosses between dotted lines). For some parts of the year, the interior temperature increases to the point where "negative" heating degree days start (that is, we need mechanical cooling); this part of annual operation is shown on the right end of the graphic.

Note also that in this particular site, a consistent cooling setpoint appears not to be used (since the interior temperature is sometimes in excess of 80° F). This indicates the cooling is not controlled by a regular operation schedule but is more likely controlled by irregular manual operation of the thermostat. This is a common pattern in the Northwest, especially in the marine climates.

A second air source heat pump site shows an even more pronounced division between the heating provided by the compressor and that provided by the electric resistance elements at colder temperatures. Figure 4 displays the annual performance. At this site, the "elbow" begins at about 15 heating degree days, and given the house balance point of 54.5° F, this means the electric resistance elements are free to operate at an outdoor temperature of about 40° F. The installer did not install an outdoor lockout control at this site; it appears the actual balance point of the house is such that electric resistance heat is needed to maintain the desired indoor temperature even at 40° F outdoor temperature.

In this case, the two-part regression of the heating usage produces two distinct slopes. The compressor heating slope is about 1.8 kWh/day and the compressor plus element slope is almost twice this, at 3.5 kWh/day. The figure further serves to illustrate the analytical process. In addition to the heat pump system, this house has a separate electric resistance system (240 VAC-wall heaters). Therefore, there are multiple, independently controlled heating systems for the house. The electric resistance wall-heater energy use is plotted as the orange "ER" circles on the graph. Again, the "all heating" points on the graph are the sum of the compressor, indoor unit (fan and auxiliary heat), and the secondary ER heating system. Given the location in the upper Willamette Valley, the cooling usage is modest. Crucially, the heat pump vapor line temperature (VLT) was measured so it was always clear if the system was in heating or cooling mode.

Figure 4. Second Seasonal Regression Example



ER: additional electric resistance load

2.5.3. Appliances

The analysis of major appliance data in RBSA Metering combined simple arithmetic averages, mostly of annual usage, with more finely resolved load shapes, which show energy usage on a daily or weekly basis and power by the hour. Most sites had only one each of these appliances. Metering coverage of the appliances was excellent, with a near census of all appliances achieved. ANOVA tests showed no statistical difference in energy use across geographic regions. Consequently, all the appliances are reported as a single group. However, usage by age category (vintage) is typically summarized because the ever-improving federal appliance standards would suggest that usage should change over time.

The nomenclature used throughout this report bears a quick mention. "Freezer" refers to stand-alone appliances whose purpose is to keep food frozen. "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.

A nearly complete metering of all appliances was achieved for all the electric appliances except where a datalogger failed to provide usable information. Table 13 shows the appliances found onsite at all of the 104 metered sites. Further, the table shows which appliances were metered and, of those metered, which provided viable data for inclusion in the analysis. As Table 13 shows, nearly every clothes washer, clothes dryer, freezer, and refrigerator was metered. A smaller percentage of dishwashers were metered. The number of cooking ranges found onsite includes both electric- and gas-fueled ranges. Nearly every electric range was metered. However, due to the challenging nature of the measurement, no gas ranges were monitored.

Table 13. Appliance Metered Count

Appliance	Number of Observations (n)		
	Found on Site	Metered	Provided Viable Data
Clothes Washer	103	102	97
Clothes Dryer	103	99	93
Dishwasher	93	64	58
Freezer	60	52	46
Range (Elec or Gas)	103	71	63
Refrigerator	133	131	120

The data show that some sites had more than one refrigerator, so usage for the "primary" (located in the kitchen) and "secondary" (located elsewhere) refrigerator is reported in summary tables. Load shapes include all refrigerators. In a very few cases, data problems prevented reporting and summarization of annual usage; the number of cases in each average is always reported, as is the number of cases that are found in various graphical treatments of the data.

The end of the appliance section contains an analysis of major appliance electricity usage in the "typical" site. In this case, because not all sites have the same major appliance counts, the average usage will include the overall appliance saturations typical to the Northwest. For example, lack of a dishwasher will decrease a site's contribution to appliance electricity usage.

2.5.4. Consumer Electronics

The primary analysis of consumer electronics data in RBSA Metering combined simple arithmetic averages, mostly of annual usage, with more finely resolved load shapes that show energy usage on a daily or weekly basis and power by the hour.

Consumer electronics often have multiple modes – active, standby, and sleep. Ideally, one would want to distinguish between these modes in the analysis. For the purposes of this study, only the plug load energy use over time was recorded. Ecotope did not record the energy use of individual devices in their various modes onsite. Thus, rather than distinguish among active, standby, and sleep modes, energy use was grouped into high-power, low-power, and off modes. In order to identify modes of performance, histograms were produced for each class of device. By means of visual inspection, a wattage threshold was recorded that captures the smallest mode. It is important to note that these distinct modes do not reflect the utility or performance of the device, but merely describe energy consumption behavior. Observing energy behavior does not allow one to infer standby modes.

Slightly different methods were used for televisions, game consoles, and cable boxes. In the case of televisions, separate thresholds were given to cathode ray tube (CRT), flat screen, liquid crystal display (LCD), plasma, and projection televisions.

Energy use varies greatly by type of game console. As a result, a collective histogram of game console energy use showed roughly six distinct modes. Fortunately, when viewed individually, each game console showed only two modes of energy consumption. Thus, each game console was given its own personal mode threshold.

Set-top boxes presented the same multimodal problem as game consoles. Again, when viewed individually, set-top boxes showed bimodality. Set-top boxes were also given individual mode thresholds.

2.5.5. Lighting

The objectives of the lighting study within the RBSA Metering project include establishing daily and annual load shapes, average daily on-time, and overall lighting system energy use. The general approach to energy efficiency in this sector has been to assume a relatively flat load shape that is based on an estimate of total annual lighting on-time, but because the data collected in RBSA Metering are much more granular, it is possible to produce a more finely tuned load shape.

Due to budgetary limitations, not all fixtures could be monitored at all sites. In the end, 34% of all lighting fixture groups at the sites were directly metered. The analysis focused on determining on-time for *room types* and *fixture groups* across the entire sample. Because not every lamp was metered, it was necessary to devise a method to estimate the on-time of these fixtures. Approximately 1,965 lighting loggers were deployed on fixture groups representing 60% of all the lighting in the metered houses.

2.5.5.1. Logger Attrition

Because the lighting loggers were not part of the automatic download system that characterized the other load metering options, the quality could not be monitored during data collection. There were several problems that compromised some of the lighting loggers. The majority of these problems were in three categories:

- Deployment failure: The lighting loggers were deployed on a variety of fixtures including portable lamps such as stand lights and desk lights. Some of this category failed because the fixture was moved or removed or the lamp was replaced by the occupant and the logger misplaced or removed.
- Light intrusion: Despite careful placement of the light sensor, the readings were often compromised by ambient light, usually sunlight, which registered false positive on-times. Quality control checks often showed greatly increased on/off events and on-times near the summer solstice, indicating that ambient light was falsely tripping the sensor. Much of the data cleaning process focused on identifying this fault and eliminating the data from further summary. An additional 25% of the original deployment suffered from ambient light intrusion and did not produce usable data.
- Meter failure: In some cases, the loggers ceased to collect data in the period of deployment. This equipment failure was usually due to logger placement where the lamp temperature was able to “toast” the logger. Battery failure also constituted some of these failures. Approximately 25% of all meters deployed never provided readable data either because of meter or deployment failure.

The result of these issues was that about half of the deployed lighting loggers were lost or compromised. As a result, data were available from about 48% of all the loggers originally deployed. A total of 939 loggers were available for the overall lighting summary. These loggers covered 874 rooms, 1,115 fixtures, and 1,943 lamps throughout the sample. The on-times derived from this set of meters, rooms, and fixtures are the basis for estimating lighting use across all fixtures in all houses.

The hourly, monthly, and yearly load shapes were created using the average on-times across all the metered fixtures. For the annual load shapes, a second order trigonometric fit of daily on-time data was employed. For the hourly and monthly load shapes, both hourly and monthly averages, as observed, were used.

2.5.5.2. On-Time Estimation Methods

The major analytical work was to estimate on-times at fixture groups that were not directly metered. The analysis begins with the observed on-times for the directly metered loggers and then extends the results to both unmetered fixtures within RBSA Metering houses and to all houses within RBSA. At all RBSA sites, a field surveyor counted all fixtures and lamps by room and assigned wattages based on lamp type. Consequently, the location and total amount of lighting installed is known across all houses. That survey, combined with the metered fixtures, provided the basis for generalizing overall lighting on-time and load shape for the study.

In the first phase of the analysis, a linear regression approach was used to evaluate the on-time use across all metered fixtures. To start, we used ANOVA tests to explore variables for inclusion in the regression, including room type, fixture type, lamp type, number of fixture groups in the individual room, house floor area, and house occupant count. The investigation showed that only room type and fixture type had meaningful correlations with on-time usage. Accordingly, the final regression included only those variables. For the regression, each room type and fixture type was assigned an indicator variable and then regressed against the observed annual on-time usage. The regression results were then able to predict the on-time of the non-metered lights for any given room type and fixture type.

2.5.6. Relative Energy Consumption by End Use

The meters in the study measured the entire service drop and most of the individual loads at each house. Combining the information shows how energy in houses is used on the residential side of the utility meter and how those uses compare to one another. Following the same categories throughout the report, the analysis of all electric houses splits the consumption into heating, cooling, water heating, lighting, consumer electronics, appliances, known “other”, and unmetered. For houses with natural gas service, the primary metered loads were heating, water heating, and the electric portions of that use (gas furnace air handler, for example). Although the whole-house energy consumption analysis draws heavily on the methods used in the other sections, some changes and expansions are made and described below.

The total energy use on site comes from the data loggers on the house electric service drop and utility bills in the case of natural gas service.[9] The appliance energy comes directly from the metered totals, as do the water heating and consumer electronics. The lighting energy is a combination of directly measured and estimated energy. Approximately one-third of the lighting energy was directly measured. Using techniques discussed in sections 2.5.5.2 and 3.6, Ecotope estimated the annual consumption of unmetered lighting.

The heating and cooling energy use were derived directly from the metered data. Unlike other parts of the report, they are not weather-normalized values. This is mainly because doing so would necessitate normalizing the total energy used on-site as well. In addition to the directly metered heating and cooling, Ecotope examined the unmetered ("residual") electricity consumption at each site to test for an outdoor temperature dependence. This was done with a variable base degree day (VBDD) process. The VBDD analysis of the residual can show a strong relationship with either cold (indicative of heating) or hot (indicative of cooling) outdoor temperatures. Section 2.5.2.2 shows an example of a site where most, but not all, of the heating devices were metered. The analysis of the residual in the service energy shows the heating dependence. When this was present, Ecotope attributed the energy use to heating and cooling for the whole-house analysis. Note that only electric devices and not gas devices are used by occupants in this way so there is no temperature-dependent gas heating residual. In other words, on-site meters captured all the gas heating energy.

The last known category contains the "other" large, unusual loads which do not fit neatly in to other categories. Their energy is reported as directly metered. The final amount of energy remaining is the unmetered electric and gas portion. The unmetered (or residual) amount of energy use is defined as the difference between the total observed energy and the sum of all the known, individual loads. Future work could extend the analysis in a few areas to infer more "known" energy use. The few unmetered appliances and the many unmetered consumer electronics in each house could be assigned an energy use based on their measured peers. The approach would reduce the "unknown" residual energy amount somewhat but not dramatically because most appliances in the house were, indeed, metered.

[9] The metering conducted on each home did not allow direct metering of natural gas usage. On time and staging on the major natural gas uses was metered. Thus the utility bills could be used to calibrate overall gas usage.-

3. Findings

3.1. Occupancy and House Characteristics

This section summarizes occupancy, overall house characteristics, and heating systems for the RBSA Metering sites. For summaries and comparisons of house vintage, energy use, cooling, water heaters, appliances, electronics, and lighting, see Appendix 5. In the summaries below, the metered sites are compared to the RBSA single-family sites for the same geographic regions in order to illustrate the strong statistical link between the two samples. As discussed in section 2.1.5, the characteristics of the metered sample are similar to the RBSA single-family sites, demonstrating the reliability of the load shapes and annual energy use presented in this report. The RBSA Metering site characteristics are also fairly homogeneous across sampling regions within the metered sample.

Of the 104 sites recruited to participate in RBSA Metering, 93 remain active in the field, including three sites that were recruited to replace decommissioned sites over the course of the study (Table 14). Characteristic summaries for metered sites include data from all sites regardless of current status.

Table 14. Metered Site Status over the Course of RBSA Metering Study

Site Status		Site Status Over Course of RBSA Metering			
		Puget Sound	Western Oregon	Eastern Region	n
Continuously Active	**n**	31	28	31	90
Decommissioned	**n**	5	2	4	11
Replaced	**n**	1	0	2	3
All Sites	**n**	37	30	37	104

3.1.1. Occupancy

Overall, the occupancies (total and by age) across both studies are equivalent, as seen in Table 15 and Table 16, which show the mean and the error bound (EB) for each age category. The average occupancy is about 2.7 for both RBSA Metering and RBSA single-family. There are subtle differences in some regions, such as Puget Sound and the eastern region, but they are not statistically significant. This small variation indicates that any overall biasing effects of occupancy in RBSA Metering are minimal. Nonetheless, some metering results in this report are normalized per occupant to minimize any effects of occupancy variance.

Table 15. Average Number of Occupants by Age Category and Region (RBSA Single-Family)

Age Category		Number of Occupants, RBSA SF (n= 1,193)			
		Puget Sound	Western Oregon	Eastern Region	All Regions
Minors (0 to 17)	Mean	0.85	0.53	0.83	0.72
	EB	0.49	0.39	0.65	0.32
Adults (18 to 64)	Mean	1.60	1.23	1.13	1.28
	EB	0.36	0.30	0.46	0.23
Seniors (65 and over)	Mean	0.52	0.65	0.81	0.68
	EB	0.30	0.32	0.37	0.20
All Occupants	Mean	2.52	2.49	3.07	2.71
	EB	0.12	0.17	0.23	0.11

Table 16. Average Number of Occupants by Age Category and Region (RBSA Metering)

Age Category		Number of Occupants, RBSA Metering (n=104)			
		Puget Sound	Western Oregon	Eastern Region	All Regions
Minors (0 to 17)	Mean	0.89	0.47	0.78	0.73
	EB	0.24	0.19	0.24	0.13
Adults (18 to 64)	Mean	1.76	1.30	1.16	1.41
	EB	0.18	0.17	0.19	0.11
Seniors (65 and over)	Mean	0.38	0.57	0.73	0.56
	EB	0.12	0.15	0.15	0.08
All Occupants	Mean	3.05	2.33	2.68	2.71
	EB	0.30	0.23	0.29	0.16

3.1.2. House Characteristics

3.1.2.1. Conditioned Floor Area

Average house square footage is similar overall between the two studies (Table 17 and Table 18). Houses trended slightly larger in the metering study overall. The western Oregon houses showed a small difference beyond the confidence interval, albeit extremely small. The average conditioned floor area for the metered sample is 2,145 square feet (sq.ft.).

Table 17. Average Conditioned Floor Area by Region (RBSA Single-Family)

Study Region	Conditioned Floor Area (sq.ft.), RBSA SF		
	Mean	EB	n
Puget Sound	2,006	72	470
Western Oregon	1,890	108	252
Eastern Region	2,160	88	463
All Regions	2,028	51	1,185

Table 18. Average Conditioned Floor Area by Region (RBSA Metering)

Study Region	Conditioned Floor Area (sq.ft.), RBSA Metering		
	Mean	EB	n
Puget Sound	2,132	127	37
Western Oregon	2,223	206	30
Eastern Region	2,095	140	37
All Regions	2,145	89	104

3.1.2.2. Overall Heat Loss Performance

The heat-loss rate (UA)[10] of the surveyed houses was calculated using the insulation values reported in the house surveys. The heat-loss rate reported in these summaries excludes that from infiltration or ventilation occurring in these houses.

Table 19. Average Heat-Loss Rate by Region (RBSA Single-Family)

Study Region	House Total UA, RBSA SF		
	Mean	EB	n
Puget Sound	650	33	429
Western Oregon	624	48	243
Eastern Region	576	25	437
All Regions	616	20	1,109

Table 20. Average Heat-Loss Rate by Region (RBSA Metering)

Study Region	House Total UA RBSA Metering		
	Mean	EB	n
Puget Sound	607	45	35
Western Oregon	680	74	29
Eastern Region	538	48	37
All Regions	603	32	101

Table 21 and Table 22 show the UA/sq.ft. of conditioned floor area for the RBSA single-family and RBSA Metering studies. Metered sites in the Puget Sound region have a lower average UA/sq.ft. than those in the RBSA single-family study. This is likely due to the presence of more basements in the metered group, which tend to lower the UA/sq.ft. compared to other ground contact types. In the remainder of the region, the UA/sq.ft. values are roughly equivalent in both studies. The eastern region shows an expected increased insulation level over other geographic areas (lower heat loss per sq.ft.) due to the greater insulation requirements in generally colder climates. This improvement is seen in both samples.

[10] The sum of the thermal transfer coefficient (U in Btu/hr°Fft^2) times the area (A) of the components of the building, not including infiltration.

Table 21. Average Normalized Heat-Loss Rate by Region (RBSA Single-Family)

Study Region	House UA per Sq.Ft., RBSA SF		
	Mean	EB	n
Puget Sound	0.35	0.02	427
Western Oregon	0.34	0.02	240
Eastern Region	0.29	0.02	433
All Regions	0.32	0.01	1,100

Table 22. Average Normalized Heat-Loss Rate by Region (RBSA Metering)

Study Region	House UA per Sq.Ft. RBSA Metering		
	Mean	EB	n
Puget Sound	0.29	0.02	35
Western Oregon	0.32	0.03	29
Eastern Region	0.27	0.02	37
All Regions	0.29	0.01	101

3.1.2.3. House Air-Tightness

The final step in evaluating the heat-loss rate of the house envelope included the air tightness or air infiltration of the house. This measurement was conducted on a subsample of houses in the RBSA single-family study. All metered sites were included in this group. The blower door test depressurizes the entire conditioned house volume at two test pressures. It is common in research studies to report the amount of air flowing through the blower door at the higher test pressure (50 Pascals [Pa]) and to normalize this flow using the house volume. The result is reported as air changes per hour at 50 Pa (ACH50).

Table 23 and Table 24 show the average blower door test results across the regions in the metering study. Houses in the eastern region are noticeably tighter on average. This difference is partly due to the addition of a basement as part of the conditioned area. The envelope associated with the basement itself is not very leaky. As a result, the normalized leakage rates expressed as air changes per hour (ACH) decrease because of the extra volume from the conditioned basement. Nearly half of eastern region sites, overall, and, in the metered study, had at least some conditioned basement space; one-third of western Oregon sites overall had a conditioned basement, versus approximately 40% in the metered sample; and only approximately 15% of Puget Sound houses had conditioned basements in both studies. In the eastern region, building practices favoring tighter envelopes may also have influenced this result. The higher prevalence of conditioned basements in the RBSA Metering western Oregon sample compared to the RBSA sample may explain the increased tightness seen.

Table 23. Average Blower Door Air Tightness by Region (RBSA Single-Family)

Study Region	Blower Door Air Tightness (ACH50), RBSA SF		
	Mean	EB	n
Puget Sound	10.87	0.74	128
Western Oregon	11.38	0.77	108
Eastern Region	7.82	0.60	173
All Regions	9.93	0.40	409

Table 24. Average Blower Door Air Tightness by Region (RBSA Metering)

Study Region	Blower Door Air Tightness (ACH50), RBSA Metering		
	Mean	EB	n
Puget Sound	10.91	0.89	36
Western Oregon	8.82	0.51	30
Eastern Region	7.68	0.55	36
All Regions	9.16	0.42	102

3.1.2.4. Heating Systems

The distribution of primary heating systems and fuel types is summarized in Table 25 through Table 28. The ratio of electrically heated houses is not significantly different between the two studies. Within electrically heated houses, however, there is a larger fraction of heat pumps versus electric resistance in RBSA Metering. The fraction of houses that are gas-heated in all metered regions is not significantly different than gas-heated houses in RBSA single-family. Overall, air source heat pumps accounted for 11% of primary systems in the RBSA, and 18% of sites in the RBSA Metering study. The difference is intentional because, at the request of the project sponsors, heat pumps were recruited at a higher rate in the final sampling stages. Nevertheless, the differences between heating system types remains surprisingly small. Sites using non-utility primary fuel were not recruited into RBSA Metering.

Table 25. Distribution of Primary Heating Systems (RBSA Single-Family)

System Type		Percent of Primary Heating Systems, RBSA SF				
		Puget Sound	Western Oregon	Eastern Region	All Regions	n
Baseboard Heater	%	14.8%	8.4%	11.4%	11.8%	161
	EB	3.0%	3.1%	3.2%	1.8%	
Boiler	%	6.1%	0.9%	7.6%	5.2%	77
	EB	2.1%	1.4%	1.6%	1.0%	
Ductless Heat Pump	%	0.8%	2.3%	0.1%	1.0%	13
	EB	0.7%	1.7%	0.1%	0.5%	
Forced Air Furnace	%	59.1%	57.7%	53.9%	56.9%	627
	EB	4.3%	5.9%	5.0%	2.9%	
Ground Source Heat Pump	%	–	0.5%	1.0%	0.5%	11
	EB	–	0.5%	0.7%	0.3%	
Air Source Heat Pump	%	8.3%	14.4%	10.3%	10.7%	127
	EB	2.5%	4.3%	3.4%	1.9%	
Dual Fuel Heat Pump	%	0.4%	2.5%	1.0%	1.2%	14
	EB	0.4%	2.0%	0.8%	0.6%	
Heating Stove	%	8.9%	12.2%	14.0%	11.7%	12
	EB	2.7%	4.1%	3.4%	1.9%	
Plug-In Heater	%	1.4%	1.0%	0.8%	1.1%	12
	EB	1.0%	1.4%	0.7%	0.6%	
All Systems	%	100.0%	100.0%	100.0%	100.0%	1,189
	EB	0.0%	0.0%	0.0%	0.0%	

Table 26. Distribution of Primary Heating Systems (RBSA Metering)

System Type		Percent of Primary Heating Systems, RBSA Metering				
		Puget Sound	Western Oregon	Eastern Region	All Regions	n
Baseboard Heater	**%**	13.5%	3.3%	18.9%	12.5%	13
	EB	1.5%	1.0%	1.7%	0.5%	
Boiler	**%**	2.7%	—	2.7%	1.9%	2
	EB	0.7%	—	0.7%	0.2%	
Ductless Heat Pump	**%**	5.4%	3.3%	—	2.9%	3
	EB	1.0%	1.0%	—	0.3%	
Forced Air Furnace	**%**	59.5%	63.3%	56.8%	59.6%	62
	EB	2.2%	2.6%	2.2%	0.8%	
Ground Source Heat Pump	**%**	—	3.3%	—	1.0%	1
	EB	—	1.0%	—	0.2%	
Air Source Heat Pump	**%**	13.5%	23.3%	18.9%	18.3%	19
	EB	1.5%	2.3%	1.7%	0.6%	
Dual Fuel Heat Pump	**%**	2.7%	3.3%	—	1.9%	2
	EB	0.7%	1.0%	—	0.2%	
Heating Stove	**%**	2.7%	—	2.7%	1.9%	2
	EB	0.7%	—	0.7%	0.2%	
All Systems	**%**	100.0%	100.0%	100.0%	100.0%	104
	EB	0.0%	0.0%	0.0%	0.0%	

Table 27. Distribution of Primary Heating System Fuel by Region (RBSA Single-Family)

Fuel Type		Percent of Primary Heating System Fuel, RBSA SF				
		Puget Sound	Western Oregon	Eastern Region	All Regions	n
Electric	**%**	23.7%	20.2%	20.3%	21.5%	289
	EB	3.6%	4.8%	3.8%	2.3%	
Gas	**%**	56.3%	53.7%	55.6%	55.3%	606
	EB	4.3%	6.0%	5.0%	2.9%	
Heat Pump	**%**	8.3%	14.4%	10.3%	10.7%	127
	EB	2.5%	4.3%	3.4%	1.9%	
Oil	**%**	4.9%	2.7%	2.0%	3.3%	47
	EB	1.6%	2.0%	1.7%	1.0%	
Pellets	**%**	0.9%	1.7%	1.9%	1.5%	19
	EB	0.8%	1.3%	1.7%	0.8%	
Propane	**%**	1.6%	0.2%	1.4%	1.1%	15
	EB	1.3%	0.3%	0.8%	0.5%	
Wood	**%**	4.4%	7.0%	8.6%	6.6%	87
	EB	1.9%	3.2%	2.8%	1.5%	
All Fuels	**%**	100.0%	100.0%	100.0%	100.0%	1,190
	EB	0.0%	0.0%	0.0%	0.0%	

Table 28. Distribution of Primary Heating System Fuel by Region (RBSA Metering)

Fuel Type		Percent of Primary Heating System Fuel, RBSA Metering				
		Puget Sound	Western Oregon	Eastern Region	All Regions	n
Electric	%	27.0%	23.3%	27.0%	26.0%	27
	EB	2.0%	2.3%	2.0%	0.7%	
Gas	%	59.5%	53.3%	54.1%	55.8%	58
	EB	2.2%	2.7%	2.2%	0.8%	
Heat Pump	%	13.5%	23.3%	18.9%	18.3%	19
	EB	1.5%	2.3%	1.7%	0.6%	
All Fuels	%	100.0%	100.0%	100.0%	100.0%	104
	EB	0.0%	0.0%	0.0%	0.0%	

Sites in RBSA Metering have a higher prevalence of plug-in heaters than the RBSA – an average of 0.47 and 0.15, respectively (Table 29 and Table 30). Two factors may have contributed to this result. The majority of metering surveys were performed in winter months, and the majority of surveys for the larger study were performed in the summer, when plug-in heaters would be most likely to be stored away. Additionally, metering surveyors were charged with attempting to meter all heating loads at each site, and would have been more likely to seek out plug-in heaters to monitor when possible.

Table 29. Average Number of Plug-In Heaters per House by Region (RBSA Single-Family)

Study Region	Plug-In Heaters per House, RBSA SF		
	Mean	EB	n
Puget Sound	0.15	0.03	472
Western Oregon	0.17	0.05	254
Eastern Region	0.13	0.04	465
All Regions	0.15	0.02	1,191

Table 30. Average Number of Plug-In Heaters per House by Region (RBSA Metering)

Study Region	Plug-In Heaters per House, RBSA Metering		
	Mean	EB	n
Puget Sound	0.65	0.10	37
Western Oregon	0.40	0.12	30
Eastern Region	0.35	0.09	37
All Regions	0.47	0.06	104

3.2. Water Heating

The major factors determining the amount of energy used to heat water are the volume of water required, incoming water temperature, delivery water temperature, efficiency with which the water is heated, and level of storage tank insulation. The behavior of household occupants exclusively drives the volume of water. The occupants take showers or wash hands. They also employ machines that use hot water to wash their dishes or clothes. The more people, the more of these hot water events occur and the greater the water volume required. Environmental conditions set the inlet water conditions, while occupants establish a tank setpoint.

The properties of the water heater itself set the tank efficiency. The standby losses occur while the tank is holding hot water to be readily available for use. For natural gas-fired DHW tanks, the tank losses are both from jacket losses and flue losses. In standby mode, the flue is in contact with the stored hot water in the tank, thus increasing the overall heat loss (versus an electric tank). In addition, the efficiency of gas combustion contributes to a reduction in the overall efficiency of gas tanks versus electric tanks. When compared with electric resistance tanks, gas water heaters use more energy onsite to provide the same amount of hot water to the occupant (but they also recover faster than electric tanks due to their higher capacity).

In this dataset, some of the determinants of DHW energy use (such as inlet and outlet water temperatures and actual mass of hot water used) were not measured directly or indirectly. This study never intended to measure these factors. Still, a great deal about hot water use can be determined from knowing overall energy use and the number of people using the water. The study included only tank water heaters and not instantaneous (on-demand) water heaters, given the extra metering complexity and cost. This section reports overall energy use and presents energy use load shapes.

3.2.1. DHW Energy Use across the Pacific Northwest

Table 31 and Table 32 show the annual average energy use per water heater (also per site) across the region for both electric and gas DHW tanks, respectively. As discussed in section 2.5.1, the monitoring of gas water heaters was conducted using changes in flue temperature as an estimator of the actual flow of natural gas to the water heater. This technique was successfully applied in most cases, such that a total of 33 gas water heaters are included in the current analysis.

Table 31. Annual Average Electric Water Heating Energy by Site

Region	Electric Water Heater Energy Use (kWh/yr)		
	Mean	EB	n
Puget Sound	3,051	325	16
Western Oregon	2,519	227	15
Eastern Region	3,439	386	18
Total	3,030	194	49

Table 32. Annual Average Gas Water Heating Energy by Site

Region	Gas Water Heater Energy Use (Therm/yr)		
	Mean	EB	n
Puget Sound	140	20	13
Western Oregon	165	25	10
Eastern Region	142	22	10
Total	148	12	33

The major determinant of hot water energy use is the number of people in the household. Table 33 and Table 34 show the annual energy use normalized by number of occupants. During the course of metering, some occupancy numbers changed. Occupant interviews revealed the date of the change. These dates were used to keep an accurate, annual, average count of occupants.

Table 33. Annual Average Electric Water Heating Energy per Occupant

Region	Electric Water Heater Energy Use Per Occupant (kWh/yr)		
	Mean	EB	n
Puget Sound	1,290	160	16
Western Oregon	1,316	84	15
Eastern Region	1,530	184	18
Total	1,386	89	49

Table 34. Annual Average Gas Water Heating Energy per Occupant

Region	Gas Water Heater Energy Use Per Occupant (Therm/yr)		
	Mean	EB	n
Puget Sound	48	4	13
Western Oregon	67	11	10
Eastern Region	52	4	10
Total	55	4	33

Table 33 shows that the electric DHW energy use is equivalent in the Puget Sound and western Oregon regions but larger in the eastern region. One possible reason is colder average water supply temperatures. The water temperature supplied to the house is subject to the ground temperature through which the water mains run. That ground temperature, in turn, is linked to the annual average air temperature of a location. Table 34, for gas water heaters, shows a different pattern, but there are fewer gas DHW tanks in the table, so caution should be used in drawing conclusions.

3.2.2. DHW Energy Use Correlation with Occupancy

Previous studies of residential water heating energy use in the Northwest correlated annual electricity usage for water heating with the number of household occupants (Roos & Baylon 1993, Quaid et al. 1991, Palmiter 1982). Those studies showed that the relationship of energy use to people changes when the number of occupants begins to exceed four (Palmiter 1982, Perlman & Mills 1985, Roos & Baylon 1993). The RBSA Metering study is no exception. Roos found that Equation 1 predicted energy use for houses with fewer than five occupants (1993).

Equation 1 $Q_{DHW}=624+1169*N$ (for $N < 5$)

Where Q_{DHW} = annual DHW electric consumption (kWh/year)
and N = total number of occupants

Using the same techniques as Roos, Ecotope conducted several linear-fit regressions on the dataset. Unlike Roos, there was no advantage to using a robust regression. Instead the simpler, typical least-squares approach was employed. Figure 5 shows the fits used for electric tanks. The results of the first regression specification attempted are given in Equation 2 and correspond to the red line in Figure 5. The outcome implies there are over 1,300 kilowatt hours per year (kWh/yr) of standby energy lost (the constant term in the equation). This, however, strains the bounds of credulity. Further inspection of the data shows the sample is dominated by two-person households with some one- and three-person houses but not many. Unlike the Roos study, there essentially is not a useful distribution of occupancies from which to get a reasonable answer.

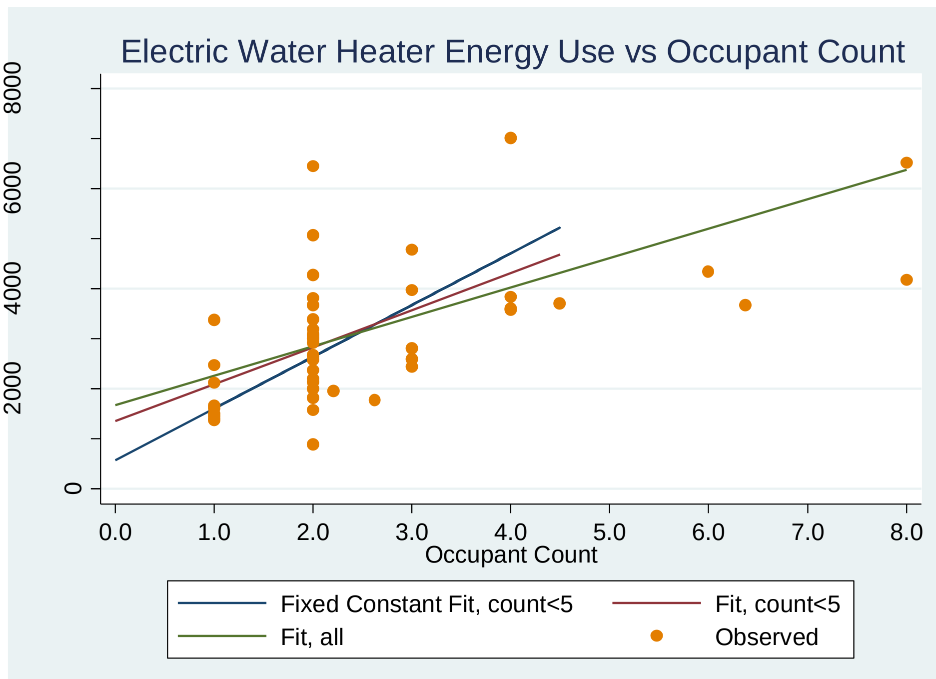
Equation 2 $Q_{DHW} = 1315 + 731*N$ (for N<5)

To find a useful and reasonable fit, Ecotope calculated estimates of standby losses for each tank given its installation location and a 125°F setpoint. The results suggest a standby loss of 570 kWh/yr across the sites. Using this standby as a new constant, Ecotope reran the regression to produce Equation 3. There were too few houses with five or more occupants to make a reliable fit for those cases.

Equation 3 $Q_{DHW} = 570 + 1034*N$ (for N < 5)

Figure 5 displays the results of three possible fits: Equation 2 is in red, Equation 3 – the best fit – is in blue, and a fit like Equation 2 but for all occupant counts is in green.

Figure 5. Electric Water Heater Energy Use vs. Occupancy



Upon conducting a similar analysis for gas water heaters, an identical problem is encountered. The results of a regression give a much larger standby loss than would be expected, while under estimating the expected per person energy use. Due to the physical construction of a gas water heater, standby losses are expected to be higher than electric units. The factors which make the gas water heater use more energy in standby also make estimating their standby loss more difficult, so a constrained fit was not done. Accordingly, no equation is given but Figure 6 shows energy use and occupant relationship. Ultimately, more sites with a wider spread of occupants are needed to develop a useful fit.

Figure 6: Gas Water Heater Energy Use vs. Occupancy

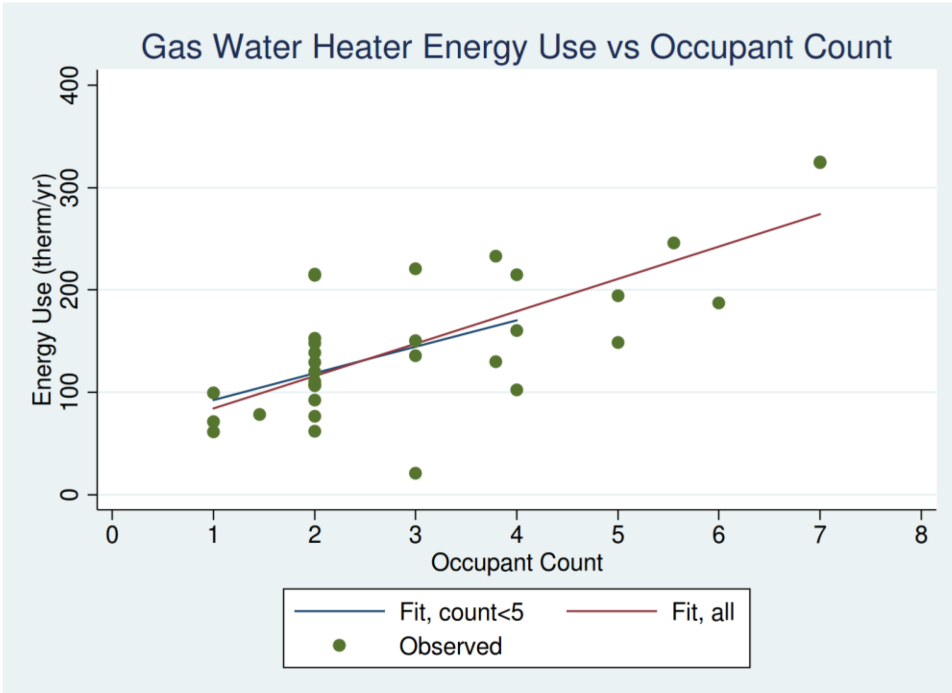


Table 35 and Table 36 present the average amount of energy used for a given number of occupants. For clarity, houses where people moved in or out in the middle of the year, and thus had a non-integer occupancy count, were excluded from these tables (but not from previous graphs or other summaries in this section). Table 35 agrees with results of a recent water heater metering study in the Northwest that measured energy use of 93 electric tank water heaters (Baylon et al., May 2012).

Table 35. Electric DHW Use by Occupant Total

Occupant Count	Electric Water Heater Energy Use (kWh/yr)		
	Mean	EB	n
1	1,848	203	10
2	2,989	256	22
3	3,313	454	5
4	4,508	835	4
6	4,344	0	1
8	5,344	1,169	2
Total	3,043	212	44

Table 36. Gas DHW Use by Occupant Total

Occupant Count	Gas Water Heater Energy Use (therm/yr)		
	Mean	EB	n
1	77	11	3
2	127	12	14
3	132	41	4
4	159	32	3
5	171	23	2
6	187	0	1
7	325	0	2
Total	145	13	29

Average household size in Roos and Baylon (1993) was about 3.0 occupants, and average household size in RBSA Metering for the analyzed electric tanks is 2.2 occupants. By comparing the slopes in Equation 1 and Equation 3 as shown in Figure 5, we can see that DHW energy use has decreased approximately 10% in two decades.

3.2.3. Seasonal DHW Energy Use

In addition to occupant water usage and standby losses, a significant driver of water heating energy is the temperature of incoming water. That temperature depends on the fresh water source and ground temperature. Houses with deep wells tend to experience the stable incoming water temperatures of the deep ground. Houses connected to a municipal system have more varied temperature throughout the season as the ground temperature varies. Shallow ground temperatures are linked to air temperatures.

Figure 7 and Figure 8 plot the daily average energy use across all sites for electric and gas DHW tanks, respectively. The graphs show a trigonometric model fit to the data placing maximum energy use in late January and minimum use in late August. The maximum occurs one month after the winter solstice, and the minimum occurs two months after the summer solstice. The pattern is the same for both gas and electric water tanks. One would initially expect the extremes to be equidistant from the solstices if the driver was purely sensitive to temperature. The finding that the summer minimum is delayed an additional month over the winter maximum suggests the possibility of annually asymmetric city or well water supply temperature or some additional behavioral component to the seasonal shape, implying relatively less water use in August than July.

Ecotope conducted the fit with five terms: a constant, sine, cosine, sine-squared, and cosine-squared functions. The results are shown at the bottom of Figure 7 and Figure 8, respectively. The first fit was attempted with a constant term, sine, and cosine function, but due to the asymmetric nature of the data, the fit was poor. The fit with sine and cosine terms is plotted in green on the graphs for comparison purposes. It was necessary to use more terms in order to reflect the asymmetric extremes. In both the electric and gas cases, the full model fit demonstrates that the summer minimum is delayed and the winter maximum comes sooner than one would expect out of the simpler model. The fits show that the average daily electric use across the year is 8.30 kilowatt hours per day (kWh/day) per site and average daily gas use is 0.41 therms per day (therm/day) per site. Further, the fits reveal the seasonal variation to be ±1.64 kWh/day (±20%) about the mean for electric and ±0.11 therm/day (±27%) for gas.

Figure 7. Seasonal Electric DHW Usage

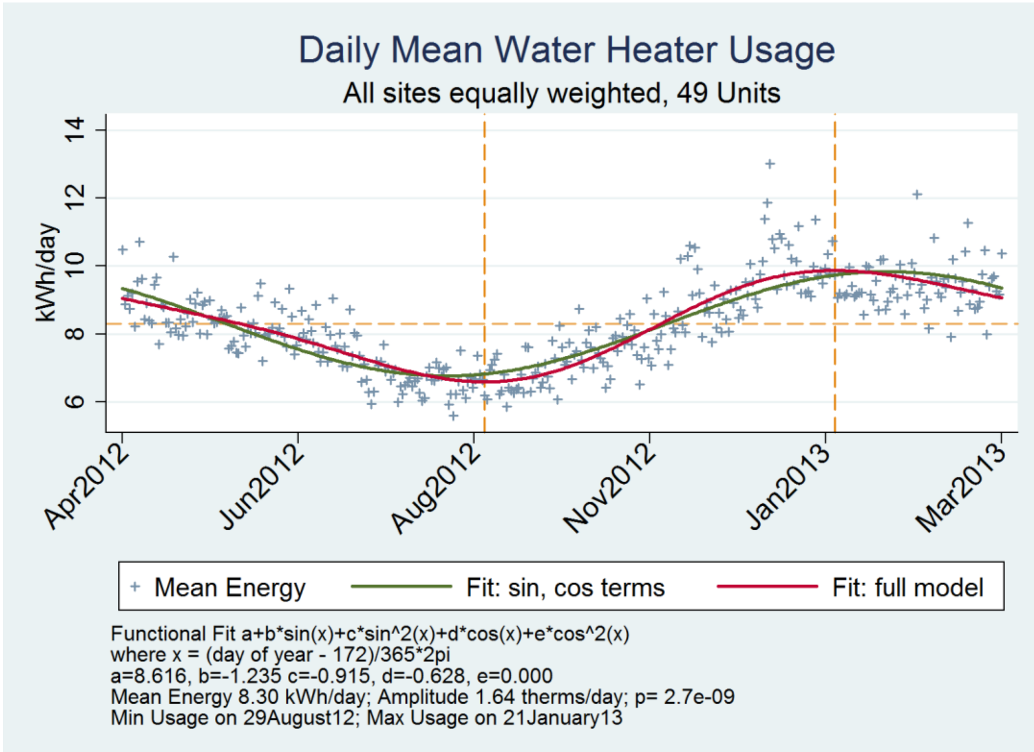
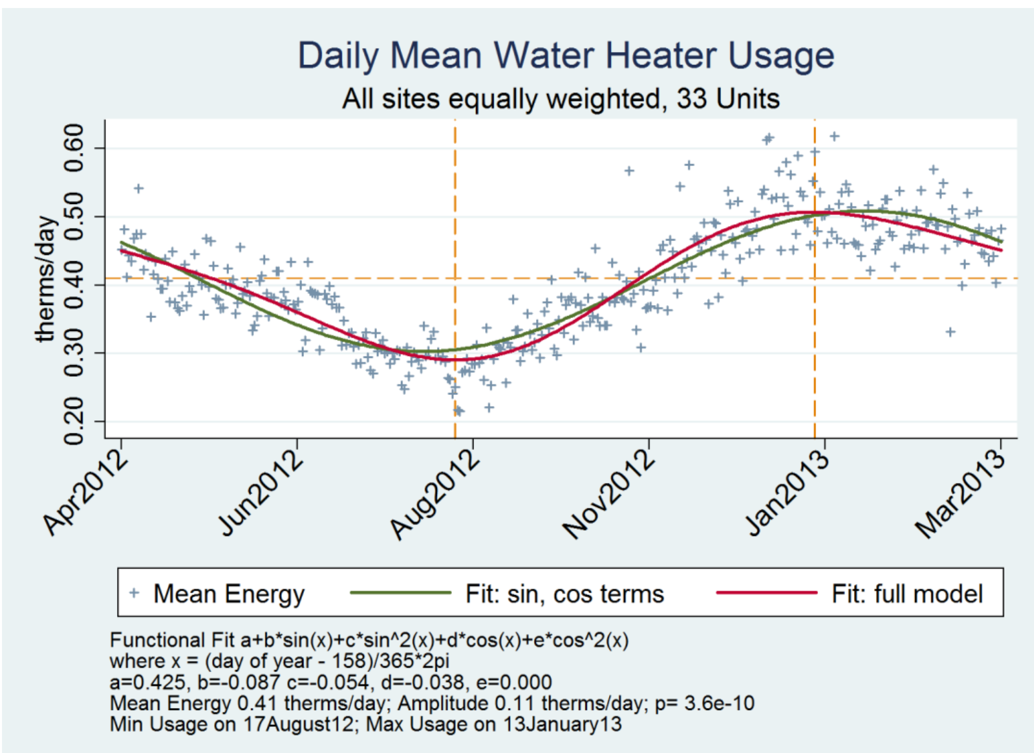


Figure 8. Seasonal Gas DHW Usage



3.2.4. Daily DHW Energy Use

In addition to varying with season, DHW use varies within a single day. The timing of the energy use is an important load for both electric and gas utilities, especially in the heating season. Typically, the biggest hot water uses in a house consist of showers, which occur most often in the morning. This leads the tanks to heat new, incoming cold water. Winter mornings are often the coldest part of the year, requiring the largest space heating load. When space and water heating loads overlap, they combine to create large peak power demands.

Figure 9 and Figure 10 show the electric tank hourly average load for both weekdays and weekends. The graphs plot each site individually plus the average across all sites. The individual site plots illustrate the enormous variation in hot water use patterns. Nonetheless, when aggregated across a large number of sites, the energy demand can be predicted by the average line. The weekday graph shows multiple sites with large morning peaks; presumably the result of showers. The weekend graph shows far fewer of these distinct peaks. On the weekends, the peak is delayed with the overall usage sustained slightly higher for a longer. The appliance load shapes in section 3.3 demonstrate more clothes washing is done on the weekends, which can easily lead to the behavior seen in Figure 10. The load shapes for water heaters, on weekly scales, monthly scales, and for gas DHW tanks are presented in Appendix 8. The daily load shape for gas tank water heaters is similar to electric tanks except the peak is higher and the valley lower. Essentially, the gas water heaters have a higher output capacity so heat the tank faster and shut off more quickly than electric tanks.

Figure 9. Weekday Electric Water Heater Load Shape

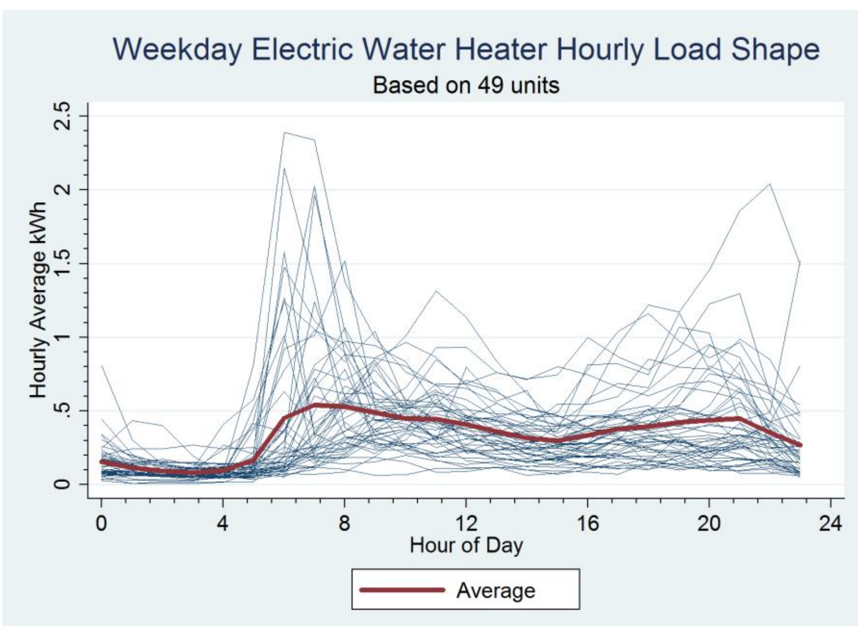


Figure 10. Weekend Electric Water Heater Load Shape

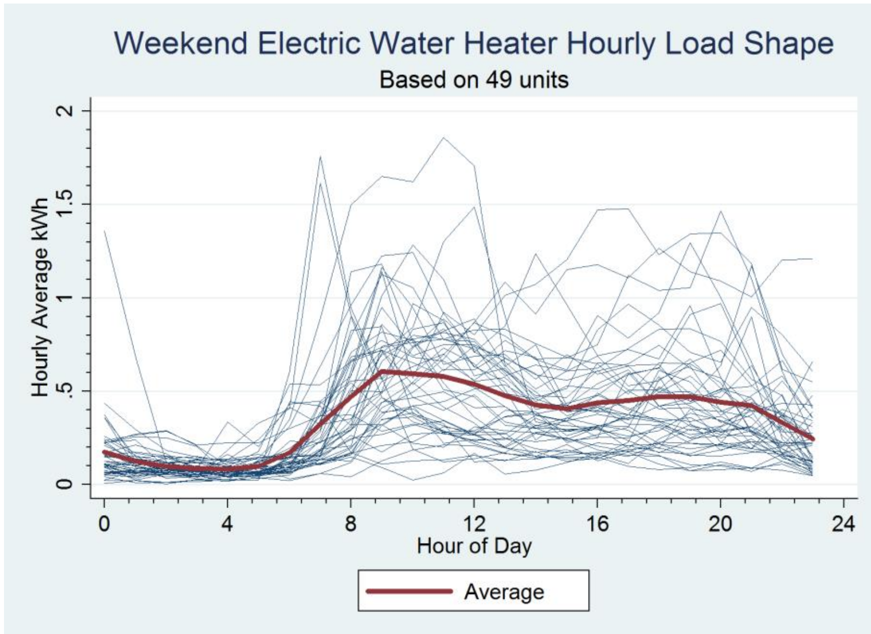
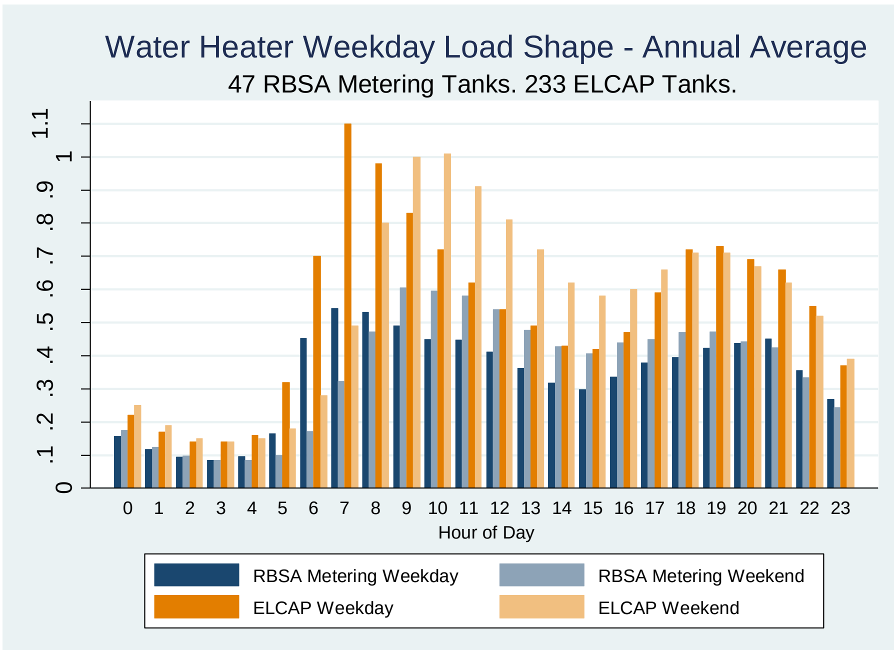


Figure 11 compares the observed hourly load shapes for both weekdays and weekends from RBSA Metering to the ELCAP study from 25 years ago (Pratt et al.,1990). ELCAP observed only electric tanks, so no comparable graph is available for gas water tanks. There are two notable changes between the older and current data. First, the ELCAP study shows a much higher energy use. Second, the shape of the use is different, with RBSA Metering data showing less of a difference between the peaks and a smaller relative decline in load in the evening. The data are presented per site and not normalized by occupant count because the number of people per site is not known for the ELCAP study. Most likely, the occupant count is higher which explains some of the difference in energy use. Since the ELCAP study, federal standards have been implemented for shower head flow rates, clothes washers, and dishwashers. All of those would significantly lower the hot water draw leading to lower energy use.

Figure 11. Electric Water Heater Load Shape Comparison



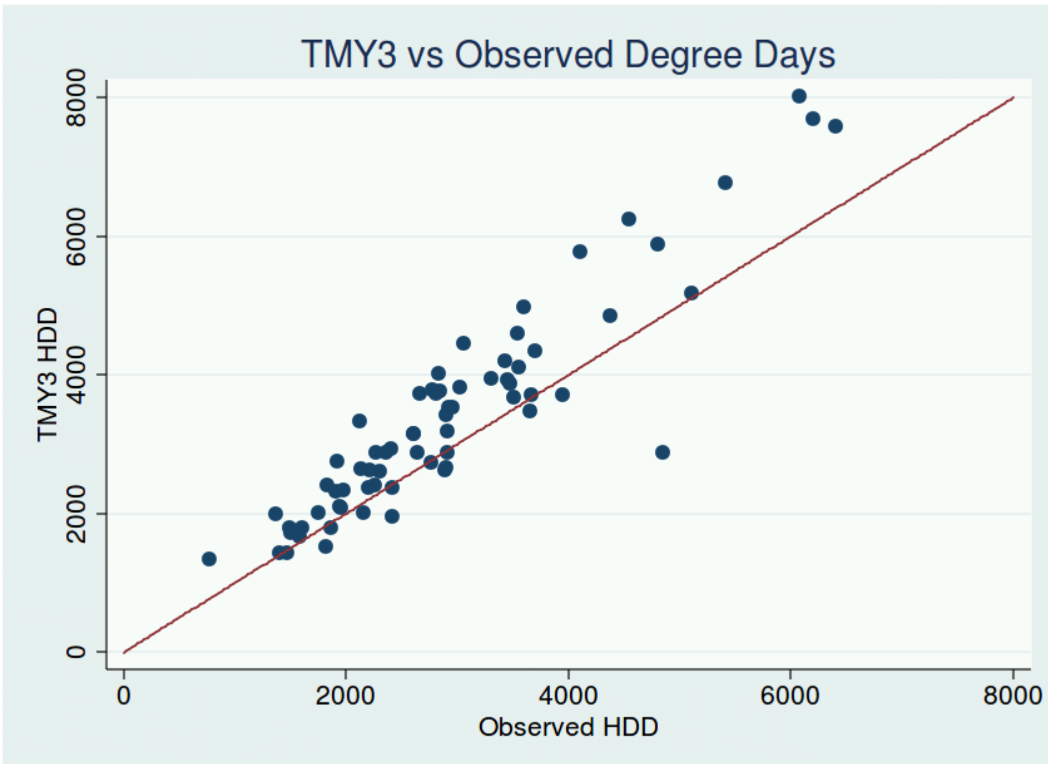
3.3. Heating and Cooling

3.3.1. Weather Comparison

The TMY3-normalized energy use is valuable for comparing results across the region and for planning purposes. However, limitations discussed earlier prevent generalized comparisons and analysis for sub-daily timescales. In the case of the degree-day analysis, the largest limitation in working with the non-normalized results is whether conditions for the metering period roughly match the typical weather. Figure 12 below compares the metered degree-days with the TMY3 degree-days. The red line is the unity line, where the metered and TMY3 values are equal. If the metered period weather matched the typical weather, the points would fall along the red line, but most points fall above the line, meaning the metering period was warmer than a typical year.

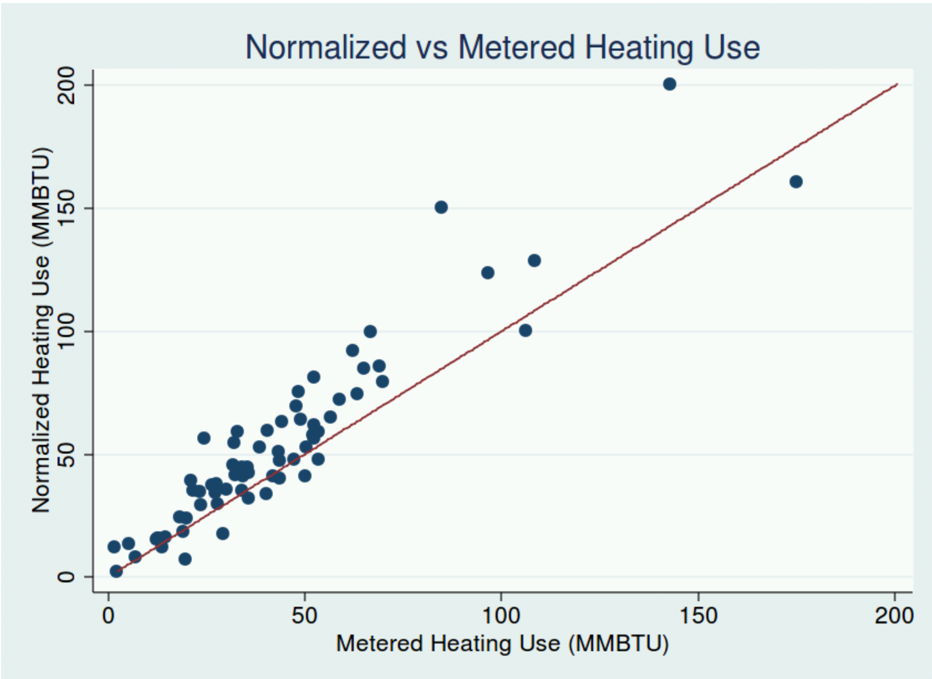
Thus when the non-normalized results are presented later, we can assume energy use would typically be lower than any of the normalized results for heating. The degree day base for the following figures is site-specific based on the variable degree day analysis. For a given site, the degree day base is constant between the observed and TMY3 calculations.

Figure 12. Comparison of Metered HDD and TMY3 HDD



A similar plot showing the metered energy use and TMY3-normalized energy use can be used to show the same trend. Figure 13 shows the heating energy use is mostly above the red unity line, indicating houses used less heating energy during the metering period than expected during a typical year. An example is to look at houses with a metered heating energy use of 50 MMBtu (MMBtu= 10^6 Btu) and then move vertically on the graph to view those points fall roughly between 50 and 70 for TMY3 heating energy use.

Figure 13. Comparison of Metered Energy Use and TMY3 Normalized Energy Use



3.3.2. Heating Systems Metered

Heating systems in RBSA Metering included baseboard (zonal electric resistance), a gas boiler, ductless heat pumps, electric forced air furnaces, gas forced air furnaces, a gas heating stove, and heat pumps. Table 11 and Table 12 in the methods section above show a count of primary system types by climate zone. Gas furnaces dominate the sample. The two tables below show the heating energy use by system type as well as a count by system type of the usable metered sites. Table 37 shows the TMY3 EUI (kBtu/sqft/yr) for each of the major system types.

Table 37. TMY3 EUI (kBtu/sqft-yr) by Heating System Type

Heating	TMY3 EUI by Heating System Type		
	Mean	EB	n
Baseboard	17.74	3.33	6
DHP	1.68	0	1
Electric FAF	23.37	4.12	7
Gas FAF	29.41	2.31	43
Heat Pump	10.55	1.94	10

For comparison, Table 38 shows the non-normalized results based directly on the metering data.

Table 38. Metered EUI (kBtu/sqft-yr) by Heating System Type

Heating	Metered EUI by Heating System Type		
	Mean	EB	n
Baseboard	12.53	2.78	6
DHP	1.52	0	1
Electric FAF	20.22	2.50	7
Gas FAF	23.95	2.01	43
Heat Pump	8.92	1.66	10

Details for the most common systems are given in the following subsections.

3.3.2.1. Gas Forced Air Furnace

Natural gas forced-air furnaces are the largest group of heating systems in RBSA Metering. Forty-three systems provided viable data that could be weather-normalized for inclusion in the study. Usage for these systems was measured using a combination of directly measuring gas valve on time and furnace firing rate (measured in the field when metering gear was installed and done for both furnace stages, where applicable). Combustion efficiency and flue gases were also evaluated to find systems that might need maintenance.

As Table 39 indicates, we see an expected increase in the energy use intensity for gas furnaces in colder climate zones (Heating Climate Zones 2 and 3) versus what we see in Heating Climate Zone 1. There are only nine sites in Zones 2 and 3, but the expected relationship is still present, with the EUI increasing from 28kBtu/sqft-yr to 34kBtu/sqft-yr. Table 40 also shows an expected decrease in energy usage as gas furnaces become more efficient as indicated by the annual fuel utilization (AFUE) category.[11] Non-condensing furnaces used about 30.5kBtu/sqft/yr and the

[11] A direct measure of gas furnace efficiency, an AFUE of 80% means 80% of the energy in the gas becomes heat for the house while 20% escapes up the chimney. Furnaces with an AFUE of 90% and above generally condense water vapor out of the exhaust to claim its heat (a so-called “condensing” furnace). Furnaces with AFUE ratings below 90% are typically the “non-condensing” variety.

more efficient furnaces used about 15% less on average. The error bounds overlap between the two groups, making broad generalizations tenuous, but this is mostly an artifact of the wide variation in use between specific sites (see Figure 15 below). We expect the difference in usage by furnace efficiency category would remain in a larger set of sites.

Table 39. Weather Normalized EUI (kBtu/sqft-yr) for Gas Forced Air Furnaces by Heating Zone

Heating Zone	TMY3 EUI for Gas Forced Air Furnaces		
	Mean	EB	n
Heating Zone 1	28.14	2.62	34
Heating Zones 2 and 3	34.24	4.88	9
Total	29.41	2.31	43

Table 40. Weather Normalized EUI (kBtu/sqft-yr) for Gas Forced Air Furnaces by AFUE

AFUE	TMY3 EUI for Gas Forced Air Furnaces		
	Mean	EB	n
Less than 90%	30.45	2.69	32
90% and Greater	26.39	4.64	11
Total	29.41	2.31	43

Next, we turn to load shapes for gas forced-air furnaces. Figure 14 shows the monthly load shape with the expected peak in January and December (just under 4 therms per day). As the heating season wanes, average gas usage drops. There are still mornings in July and August that have temperatures below the HDD base, so the usage is not quite zero (we also see in the metered usage homeowners turning on their furnace during some summer mornings). Figure 15 shows the monthly usage site-by-site. The red line shows the average for all the sites but as the blue lines show, there is quite a bit of variation at individual sites, both in terms of the absolute magnitude of therms per day usage and also in the shape of the usage.

Figure 14. Monthly Load Shape for Gas Forced Air Furnace

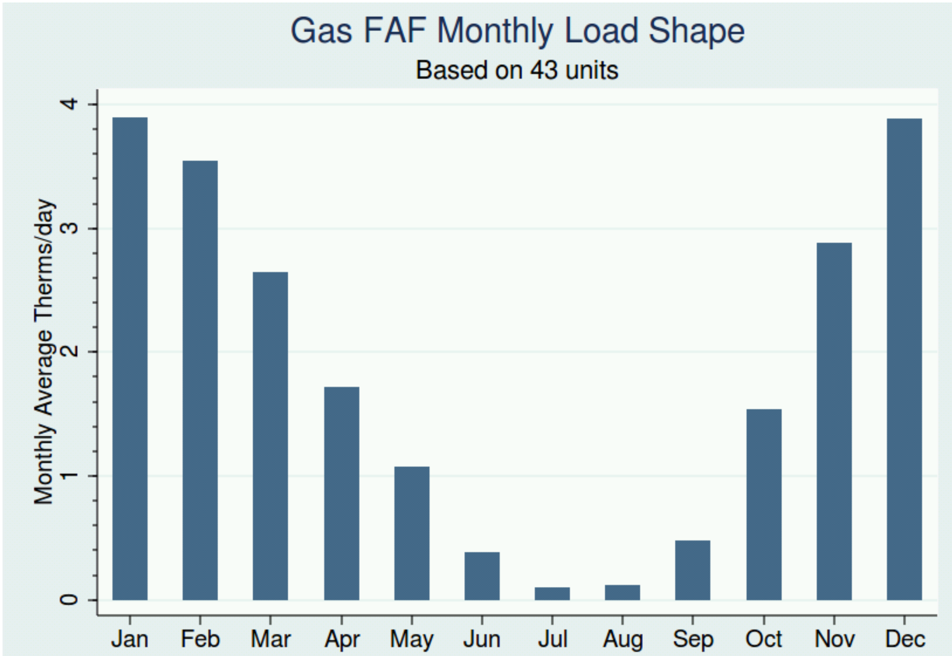


Figure 15. Monthly Load Shape for Gas Forced Air Furnace by Site

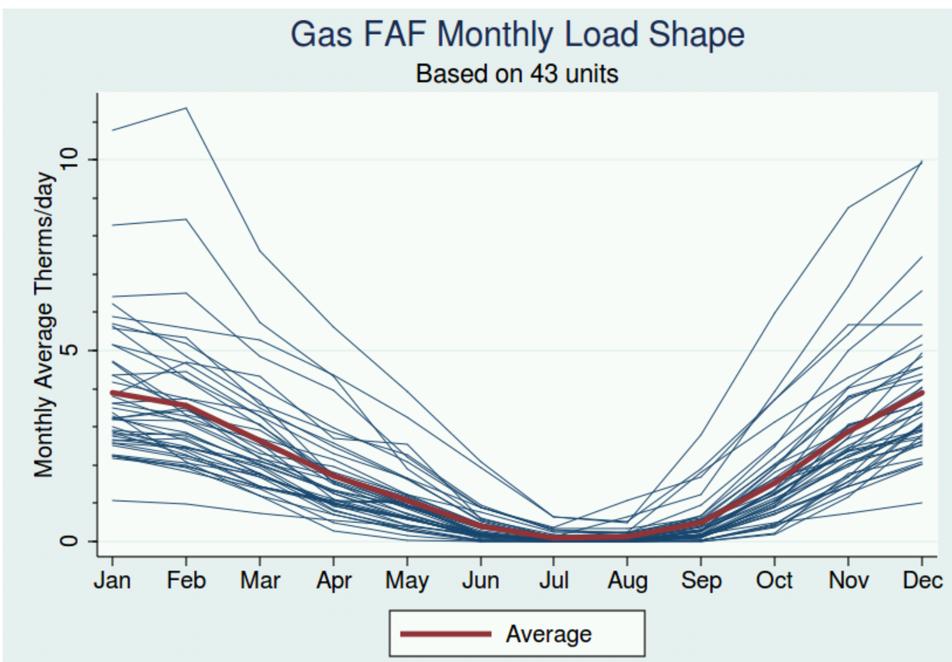


Figure 16 shows the data which are probably the most useful in terms of load shapes. The graph is an *hourly* load shape during the month of January 2013, with the hour of day along the horizontal axis and the usage plotted along the vertical axis. Overnight, starting at the left with zero equaling midnight, there is some system usage, especially at sites where it is either quite cold or the owner did not use any setback or a small setback. But then, as dawn approaches, the usage starts to increase and peaks at about 7:00 a.m. Leading up to that peak, we see the effects of morning warm-up as either people manually adjust thermostats or the automatic programming of the thermostat brings the furnace on in advance of the peak to bring the house up to temperature. Then the usage decreases. People tend to use the setback feature if they go off to work. The usage is relatively flat through late morning into late afternoon; we see a much smaller peak at around 6:00 p.m. after which usage tails off gradually into the nighttime sleeping hours.

Figure 16. Metered Monthly Load Shape for Gas Forced Air Furnace During January 2013

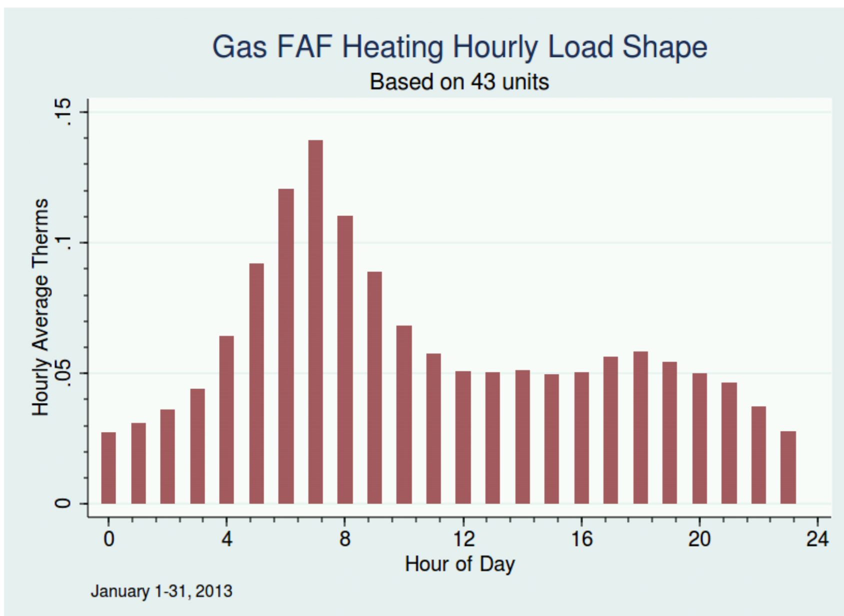
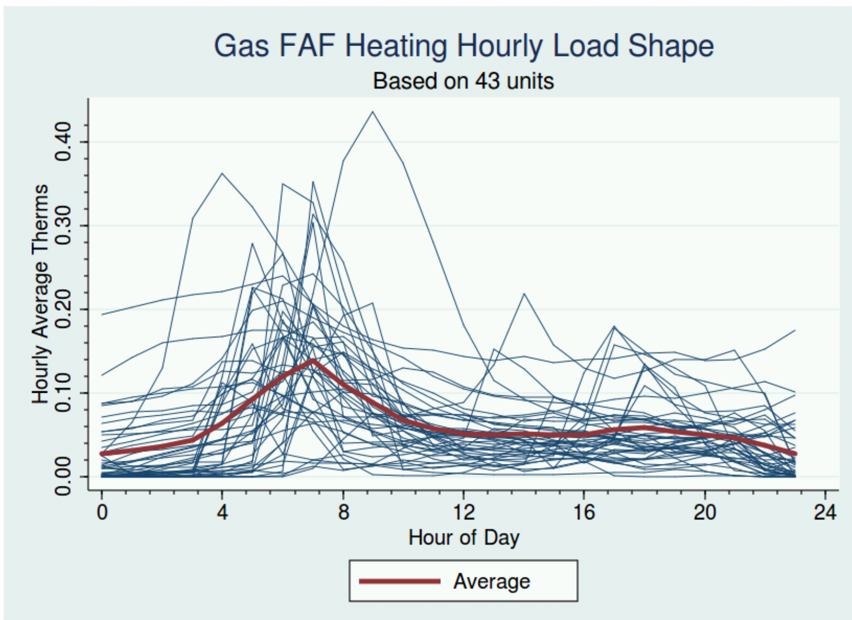


Figure 17 is analogous to the monthly load shape for each site graphic that was shown above and shows all the hourly load shapes for the 43 sites for the month of January 2013. Here, because of the more granular data, we see quite a bit more skew, at least in terms of the morning peak. There are some large peaks; for example, 4:00 a.m. at one site and 9:00 a.m. at another. Also, it appears at least in one household that people were home during the day and there was a relatively high peak about 3:00 in the afternoon. This sort of graphic shows the value of smoothing, that is, averaging the hourly load shapes, to get an average profile, but also indicates that there are cases where there is considerable variance from that average pattern.

Figure 17. Metered Monthly Load Shape for Gas Forced Air Furnace During January 2013 by Site



3.3.2.2. Heat Pumps

The heat pump analysis was divided into two parts. The first part focuses on the seasonal relationship between electricity usage and outdoor temperature – the attempt here being to express consumption as a function of outdoor temperatures so that the results can be more easily generalized. The second part of the analysis is to provide measures of central tendency where possible for heat pumps. The latter presentation is complicated by a number of factors, including multiple heat sources at heat pump houses, problems with data at sites in some cases, and the use of non-electric space heat in some heat pump houses.

The main focus in analyzing heat pump metered results is heating season electricity usage. Along the Interstate 5 corridor, annual cooling usage is generally well under 500 kilowatt hours. In parts of Cooling Climate Zones 2 and 3, annual cooling loads might be as high as 1500 kilowatt hours or even slightly higher, but they are still only a small fraction of the total annual space conditioning usage.

Each site was analyzed to determine if there was a well-defined relationship between heating electricity usage and outdoor temperature. At ten of the air source heat pump sites the relationship was strong, but for the other eleven sites, there were a variety of problems which complicated the analysis (Table 41).

Table 41. Heat Pump Site Attrition for VBDD Analysis Inclusion

Reason for exclusion (22 possible ducted heat pumps at start)	Number
Deferred maintenance/system malfunction[1]	5
Multiple non-metered non-electric heating sources[2]	1
Erratic system control	1
Homeowner rarely used HP for heating[3]	1
Partial heating season	2
Other data problem	2

[1]Two cases had no compressor usage; the system behaved as an electric forced-air furnace

[2]Two gas fireplaces

[3]Dual fuel heat pump site; gas furnace accounted for over 90% of heating usage

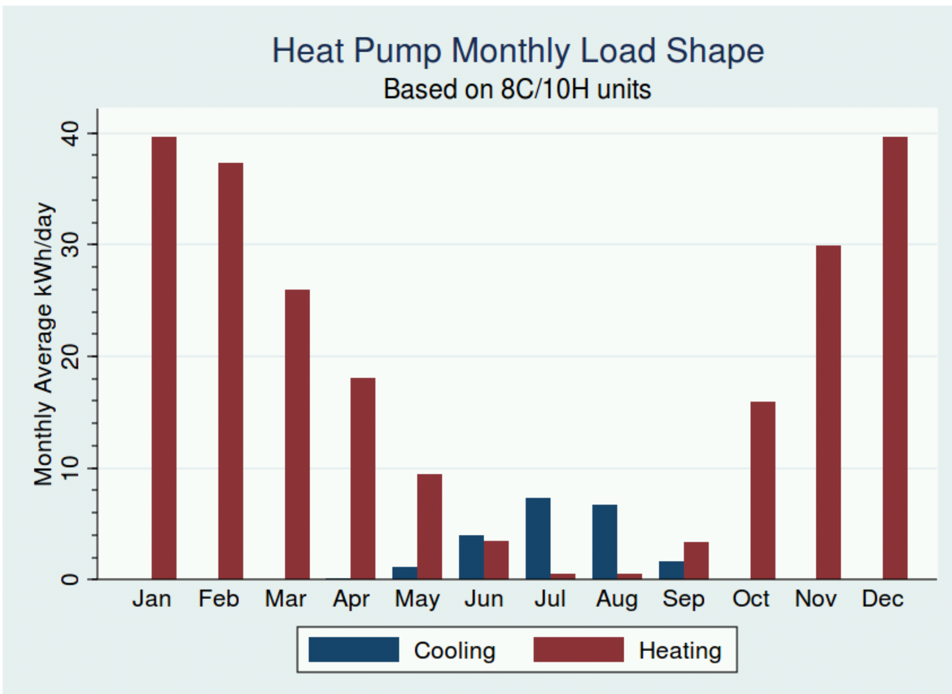
Because there are only limited cases in this final set, the findings focus on notable issues such as control settings, occupant operating decisions, and electric resistance lockout controls. Most of this section will concern standard air source heat pumps with electric resistance backup coils in the indoor unit. Graphics and discussion for the two dual fuel systems, (natural gas furnace in indoor unit), ground source and one of the ductless heat pump systems are provided in Appendix 6.

3.3.2.2.1. General Heat Pump Energy Use Findings

Table 37 shows the normal weather EUI for heat pumps as 10.55 ± 1.94 kBtu/sqft-yr. With only a small number of sites, any further breakdown by climate zone or equipment efficiency would be subject to large uncertainty, but we can review the load shapes before getting into more details about the heat pumps.

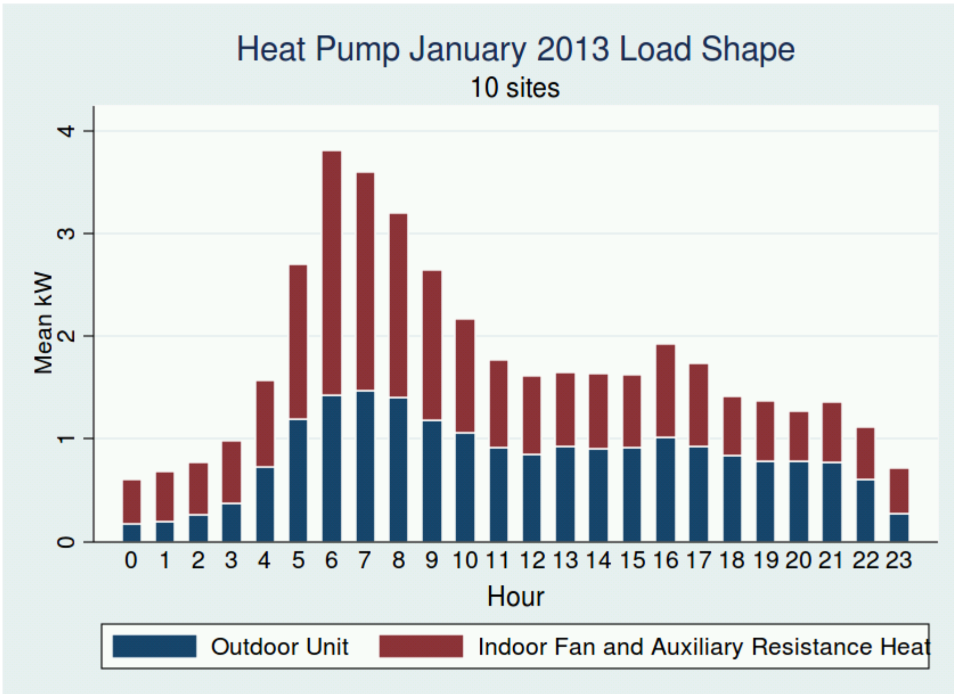
Since heat pumps perform both heating and cooling functions, it makes most sense to review the shapes together. The combination will show the relative contribution of heating versus cooling to the overall space conditioning energy use. Figure 18 is a monthly combined load shape for ASHPs including the electric resistance elements that can supplement the heat pump compressor during colder weather. Cooling loads account for a small portion of the load compared to heating. The variation between sites for heat pumps looks similar to the variation for gas furnaces, so the line graph for heat pumps is omitted here.

Figure 18. Monthly Air Source Heat Pump Load Shape



In Figure 18, the heating includes all of the components of the heat pump – compressor, fan, and auxiliary heat. Figure 19 shows the pooled load shape for January 2013. During the morning warm-up period (4-8 am), overall usage peaks. Some sites use setback thermostats; the coldest temperatures are typically in this time interval as well, since the sun has been below the horizon the longest. Depending on the length of the setback, the house heating load, and the heat pump's nominal capacity, different combinations of compressor and electric resistance heat will be used to meet the house heating load.

Figure 19. January 2013 Heat Pump Load Shape

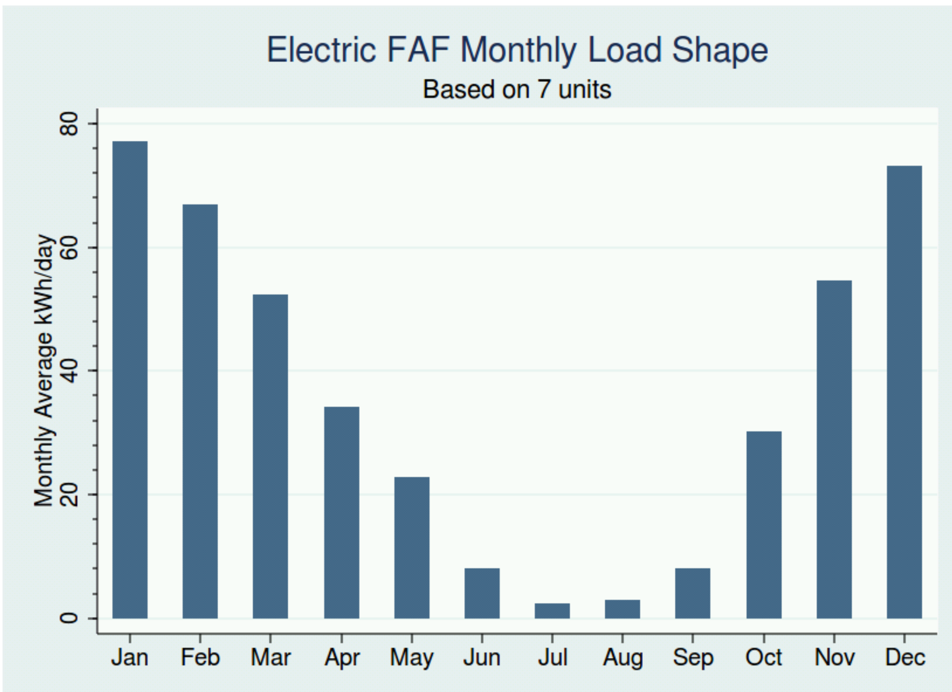


A detailed discussion of air source heat pump sizing, controls and case studies is available in Appendix 6. Case studies of ground source heat pumps, dual fuel heat pumps, and ductless heat pumps are also in the same appendix.

3.3.2.3. Electric Forced Air Furnace

There are only seven electric forced-air furnaces in the RBSAM dataset, so a breakdown by heating zone is not prudent. The average usage from Table 37 is 23.37 ± 4.12 kBtu/sqft-yr. Electric forced-air furnaces follow a similar pattern to gas furnaces, as far as the peak usage by month, shown in Figure 20. The scale for electric forced air furnaces is in kilowatt hours per day versus therms per day for gas forced air furnaces.

Figure 20. Monthly Load Shape for Electric Forced Air Furnace



The monthly load shapes in Figure 21 are relatively homogeneous. This is not so surprising by month, although there is one site with less usage versus the other sites and shows up below the rest of the group. The hourly load shape in Figure 22 is similar to the gas forced-air sites, with the peak near 7:00 a.m. during the morning warm-up period. We also notice a similar amount of reduction during the sleeping hours, indicating a likely use of a central thermostat set back. This will be contrasted later with the pattern in zonal electric heat.

Figure 21. Monthly Load Shape for Electric Forced Air Furnace by Site

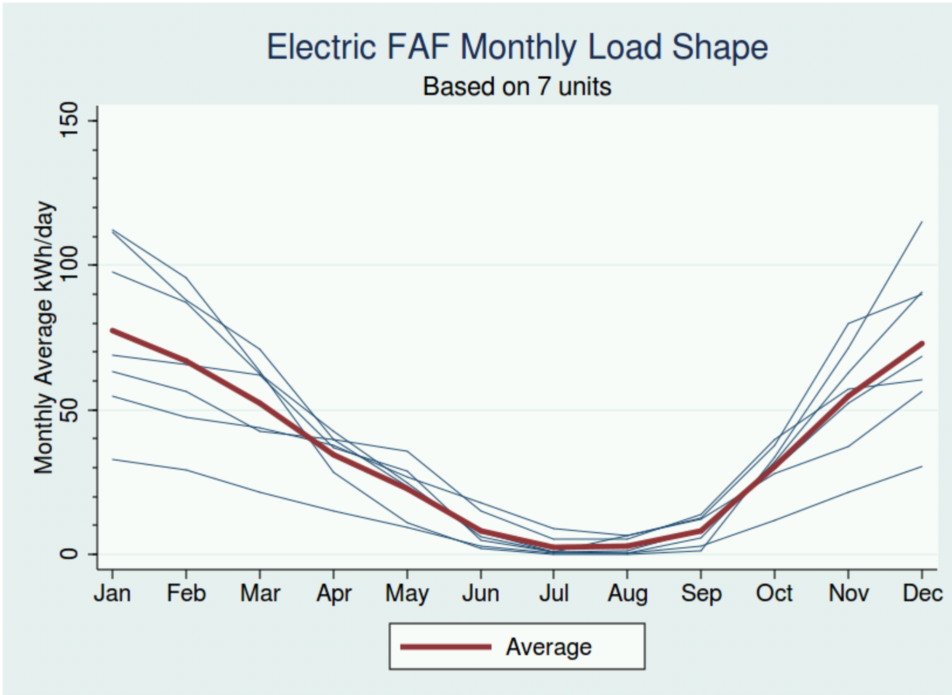
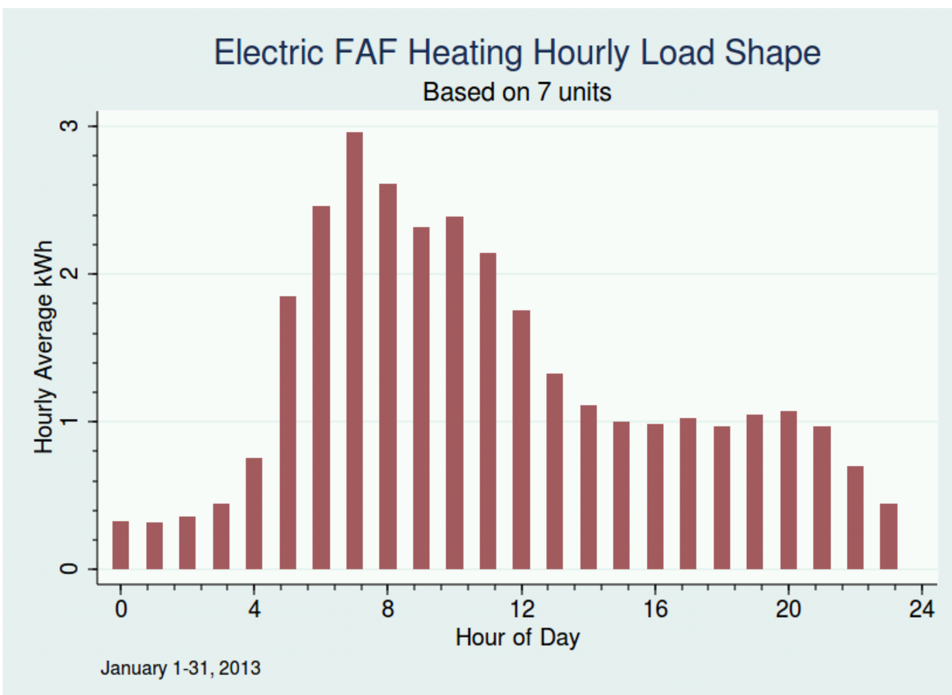
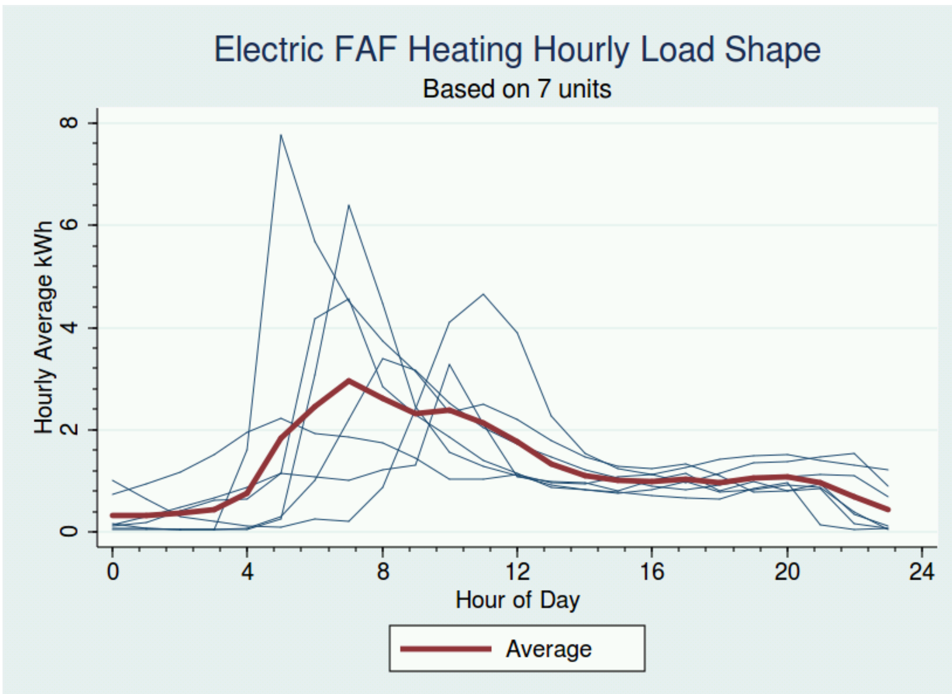


Figure 22. Metered Hourly Load Shape for Electric Forced Air Furnace During January 2013



The final graphic, Figure 23, shows the individual hourly load shapes versus the average, which is the red line. The average peak is around 7:00 a.m. Even with this small number of sites, we can see variation in the morning peak – one site peaks at 5:00 a.m. while another at 11:00 a.m., indicating likely a stay/work-at-home household versus one that sets the house thermostat back to go to work during the day.

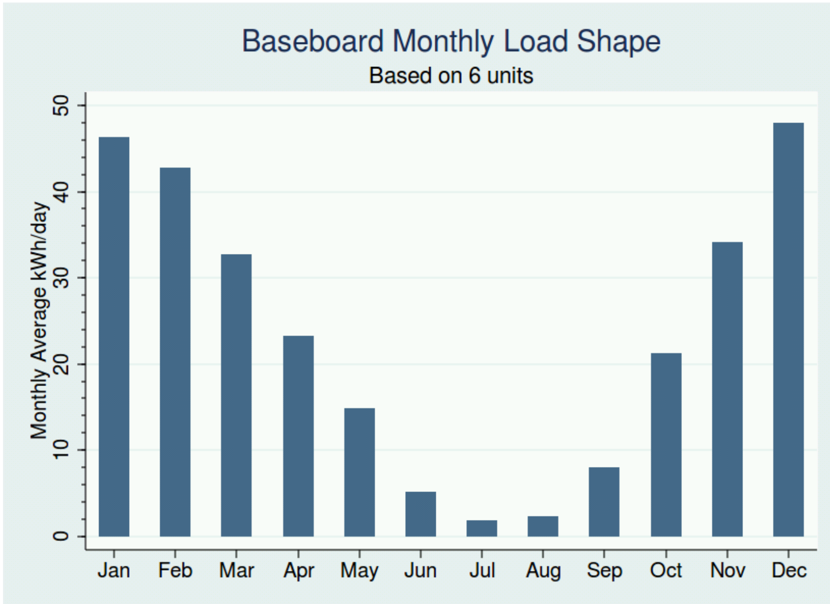
Figure 23. Metered Hourly Load Shape for Electric Forced Air Furnace – January 2013 by Site



3.3.2.4. Zonal Electric Resistance

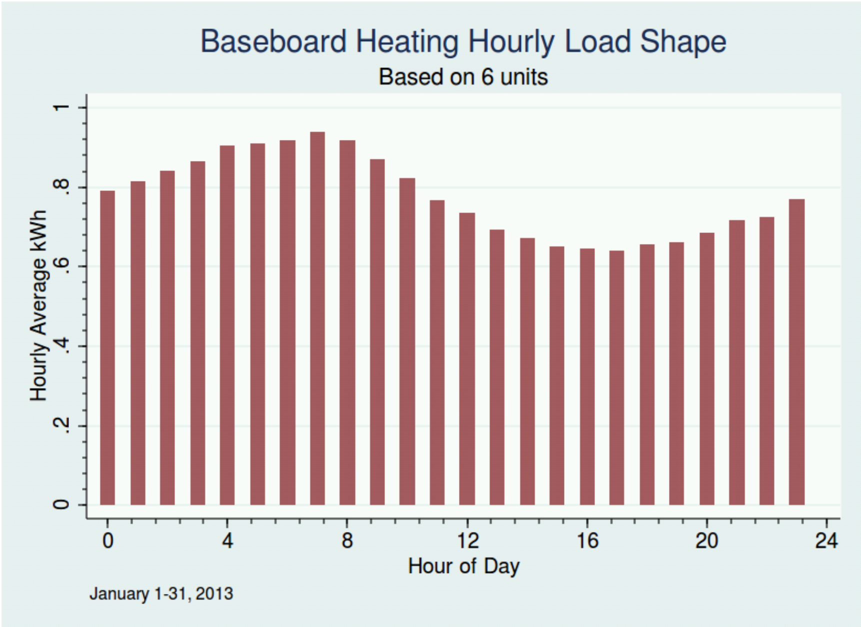
Zonal electric heating is another small category in RBSA Metering. Six sites survived the rigorous data quality control checks which use zonal electric heat as the primary heating system, so it is again difficult to generalize about the summary statistics. The average use from Table 37 is 17.74 ± 3.33 kBtu/sqft-yr. The monthly load shape shown in Figure 24 conforms to what we have seen with the other system types: The maximum usage is in January and December, and there is little usage during summer months.

Figure 24. Monthly Load Shape for Electric Zonal Heat



The load shape graphics by month and by hour show some similarity to central systems. However, since zonal systems do not use central control, there tends to be less overall variation from one part of the day to another, which the hourly load shape in Figure 25 shows. In Figure 25 we still see an overall peak at about 7:00 a.m. but the usage overnight, that is at midnight or 1:00 a.m. or 2:00 a.m., is closer to the peak value, probably because occupants are not turning off heaters in all rooms of the house. Centrally controlled systems are subject to an overnight setback and therefore, on average, show much more range between the highest and lowest use hours.

Figure 25. Metered Hourly Load Shape for Electric Zonal During January 2013



3.3.2.5. Cooling Systems

Analyzing cooling use across the region tends to be less robust because there is much less of a need for cooling than heating. Daily temperatures typically fall both above and below the cooling balance point during most days of the cooling season. Moreover, people use cooling in a discretionary way (not tightly regulated by a thermostat), which means there is a much larger variation in the data for a much smaller magnitude of energy used.

Table 42 shows the cooling energy use normalized by house area (kWh/sqft-yr) by system type. Included in the table is a roll-up of the central systems – Central AC, Heat Pump, and Dual Fuel Heat Pump.

Table 42. Weather Normalized Energy Use (kWh/sqft-yr) by Cooling System Type

Cooling	TMY3 EUI by Heating System Type		
	Mean	EB	n
Central AC	0.3	0.06	12
DHP	0.02	0.02	2
Heat Pump	0.5	0.2	9
Heat Pump Dual Fuel	0.3	0.1	2
PTAC	0.3	0.2	2
Central Systems (AC/HP)	0.4	0.07	23
All Systems	0.3	0.06	28

Central systems, as a group, are the only type with enough systems to create meaningful load shapes and summaries. Figure 26 is the monthly load shape for central systems and Figure 27 show there are three systems that are using much more energy than the rest. All of the high users are in eastern Washington, two of which are in cooling zone 3 and one in cooling zone 2.

Figure 26. Monthly Load Shape for Central Air Conditioning (Air Conditioners and Heat Pumps)

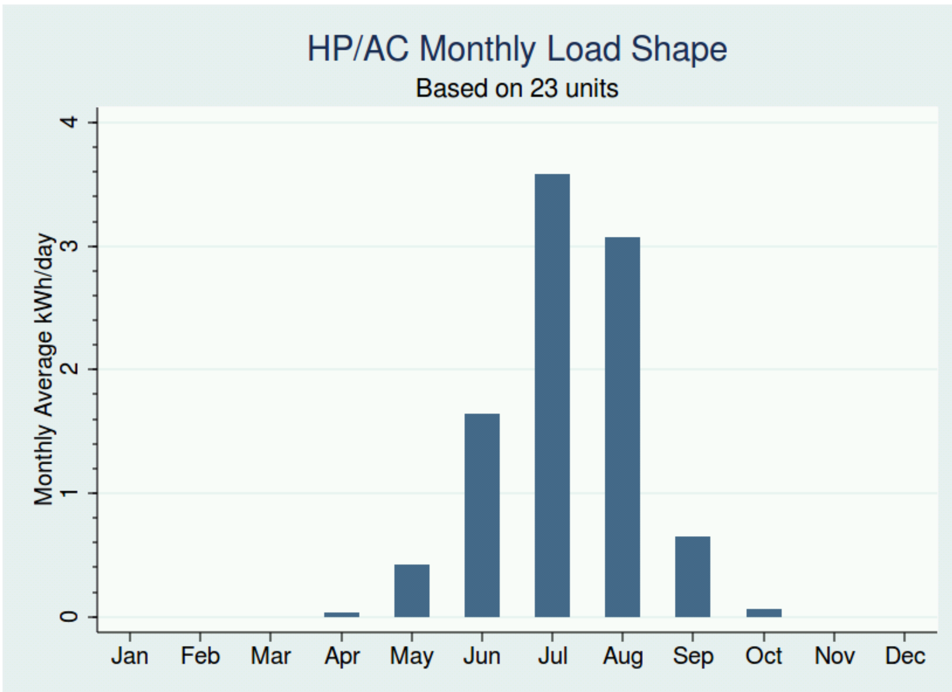
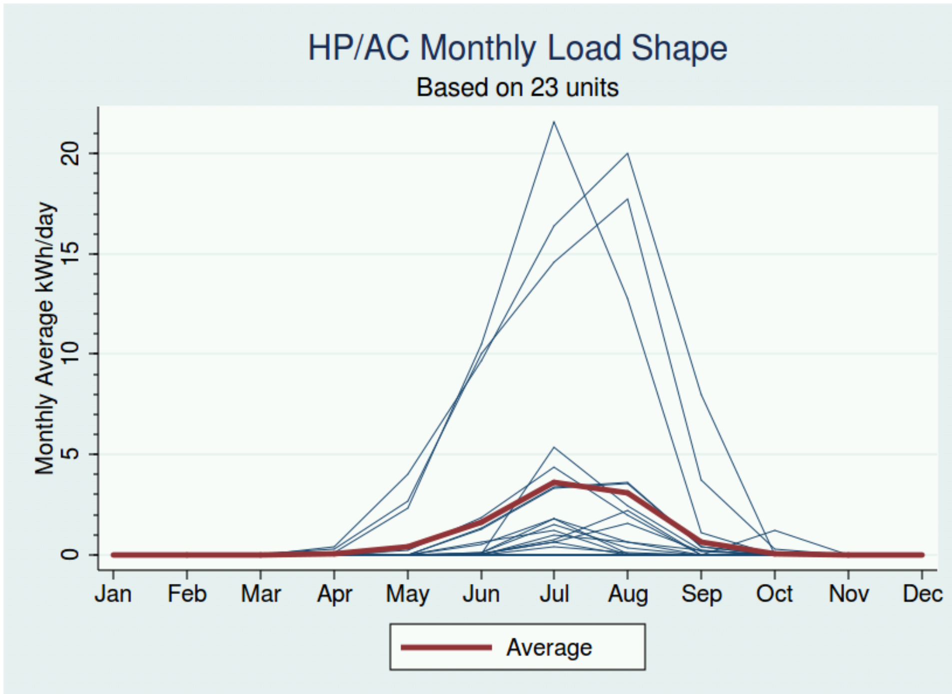


Figure 27. Monthly Load Shape for Central Air Conditioners by Site



The hourly load shape for central cooling in Figure 28 is shifted dramatically from heating because of the opposite nature of the system's primary function. Cooling usage appears to be tied more to the daily temperature swing than to consistent setup thermostat behavior, as indicated by the smooth increase and decrease of the load shape. In contrast, heating systems see large spikes in heating use in the morning and a smaller spike in the afternoon, indicating more programmed thermostatic control. However, there are some sites in Figure 29 that show more dramatic thermostat behavior.

Figure 28. Metered Hourly Load Shape for Central Cooling During July 2012

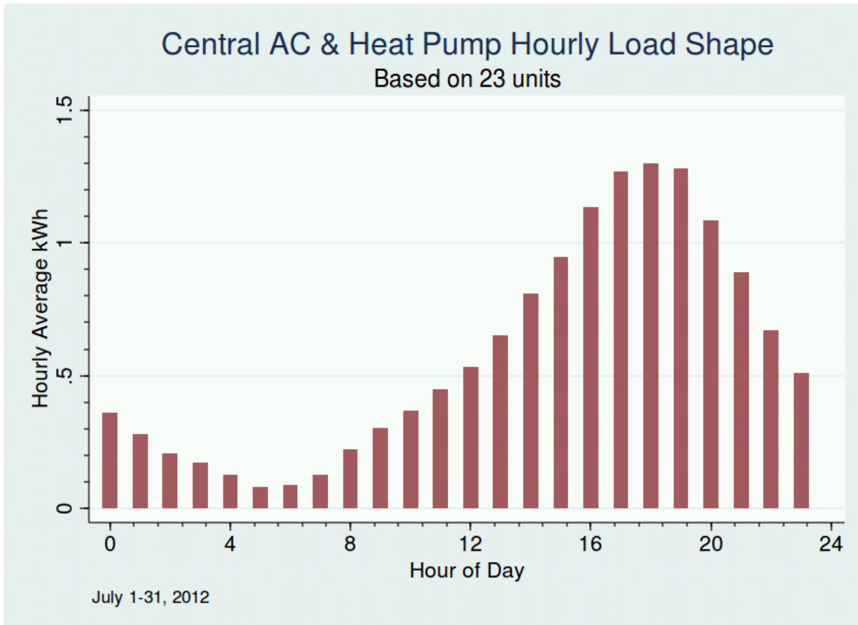
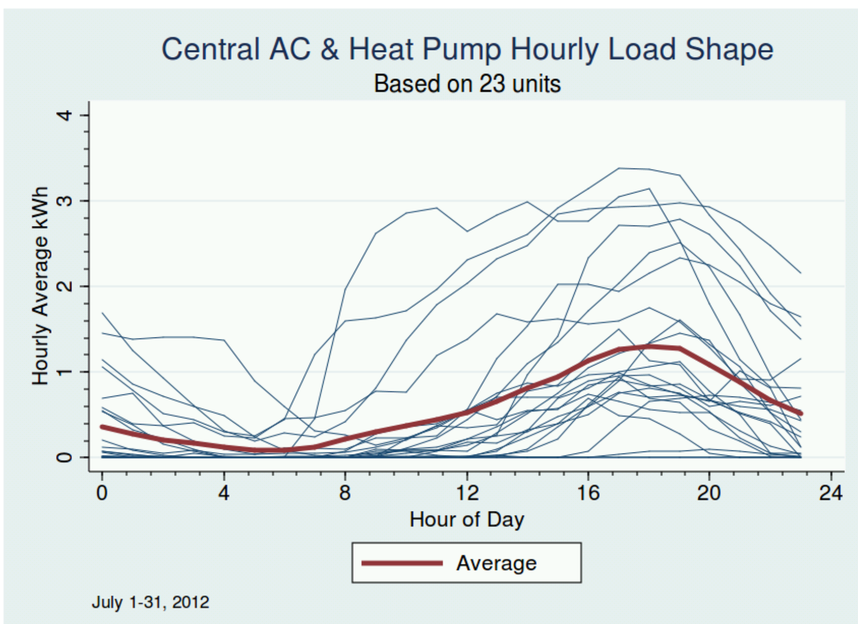


Figure 29. Metered Hourly Load Shape for Central Cooling During July 2012 by Site



3.4. Major Appliances

This section discusses electricity usage patterns of major household appliances (also called "white goods"). Some of these appliances are measured at the electrical panel (when there is a dedicated circuit; these are typically only 240 VAC machines but some run on 120 VAC). Others, installed at 120 volt receptacles throughout the house, are picked up by individual meters at the appliance and a wireless internal network. All of these appliances are important both in terms of their contribution to overall household electricity use and as potential conservation measures. Some of the appliances, such as laundry equipment and refrigerators, are already subject to national level standards. Others, most notably the electric range, offer less conservation potential because of their inherent function. All are important in the characterization of the non-heating/cooling, non-DHW, and non-lighting usage in the home.

For the sites, 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 any additional refrigerators as secondary. The secondary refrigerators were most commonly found in garages. A single house also had a third refrigerator which we included in the "secondary" category.

First, we summarize the overall contributions from these end uses. Table 43 shows a listing of major appliances in terms of annual electricity usage. The appliance that uses the most electricity is the dryer; its usage is well ahead of the energy use of any other appliance. The next biggest contributors are the refrigerators and freezers; after that come electric range, dishwasher, and clothes washer. In addition to reporting annual energy use values, this section describes detailed time of use information in the form of load shapes. The comprehensive list of load shapes is in Appendix 8. All error bounds (EBs) reported in this section are for the 90% confidence level. That is true of the EB in the tables as well as the red lines in the figures showing the range above and below the mean value.

Table 43. Major Appliance Yearly Usage (Averages)

End Use	Annual kWh		
	All Regions Mean	EB	N
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

3.4.1. Refrigerators and Freezers

The classification of primary and secondary refrigerator is of most importance in regard to the ambient temperature surrounding the equipment. Although we can reasonably assume that the ambient temperature in living spaces is similar from house to house, we know that the temperature in secondary locations, such as garages, varies more widely and is annually lower on average than the living space. Consequently, we conduct all the comparisons on primary refrigerators only.

Residential refrigerators and freezers have gone through two major federally mandated efficiency upgrades, one in 1993 and one in 2001. Figure 30 and Table 44 show the expected downward trend in annual energy use. 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 is -13.5 kWh/yr, which suggests that in a 20-year time period, refrigerator energy use has decreased 270 kWh on average.

Other factors influence the annual electricity usage, such as occupant preferences 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. These results also indicate that to the extent older equipment is still being used, there is potential for significant savings through utility-based programs.

Figure 30. Annual Refrigerator Energy Use by Year of Manufacture

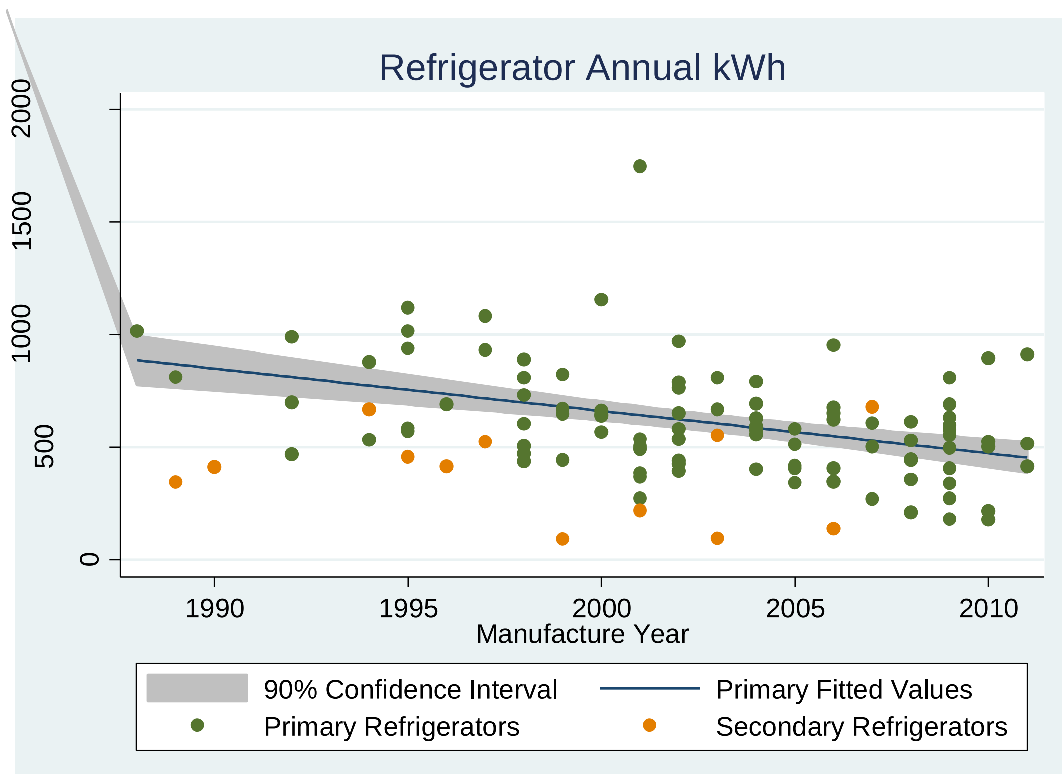


Table 44. Refrigerator Annual Energy Use by Vintage

Manufacture Date Bin	Primary Refrigerator Annual kWh by Vintage		
	Mean	EB	n
Pre 1994	699.4	99.8	8
1995-1999	734.8	49.6	19
2000-2004	636.2	49.4	31
2005-2009	496.7	29.6	33
Post 2009	520.2	95.9	8
Total	604.4	24.8	99

The hourly load shape for refrigerators (Figure 31 and Figure 32) deserves mention. The shape is plotted for all of the refrigerators in the study (whether primary or secondary). 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.

Figure 31. Refrigerator Hourly Load Shape

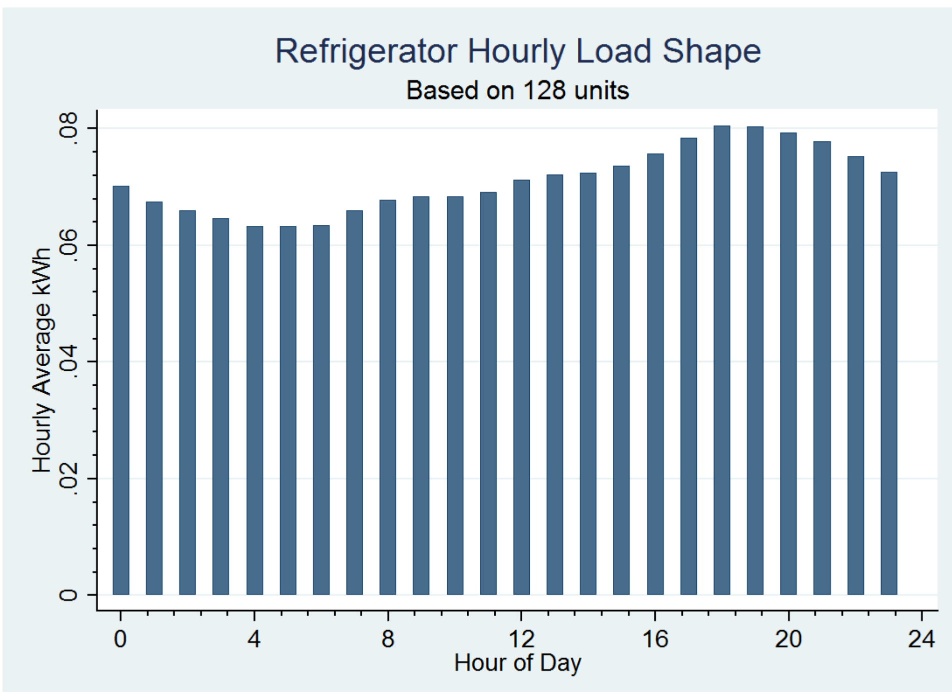
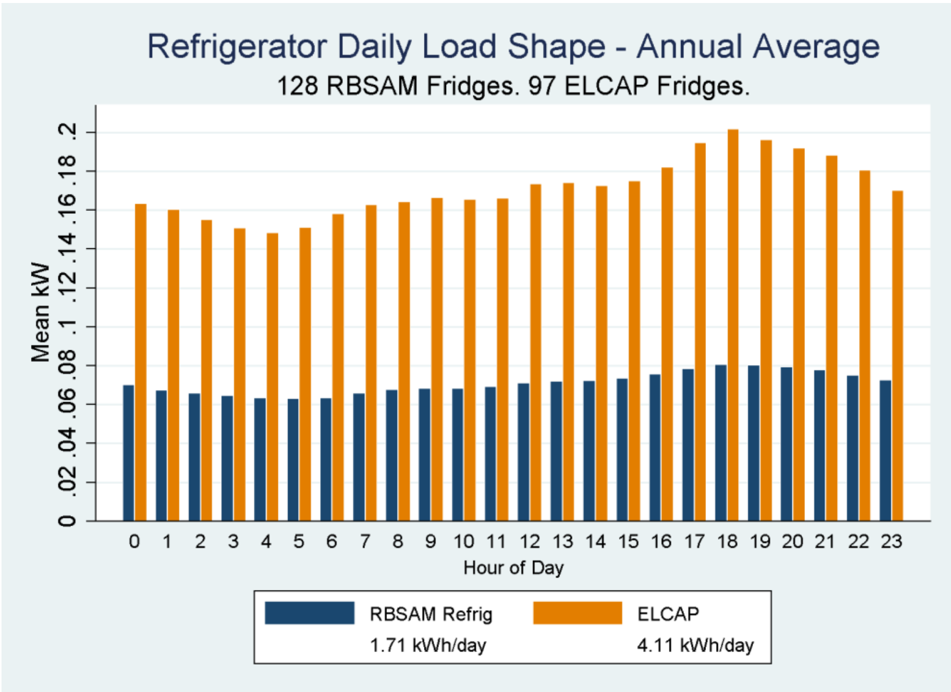


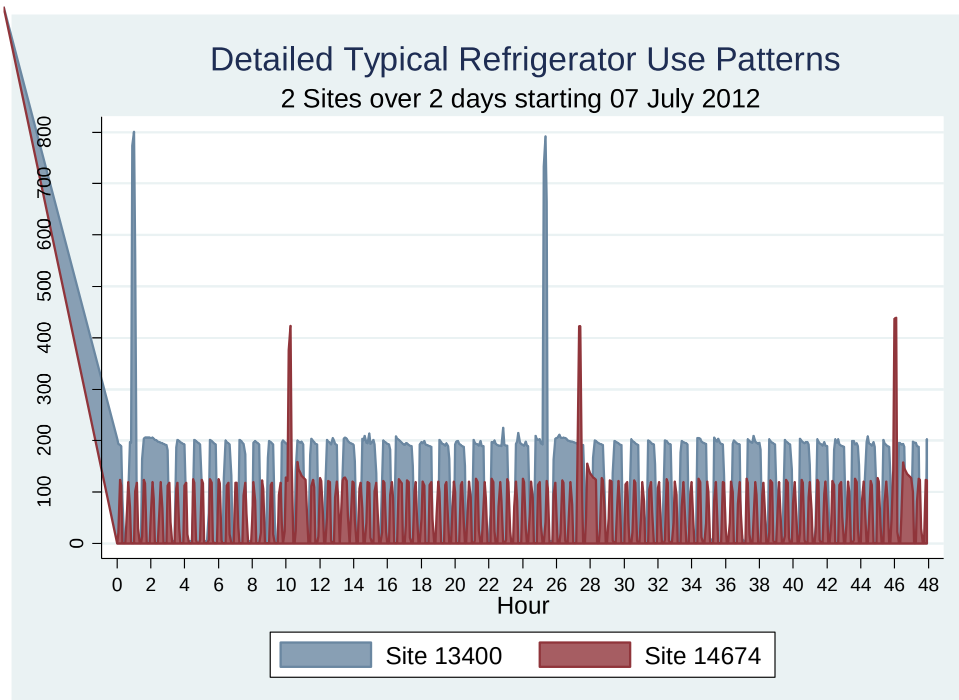
Figure 32 compares the observed hourly load shapes in the current study to the ELCAP study from 25 years ago (Pratt et al., 1990). Notably, the magnitude of refrigerator energy use is 40% today of what it was two decades ago. More subtly, the shape of the energy use has not substantially changed. The relative height between the peak and valley is still about 25% of the peak power draw although total daily use is less.

Figure 32. Refrigerator Hourly Load Shape Compared



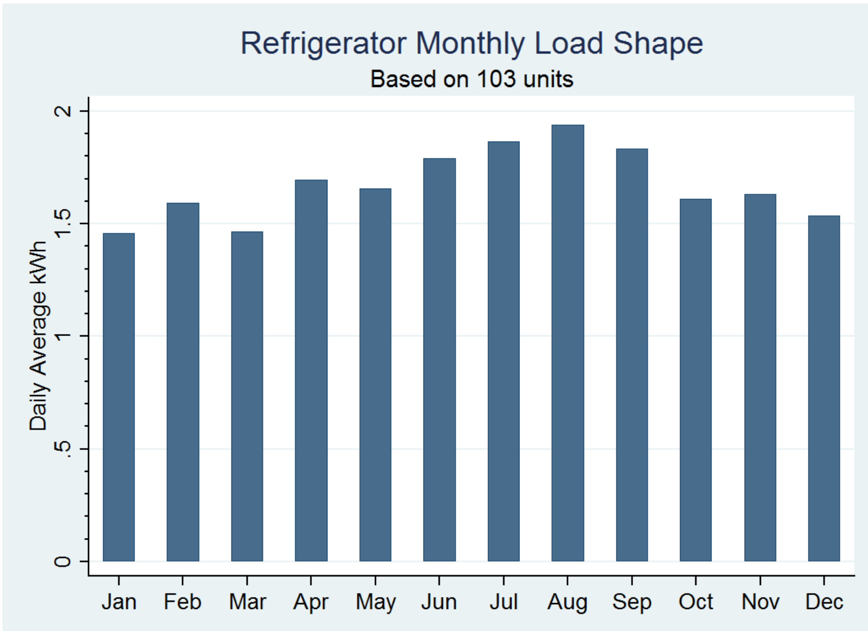
Metering energy use at a five-minute time scale reveals load patterns that can be useful in demand response programs. For example, Figure 33 shows the power measurements of two refrigerators, each in a different house, for two days in the summer. Both are located in kitchens. The refrigerator at site 13400 was manufactured in 1995, and the refrigerator at 14674 was manufactured in 2006. Although both refrigerators show a typical cyclic behavior, 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 any obvious frequency. Post-defrost, both compressors run for a longer period of time, presumably to reduce the 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.

Figure 33. Detailed Typical Refrigerator Use Patterns



Monthly use also increases during summer months. Figure 34 shows the energy use for primary refrigerators, which are all inside the conditioned space. Usage in August averages about 1.7 kWh/day versus about 1.2 kWh/day in January. Many houses have mechanical cooling, but interior temperatures are overall higher in summer. Refrigerators in garages or basements show a different annual profile because those spaces are subject to larger temperature swings (see Appendix 8 for load shape).

Figure 34. Refrigerator Monthly Load Shape



There are far fewer stand-alone freezers than refrigerator/freezer combinations. Nevertheless, we see a similar trend in annual freezer usage, with older equipment using in some cases more than 1,000 kWh/yr (see Table 45). Newer equipment uses half of that. Further,

Table 46 shows that upright freezers use more energy annually than chest freezers. The number of cases is small, but the vintage is evenly distributed across the types and the pattern is clear. The continued persistence of extremely old (pre 1990) equipment indicates there is some 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.

Table 45. 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 46. 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

3.4.2. Dishwashers

Dishwashers, interestingly, do not follow the same trend as refrigerators and freezers. There is no persistent trend in energy usage for dishwashers over three rounds of federal standards upgrades (1988, 1994, and 2010). This observation is not surprising, given that the standards have focused mostly on the amount of hot water used in dishwashers which is not captured by this measurement but is implicitly covered in the water heating section of the report. Further, this study did not collect extensive information on wash cycle type, which could be important to understanding the energy trends. A useful follow-up study would be to examine both the water used by the dishwasher and the cycle types selected by the occupants.

In Figure 35, the bar widths are proportional to the number of cases in each age bin and the white number at the bottom shows the exact count. The vertical, dashed lines in the figure indicate the year of a federal standard change. Table 47 summarizes the dishwasher energy use by vintage.

Figure 35. Annual Dishwasher Energy Use

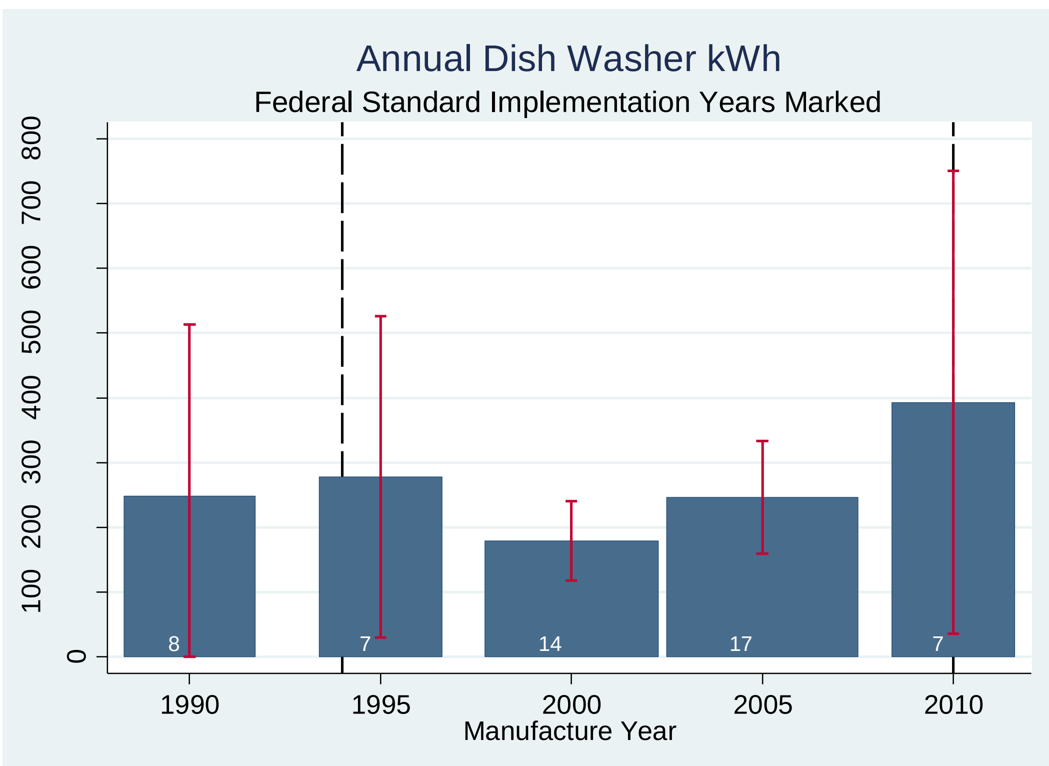


Table 47. Annual Dishwasher Energy Use by Vintage

Manufacture Date Bin	Dishwasher Annual kWh by Vintage		
	Mean	EB	n
1990-1994	247.9	140.2	8
1995-1999	277.9	127.7	7
2000-2004	179.0	34.6	14
2005-2009	246.5	49.7	17
Post 2009	393.0	184.2	7
Total	252.4	39.6	53

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

3.4.3. Laundry Equipment

The final major appliance category we examine is laundry equipment (washers and dryers). Nearly every house had a washer and dryer. There were 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.

Average dryer usage in RBSA Metering sites is relatively flat by vintage category (Figure 36 and Table 48). The newest dryers (2010 or newer) appear to use less energy, but there are only five dryers in this group. Fundamentally, the consistency among vintages is unsurprising given that a dryer must always 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.

Figure 36. Annual Clothes Dryer Energy Use

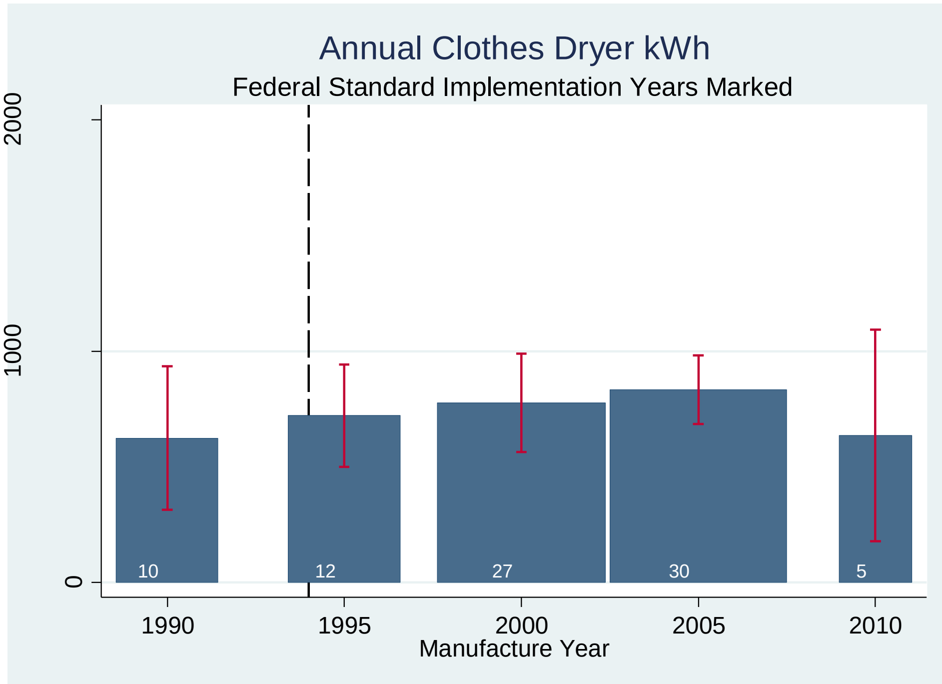


Table 48. Annual Clothes Dryer Energy Use by Vintage

Manufacture Date Bin	Clothes Dryer Annual kWh by Vintage		
	Mean	EB	n
1990-1994	624.2	169.1	10
1995-1999	721.7	123.2	12
2000-2004	775.2	124.7	27
2005-2009	832.8	87.2	30
Post 2009	635.5	214.8	5
Total	761.8	58.0	64

Direct clothes washer energy use is an order of magnitude less than that of dryers (see Figure 37 and Table 49). As in the case of dishwashers, a substantial part of the federal efficiency standard targets overall water usage. Those savings are realized at the water heater and not necessarily the clothes washer. Table 50 shows that horizontal axis washers use less energy than vertical axis washers, although both are relatively small compared to dryers. Note, in some cases, vintage or washer type is unknown, so washer count varies in Table 43, Table 49, and Table 50.

Figure 37. Clothes Washer Annual Energy Use

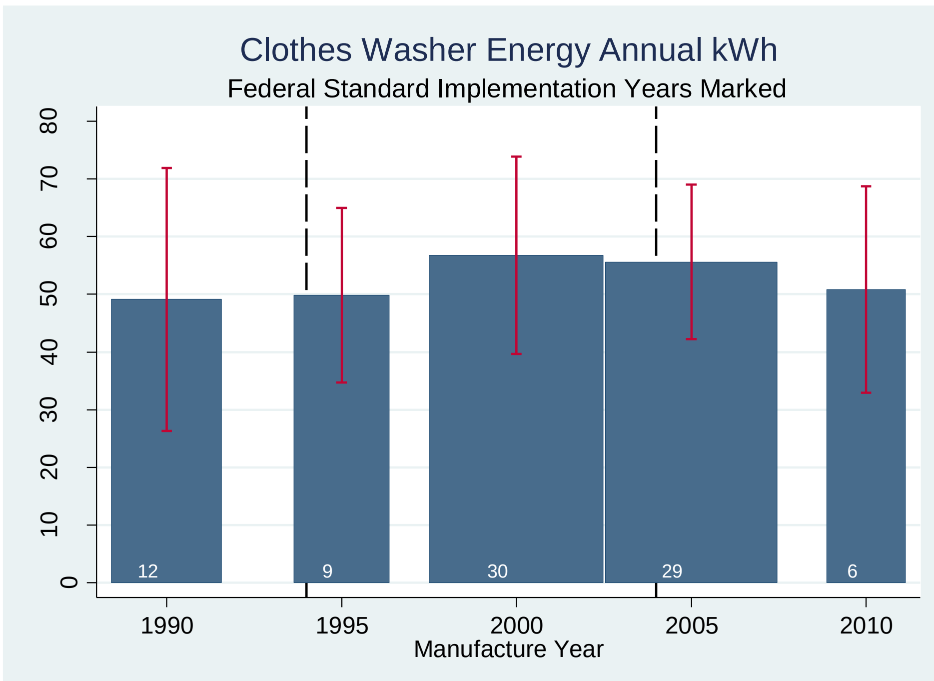


Table 49. Clothes Washer Annual Energy Use by Vintage

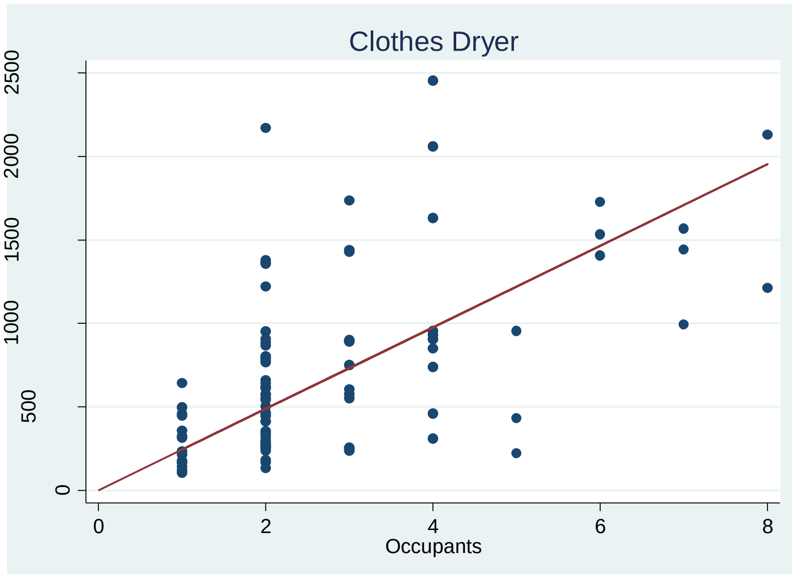
Manufacture Date Bin	Clothes Washer Annual kWh by Vintage		
	Mean	EB	n
1990-1994	49.1	8.1	12
1995-1999	49.8	8.1	9
2000-2004	56.8	10.1	30
2005-2009	55.6	7.9	29
Post 2009	50.9	8.9	6
Total	54.2	4.8	86

Table 50. Clothes Washer Annual Energy Use by Type

Axis Type	Clothes Washer Annual kWh		
	Mean	EB	n
Horizontal Axis	48.3	5.8	39
Vertical Axis (with agitator)	64.1	8.8	50

The annual use depends on the number of loads dried, which in turn depends on the number of occupants in the house. Figure 38 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 zero point 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.

Figure 38. Clothes Dryer Annual Energy Use per Occupant



Load shapes for laundry equipment are shown in Figure 39, Figure 40, and Appendix 8. Figure 39 displays the laundry equipment use patterns during the average weekend day. As expected, clothes washer energy use is a tiny fraction of dryer energy use. The peak 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 40 confirms that more laundry is done on weekends than weekdays. The clothes washer shape for day-of-week is nearly identical (but 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.

Figure 39. Laundry Weekend Hourly Load Shape

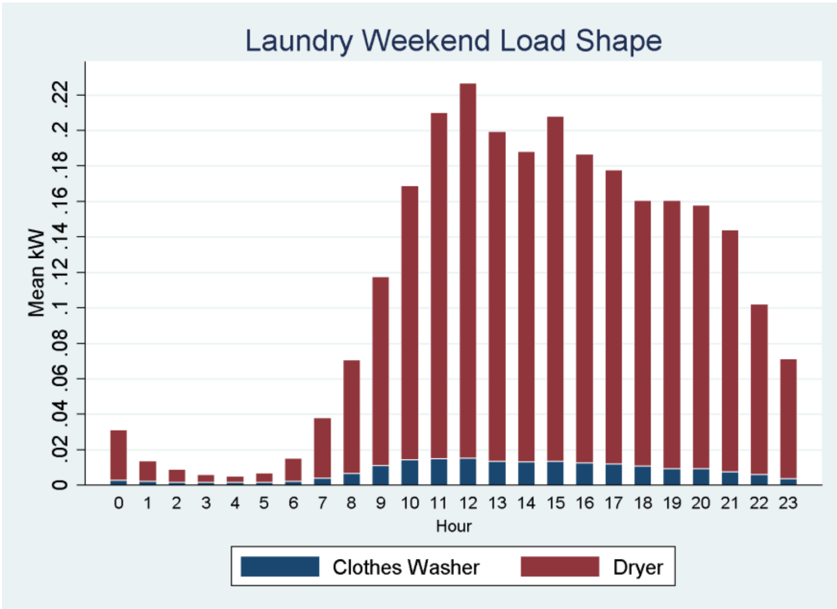
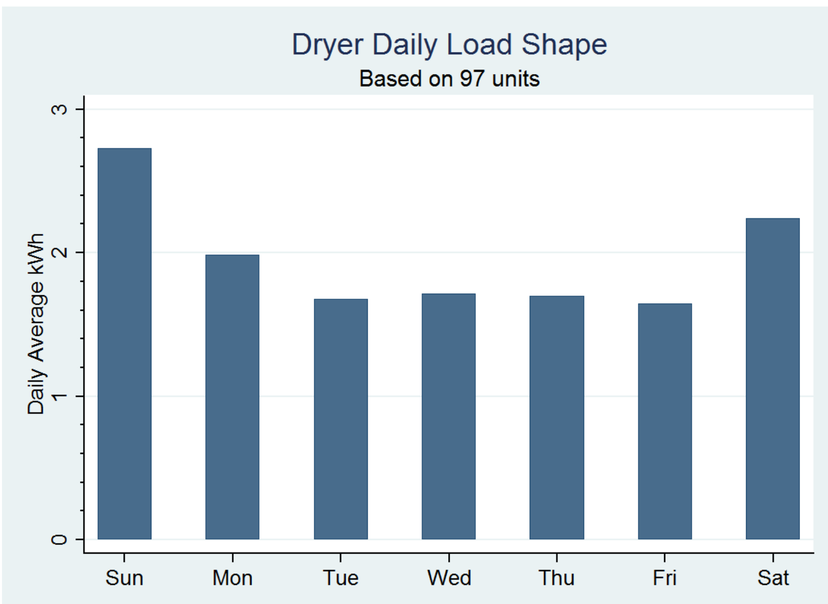


Figure 40. Dryer Weekly Load Shape



3.4.4. Appliances in the "Average" House

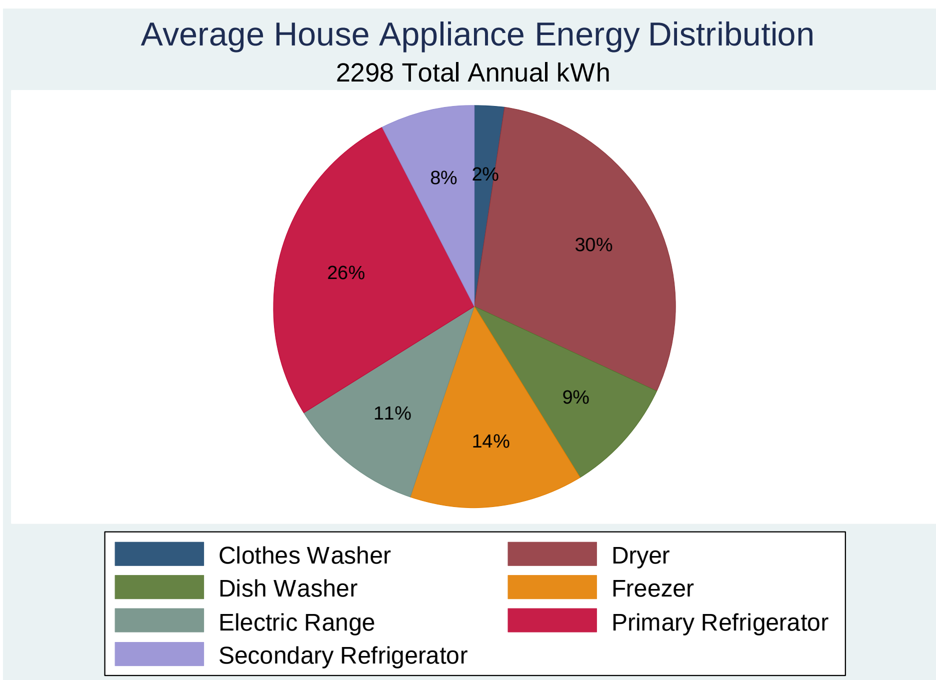
What does the "average" house look like, in terms of the distribution of major appliance electricity usage? Using the RBSA single-family survey and the metered results from this report, it is possible to show that the average house in the Northwest uses 2,300 kWh/yr to run the electric appliances. Table 51 shows the numbers used in the calculation, which multiplies the regional appliance saturation by the measured energy use.

Table 51. Electric Appliance Energy across the Northwest

Appliance	Energy Use per Appliance kWh/yr	RBSA Single-Family Survey Saturation[12]	Energy Use per House kWh/yr	Percent of Total Energy %
Clothes Washer	55	0.99	54	2%
Clothes Dryer[13]	725	0.94	679	30%
Dishwasher	239	0.89	213	9%
Freezer	609	0.53	323	14%
Electric Range[14]	314	0.80	251	11%
Refrigerator (primary)	604	1.00	604	26%
Refrigerator (secondary)	600	0.29	174	8%
Overall	na	na	2,298	100%

Both Table 51 and Figure 41 show the most significant appliance energy users are the dryer, refrigerator, and freezer, comprising 78% of the electric appliance energy. Although a single electric dryer uses more energy than a single refrigerator, houses have more refrigerators on average and, thus, slightly more refrigerator usage. Likewise, other appliances, such as freezers, dishwashers, and electric ranges, do not appear in every house so have less influence on the pie chart in Figure 41.

Figure 41. Major Appliance Electricity Breakout for Average House in Pacific Northwest



[12] Data from RBSA SF Report Tables 87, 101, and 102 (Baylon et al. 2012).

[13] Approximately 5% of all houses have gas-fueled dryers. The table reports on electricity only.

[14] Seventy-five percent of houses have electric ranges and 85% have electric ovens. The table assumes a combined effective saturation of 80%.

3.5. Consumer Electronics

Consumer electronics is a rapidly evolving category of devices that are, in the larger scope of efficiency programs, relatively new on the scene. Efficiency programs have been in place for 30 years or more; in that time, consumer electronics have increased their share of home energy use. However, few studies have been done to quantify how much of the house's energy they are actually using; and the amount of energy used will change over time.

Two broad categories of devices were metered: (1) televisions (TVs) and TV accessories, and (2) computers and computer accessories. Small loads like toasters, hair dryers, microwaves, etc. were not metered.

Consumer electronics may have three modes: an active mode, a standby mode, and an off mode. Some devices use all three modes; some use active and standby; some use active and off. Some devices further differentiate between active and passive standby modes; for example, a digital video disc (DVD) player may be turned on but not spinning its motor. This differentiation is usually limited to devices with a motor (Maruejols and Ryan, 2011). The modes are defined as:

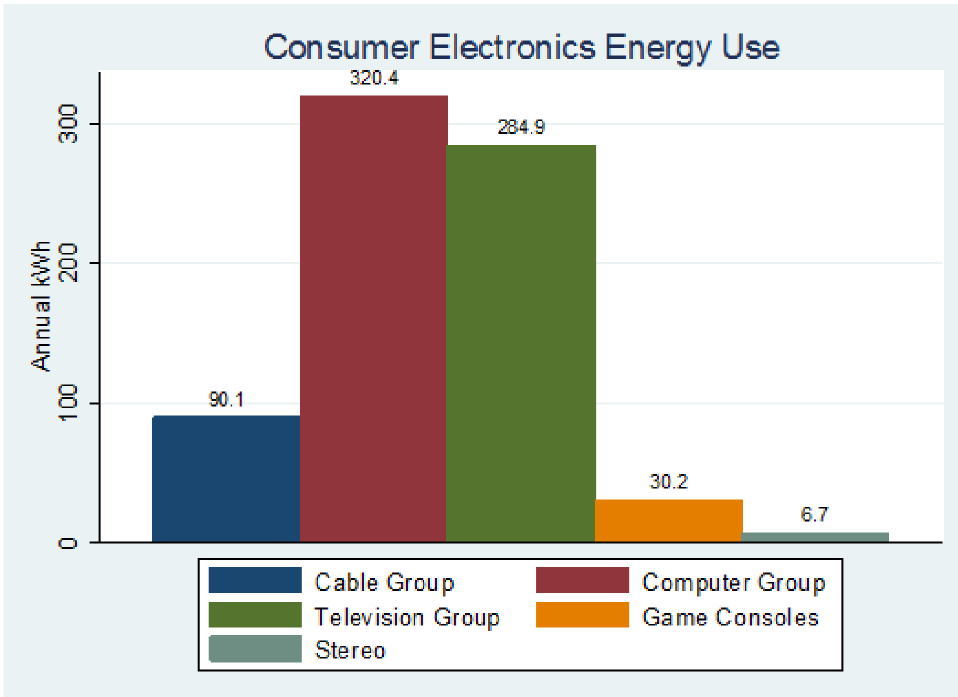
- **Active:** The device is performing the function for which it was designed.
- **Standby:** The device is on but not performing its main function. It may be maintaining a clock, a channel index (e.g., set-top boxes), internal memory, or the capability to respond to a remote control.
- **Off:** The device has been turned off with a physical power button or unplugged. No display is active. It will not respond to reactivation by remote control and all but the most basic functions, such as keeping internal track of time, are no longer active. Power draw is minimal or none.

Ecotope did not test individual devices in various operational modes; we looked at different levels of energy use. For example, for some devices that use almost the same amount of energy in active and standby modes, the different modes were indistinguishable. For this analysis, three states for each class of consumer electronics were defined: high power, low power, and off.

Ecotope found that 77% of the consumer electronics devices metered had a low power mode. On average, devices spent 38% of their time in high power mode, 31% in low power mode, and 31% off. 82% of total energy use was in high power mode and 18% in low power.

Of the consumer electronics devices metered, computers and computer-related devices used the most energy; televisions and television-related devices came in a close second (Figure 42). Full lists of the energy use of different devices are in Appendix 7.

Figure 42. Consumer Electronics Energy Use



This section refers throughout to primary, secondary, and tertiary devices. Primacy is defined by duty cycle. In other words, the television that was used the most is the one that is defined as the primary television and so on.

3.5.1. Televisions

The conservation potential in this sector focuses on two areas: shifting CRTs to flat screens and optimizing the power use of flat screens. The former task is largely complete. Flat screens represent 96% of all televisions purchased in the Pacific Northwest between 2010 and 2011 (Baylon et al., 2012). Still, there remains a significant stock of CRTs in houses. Across the Northwest, there are an average of 2.29 televisions per house, half of which are CRTs and half are "Other," including LCD, plasma, and projection TVs (Baylon et al., 2012). In the RBSA Metering population, only 22% of monitored televisions are CRTs. If one looks at primary televisions, the numbers shift even lower to 10%. About 74% of all metered TVs are some type of flatscreen (LCD or plasma).

Keeping with the typology from the single family survey, which divided televisions by CRTs and "Others" (Baylon et al., 2012), Figure 43 shows the measured annual energy use of TVs in the RBSA Metering population for all modes of operation. The figure includes all primary, secondary, and tertiary TVs. The fact that annual energy use of CRTs is lower suggests that CRT on-time is far less than the others. It stands to reason that as consumers purchase newer TVs of a different screen type, they use those as the primary device and move the CRTs to less used locations.

Figure 43. Television Energy Use by Type

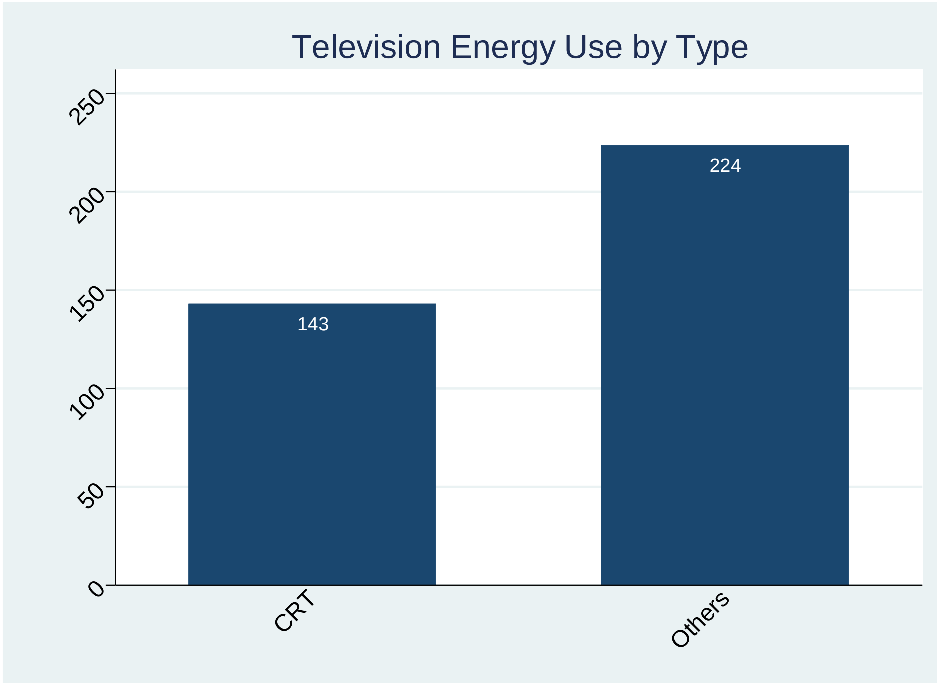


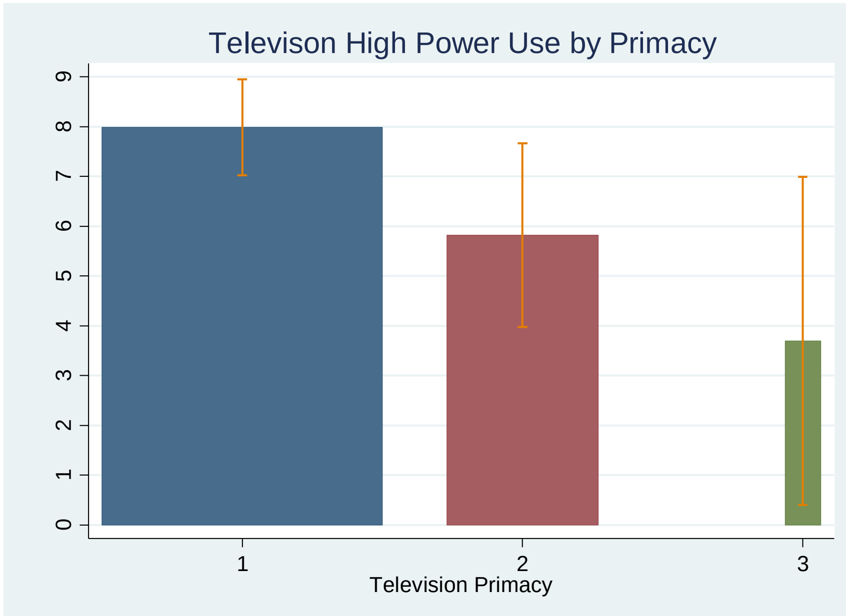
Table 52. Television Annual kWh by Region

End Use		Television Annual kWh			
		Puget Sound	Western Oregon	Eastern Region	All Regions
Primary TV	**Mean**	269.1	271.7	327.8	292.7
	EB	33.6	38.6	42.1	22.5
Secondary TV	**Mean**	58.7	77.9	121.2	93.3
	EB	18.5	24.6	23.6	14.1
Tertiary TV	**Mean**	37.1	62.3	68.4	57.7
	EB	19.5	29.5	26.4	14.4

On average, metering shows primary televisions are in high power mode eight hours per day (see Figure 44). In the figure, the width of the bar indicates the relative number of primary, secondary, and tertiary televisions in the study. By definition, the hours of use decline based on primacy.

According to occupant interviews in the RBSA (Baylon et al., 2012), primary televisions are turned on an average of 5.4 hours per day. The difference between the measured data (8 hours) and interviews (5.4 hours) could indicate televisions that are on but unwatched, standby modes that use almost as much energy as on modes, or that self-reports of television use time underestimate real use. With potentially 2.6 hours of unwatched time per day, there is a savings opportunity by simply turning the device off or putting it in a low power state.

Figure 44. Television Use by Primacy



There is some regional variation in television viewing habits. Western Oregon and eastern region participants have their primary televisions on for 63 hours per week, on average; Puget Sound residents have their primary televisions on less often. Table 53 shows the distribution of high power mode.

Table 54 and Table 55 show the distribution of low power and off modes, respectively.

Table 53. Television Daily Hours of Use

End Use		Television Daily Hours of Use			
		Puget Sound	Western Oregon	Eastern Region	All Regions
Primary TV	Mean	6.0	9.0	9.0	8.0
	EB	0.6	1.3	1.0	0.6
Secondary TV	Mean	4.1	7.2	5.0	5.4
	EB	2.0	2.5	1.2	1.0
Tertiary TV	Mean	7.8	1.8	2.5	3.7
	EB	6.9	0.5	0.6	1.8

Table 54. Television Daily Hours of Standby

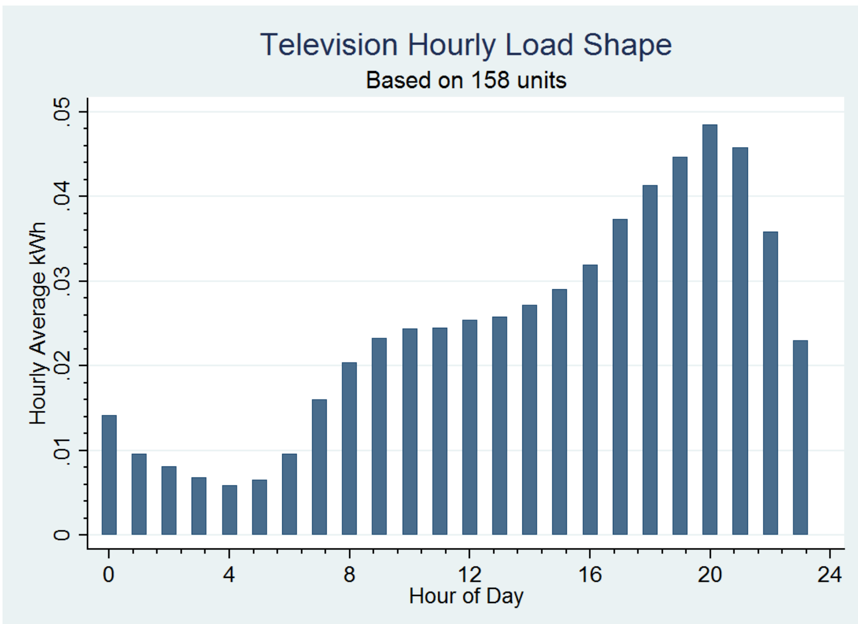
End Use		Television Daily Hours of Standby			
		Puget Sound	Western Oregon	Eastern Region	All Regions
Primary TV	Mean	3.4	7.0	3.8	4.5
	EB	1.1	1.9	1.2	0.8
Secondary TV	Mean	7.5	7.5	9.3	8.3
	EB	2.8	2.8	2.3	1.5
Tertiary TV	Mean	7.5	11.1	5.9	8.2
	EB	7.5	6.4	5.6	3.4

Table 55. Television Daily Hours Off

End Use		Television Daily Hours Off			
		Puget Sound	Western Oregon	Eastern Region	All Regions
Primary TV	**Mean**	14.6	8.0	11.2	11.5
	EB	1.3	1.7	1.4	0.9
Secondary TV	**Mean**	12.4	9.3	9.7	10.3
	EB	2.9	3.0	2.1	1.5
Tertiary TV	**Mean**	8.7	11.1	15.6	12.1
	EB	7.1	6.4	5.2	3.3

As shown in Figure 45, televisions are used primarily between the hours of 8:00 and 11:00 p.m. However, significant television use occurs throughout the day, between 9:00 a.m. and 11:00 p.m.

Figure 45. Television Hourly Load Shape



3.5.2. Set-Top Box/DVRs

Set-top boxes are generally supplied to the consumer by the cable company. Thus, the best way to improve set-top box efficiency is by changing codes and standards. There is an Energy Star rating for set-top boxes, and considerable energy savings are available if the set-top box is set up to go into sleep or deep sleep mode when not in use, but there is no current Department of Energy (DOE) standard to require that. A new standard is expected from DOE in 2013 that will address the efficiency of set-top box power supplies and standby modes.

Set-top boxes used 161 kWh/yr (Table 56). Devices that combine a set-top box with a digital video recorder (DVR) used 236 kWh/yr (Table 57). On average, set-top boxes and set-top box/DVRs both spend 20 hours per day in high power mode (Table 58). On average, set-top boxes spend more time per day in low power mode than set-top box/DVRs (Table 59).

Table 56. Set-Top Box Annual Energy Use

Region	Set-Top Box kWh/yr		
	Mean	EB	n
Puget Sound	140.1	25.9	10
Western Oregon	201.5	38.3	3
Eastern Region	168.5	28.9	10
All Regions	160.5	17.5	23

Table 57. Set-Top Box/DVR Annual Energy Use

Region	Set-Top and DVR Box kWh/yr		
	Mean	EB	n
Puget Sound	208.6	31.4	13
Western Oregon	251.2	9.3	10
Eastern Region	262.8	39.6	8
All Regions	236.4	16.9	31

Table 58. Set-Top and Set-Top/DVR Annual Energy Use from High Power Mode

	Annual kWh From High Power Mode		
	Mean	EB	n
Set-Top Box	134.2	18.1	23
Set-Top/DVR	231.9	18.2	31

Table 59. Set-Top and Set-Top/DVR Annual Energy Use from Low Power Mode

	Annual kWh From Low Power Mode		
	Mean	EB	n
Set-Top Box	26.3	10.4	23
Set-Top/DVR	4.5	3.6	31

Given that primary televisions are in use for approximately eight hours per day, set-top boxes could theoretically go into low power mode for approximately 15 hours per day (assuming an hour in high-power standby). Across the region, 80.6% of houses have set-top boxes (with and without DVRs). Those houses have 1.5 set-top boxes on average (Baylon et al., 2012). An average of 0.47 of these are set-top box/DVRs and 1.03 are set-top boxes without DVRs. This leads to a conservation potential of 60 kWh/yr for set-top boxes and 65 kWh/yr for set-top boxes with DVRs. Table 60 and Table 61 show that western Oregon and eastern region participants, who watch more television than Puget Sound participants, have higher energy use for both set-top boxes and set-top boxes with DVRs.

Table 60. Set-Top Box/DVR Annual Energy Use

Region	Cable and DVR Box kWh/yr		
	Mean	EB	n
Puget Sound	208.6	31.4	13
Western Oregon	251.2	9.3	10
Eastern Region	262.8	39.6	8
All Regions	236.4	16.9	31

Table 61. Set-Top Box Annual Energy Use

Region	Cable Box kWh/yr		
	Mean	EB	n
Puget Sound	140.1	25.9	10
Western Oregon	201.5	38.3	3
Eastern Region	168.5	28.9	10
All Regions	160.5	17.5	23

3.5.3. Gaming Consoles

Gaming consoles do not appear to be a particularly fertile field for energy conservation. Consumers generally make their purchasing decisions based on other factors; thus, impacting codes and standards appears to be the best path to improving energy efficiency. Gaming consoles in this study use only an average of 90.5 kWh/yr (Table 62), indicating that there is not a lot of room for improvement. Across the region, only 33.2% of houses have a gaming system. Those houses have an average of 1.48 gaming systems per house (Baylon et al., 2012).

Table 62. Game Console Annual Energy Use

Region	Game Consoles kWh/yr		
	Mean	EB	n
Puget Sound	112.3	27.3	17
Western Oregon	58.4	21.4	11
Eastern Region	88.8	25.9	11
All Regions	90.5	15.3	39

Gaming consoles in this study appear to have a low power mode, and they spend a significant amount of time in that mode. Figure 46 summarizes the distribution of game console usage among high power, low power, and off modes. Table 63 and Table 64 show the hours of gaming console use in high power and low power modes, respectively.

Figure 46. Annual Game Console Use Time

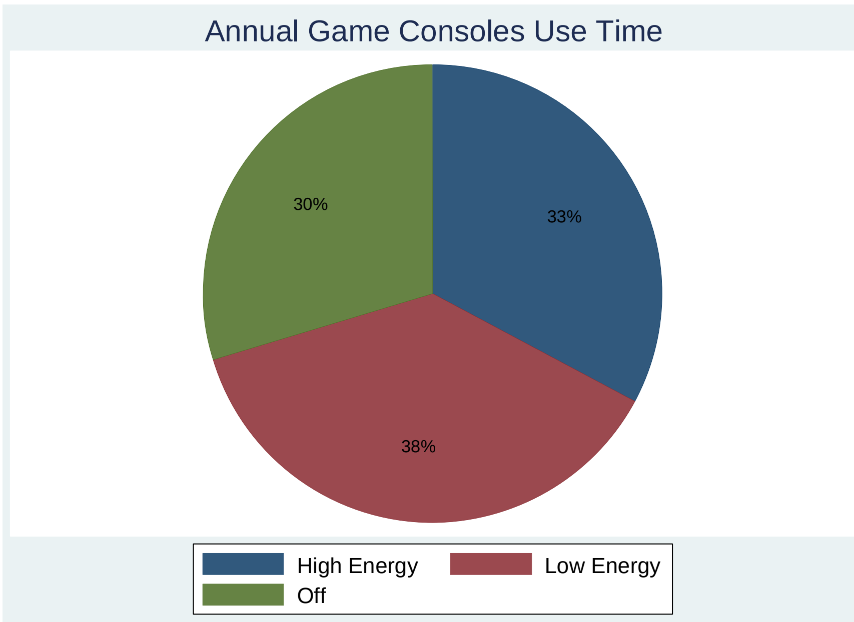


Table 63. Game Console Hours of Use

Region	Game Consoles Daily Hours of High Power Mode		
	Mean	EB	n
Puget Sound	8.6	2.1	17
Western Oregon	7.3	3.2	11
Eastern Region	7.3	2.5	11
All Regions	7.9	1.4	39

Table 64. Game Console Hours of Low Energy Mode

Region	Game Consoles Daily Hours of Low Power Mode		
	Mean	EB	n
Puget Sound	11.4	2.5	17
Western Oregon	7.2	3.0	11
Eastern Region	7.1	3.0	11
All Regions	9.0	1.6	39

3.5.4. Computers

Desktop computers show a fair amount of potential for energy conservation. There is long-term potential in influencing manufacturers to build computers using more efficient components and to ship computers with more efficient power management strategies enabled; there is also short-term, more easily realized potential in getting consumers to move their computer to a more efficient power management strategy after purchase. This analysis addresses the latter possibility.

Table 65, Table 66, and Table 67 show the average desktop computer's central processing unit (CPU) energy use across the region. Table 68, Table 69 and Table 70 show average hours in high power, low power, and off modes. It appears that computers in the Puget Sound region are in high power mode approximately 30% more than those in the other regions. These computers use about 60% more energy, indicating not only that they are used more, but also that they are slightly more powerful (or simply less efficient). Across the study, computers use an average of 80.9 watts in high power mode and 2.4 watts in low power mode. They spend 45% of their time in high power mode, 45% in low power mode, and only 10% of the time off (see Figure 47).

Table 65. Computer Annual Energy Use

Region	CPU kWh/yr		
	Mean	EB	n
Puget Sound	415.9	72.2	25
Western Oregon	268.1	63.2	16
Eastern Region	196.1	30.0	8
All Regions	331.7	43.9	49

Table 66. Computer Annual Energy Use in High Power Mode

Region	CPU kWh/yr From High Power Mode		
	Mean	EB	n
Puget Sound	407.4	73.1	25
Western Oregon	258.6	64.2	16
Eastern Region	183.0	31.6	8
All Regions	322.2	44.5	49

Table 67. Computer Annual Energy Use in Low Power Mode

Region	CPU kWh/yr From Low Power Mode		
	Mean	EB	n
Puget Sound	8.5	2.1	25
Western Oregon	9.5	2.2	16
Eastern Region	13.1	2.0	8
All Regions	9.6	1.3	49

Table 68. Daily Computer Hours of Use

Region	CPU Daily Hours of Use		
	Mean	EB	n
Puget Sound	12.5	1.8	25
Western Oregon	9.4	1.9	16
Eastern Region	9.1	1.9	8
All Regions	10.9	1.1	49

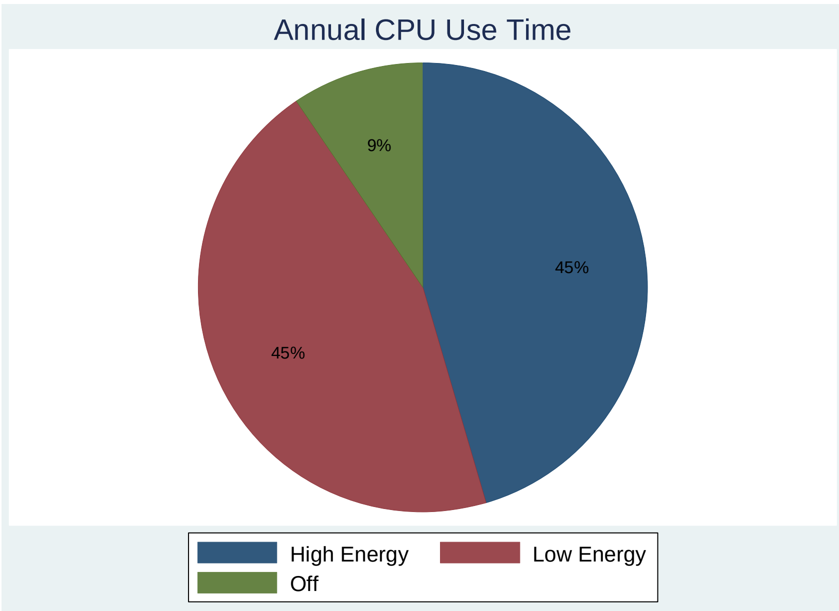
Table 69. Daily Computer Hours in Low Power Mode

Region	CPU Daily Hours of Low Power Mode		
	Mean	EB	n
Puget Sound	9.3	1.7	25
Western Oregon	11.6	1.8	16
Eastern Region	13.9	2.0	8
All Regions	10.8	1.1	49

Table 70. Daily Computer Hours Off

Region	CPU Daily Hours Off		
	Mean	EB	n
Puget Sound	2.2	1.3	25
Western Oregon	3.0	1.4	16
Eastern Region	1.0	0.6	8
All Regions	2.3	0.8	49

Figure 47. Annual Computer Use Time

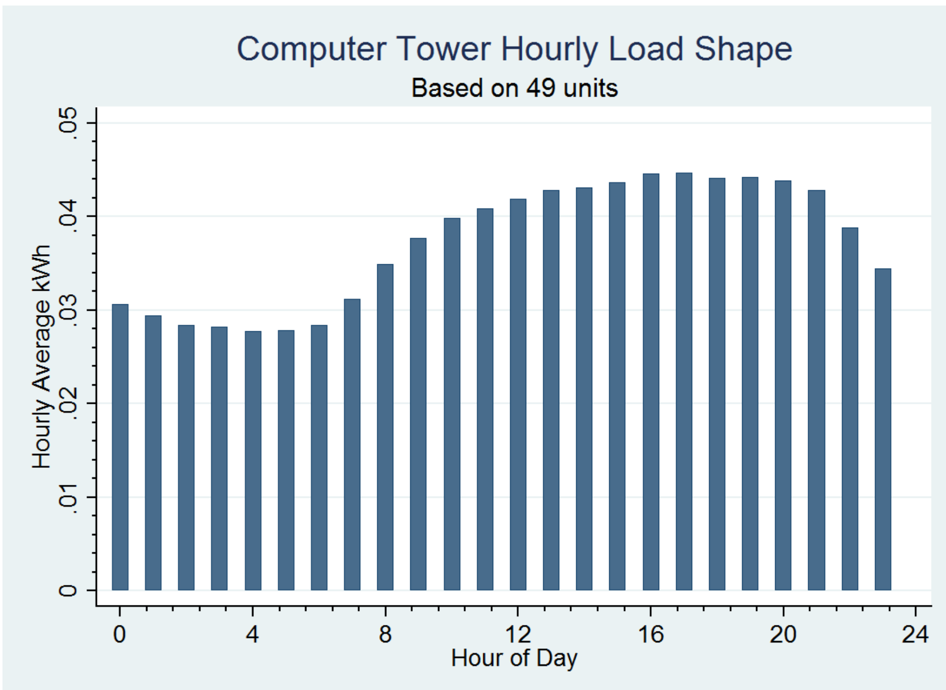


Bensch et al. (2010) found, by using occupancy sensors as well as energy monitors, that desktop computers are left on but idle for large portions of the day. Their data suggest enabling sleep/hibernate mode for these computers could reduce energy use among these systems by 50%. We found desktop computers (exclusive of monitors and accessories) use 332 kWh/yr on average; assuming equivalent use patterns, there is a savings potential of around 156 kWh per year. Bensch et al. further reported that consumers were often unaware the computer was not set to hibernate, and they were quite willing to change the power management settings. Thus, a reasonable fraction of this potential is achievable. However, this could require scheduling virus scan and backup activity for times other than the middle of the night.

Across the region, 90.5% of houses have computers (desktops and laptops together). Those houses have an average of 1.67 computers per house (Baylon et al., 2012). Desktop saturation alone is 0.94 computers per household.

Computer use is surprisingly flat over the hours of the day, possibly because of the amount of time these systems spend in high power mode but unused. There is a rise in use during waking hours, albeit gradual and sustained (see Figure 48).

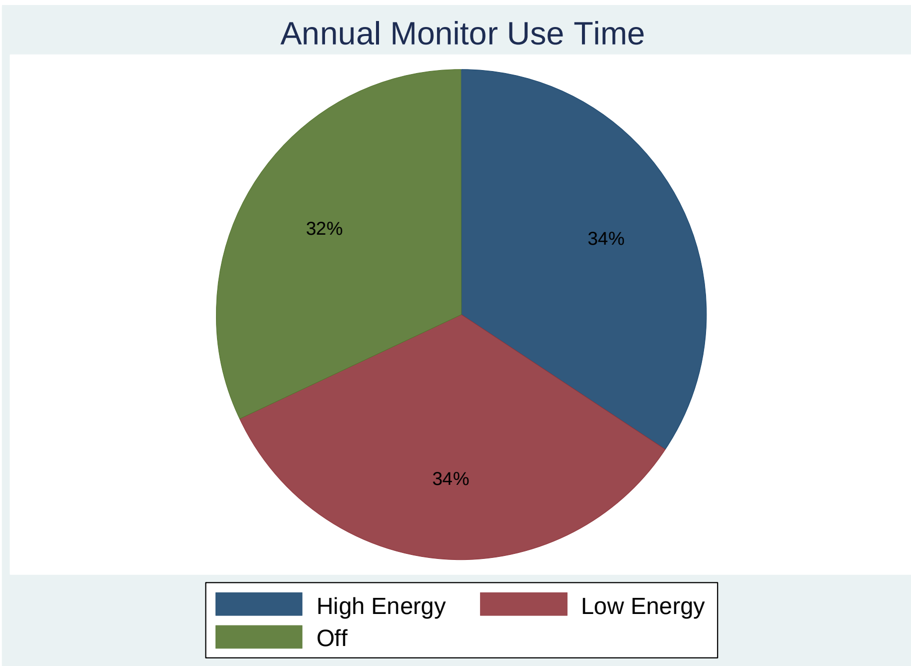
Figure 48. Computer Hourly Load Shape



3.5.5. Monitors

Monitors spend more time off and less time in high power and low power modes than computers (Figure 49). This supports a finding by Bensch et al. (2010) that monitors are more likely to have their sleep mode activated.

Figure 49. Annual Monitor Use Time



Monitors in this study used an average of 47 watts in high power mode and 2 watts in low power mode. Not only are monitors more aggressive than CPUs about powering down, but also low power mode is lower than CPUs.

Monitors use an average of 144.7 kWh/yr (Table 71). A program that addresses CPU power management could easily include monitor power management as well.

As one might expect from the computer results, monitors in the Puget Sound region appear to be more powerful than monitors in western Oregon or the eastern region.

Table 71. Monitor Annual Energy Use

Region	Monitor Annual kWh		
	Mean	EB	n
Puget Sound	197.4	98.5	7
Western Oregon	140.5	58.9	8
Eastern Region	88.7	21.3	6
All Regions	144.7	39.5	21

3.6. Lighting

The data analysis for lighting runs along two parallel tracks: one is the measured on-time of the lights and the other is energy use. Energy use depends entirely on the type of lamp installed and how often it is on. The technology to provide the light, be it incandescent, fluorescent, halogen, or light-emitting diode (LED), is highly fungible. Therefore, the more fundamental measurement is of on-time. Throughout the lighting section, the findings are presented both in terms of on-time and energy use.

The lighting findings section opens with summary characteristics of the amount and location of lighting installed in houses (section 3.6.1). That survey is the basis for developing overall, average on-time. The next section shows the results of a predictive regression model that extrapolated on-time from metered to unmetered lamps (section 3.6.2). The third part discusses the changing amount of lighting on-time over the year (section 3.6.3). Finally, the analysis reports the total energy use (section 3.6.4).

3.6.1. Lighting Characteristics

Table 72 and Table 73 compare the overall RBSA sample to the sites that participated in the metering program. The tables compare the average lighting characteristics and show the distinction between the metered lamps and fixtures and the total connected power (Watts) across the metered sample. The mean number of fixtures in the RBSA Metering sample differs somewhat from the larger group of all RBSA sites, but there is no statistical difference between the overall lighting power density (LPD), expressed as Watts per square foot (W/sq.ft.), in the two samples.

Table 72. Lighting Characteristics by Sample Group

Population	Lamps	Fixtures	Watts	Sites
	Mean Count	Mean Count	Total	n
RBSA all fixtures	59.4	35.6	2531	1266
RBSA Metering (all fixtures)	73.2	47.6	3239	97
RBSA Metering (observed fixtures)	25.8	15.6	1118	92

Table 73. Overall LPD by Sample

Population	LPD (W/sq.ft.)		
	Mean	EB	n
RBSA	1.42	0.033	1367
RBSA Metering	1.47	0.087	101

Not only does the analysis produce summaries for the entire house, it also considers rooms on an individual basis. Table 74 shows the LPD for each room type for the metered houses. Again, the findings compare well with the entire RBSA population (see Baylon et al., 2012 for details).

Table 74. LPD by Room Type (metered sample)

Room Type	LPD by Room - Metered Sites		
	Mean	EB	n
Bathroom	3.64	0.21	104
Bedroom	1.09	0.10	93
Closet	2.01	0.18	62
Dining Room	1.88	0.16	85
Family Room	1.05	0.10	56
Garage	0.51	0.04	71
Hall	1.54	0.13	100
Kitchen	1.79	0.12	104
Laundry Room	1.45	0.14	81
Living Room	1.08	0.07	95
Master Bedroom	1.05	0.06	92
Office	1.28	0.15	61
Other	0.85	0.08	51
Total	1.47	0.09	1055

Table 75 reports the final number of fixtures, lamps, and wattage directly metered in each room type. The table confirms that 1,115 fixtures were observed, covering 1,943 lamps, comprising 83 kW, and 874 different rooms.

Table 75. Measured Lighting Characteristics – Useable Meters Only

Room Type	Fixtures	Lamps	Watts	n
Bedroom	90	162	6,708	84
Master Bedroom	101	136	5,744	94
Basement	24	27	1,492	16
Bathroom	162	395	17,614	138
Closet	40	62	3,686	35
Dining Room	41	139	5,357	37
Exterior	13	14	598	10
Family Room	53	63	2,591	35
Garage	57	87	4,594	28
Hall	121	193	7,458	92
Kitchen	113	188	6,825	68
Laundry Room	62	94	3,928	50
Living Room	109	171	6,693	92
Office	70	128	5,861	59
Other	59	84	4,185	36
Total	1,115	1,943	83,334	874

3.6.2. Lighting On-Time

The key feature of lighting energy use is the on-time of the lighting system. In the findings, there are three tiers of lighting on-time. The first comes from the loggers for the metered fixtures. This measurement of on-time is simply that which was observed. The second tier is an estimate of on-time for all fixtures in all of the metered sites. Because 34% of all fixtures were metered, the estimate predicts the behavior for the remaining 66%. The third tier is an estimate of on-time for all the fixtures in the metered and non-metered houses alike. For houses not part of the RBSA Metering study, the on-time is estimated for every fixture.

Table 76 summarizes the average, observed on-time by room type (the first tier). The summary uses only data reported directly by the loggers that passed the quality control checks.

Table 76. Hours of On-time by Room Type, Sampled Fixtures

Room Type	Metered Hours of Use By Room		
	Mean	EB	n
Bedroom	1.1	0.3	84
Master Bedroom	.87	0.11	94
Basement	.33	0.097	16
Bathroom	1.2	0.25	138
Closet	.49	.097	35
Dining Room	1.5	0.29	37
Exterior	4.7	2.0	10
Family Room	4.3	1.1	35
Garage	.95	0.23	28
Hall	1.9	0.37	92
Kitchen	2.9	0.47	68
Laundry Room	1.2	0.32	50
Living Room	3.1	0.43	92
Office	1.7	0.3	59
Other Room	.54	0.17	36
Overall	1.7	0.16	874

To reach to the second and third tier of lighting on-time, we projected the metered results to the unmetered fixtures using a linear regression with indicator variables, as discussed in the methods section (section 2.5.5). The measured on-time was used as the dependent variable, and the output provided a coefficient for each room and fixture type. The regression specification is based on the combination of fixture and room types with usable lighting loggers (essentially Table 76). All the components, except the measured on-time, are expressed as dummy variables. There are 15 room types and 16 fixture types that go in to the regression.

It is essential to extrapolate the on-times to the unmetered fixtures for one major reason. The mix of loggers that survived the metering process represented only the lights that the loggers metered. In contrast, a given house has a certain distribution of room and fixture types that is most definitely not the same as those that were metered. Therefore, in extrapolating the findings to the larger populations of both the RBSA Metering and RBSA groups, we are essentially finding an average on-time for a typical house given the exact room and fixture type weighting of each house group. Consequently, we expect the overall, average on-time for each of the three tiers to differ because they are composed of a different mix of rooms and fixtures.

As mentioned in section 1.3, extrapolated on-times could have been overestimated. Still, the findings compare well with another significant lighting study (discussed below in section 3.6.2.1) suggesting the results are valid. To fully determine the extent of the bias, if there is any, a further study of lighting in houses is needed. The best study design would meter every fixture in every house. Perhaps only 10 such sites would be needed for comparison to the current results.

Table 77 shows the predicted on-times, using the regression model of rooms across the entire RBSA population (where n is the number of rooms in the full RBSA sample). Refer to Table 79 for the predicted on-times projected only across the metered sites.

Table 77. Predicted Hours of On-time by Room Type, Full Population

Room Type	Predicted Hours of Use By Room – Full Population		
	Mean	EB	n
Bedroom	1.4	0.041	1,649
Master Bedroom	1.1	0.031	1,454
Bathroom	1.2	0.039	1,368
Closet	.08	0.035	566
Dining Room	1.9	0.045	1,066
Exterior	3.7	0.059	959
Family Room	3.3	0.038	1,165
Garage	1.1	0.037	1,159
Hall	2.0	0.035	1,348
Kitchen	3.6	0.072	2,007
Laundry Room	1.5	0.034	1,018
Living Room	2.8	0.03	2,209
Office	1.8	0.04	965
Other Room	.21	0.053	842
Total	1.8	.015	17,775

Table 78 summarizes the aggregate lighting on-time derived from the regression results and applied to the aggregate census of the rooms and fixtures in each house.

Table 78. Average Lighting On-Time, Metered and Predicted Across RBSA Samples

Sample	Mean	EB	N
Metered Lighting	1.7	.16	92
RBSA Metered Sample	1.9	.17	101
Full RBSA Sample	1.8	.17	1,355

3.6.2.1. Comparison to Metered Data in Other Studies

In 2009 and 2010, an evaluation of the California private electric utilities' residential "upstream" lighting program was conducted (KEMA 2010). The evaluation included a detailed review of lighting on-time for a large portion of California, studying the entire state from San Diego to the Oregon border (about 13 degrees of latitude). The study approach in RBSA Metering differed in significant ways from this review, but the analytical methods and the overall results are similar and comparable.

Table 79 shows the comparison between this study and the lighting on-time from the California study. The overall results are similar although the individual room definitions and observed hours of use by room differ between the two studies.

Table 79. Hours per Day On-time Comparison to California 2010 Study

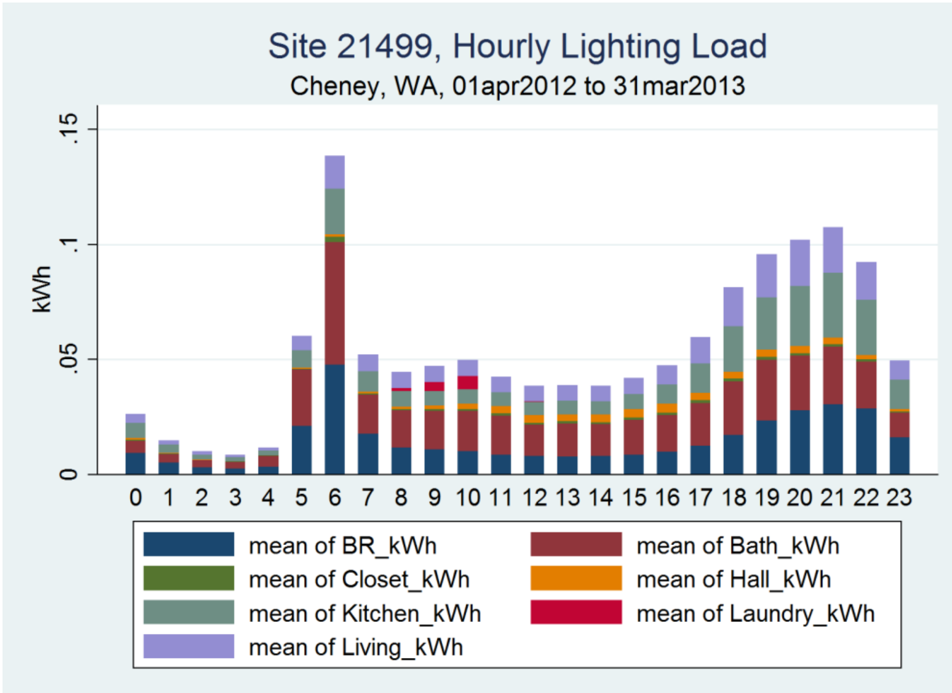
Room Type	RBSA Metered Sample		California Metered Sample	
	Mean	EB	Mean	EB
Bedroom	1.2	0.3	1.5	0.3
Master Bedroom	1.0	0.1	1.5	0.3
Basement	0.8	0.1	*	
Bathroom	1.2	0.2	1.3	0.3
Closet	0.5	0.1	*	
Dining Room	1.7	0.3	1.7	0.4
Exterior	3.4	1.3	3.8	0.3
Family Room	3.6	0.8	*	
Garage	1.3	0.2	1.8	0.5
Hall	2.1	0.3	1.3	0.3
Kitchen	2.9	0.3	2.4	0.3
Laundry Room	1.4	0.3	*	
Living Room	2.8	0.4	2.3	0.3
Office	1.7	0.3	1.3	0.4
Other Room	0.6	0.1	1.5	0.3
Overall	1.9	0.2	1.9	0.3

3.6.3. Time of Use during a Day, Month, and Year

The second phase of the analysis combined all metered data points, but not the projected ones, into a single dataset to create hourly, monthly, and yearly load shapes. A distinct geographic feature of the sites is that only about five degrees of latitude account for all of their locations. Thus the amount of daylight in any one house is similar seasonally regardless of the heating and cooling climate. Therefore, the analysis did not make a distinction among the houses or among the lighting loggers based on latitude, longitude, or climate zone.

To develop an overall energy load shape for lighting requires that the diversity of occupants, rooms, and house characteristics be combined to inform an overall lighting pattern. Any less aggregation would make the lighting characteristics more specific to a particular condition or household than is helpful for characterizing the lighting load across the sector. Figure 50 shows the particular use patterns in one house. It shows the use diversity across rooms during the day. It is apparent from the graphic that producing a single lighting load shape will require considerable aggregation to avoid the vagaries of a particular site.

Figure 50. Single-Site Energy use by Room Type

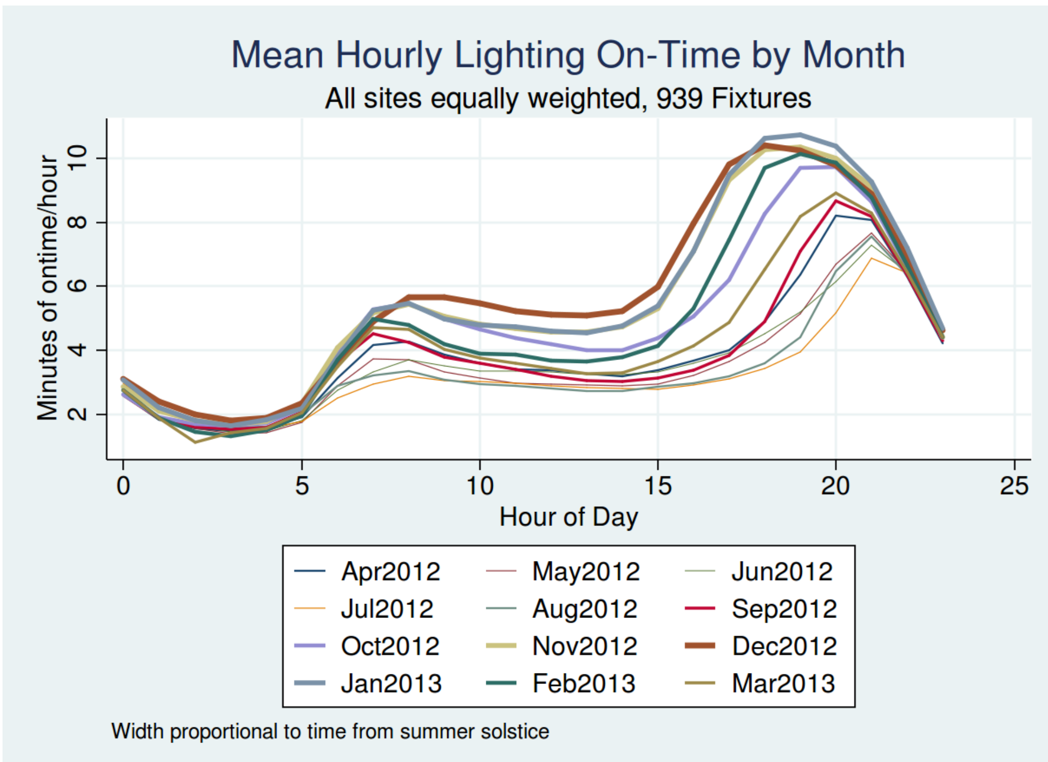


The overall lighting load shape is based on the aggregate on-time from the metered sample. It is important to note that the energy associated with this load shape is extremely mutable. The region's residential lighting has undergone a substantial change in the last decade. This trend can be expected to continue in the next decade with the advent of higher lighting standards and with new technologies, such as LEDs, that promise to further reduce the connected lighting load.

That said, the pattern of lighting *on-time* is expected to remain constant by room and fixture type over a day, month, or year. Indeed, as lighting is often used in response to dark ambient conditions, and assuming the Earth's revolution and rotation are stable in the near cosmic future, one expects the on-time profiles to remain unchanged for years, if not millennia. Thus, the load shapes presented are designed to accommodate technological shifts by providing a description of the underlying lighting use patterns regardless of the efficiency of the particular lamps that were measured.

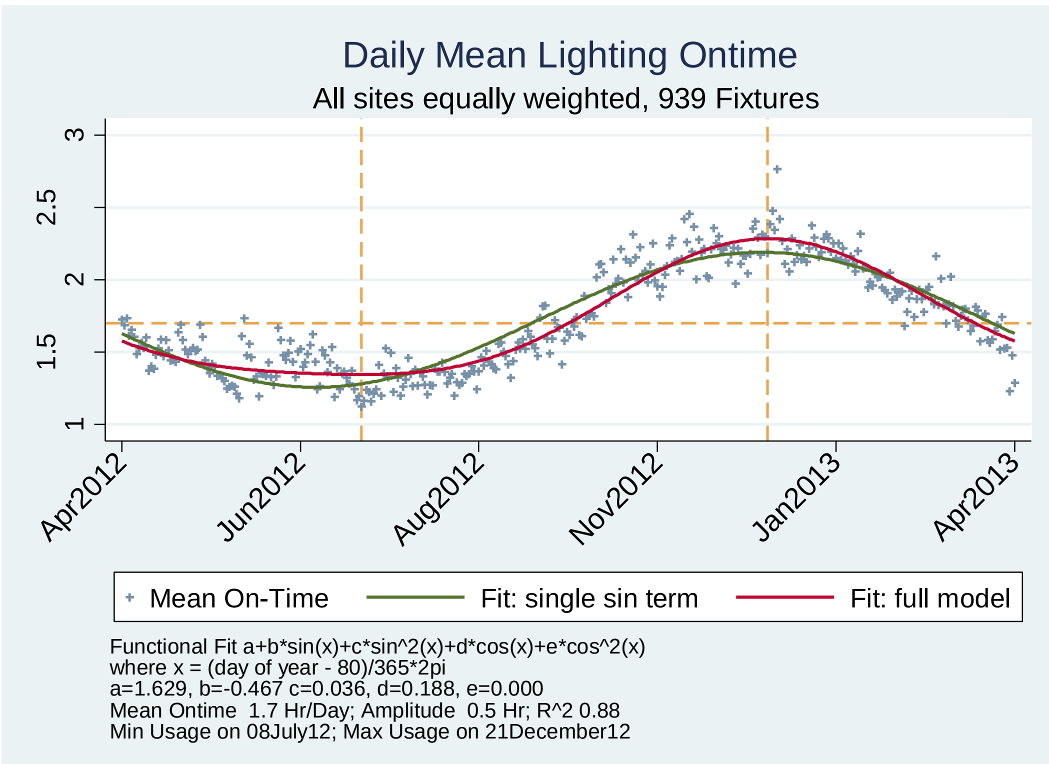
The overall load shape varies by time of day and season of year. In Figure 51, the minutes of on-time per hour over the course of a day is presented as a series of monthly results. For a given hour of the day, there is an on-time difference of up to a factor of 2 between the maximum daylight hours of summer solstice (June and July months) and the minimum daylight hours of winter solstice (December and January). Regardless of season, the peak lighting use is in the evening with a second, lower peak in the early morning hours. As the seasons vary from summer to winter and back, the evening peak shifts earlier in the evening from 9:00 p.m. to 6:00 p.m., while the morning peak stays relatively stable between 7:00 a.m. and 8:00 a.m. Note that all the times are reported in local time at a given site regardless of time zone and daylight savings time.

Figure 51. Hourly On-time Profile by Month



In Figure 52, the same data are aggregated *by day* for all monitored fixtures. The graphic illustrates the systematic change in lighting on-time across the year. The predictive fit is a modified sine function. The parameters of this fit are shown at the bottom of Figure 52. The fit shows the annual variation in on-time to be ±0.5 hours about the mean. Overall, that is a variation from 1.3 hours/day in the summer to 2.3 hours/day in the winter. For the graph, the lighting runtime is unweighted in regard to the full metered population – it is the monitored fixtures only. Because the driver of lighting use on an annual basis is the daily hours of sunlight, the amplitude and form of this fit is applicable across the unmetered fixtures in RBSA Metering sites and the RBSA as a whole.

Figure 52. Average Daily On-time, Annual variation



3.6.3.1. Annual Variation in Time of Use Compared

Like the analysis here, the California study used a metered on-time sample to derive the aggregate on-time across a representative sample of buildings (KEMA 2010). In that study, no cohort of the analysis was metered more than six months, and generally the metering period was about four months. On the other hand, more than 1,200 houses were visited, and about seven lighting fixture groups were metered at each site. The metering took place over a year and a half in four “waves” which were smaller, independent samples scattered across the California service territories.

In the California study, in order to derive the annual on-time for the lighting systems monitored, the metered portions of each house were fit with a sine function that was designed to accommodate the variations in on-time in each sample wave caused by metering at differing times of year. The function, fit empirically to the variations observed in the partial year data, was essentially a single parameter that allowed the on-times to be extended to the entire year. Although the form of the equation is similar to the equation shown in Figure 52, there are some differences. The important distinction is that the results of RBSA Metering are annual and are used to scale the load shape over the year. The California study approach was to observe portions of the year and meld them together to get an annual picture. The functional fit to that data shows a variation of ±0.3 hours/day about the mean, which is 40% less than observed in RBSA Metering. It is important to keep in mind the relative locations of California and the Pacific Northwest. The variation in amplitude is smaller in California, as would be expected from a population that is about 12º further south.

Figure 52 plots both a single sine term and full model fit. The single term fit is similar to the one KEMA used with the yearly minimum on-time fixed at the summer solstice. Accordingly, the maximum occurs on the winter solstice. The full model fit, which ends up employing three terms, shows that the measured on-time patterns are at a minimum 2.5 weeks after the summer solstice. The maximums are identical. Further, the shape of the full model fit shows the average on-time never dips as low as the single model fit would predict. Accordingly, the peak is also higher. Largely, the two fits agree, but the full model provides a more nuanced view into the seasonal load shape patterns.

3.6.4. Lighting Energy Use

Lighting energy use is inferred from the combination of lighting power from the detailed lighting audit for each house and on-time measured by dataloggers. Table 80 summarizes the measured energy use, the predicted RBSA Metered site use, and the predicted use for the full RBSA population (essentially the average house in the Northwest). Approximately 600 kWh/yr of lighting energy was directly metered by our loggers. The on-time extrapolation shows that a total of 2,200 kWh/yr was used in the entire house for lighting across the metered sites. Combining the measurements shows that 27% of all lighting energy was directly metered. Making further extrapolations to the full RBSA single-family dataset shows that, based on the current lamp type mix, Pacific Northwest houses use on average 1,900 kWh/yr for lighting.

Table 80. Lighting Energy Use – Measured and Predicted

Sample	Lighting Energy Use (kWh/yr)		
	Mean	EB	n
Metered Lighting	586	60	92
RBSA Metered Sites	2,198	139	94
Full RBSA Population	1,914	36	1,266

3.7. Whole-House Energy Use

3.7.1. Total Energy Use

The complete picture of how houses use energy emerges from the component end uses and the total metered energy. Both the total amount of energy used on site and the relative distribution within the residence are of interest. As with all other sections of the report, energy is reported in terms of that consumed on site. Throughout the section, the sites are commonly divided by the primary heating system: electric-only sites and gas primary heating sites. Notably, there was no site that used gas for just water heating or cooking. In other words, if there was natural gas at the site, it was always used as the primary heating fuel. Appendix 8 shows the electric service load shapes. Total site energy use by fuel type is:

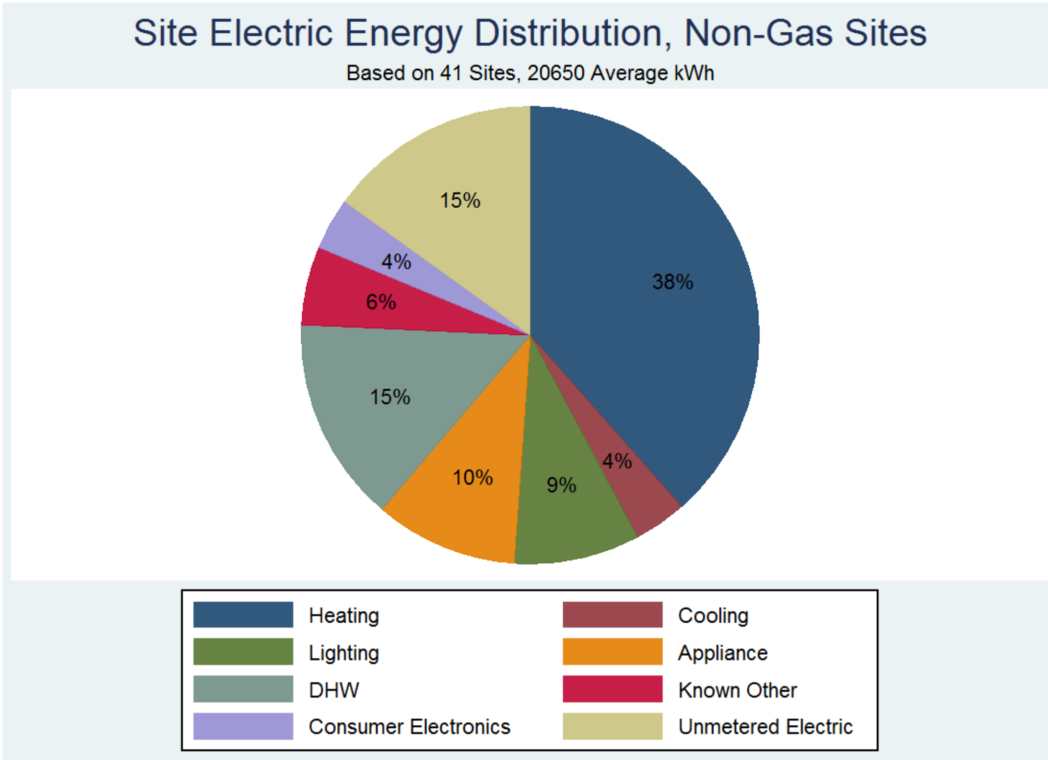
- 41 electric-only sites: 20,650 kWh/yr ± 1,337 kWh/yr
- 57 gas primary heat sites:
    - 663 therms/yr ± 39 therms/yr and
    - 9,541 kWh/yr ± 592 kWh/yr

To encompass total site energy at the gas primary sites, it is necessary to track both the gas and electric end uses. In the case of these homes some of the electricity use is the result of electric DHW loads in those homes. This group represents about 20% of the homes with gas heating.

3.7.2. Relative Energy Consumption by End Use

When examining the energy consumption of various end uses relative to one another, it is important to keep in mind distinctions between houses with and without natural gas service. Because the metered data are all site energy, including gas in the makeup will greatly change the distribution. Figure 53 shows the relative distribution of energy among 8 categories for the 41 all-electric sites in the study. Of the 20,650 kWh/yr used for the entire house, 42% goes to space conditioning. Only one tenth of that energy is used for cooling. After space conditioning, the next biggest load, as expected, is water heating. Appliances and lighting constitute equal shares.

Figure 53. Whole House Energy Distribution – Electric-Only Sites



"Consumer Electronics" are defined as the familiar group of plug-in devices inside the house including televisions, television accessories, set-top boxes, gaming consoles, DVD players, computers, computer accessories, and stereos. The "Known Other" category includes miscellaneous large loads like hot tubs, well pumps, sump pumps, and electric cars plus some other electronics like microwaves and aquarium accessories. The miscellaneous large loads group dominates the energy use of the "Known Other" category. A commonality between the "Known Other" loads is that, with few exceptions, they all occur outside the building envelope. That is, they are plug-loads but do not contribute to internal house heat gains.

The "Unmetered Electric" category consists of all the final residual energy at the houses. That is, this category is electricity measured as part of the total house service but not captured as a known, individual load. Overall, at the 41 electric-only houses, the unknown portion was 15% of the total, or about 3,000 kWh/yr.

Table 81 shows the detailed breakdown of the all-electric sites. It adds two categories not included in the pie graph (“unmetered” heating and “unmetered” cooling). The figures for these categories are estimated by a VBDD regression applied to the residual electricity use.

Table 81. Whole-House Energy Distribution – Electric-Only Sites

category	Energy for Electric-Only Sites (kWh/yr)		
	Mean	EB	n
Appliance	2086	183	41
Cooling	719	242	41
DHW	3005	224	41
Heating	7068	835	41
Known Other	1143	473	41
Consumer Electronics	755	73	41
Lighting	1836	165	41
Unmetered Electric	3108	497	41
“Unmetered” Cooling	51	31	41
“Unmetered” Heating	880	396	41
Total	20650	1337	41

Figure 54 shows the distribution of both electric and gas energy use for houses that use natural gas. The same 8 electric categories as in Figure 53 are shown in Figure 54 plus another chart with three slices for gas consumption. Houses in the metering study have various combinations of space heating and water heating fuel. For instance, some with gas furnaces had electric water heaters. Further, those houses supplemented the gas heating system with electric heat sources in a few cases (e.g. dual fuel heat pumps) which used both gas and electric heat within the same year. Thus, DHW and heating show up in both the electric and gas pies. The unmetered gas slice consists primarily of fireplaces, dryers, and cooking ranges.[15] Table 82 gives the detailed energy breakdown for all the gas primary sites.

[15] Most but not all fireplaces were metered.

Figure 54. Whole House Energy Distribution – Gas Primary Heating Sites

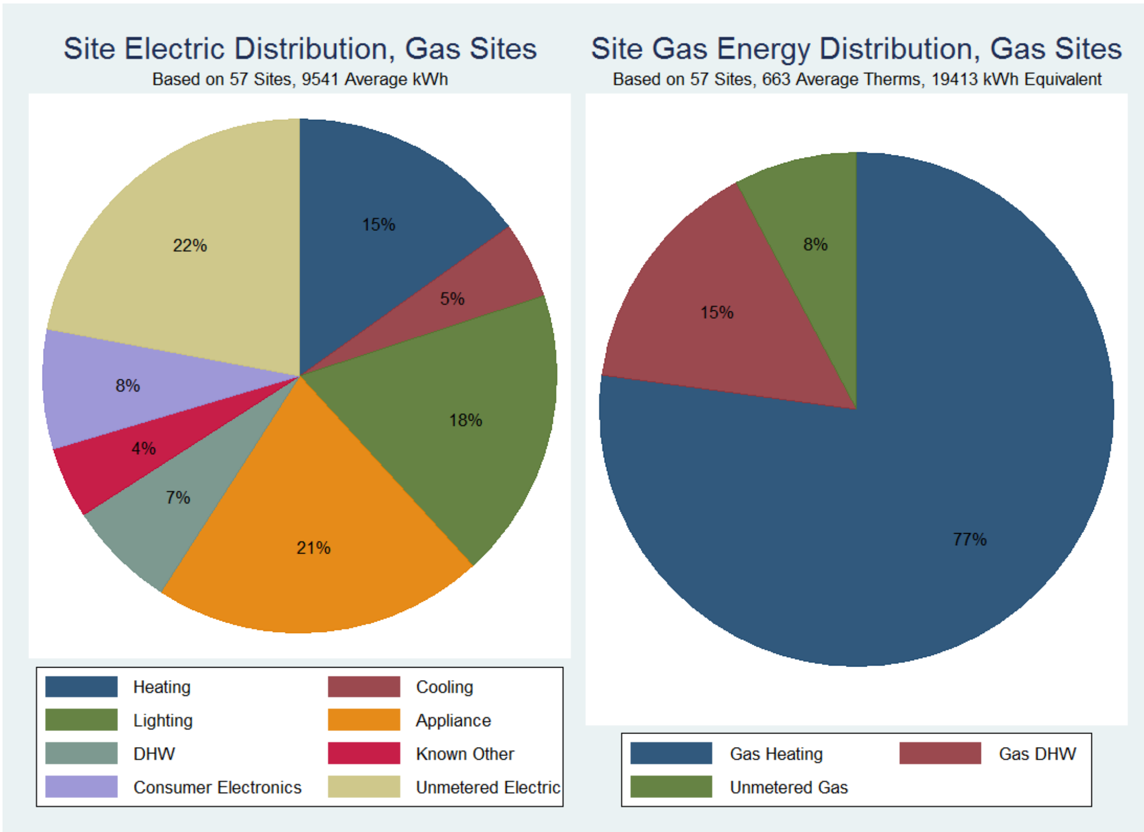


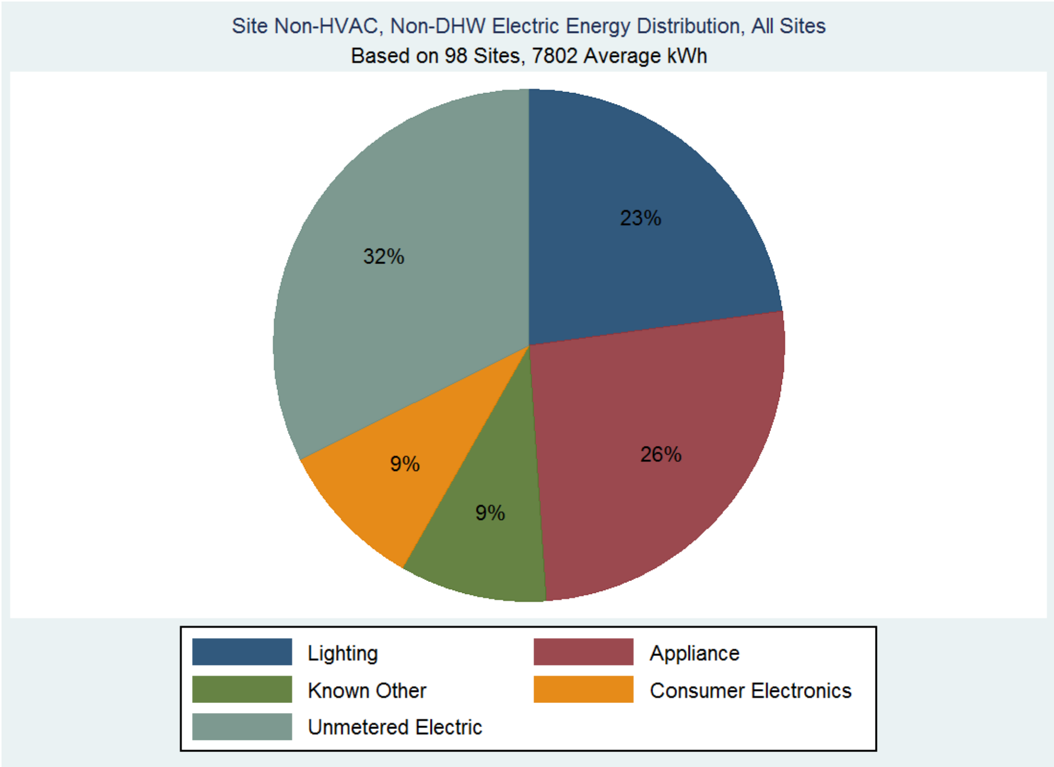
Table 82. Whole-House Energy Distribution For Gas-Primary Heating Sites

Category	Gas Energy for Gas-Primary Sites (therms/yr)		
	Mean	EB	n
Gas Heating	511	52	57
Gas DHW	100	12	57
Unmetered Gas	52	50	57
Total Gas	663	39	57

Category	Electric Energy for Gas-Primary Sites (kWh/yr)		
	Mean	EB	n
Appliance	1992	151	57
Cooling	371	91	57
DHW	649	167	57
Heating	1054	150	57
Known Other	429	138	57
Consumer Electronics	717	90	57
Lighting	1748	105	57
Unmetered Electric	2106	327	57
“Unmetered” Cooling	87	34	57
“Unmetered” Heating	387	97	57
Total Electric	9541	592	57

To better understand electricity usage beyond the dominant loads of space conditioning and water heating, Figure 55 shows the distribution of lighting, appliances, consumer electronics, "Known Other", and unmetered electric loads across all sites. In round numbers, the total of this electric consumption, common to all houses regardless of fuel type, averages nearly 8,000 kWh/yr. Within the pie, appliances and lighting are roughly one quarter each, consumer electronics and known other are one tenth, and the unknown loads are one third.

Figure 55. Non-Space Conditioning, Non-Water Heating Electric Loads



Comparing Table 81 and Table 82 shows that the unknown electric residual is about 3,000 kWh for all electric sites and 2,000 kWh for gas sites. The difference of 1,000 kWh/yr is intriguing since the other electric end uses of lighting and appliances are similar between electrically heated and gas heated sites. When Ecotope split the houses based on zonal heat and central systems (both electric and gas), the 1,000 kWh/yr spread persists. Although, by definition, what the electricity is used for is unknown, it is likely that the occupants are using it for additional, supplemental heating. We offer two ideas on why there is more unknown residual electricity usage in primary electric-heated houses (vs primary gas-heated houses). These ideas center around the use of unmetered 120 VAC electric space heaters.

First, gas heating systems typically cost one third the amount to operate as an electric resistance heat source. Gas furnaces are also central systems providing more even heat to the entire house. Therefore, less use of transitory electric space heat should be expected. Second, we theorize that many site occupants operate one or more unmetered space heaters at many times of the year, even during non-heating weather. (Ecotope attempted to monitor all plug-in space heaters but it is likely that there are many sites where heaters were added later or were moved around from their original location.) Electric space heaters have poor thermostatic control and tend to be controlled more by occupant whim than by outdoor temperature. The VBDD analysis would not pick up this type of heating. Consequently, there is circumstantial evidence to believe the 1,000 kWh/yr is used for space heating in the electric houses. This load however was sufficiently intermittent that no strong temperature dependence could be observed.

4. Conclusions

RBSA Metering is a project of unusually large scope in a region already uncommonly committed to large-scale primary research. Its goals are broad: update a swath of load shapes for the first time in twenty-five years, assess the major determinants of residential energy use, and identify opportunities for energy savings for programs across the region.

The project lays the foundation for updating the region's approach to a whole host of subjects including load forecasting, wind integration, capacity planning, demand response, the smart grid, and energy efficiency. All the topics benefit from, if not require, direct time-of-use measurements of energy use. Work by Ecotope and the RTF suggests the need to monitor 350-550 sites to obtain statistically representative results across the Northwest (KEMA 2012). The 100 sites in RBSA Metering is a sizable start for some end uses (HVAC), while for others (appliances and lighting) it may be sufficiently comprehensive to be representative.

This report on the RBSA Metering project is as much a window into the analytical possibilities created by the RBSA Metering dataset as it is a stand-alone document. The dataset, to be delivered shortly after the report, is a rich trove of energy and energy-related measurements at over one hundred houses spanning more than a year. Aggregated at fifteen minute intervals, the data not only show total energy use but the time of the use for all the devices monitored. Given the breadth and depth of the dataset, the analytical possibilities are nearly boundless and are likely to provide fodder for investigations for years, if not decades, to come.

4.1. Highlighted Findings

Several findings, ranging from cooling energy, gas load shapes, DHW load shapes, refrigerator time of use, lighting system on time, to heat pump operation highlight the relevance of the data to meeting project objectives and regional need. The study shows that cooling energy remains a fraction (one tenth) of the energy used for heating. Still, the load in severe cooling climates can be important for utilities concerned with summer peak. The gas load shapes provide new information on when gas is used. The measurements demonstrate that although gas furnaces and water heaters are similar to their electric resistance counterparts, they have higher peaks (explained by higher output capacity).

In the DHW instance, the load shapes show when water heating energy is currently used and inform how it could be shifted off-peak to avoid grid capacity constraints. Importantly, the DHW load shape is different from the older ELCAP shape. Consequently, making grid decisions on the old shape will lead to unexpected results.

The refrigerator data in the report verify the decline in annual energy use predicted by increasingly stringent federal standards. Further, the time-of-use information shows how and with what sort of benefit a "smart grid" enabled refrigerator could operate. Namely, the defrost cycle itself is a spike in energy use followed by an extended compressor runtime to offset the added heat. A smart appliance could choose (or be controlled) to run the defrost cycle not at random, but at off-peak times.

The lighting on-time and energy use findings are the first of their kind for the Northwest. The data suggest the average fixture on-time per house is 1.8 hrs/day. Previously, to estimate energy efficiency improvements from CFLs and LEDs, the region had to guess at on-time based on small studies within the Northwest or use studies from different geographic regions. Additionally, the lighting study shows when lights are used daily and how much during the year the usage changes.

The study of the 19 ducted, air-source heat pumps demonstrates there are still significant opportunities for efficiency improvements along the lines suggested by previous research (Baylon 2005). The following lists some, but not all, of the efficiency improvements still possible: increase nominal heat pump HSPF; size the compressor large enough for a heating climate; install outdoor temperature lockouts to prevent resistance heat from operating at mild temperatures; configure thermostat controls to run the compressor as the first stage of heating instead of wiring it simultaneously with the backup elements. All of these efficiency improvements are addressed by the PTCS specifications, but the metered data demonstrate that consistent, widespread program delivery (which includes review of system sizing before the heat pump is installed and skilled field verification of the installation) has yet to be achieved.

4.2. Future and Follow-On Studies

This report is only one of many possible deliverables from this research. By its nature and constraints, it only skims the surface of many topics. The other primary deliverable is a dataset which can be used by planners and analysts across the region and nationally to answer questions of their own. In addition, Ecotope has identified several topics of interest for follow-on work:

- Assess any biases in VBDD billing analysis by comparing the method to daily metered heating energy. The assessment could be conducted for every heating system type to see if there are differences between groups. The analysis would be an important assessment of the VBDD method (which is a critical tool in many conservation program evaluations).
- Expand the analysis of both heating and cooling energy use to sites with multiple fuel sources. The current report considers houses with only one heating type while excluding the more complicated mixed gas, electric, and wood heated sites. Expanding the analysis would increase the understanding of how houses use multiple fuel types.
- Extend the weather normalization model to predict heating and cooling response on a sub-daily basis. The current report only creates generalized heating load shapes on a daily scale but utility system peaks occur at hourly and sub-hourly timescales. Improving the method and techniques of taking real, measured data and applying it to any weather pattern would create better predictive tools for load forecasting.
- Examine coincident demand of cross-over categories including DHW and HVAC. For emerging technologies that combine traditionally separate end-uses into a single device, it is useful to see how they might interact or conflict.
- Expand the metered site count of all HVAC system types. Currently, the only category with a lot of sites is gas furnace. Making generalizations from a small sample size is

undesirable. Adding more heat pumps, electric furnaces, and electric baseboards would allow for greater generalization.

- Deploy lighting loggers at 10-20 houses to completely monitor every light in the house. Measuring all of the lights, instead of a sub-population, would provide a valuable reassessment to average on-time estimates.
- Use all the measured data to update standard simulation inputs, including internal gains, temperature set points, and schedules used in the Northwest by the RTF. Current, standard simulation inputs have been reasonable; however, improving the accuracy of the inputs will improve the accuracy of the answers. Further, as household energy use changes from one end use category to the next, the inputs can change. To stay current, inputs should be updated periodically.
- Create detailed computer simulations of all the houses and compare the model outputs to the measured values. As with the inputs, simulations should be constantly checked for accuracy so they can improve and make reliable predictions.
- Analyze all indoor temperature data to understand occupant settings and schedules. The heating and cooling energy time-of-use is closely tied with indoor temperature settings. This study only measured one indoor temperature, but future studies could measure indoor temperatures in multiple rooms, which is of especial interest for certain primary heating system sites. A full assessment of the indoor and outdoor temperature measurements should be conducted to support the development of simple engineering models and complex computer simulations.
- Perform a more focused study on heat pumps (with more sites). A more detailed review of the system controls (beyond the scope of what could be accommodated in RBSA Metering) would be the primary focus. An iterative, experimental approach where one changed control settings or duct characteristics to examine how much effect this had on site heating consumption would also prove worthwhile. Inclusion of SEEM runs as part of this project would add additional insight and assist in recalibrating regional models of heat pump savings used by the RTF.
- Explore Power Factor at the house level and the individual load level. The RBSA Metering report focused on energy but the dataset contains detailed power factor measurements. Power Factor at the individual load level show how certain devices like heat pump compressors behave compared to resistance heaters. Knowing the difference will help utilities adapt to changing loads. At the house level, the Power Factors can be linked to different utility meter types, be they older mechanical meters or modern electronic meters, to fully understand how each deals with Power Factors different from unity. An expanded Power Factor study could also examine finer details such as the lead-lag characteristics or could compare Apparent Power Factor to Displacement Power Factor.
- Use the measured data to update end use load shape data used for power planning, rate-making, demand-response, etc. Compare daily and hourly load shapes from RBSA to ELCAP to determine which end use load profiles have changed and to what degree.

References

Baylon, D., P. Storm, K. Geraghty, and B. Davis. 2012. *Residential Building Stock Assessment: Single-Family Home Characteristics and Energy Use*, Prepared for Northwest Energy Efficiency Alliance. Portland, OR. http://neea.org/docs/reports/residential-building-stock-assessment-single-family-characteristics-and-energy-use.pdf

Baylon, David, B. Larson, P. Storm, K. Geraghty, May 2012. *Ductless Heat Pump Impact & Process Evaluation: Field Metering Report*. Prepared for the Northwest Energy Efficiency Alliance.

Baylon, D., S. Strand, B. Davis, D. Robison and E. Kruse. 2005. *Analysis of Heat Pump Installation Practices and Performance*. Prepared for the Heat Pump Working Group, Portland, OR.

Bensch, I., S. Pigg, K. Koski, R. Belshe. 2010. *Electricity Savings Opportunities for Home Electronics and Other Plug-In Devices in Minnesota Homes.* Energy Center of Wisconsin, http://www.ecw.org/ecwresults/257-1.pdf

Brown, R., W. Rittelman, D. Parker, G. Homan, 2006. *Appliances, Lighting, Electronics, and Miscellaneous Equipment Electricity Use in New Homes.* Prepared for the American Council for an Energy-Efficient Economy (ACEEE) Summer Study.

End-Use Load and Consumer Assessment Program (ELCAP) Database. http://rtf.nwcouncil.org/ELCAP/

Fels, M. 1986. "*PRISM: An Introduction*," Energy and Buildings, Volume 9 (1986), pp. 5-18.

Geraghty, K. and D. Baylon. 2009. *Residential Ductless Mini-Split Heat Pump Retrofit Monitoring*, Bonneville Power Administration, Portland, OR.

KEMA, 2010. *Final Evaluation Report: Upstream Lighting Program*. Prepared for the California Public Utilities Commission. http://www.calmac.org/publications/FinalUpstreamLightingEvaluationReport_Vol2_CALMAC.pdf

KEMA 2012. *Building the Business Case: Implementing a Comprehensive Pacific Northwest Electric End-Use Data Development Project Management Report.* Prepared by KEMA, Inc. For Northwest Power and Conservation Council. 30 September 2012. http://rtf.nwcouncil.org/subcommittees/enduseload/RTF%20Executive%20Summary%2030%20SEP%202012%20v04-1.docx

Larson, B. and J. Uslan. 2013. *Ductless Heat Pump Billing Analysis Bias Assessment*. NEEA Report #13-262. http://neea.org/docs/default-source/reports/ductless-heat-pump-impact-process-evaluation--billing-analysis-report.pdf?sfvrsn=6

Maruejols, L., and D. Ryan. 2011. *Measurement in Retail Stores of Standby Power Consumption of Household Electrical Appliances.* For Natural Resources of Canada.

Northwest Energy Efficiency Alliance, Residential Building Stock Assessment Data Resources. http://neea.org/resource-center/regional-data-resources/residential-building-stock-assessment

Northwest Power and Conservation Council. 2010. *Sixth Northwest Conservation and Electric Power Plan*. Appendix F. Portland, OR. http://www.nwcouncil.org/media/6308/SixthPowerPlan_Appendix_F.pdf

Northwest Power and Conservation Council. September, 2012. *Regional Technical Forum 2011 Annual Report and 2012 Progress Update*. More in-depth information can be found at http://rtf.nwcouncil.org/

NSRDB. 2008. *National Solar Radiation Database 1991-2005 Update: Typical Meteorological Year 3.* Prepared by National Renewable Energy Lab. http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/

Palmiter, L. June 1982. *Potential for Conservation of Electrical Energy in Northwest Residences.* Prepared for Pacific Northwest Laboratory.

Perlman, M., and B.E. Mills. 1985. *Development of Residential Hot Water Use Patterns*. ASHRAE Transactions, Volume 2a.

Pigg, S. and D. Cautley, 2010. *Energy Use by Residential Gas Water Heaters: A Technical Field Study in 10 Wisconsin Homes*. Wisconsin Energy Center. http://www.ecw.org/resource_detail.php?resultid=452

Pratt, R., et al., December, 1990. *Significant ELCAP Analysis Results: Summary Report. End Use and Consumer Assessment Program*. Pacific NW National Laboratory, Report PNL-6659. Prepared for Bonneville Power Administration under Related Services Agreement for US Dept. of Energy, Contract DE-AC06-76RLO-1830.

Pratt, R.G., C.C. Conner, E.E. Richman, K.G. Rigland, W.F. Sandusky, M.E. Taylor, 1989. *Description of Electric Energy Use in Single-Family Residences in the Pacific Northwest, End-Use Load and Consumer Assessment Program*. Prepared for the U.S. Department of Energy under contract DE-AC06-76RL0 1830.

Quaid, M., R. Kunkle, and B. Lagerberg. August 1991. *RCDP Cycle 2 Appliance Analysis*. Washington State Energy Office.

Regional Technical Forum. 2007. *Performance Tested Comfort Systems - Air-Source Heat Pump System Installation Standards.* 15 April 2007. Can be accessed at: http://www.bpa.gov/energy/n/residential/ptcs/ASHP_Specifications_2007_with_2011_mark-up.pdf

Reichmuth, H., D. Robison and B. Davis. 2005. *High Efficiency Heat Pump Monitoring Project.* Draft Final Report. Prepared for Oregon Department of Energy and Northwest Power and Conservation Council.

Roos, C. and D. Baylon. May 1993. *Non-Space Heating Electrical Consumption in Manufactured Homes, Residential Construction Demonstration Project Cycle II*.

Tribwell, L. and D. Lerman, 1996. *Baseline Residential Lighting Energy Use Study*. Tacoma Public Utilities.

U.S. Census Bureau. *State and County QuickFacts*. http://quickfacts.census.gov/qfd/index.html

Appendix 1. Data Security

There are multiple layers of security at every level of the system so that data and participant privacy are protected. Within each site, the dataloggers, networking equipment, and wireless networks are all locked down to prevent access. The network between the sites and Ecotope is a private network, so unauthorized access is not available from the public Internet. In addition, there are firewalls both at the entrance to the house and at the gateway to Ecotope's servers. The network runs over a virtual private network (VPN) to enhance security further.

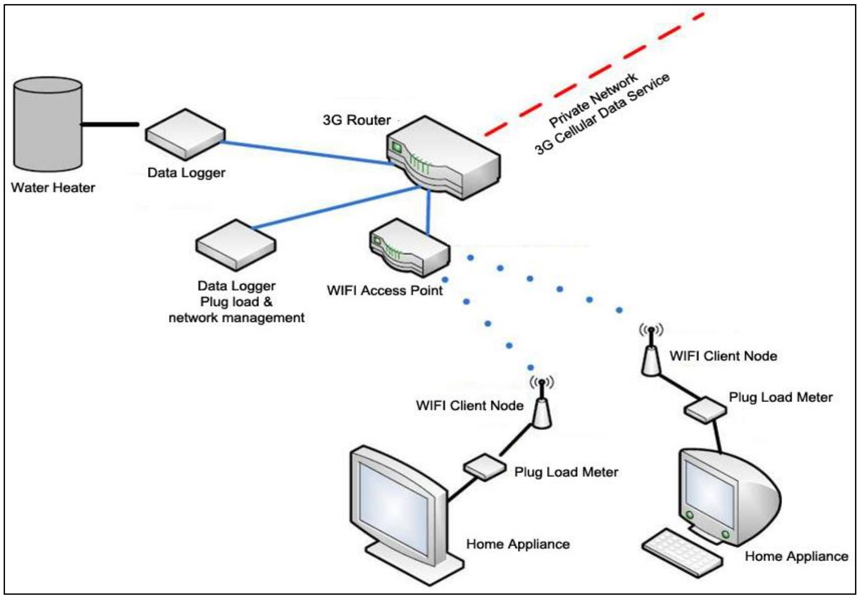
Site, datalogger, and sensor status is monitored continuously, primarily for network latency and uptime. Data streams are automatically checked for a variety of issues including unusual gaps and out-of-range values. Problem reports are generated automatically and reviewed by program staff. This monitoring system enables Ecotope to quickly address issues with equipment that may have broken or been moved by participants.

Many network issues can be handled remotely. The custom datalogger also acts as a management platform with tools that allow other networking equipment to be updated and fixed remotely. The ability to perform these tasks remotely delivers better overall uptime and reduces the number of site visits.

Redundancy is built into the system in a number of ways. The dataloggers store log files locally in addition to transmitting them to Ecotope's servers. If an issue arises with a file on the server end, the original can be manually retrieved. The two VPN servers that run the network each have the capacity to support the entire network on their own, so if one fails the network will not go down. The 3G router within the site can perform as a backup wireless router if the primary router fails.

The entry to the site is a 3G cellular router. The 3G router is connected to two dataloggers and a wireless router. One datalogger is an off-the-shelf product that manages the heating, domestic hot water (when heated with electricity), and any appliance that has a dedicated circuit at the electrical panel. Ecotope developed a parallel datalogger platform to support the plug load meters and provide a network management platform in the house. The wireless router runs the plug load network, directing traffic to the custom datalogger. Plug load meters communicate with the router via small wireless nodes. Figure 56 shows this network.

Figure 56. Metering System Architecture



The 3G routers connect via a private cellular data network to redundant VPN routers at Ecotope. Traffic is routed through a firewall before reaching Ecotope's servers. Because the network is a cellular data network and not a phone network, connections are always live; this factor allows active monitoring of equipment, which helps ensure data quality. Finally, as mentioned above, the network is private, with no access to the public Internet.

Appendix 2. End-Use Metering Methodology

Equipment	Metering Sensor	Logging Device	Logging interval	Values collected
Service entry (all electricity to house)	Dent PowerScout	Obvius Acquisuite	5 minutes	kW, kWh, kVa, kVAR, volts
HVAC				
Heat pumps				
Heat pump indoor unit	PowerScout	AcquiSuite	5 minutes	kW, kWh, kVa, kVAR, volts, volts
Heat pump outdoor unit	PowerScout	AcquiSuite	5 minutes	kW, kWh, kVa, kVAR, volts
Heat pump vapor line temperature	Veris temperature sensor	AcquiSuite	5 minutes	Average per period
Where possible, separate power of furnace fan	PowerScout	AcquiSuite	5 minutes	kW, kWh, kVa, kVAR, volts
Gas furnaces				
Gas furnace state (on/off); indicate if system in first or second stage by monitoring status of gas valve circuit (separate control circuit wire for each stage). Gas usage determined by clocking meter for each stage and also measuring combustion efficiency for each stage. Does not include modulating gas	Veris state sensor	AcquiSuite	5 minutes	Cumulative and per-period use; duty cycle

Equipment	**Metering Sensor**	**Logging Device**	**Logging interval**	**Values collected**
burners.				
Where possible, separate power of furnace fan	PowerScout	AcquiSuite	5 minutes	kW, kWh, kVa, kVAR, volts
Dual fuel systems: Combine above approaches				
Gas fireplaces				
Gas fireplace state (on/off); indicate status via thermocouple. Measure gas usage (one-time test).	thermocouple	AcquiSuite	5 minutes	Cumulative and per-period use; duty cycle
Water heat				
Electric water heaters	PowerScout	AcquiSuite	5 minutes	kW, kWh, kVa, kVAR, volts
Gas water heater state (on/off); indicate status via thermocouple in exhaust. Measure combustion efficiency and gas usage (one-time test). Does not include modulating gas burners.	thermocouple	AcquiSuite	5 minutes	Cumulative and per-period use; duty cycle
Temperature				
Indoor temperature (main living area)	Onset temperature datalogger (Pendant)	N/A	Hourly	Average per logging period Downloaded at the end of the annual metering

Equipment	Metering Sensor	Logging Device	Logging interval	Values collected
				period.
Outdoor temperature	Veris outdoor temp sensor	AcquiSuite	5 minutes	Average per period
Appliances				
Refrigerator	WattsUp	Plug load datalogger	5 minutes	kW, kWh, power factor
Dishwasher (if on dedicated circuit)	PowerScout	AcquiSuite	5 minutes	kW, kWh, kVa, kVAR, volts
Freezer	WattsUp	Plug load datalogger	5 minutes	kW, kWh, power factor
Clothes washer	WattsUp	Plug load datalogger	5 minutes	kW, kWh, power factor
Clothes dryer	PowerScout	AcquiSuite	5 minutes	kW, kWh, kVa, kVAR, volts
Well pump	PowerScout	AcquiSuite	5 minutes	kW, kWh, kVa, kVAR, volts
Spa	PowerScout	AcquiSuite	5 minutes	kW, kWh, kVa, kVAR, volts
Other major appliances of interest	WattsUp/ PowerScout depending on wiring	Plug load datalogger or AcquiSuite	5 minutes	kW, kWh, power factor if on WattsUp; kW, kWh, kVa, kVAR, volts if on

Equipment	Metering Sensor	Logging Device	Logging interval	Values collected
				PowerScout
Plug loads				
TVs	WattsUp	Plug load datalogger	5 minutes	kW, kWh, power factor
Set-top boxes	WattsUp	Plug load datalogger	5 minutes	kW, kWh, power factor
Gaming consoles	WattsUp	Plug load datalogger	5 minutes	kW, kWh, power factor
Other TV accessories	WattsUp	Plug load datalogger	5 minutes	kW, kWh, power factor
Computers	WattsUp	Plug load datalogger	5 minutes	kW, kWh, power factor
Computer peripherals	WattsUp	Plug load datalogger	5 minutes	kW, kWh, power factor
Window A/C units	WattsUp	Plug load datalogger	5 minutes	kW, kWh, power factor
Space heaters	WattsUp	Plug load datalogger	5 minutes	kW, kWh, power factor
Lights				
Average of 20 fixture groups per house	Lighting logger	N/A	State recorded with a date and time-stamp every time light turns on or off	On/off cycles Collected annually during the monitoring period

Appendix 3. Metering Process

Figure 57 shows a team lead assembling one of the boxes that contain the networking equipment and dataloggers. Figure 58 shows an assembled and installed equipment box. Because multiple sensors were located in the electrical panel, these boxes were generally located near the panel. Figure 59 shows a lighting logger attached to a light fixture.

Figure 57. Team Lead Assembling an Equipment Box

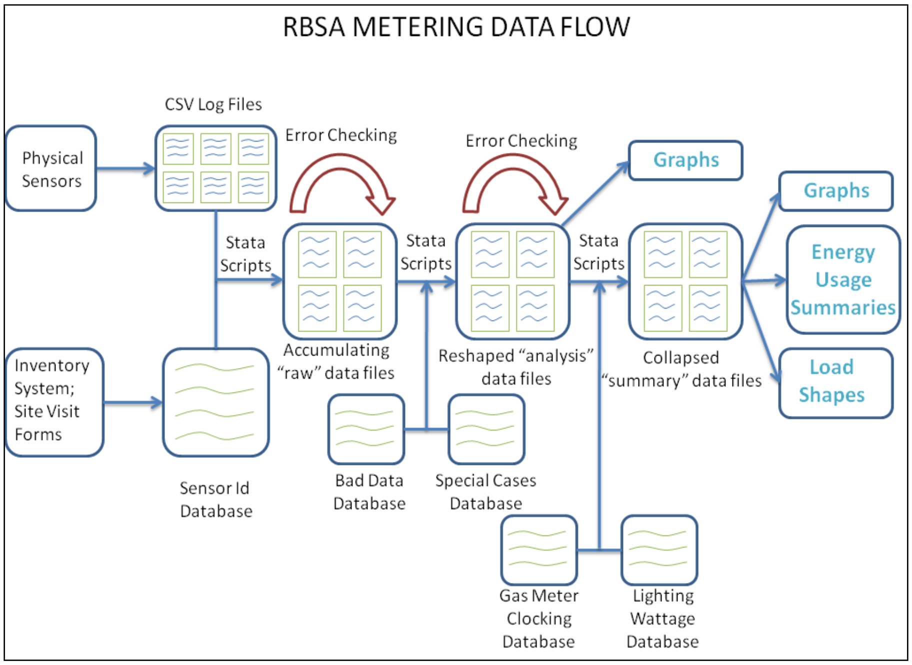
Figure 58. Equipment Box in Place

Figure 59. Lighting Logger in Place

Appendix 4. Data Flow and Quality Checks

The flowchart in Figure 60 depicts how data flow from raw sensor data and site visit forms to deliverable analysis materials. The process starts with physical sensors in the field, which send raw data in comma-separated value (CSV) log files to Ecotope's servers. From there, the data are vetted, accumulated, rearranged, and eventually collapsed into high-level summaries and charts. Exploratory data analysis software and custom scripting routines are essential to this work. Very little data storage, cleaning, or analysis is done outside of these platforms.

Figure 60. RBSA Metering Data Flow



New data are uploaded to Ecotope's servers, and aggregation code runs once daily to incorporate the most recent data. The nightly processing code performs aggregation and error checking according to two general steps.

In the first step, new log files are opened, examined, and parceled accordingly into accumulating datasets, grouped by site ID and sensor type. Stray files and files lacking usable records are discarded. Data gaps, readings in violation of preset, credible bounds, and missing or stale sensors are recorded in a nightly error report.

In the second step, accumulating files for each site are merged together into a single analysis file of raw five-minute data, with known bad data removed and special cases computed. These files are referred to as the reshaped analysis files. Residual errors (e.g., instances where the sum of metered end uses exceeds the measured service load) are tabulated and recorded in the nightly error report, along with a summary of the data fraction acquired and service fraction metered. The reshaped analysis files store the data in physically meaningful categories such as temperature, power, and time. Graphing routines referencing these files help analysts visualize the incoming data. These graphing routines prove valuable in investigating problems flagged by the error reports.

Examining each piece of raw five-minute data, even visually, quickly becomes overwhelming. Broader trends are investigated with a third analysis step, which involves collapsing the reshaped files into hourly, daily, weekly, monthly, and yearly summaries. In addition to aggregating by a coarser unit of time, all measurements of on-time from the reshaped files are converted into energy, which includes lighting and gas devices. Lighting wattages and gas appliance energy input rates are merged with the reshaped files before time aggregation. The broader time scales of the collapsed summary files assist in summarizing energy use patterns and creating end-use load shapes.

An exception to the automated file uploads and near real-time data collection are the lighting loggers, which do not upload data automatically. Each lighting logger data download includes time synchronization, to ensure that the loggers are correctly recording time, which is the basis of alignment with other data. After each download, aggregation code accumulates, reshapes, and collapses the most recent lighting data in a manner virtually identical to the continuously updating data.

The specific errors encountered are summarized and then sent to project staff in nightly reports (spreadsheet format). Gaps in the data and non-responsive sensors may indicate hardware failure, a weak wireless signal, or the fact that a participant moved or unplugged a sensor. Range checks, in which recorded values are examined against credible bounds, often indicate a malfunctioning sensor or a post-processing multiplier that must be applied or adjusted. For instance, we never expect outside air temperature to be colder than -50°F or warmer than 120°F. Power measurements should never drop below zero. Likewise, extreme energy usage data (for example, a gaming system recorded as drawing 4 kilowatts (kW)) also indicates a measurement error. Errors of this sort are bundled into the nightly report. These range checks are performed with a power "snapshot," rather than average power over the five-minute logging interval, and sometimes deliver false positives in the case of devices with motors, capturing inrush current at startup. Range violation requirements have been relaxed accordingly for devices such as gas furnace air handlers, in which we expect high inrush currents to occur periodically. Residual violations, where the metered end-use power draws add up to a value greater than the whole-house service power draw, also indicate malfunctioning sensors or incorrect post-processing multipliers.

In addition to the automated error checking, Ecotope also performs quality control spot checks. This step involves analysts examining selected sites and sensors at random intervals. Typically, the analyst visualizes the data through various graphing routines to see if the data spin a believable narrative. For example, television usage that peaks at 1:00 p.m. and is virtually zero at 9:00 p.m. would bear further investigation. It might be an accurate pattern if the house is occupied during the day, but it does not fit with "prime-time" viewing habits. Therefore, it might indicate a time synchronization error. This approach is very time-intensive and so is used sparingly, but it can sometimes find issues missed by the automated error routines or lead to the development of additional automated routines. Next, analysts also visually inspect site data after the automated error checks alert them to potential problems. Data plots allow the analyst to home in on the error and direct field staff to the specific problem, which can then be targeted in a site repair visit.

A network monitoring system tests individual dataloggers and sensors for responsiveness at each site on a daily (or more frequent) basis. This provides a backup to the automated error checking routines that can alert the team quickly if there are site-wide issues that need to be addressed immediately. Reporting sensors can also be correlated against sensors recorded in the database to ensure the accuracy of the database.

Appendix 5. Site Characteristics

Site Energy Use

The annual weather normalized energy use in utility fuels was calculated for all usable billing data in the RBSA single-family study. Table 83 through Table 88 compare RBSA energy use to the metered energy use in RBSA Metering. Table 83 and Table 84 show the total utility energy use (kWh and therms) converted to a kWh equivalent. The energy use in metered sites is slightly higher than RBSA values for overall and electric use, and slightly lower (with the exception of the eastern region) for gas use. However, these differences fall within the error bounds of the samples for most of the energy use described in these tables.

Table 83. Utility Fuel Normalized Annual Use in kWh Equivalents by Region (RBSA Single-Family)

Study Region	Total Normalized kWh Equivalent Use of Utility Fuels by Region, RBSA SF		
	Mean	EB	n
Puget Sound	24,404	1,242	458
Western Oregon	22,757	1,305	248
Eastern Region	25,104	1,072	446
All Regions	24,178	695	1,152

Table 84. Utility Fuel Normalized Annual Use in kWh Equivalents by Region (RBSA Metering)

Study Region	Total Normalized kWh Equivalent Use of Utility Fuels by Region, RBSA Metering		
	Mean	EB	n
Puget Sound	26,205	1,776	36
Western Oregon	21,962	1,887	30
Eastern Region	27,264	2,181	35
All Regions	25,312	1,145	101

Table 85. Normalized Annual Electric Use by Region (RBSA Single-Family)

Study Region	Total Normalized Electric Use kWh, RBSA SF		
	Mean	EB	n
Puget Sound	11,551	635	458
Western Oregon	11,367	649	248
Eastern Region	14,143	791	448
All Regions	12,415	406	1,154

Table 86. Normalized Annual Electric Use by Region (RBSA Metering)

Study Region	Total Normalized Electric Use kWh, RBSA Metering		
	Mean	EB	n
Puget Sound	13,033	1,873	36
Western Oregon	12,339	1,066	29
Eastern Region	15,486	1,832	35
All Regions	13,690	981	100

Table 87. Normalized Annual Gas Use by Region (RBSA Single-Family)

Study Region	Total Normalized Annual Gas Use therms, RBSA SF		
	Mean	EB	n
Puget Sound	769	43	272
Western Oregon	639	46	119
Eastern Region	724	39	216
All Regions	714	25	607

Table 88. Normalized Annual Gas Use by Region (RBSA Metering)

Study Region	Total Normalized Annual Gas Use therms, RBSA Metering		
	Mean	EB	n
Puget Sound	689	54	23
Western Oregon	596	52	17
Eastern Region	813	74	18
All Regions	700	36	58

Vintage

Overall, the percentage of older houses is similar in the RBSA Metering and RBSA single-family samples (Table 89 and Table 90). However, there are some variations in a few vintage bins for the subregions. For example, there are more pre-1951 houses in the Puget Sound metered sample. Across all regions, about 65% of the houses were built prior to 1981. These older houses, constructed prior to the advent of energy codes in the Northwest, represent the majority of houses across all regions and tend to have lower insulation levels and more air infiltration than newer houses.

Table 89. Vintage Distribution (RBSA Single-Family)

Vintage		House Vintage, RBSA SF				
		Puget Sound	Western Oregon	Eastern Region	All Regions	n
Pre 1951	%	26.9%	24.1%	18.3%	23.0%	327
	EB	3.0%	5.5%	3.8%	2.3%	
1951-1960	%	8.3%	11.5%	10.0%	9.8%	118
	EB	2.2%	4.1%	3.2%	1.8%	
1961-1970	%	15.1%	14.7%	8.0%	12.4%	142
	EB	3.1%	4.4%	2.8%	2.0%	
1971-1980	%	14.3%	17.2%	20.4%	17.3%	189
	EB	3.2%	4.6%	4.4%	2.3%	
1981-1990	%	13.5%	9.4%	8.6%	10.6%	110
	EB	3.2%	3.7%	2.9%	1.9%	
1991-2000	%	8.6%	12.1%	18.1%	13.0%	143
	EB	2.7%	4.2%	4.1%	2.1%	
Post 2000	%	13.4%	11.0%	16.6%	13.9%	165
	EB	3.2%	4.0%	3.2%	2.0%	
All Vintages	%	100.0%	100.0%	100.0%	100.0%	1,194
	EB	0.0%	0.0%	0.0%	0.0%	

Table 90. Vintage Distribution (RBSA Metering)

Vintage		House Vintage, RBSA Metering				
		Puget Sound	Western Oregon	Eastern Region	All Regions	n
Pre 1951	%	40.5%	20.0%	16.2%	26.0%	27
	EB	2.2%	2.2%	1.6%	0.7%	
1951-1960	%	2.7%	10.0%	16.2%	9.6%	10
	EB	0.7%	1.6%	1.6%	0.5%	
1961-1970	%	10.8%	10.0%	5.4%	8.7%	9
	EB	1.4%	1.6%	1.0%	0.4%	
1971-1980	%	13.5%	30.0%	18.9%	20.2%	21
	EB	1.5%	2.5%	1.7%	0.6%	
1981-1990	%	5.4%	10.0%	5.4%	6.7%	7
	EB	1.0%	1.6%	1.0%	0.4%	
1991-2000	%	8.1%	13.3%	24.3%	15.4%	16
	EB	1.2%	1.9%	1.9%	0.6%	
Post 2000	%	18.9%	6.7%	13.5%	13.5%	14
	EB	1.7%	1.4%	1.5%	0.5%	
All Vintages	%	100.0%	100.0%	100.0%	100.0%	104
	EB	0.0%	0.0%	0.0%	0.0%	

Ground Contact

The metered sites have a higher prevalence of mixed foundations with crawlspaces and conditioned basements, particularly in western Oregon and Puget Sound (Table 91 and Table 92). In parallel, conditioned floor area is slightly greater in these regions. Overall, 41% of metered sites have some portion of conditioned basement, versus 32% in the region as a whole. However, when error bounds are considered, this difference drops to about 4%. Additionally, in the western Oregon sample, crawlspace houses were underrepresented when compared with the region as a whole by 15%, though some of this difference is mitigated by an increase of partial crawlspace houses with other unconditioned space of about 17%.

Table 91. Distribution of Ground Contact (RBSA Single-Family)

Ground Contact Type		Percent of House Foundations, RBSA SF				
		Puget Sound	Western Oregon	Eastern Region	All Regions	n
>90% Crawlspace	%	50.5%	55.5%	34.4%	46.1%	481
	EB	4.5%	6.5%	5.0%	3.1%	
>90% Slab	%	7.2%	4.2%	11.3%	7.8%	84
	EB	2.6%	2.6%	3.2%	1.7%	
>90% Conditioned Basement	%	18.3%	12.6%	33.3%	22.1%	277
	EB	3.2%	4.5%	5.0%	2.5%	
>90% Unconditioned Basement	%	1.3%	1.2%	0.8%	1.1%	16
	EB	0.9%	1.4%	0.6%	0.6%	
Adiabatic Space Below	%	1.0%	0.3%	1.2%	0.9%	11
	EB	1.0%	0.4%	0.9%	0.5%	
Mixed Crawlspace and Conditioned Basement	%	6.4%	8.7%	13.1%	9.5%	114
	EB	1.6%	3.7%	3.7%	1.8%	
Mixed Crawlspace and Other Unconditioned	%	15.2%	17.4%	5.9%	12.5%	134
	EB	3.4%	5.0%	1.8%	2.0%	
All Types	%	100.0%	100.0%	100.0%	100.0%	1,117
	EB	0.0%	0.0%	0.0%	0.0%	

Table 92. Distribution of Ground Contact (RBSA Metering)

Ground Contact Type		Percent of House Foundations, RBSA Metering				
		Puget Sound	Western Oregon	Eastern Region	All Regions	n
>90% Crawlspace	%	41.9%	40.0%	35.1%	38.8%	38
	EB	2.6%	2.7%	2.1%	0.8%	
>90% Slab	%	—	3.3%	10.8%	5.1%	5
	EB	—	1.0%	1.4%	0.4%	
>90% Conditioned Basement	%	22.6%	13.3%	35.1%	24.5%	24
	EB	2.2%	1.9%	2.1%	0.7%	
>90% Unconditioned Basement	%	—	—	2.7%	1.0%	1
	EB	—	—	0.7%	0.2%	
Adiabatic Space Below	%	—	—	2.7%	1.0%	1
	EB	—	—	0.7%	0.2%	
Mixed Crawlspace and Conditioned Basement	%	19.4%	20.0%	10.8%	16.3%	16
	EB	2.1%	2.2%	1.4%	0.6%	
Mixed Crawlspace and Other Unconditioned	%	16.1%	23.3%	2.7%	13.3%	13
	EB	2.0%	2.3%	0.7%	0.6%	
All Types	%	100.0%	100.0%	100.0%	100.0%	98
	EB	0.0%	0.0%	0.0%	0.0%	

Cooling Systems

The distribution of cooling systems did not vary appreciably between the two studies (Table 93 and Table 94). Central air conditioning is the most prevalent cooling system choice in the eastern region, while heat pumps are preferred in Puget Sound.

Table 93. Distribution of Primary Cooling System by Region (RBSA Single-Family)

Cooling System Type		Primary Cooling System, RBSA SF				
		Puget Sound	Western Oregon	Eastern Region	All Regions	n
Central AC	%	23.9%	33.6%	57.2%	43.4%	158
	EB	9.2%	8.2%	6.8%	4.6%	
Ductless Heat Pump	%	7.8%	4.8%	0.7%	3.3%	18
	EB	5.7%	3.4%	0.7%	1.5%	
Dual Fuel Heat Pump	%	4.1%	4.9%	1.7%	3.2%	15
	EB	3.8%	3.8%	1.4%	1.6%	
Evaporative Cooler	%	–	–	3.5%	1.7%	10
	EB	–	–	2.1%	1.0%	
Ground Source Heat Pump	%	–	0.9%	1.2%	0.9%	10
	EB	–	0.9%	0.7%	0.5%	
Air Source Heat Pump	%	43.8%	28.9%	19.6%	26.9%	138
	EB	10.3%	7.7%	5.7%	4.2%	
Packaged Terminal Air Conditioner (PTAC)	%	–	–	–	–	21
	EB	–	–	–	–	
Window AC	%	16.4%	21.6%	12.5%	16.3%	78
	EB	7.1%	7.6%	4.1%	3.5%	
All Systems	%	100.0%	100.0%	100.0%	100.0%	446
	EB	0.0%	0.0%	0.0%	0.0%	

Table 94. Distribution of Primary Cooling System by Region (RBSA Metering)

Cooling System Type		Primary Cooling System, RBSA Metering				
		Puget Sound	Western Oregon	Eastern Region	All Regions	n
Central AC	%	7.7%	27.8%	56.7%	37.7%	23
	EB	3.4%	4.1%	2.7%	1.3%	
Ductless Heat Pump	%	15.4%	5.6%	3.3%	6.6%	4
	EB	4.6%	2.1%	1.0%	0.7%	
Dual Fuel Heat Pump	%	7.7%	5.6%	—	3.3%	2
	EB	3.4%	2.1%	—	0.5%	
Ground Source Heat Pump	%	—	5.6%	—	1.6%	1
	EB	—	2.1%	—	0.3%	
Air Source Heat Pump	%	38.5%	38.9%	23.3%	31.1%	19
	EB	6.2%	4.5%	2.3%	1.2%	
PTAC	%	15.4%	—	6.7%	6.6%	4
	EB	4.6%	—	1.4%	0.7%	
Window AC	%	15.4%	16.7%	10.0%	13.1%	8
	EB	4.6%	3.4%	1.6%	0.9%	
All Systems	%	100.0%	100.0%	100.0%	100.0%	61
	EB	0.0%	0.0%	0.0%	0.0%	

Water Heaters

Water heater fuel choice was consistent between the two studies, with electric heating chosen in about 50% to 60% of the cases (Table 95 and Table 96). The small fraction of the population with alternative fuels for water heating was not represented in the RBSA Metering study.

Table 95. Distribution of Water Heating Fuel by Region (RBSA Single-Family)

Water Heater Fuel		Percent of Water Heater Fuels, RBSA SF				
		Puget Sound	Western Oregon	Eastern Region	All Regions	n
Electric	%	50.8%	52.8%	56.4%	53.4%	703
	EB	4.4%	6.2%	4.9%	2.9%	
Gas	%	47.9%	45.8%	41.7%	45.1%	20
	EB	4.4%	6.1%	4.9%	2.9%	
Oil/Kerosene	%	0.2%	0.1%	0.2%	0.1%	1,230
	EB	0.3%	0.2%	0.3%	0.1%	
Propane	%	1.2%	1.3%	1.7%	1.4%	20
	EB	1.0%	1.4%	1.2%	0.7%	
All Fuels	%	100.0%	100.0%	100.0%	100.0%	1,230
	EB	0.0%	0.0%	0.0%	0.0%	

Table 96. Distribution of Water Heating Fuel by Region (RBSA Metering)

Water Heater Fuel		Percent of Water Heater Fuels, RBSA Metering				
		Puget Sound	Western Oregon	Eastern Region	All Regions	n
Electric	%	52.6%	65.6%	59.0%	58.7%	64
	EB	2.2%	2.4%	2.1%	0.7%	
Gas	%	47.4%	34.4%	41.0%	41.3%	45
	EB	2.2%	2.4%	2.1%	0.7%	
All Fuels	%	100.0%	100.0%	100.0%	100.0%	109
	EB	0.0%	0.0%	0.0%	0.0%	

Appliances

Appliance stock (large "white goods") in the single-family RBSA data is compared to the stock at the metered sites below. Table 97 shows the average number of household appliances per house for the metered regions. Table 98 shows the average saturation in the metered houses. Appliance saturations in the metered sample are comparable with the Northwest as a whole. The regions show little variation in appliance saturations. Overall counts of freezers in the metered sample are higher than the region overall, but this difference is barely statistically significant; all other total appliance counts are comparable.

Table 97. Average Number of Appliances per Site (RBSA Single-Family)

Appliance		Number of Appliances per Site, RBSA SF (n= 1,194)			
		Puget Sound	Western Oregon	Eastern Region	All Regions
Clothes Washer	Mean	0.99	0.98	0.99	0.99
	EB	0.01	0.02	0.01	0.01
Cooking Equipment	Mean	1.03	1.02	1.02	1.02
	EB	0.01	0.02	0.01	0.01
Dishwasher	Mean	0.91	0.89	0.84	0.88
	EB	0.03	0.04	0.04	0.02
Clothes Dryer	Mean	1.00	0.98	0.99	0.99
	EB	0.01	0.02	0.01	0.01
Freezer	Mean	0.36	0.57	0.61	0.51
	EB	0.04	0.08	0.07	0.04
Refrigerator	Mean	1.33	1.27	1.30	1.30
	EB	0.05	0.06	0.06	0.03
Water Heater	Mean	1.02	1.05	1.03	1.03
	EB	0.02	0.02	0.02	0.01

Table 98. Average Number of Appliances per Site (RBSA Metering)

Appliance		Number of Appliances per Site, RBSA Metering (n= 104)			
		Puget Sound	Western Oregon	Eastern Region	All Regions
Clothes Washer	Mean	1.00	1.00	0.97	0.99
	EB	0.00	0.00	0.03	0.01
Cooking Equipment	Mean	1.03	1.03	1.03	1.03
	EB	0.03	0.03	0.03	0.02
Dishwasher	Mean	0.92	0.90	0.86	0.89
	EB	0.05	0.06	0.07	0.03
Clothes Dryer	Mean	1.00	1.00	0.97	0.99
	EB	0.04	0.00	0.03	0.02
Freezer	Mean	0.35	0.77	0.65	0.58
	EB	0.09	0.10	0.11	0.06
Refrigerator	Mean	1.24	1.37	1.24	1.28
	EB	0.07	0.09	0.07	0.04
Water Heater	Mean	1.03	1.07	1.05	1.05
	EB	0.03	0.05	0.04	0.02

Electronics

Surveyors were asked to categorize set-top boxes as the devices that received the cable or satellite feed for the television. Other devices such as gaming systems or Internet connections were not included in the set-top box category. The surveyors noted the type of set-top box and digital video recorder (DVR) capability. The saturation of set-top boxes reported in Table 99 and Table 100 includes both recording and non-recording boxes. The DVR saturation separately reports the saturation of only those boxes with recording capabilities.

The surveyors conducted a census of computers by room. They counted only computers that were plugged in or in some way directly in use. Thus, laptops that were not immediately obvious were not included. Gaming systems and audio equipment were also enumerated room by room.

In general, metered sites have slightly higher counts of each electronic device than the region they were drawn from. However, in nearly all cases, these differences are not statistically significant. In the Puget region, there are more stereos and computers in the RBSA Metering sample; there are slightly more computers in the sample overall; there are no other statistically significant differences.

Table 99. Average Number of Electronics per Site (RBSA Single-Family)

Electronics		Number of Electronics per Site, RBSA SF (n= 1,194)			
		Puget Sound	Western Oregon	Eastern Region	All Regions
Audio Equipment	Mean	2.03	2.22	1.71	1.97
	EB	0.19	0.31	0.16	0.12
Computers	Mean	1.69	1.48	1.62	1.61
	EB	0.10	0.14	0.15	0.07
Gaming Systems	Mean	0.45	0.45	0.51	0.47
	EB	0.07	0.09	0.08	0.05
Set-Top Boxes	Mean	1.62	1.64	1.36	1.53
	EB	0.11	0.18	0.13	0.08
Recording Set-Top Boxes (DVR)	Mean	0.46	0.58	0.48	0.50
	EB	0.07	0.11	0.08	0.05
Televisions	Mean	2.04	2.27	2.35	2.22
	EB	0.10	0.17	0.14	0.08

Table 100. Average Number of Electronics per Site (RBSA Metering)

Electronics		Number of Electronics per Site, RBSA Metering (n= 104)			
		Puget Sound	Western Oregon	Eastern Region	All Regions
Audio Equipment	Mean	3.35	1.17	1.17	2.23
	EB	0.39	0.26	0.26	0.20
Computers	Mean	2.24	1.67	1.67	1.90
	EB	0.30	0.23	0.23	0.15
Gaming Systems	Mean	0.57	0.40	0.40	0.50
	EB	0.16	0.12	0.12	0.08
Set-Top Boxes	Mean	1.43	1.47	1.47	1.38
	EB	0.21	0.29	0.29	0.13
Recording Set-Top Boxes (DVR)	Mean	0.41	0.57	0.57	0.48
	EB	0.08	0.14	0.14	0.07
Televisions	Mean	2.11	2.30	2.30	2.31
	EB	0.22	0.30	0.30	0.14

Lighting

Total lighting power density (LPD) per site was calculated using the wattage information about each lamp at the site as recorded in the field, divided by the conditioned area of the house. The LPD at metered sites overall is not significantly higher than that of the region as a whole (Table 101 and Table 102). Nor are there statistically significant differences in the saturations of compact fluorescent lamps (CFLs) (Table 103 and Table 104).

Table 101. Average Lighting Power Density (LPD) by Region (RBSA Single-Family)

Study Region	House LPD, RBSA SF		
	Mean	EB	n
Puget Sound	1.34	0.05	462
Western Oregon	1.53	0.07	243
Eastern Region	1.40	0.06	452
All Regions	1.41	0.03	1,157

Table 102. Average Lighting Power Density (LPD) by Region (RBSA Metering)

Study Region	House LPD, RBSA Metering		
	Mean	EB	n
Puget Sound	1.44	0.09	36
Western Oregon	1.66	0.10	28
Eastern Region	1.38	0.09	37
All Regions	1.48	0.06	101

Table 103. Percent Compact Fluorescent Lamps Installed by Region (RBSA Single-Family)

Study Region	Percent CFLs Installed, RBSA SF		
	%	EB	n
Puget Sound	31.8%	2.2%	472
Western Oregon	25.2%	2.9%	255
Eastern Region	26.9%	2.0%	467
All Regions	28.2%	1.4%	1,194

Table 104. Percent Compact Fluorescent Lamps Installed by Region (RBSA Metering)

Study Region	Percent CFLs Installed, RBSA Metering		
	%	EB	n
Puget Sound	29.5%	4.1%	37
Western Oregon	23.1%	3.9%	30
Eastern Region	30.8%	3.3%	37
All Regions	28.1%	2.2%	104

Appendix 6. Heating Case Studies

Air Source Heat Pumps

Heat Pump Characteristics

Table 105 and Table 106 summarize key performance statistics for all categories of heat pumps; the first table is a broad accounting of system types and house/duct characteristics for the metered population and the second table provides a more detailed summary of average performance across the full RBSA sample. Note ASHP (air-source heat pump) here refers to the most populous sub-sample of the overall group. The ASHP metered sites are very similar to the overall RBSA group in terms of duct statistics, but this is not surprising given the metered sites make up a large fraction of all of the heat pump sites that received detailed duct testing in the main RBSA. On average, the metered sites have older ASHPs (and lower HSPF) than the main RBSA sample.

Table 105. Heat Pump Site Overview (Metered Sites)

Heat Pump Sites		Characteristics of Heat Pump Houses RBSA Metering					
		ASHP	DHP	Dual Fuel	GSHP	All Heat Pumps	n
Number of Sites[1]	Count	19	3	2	1	25	25
	EB	—	—	—	—	—	
House Size (Sq.Ft.)	Mean	2173	1634	2103	4779	2207	25
	EB	193	386	49	—	188	
UA (Btu/hr F)	Mean	540	512	841	836	573	25
	EB	53	135	123	—	47	
HSPF	Mean	7.7	—	8.0	—	7.7	16
	EB	0.2	—	0.5	—	0.2	
Heat Pump Size (tons)	Mean	2.9	1.1	3.0	—	2.7	24
	EB	0.2	0.2	0.0	—	0.2	
Year of Manufacture	Mean	2000	2011	2002	—	2001	22
	EB	2	1	7	—	2	
Back-up Element Capacity (kW)	Mean	15.2	—	—	10.0	14.8	12
	EB	2.0	—	—	—	1.9	
Supply Leak Fraction[2]	%	7.8%	—	5.1%	8.3%	7.7%	17
	EB	1.4%	—	—	—	1.2%	
Return Leak Fraction[3]	%	11.9%	—	7.2%	15.5%	11.8%	17

[1]One site has two ASHPs
[2]Measured supply duct leakage to exterior referenced to half of measured supply plenum static pressure then divided by air handler normal heating CFM
[3]Based on measured return duct leakage to exterior referenced to half of measured return plenum static pressure then divided by air handler operating normal heating CFM

Table 106. Characteristics of Heat Pump Houses RBSA SF Study

Heat Pump Sites		Characteristics of Heat Pump Houses RBSA SF Study					
		ASHP	DHP	Dual Fuel	GSHP	All Heat Pumps	n
Number of Sites	Count	128	16	13	11	168	168
	EB	—	—	—	—	—	
House Size (Sq.Ft.)	Mean	2341	1983	2518	3182	2376	168
	EB	76	153	287	153	71	
UA (Btu/hr F)	Mean	604	643	652	627	614	157
	EB	29	63	70	67	23	
HSPF[2]	Mean	8.1	—	8.1	—	8.1	111
	EB	0.1	—	0.2	—	0.1	
Heat Pump Size (tons)	Mean	2.9	1.5	3.0	3.9	2.8	164
	EB	0.1	0.3	0.2	0.3	0.1	
Year of Manufacture[2]	Mean	2003	2010	2006	—	2004	149
	EB	1	0	1	—	1	
Supply Leak Fraction	%	7.8%	—	5.7%	7.5%	7.5%	32
	EB	1.2%	—	1.5%	2.2%	1.0%	
Return Leak Fraction	%	12.9%	—	10.4%	11.5%	12.5%	32
	EB	2.3%	—	4.6%	4.9%	1.9%	

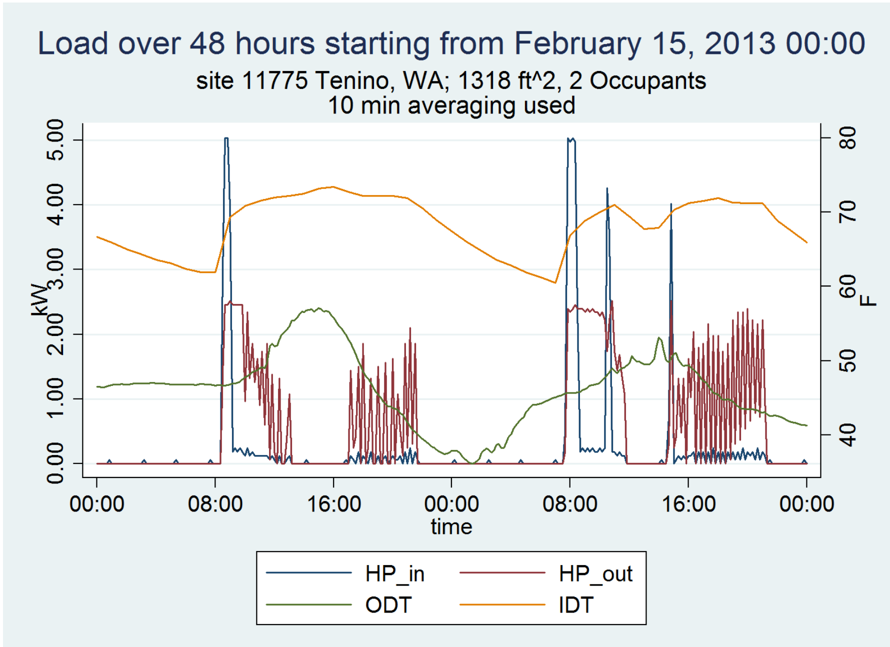
Heat Pump Control Observations

A significant issue in ASHP performance is system controls; that is, how the thermostat is operated by occupants and how electric resistance ("backup," "strip," or "auxiliary") heat is controlled. Control settings, along with system sizing (next subsection) and duct performance, are major determinants of heat pump distribution efficiency. The PTCS specifications prioritize system control settings, requiring installers to lock out strip heat above 35° F outdoor temperature. An earlier study of heat pump control settings set the "base case' against which PTCS control-related savings would be estimated (Baylon et al., 2005).

In RBSA Metering, field technicians were asked to evaluate whether a heat pump system had an operating lockout. None of the ducted systems in RBSA Metering was identified as having been installed as part of a PTCS-incentivized offering. Only 6 sites out of 19 that were evaluated were found to have operational strip heat lockout controls. Dual fuel systems were not included in the evaluation since they use a different type of control strategy. The RBSA Metering heat pump sites do not allow conclusive generalization across the Northwest but they do suggest that the PTCS specifications still have the potential to offer control-related energy savings.

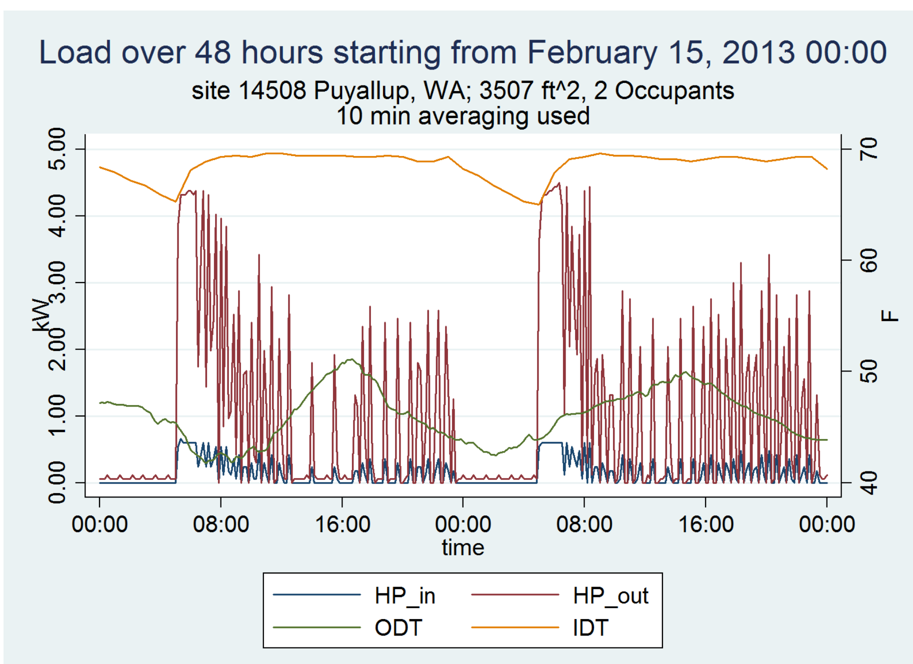
Figure 61 and Figure 62 show the different daily behavior of two sites on the same days, one with a large night-time setback (Figure 61) and the other with a more modest setback (Figure 62). The first site, located in Tenino, WA, shows use of backup electric resistance heat during the morning warm-up period, although minimal despite this large setback. This system also does not appear to use an adaptive recovery thermostat; it comes on at 8 am versus much earlier. The second site, located 50 miles away, also in the south Puget Sound region, shows an earlier start to the morning heating cycle, but has no electric resistance heat usage. The small amount of use for HP_in is due to the fan cycling. The outdoor temperature does not go below about 40 degrees, though, for this time period.

Figure 61. Heat Pump Site 11775 Morning Warm Up



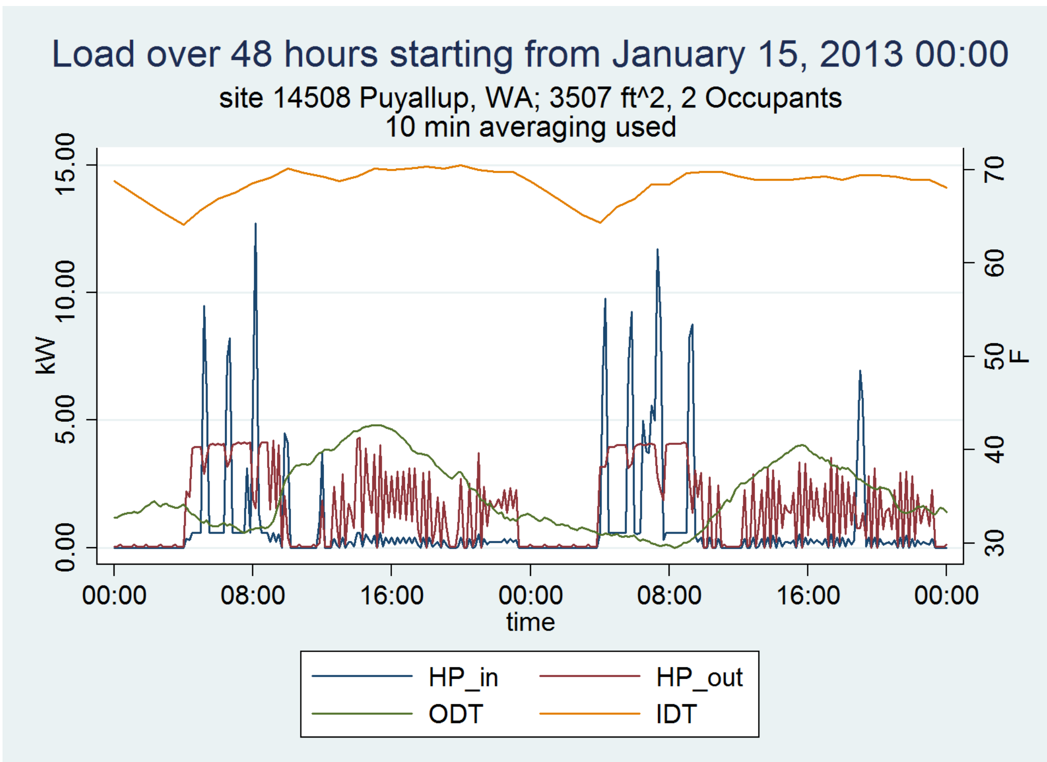
HP_in: Heat pump indoor unit
HP_out: Heat pump outdoor unit
ODT: Outdoor temperature
IDT: Indoor temperature

Figure 62. Heat Pump Site 14508 Morning Warm Up



In contrast, we can look at a day with lower outdoor temperature for this same site 14508 and see a large use of electric resistance heat. Figure 63 shows the temperature dipping down to 30 °F and both mornings and during one evening there is electric resistance heat use. Taken together, the three figures paint a picture of the relationship of night-time setbacks and outdoor temperature lockouts with heat pumps. Site 14508 has a lockout to prevent auxiliary heat use above 40°F. With that in place, the system uses only compressor heating in the morning (Figure 62) in contrast to site 11775, which uses resistance heat even at mild ambient temperatures (Figure 61).

Figure 63. Heat Pump Site 14508 Morning Warm Up for Colder Morning



Heat Pump Sizing and Balance Points

Another contributor to performance is the balance point of the heat pump. It is defined as the outdoor temperature above which the heat pump should be able to keep the house at thermostat setpoint without need of additional heat from the electric resistance elements in the indoor unit. The higher the heat pump balance point, the less efficient the heat pump system will be, since more electric resistance heat with a Coefficient of Performance (COP) of one is needed.[16] The

[16] A COP of 1 means one unit of electricity in produces an equivalent unit of heat.

compression cycle of the heat pump typically has an average winter-time COP of between two and three if the compressor coils, and fans are working properly.

To calculate the heat pump balance point temperature, the house heat loss rate (including infiltration, as estimated from the blower door test), is used (and further modified by the supply duct leakage fraction, which is based on an exterior duct leakage test that is recalculated at half of the measured supply plenum static pressure). The resulting heat loss rate is multiplied by 40° F to calculate the house heating load at 30° F outdoor temperature and 70° F indoor temperature. This heat loss rate is then compared with the nominal capacity of the heat pump at 30° F. This capacity is estimated by taking the full nominal capacity and multiplying it by 70% (since the system would be operating at 30° F outdoor temperature vs. 47° F, the usual full capacity rating temperature).

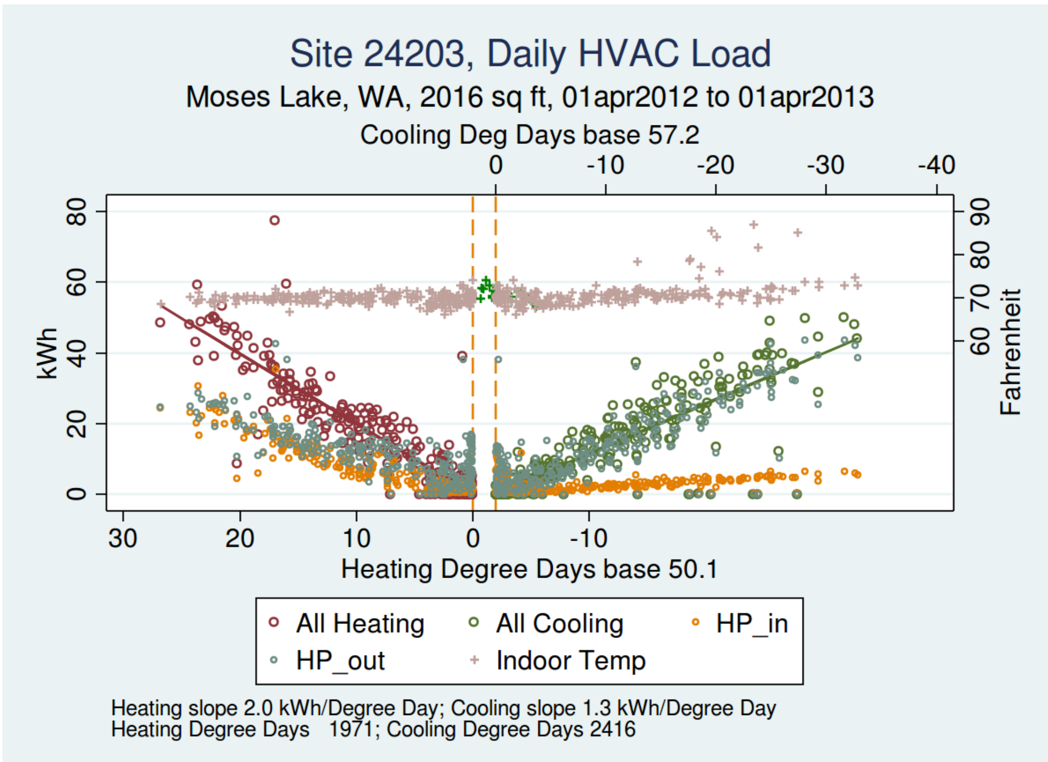
The comparison was made for 19 ducted systems. It was not known if any of these systems had ever received any formal sizing evaluation. The results were mixed, with 11 of the sites providing sufficient calculated capacity. The remaining 8 sites did not make the cut, with 3 being within one-half ton of the load at 30° F and 3 being at least one ton undersized. There is still a need for a more organized approach to sizing heat pumps for efficiency in a heating-dominated region such as the Pacific Northwest.

Air Source Heat Pump Case Studies

The following examples include sites that had strong seasonal heating signatures and also some that display the range of problems that afflict heat pumps and drive performance down. Study managers decided not to influence homeowner decisions on whether to make repairs to systems. However, we did periodically check in with these sites to see if repairs had been made.

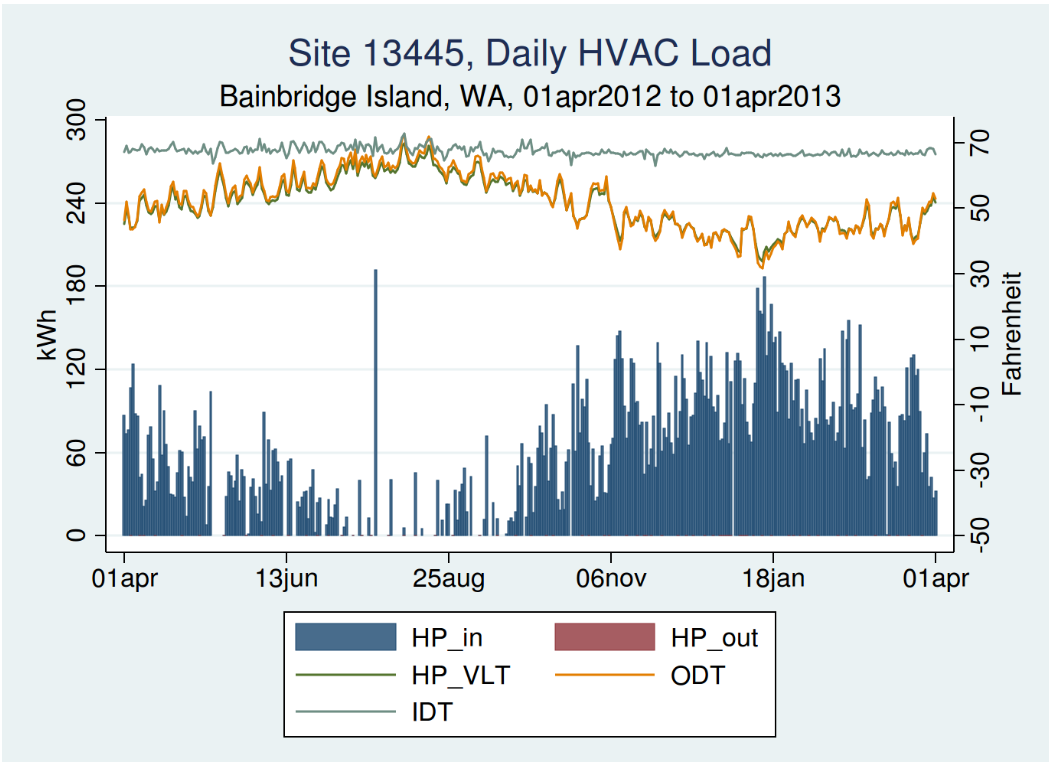
Figure 64 shows a graph for a site located in Moses Lake, WA (heating zone 2 and cooling zone 2). The relationship between electricity used for heating (and cooling) and outdoor temperature is strong, and it is not difficult to describe this relationship (as the heating and cooling slopes in the graphic indicate). This site shows more cooling than any of the other site graphs displayed thus far in this report. It should also be noted that there is almost no deadband between heating and cooling; the heat pump at this site maintains a very consistent indoor temperature (the cooling setpoint is very similar to the heating setpoint).

Figure 64. Well-Behaved Heat Pump Site



In contrast, Figure 65 shows the annual energy usage of a site that had a broken compressor when the metering team arrived in late 2011. The compressor was not repaired during the study and the system operated as an electric forced-air furnace for the entire study period which the graph indicates by plenty of indoor heat pump energy (HP_in) and no outdoor energy (HP_out). Note the scale on the left y-axis. This five ton heat pump served (or, rather, failed to serve) a 3,345 ft^2 house and heating usage was significant. The site was subsequently reclassified and analyzed with the electric forced air furnace group.

Figure 65. Heat Pump Site with Unrepaired Compressor



HP_VLT: Heat pump vapor line temperature

Site 10887 is another interesting heat pump case; the occupants use the system a great deal all year round. This system also had an obvious problem at the original installation (low refrigerant level); a service technician added more refrigerant at least once during the study period. In fact, data in the graph suggest the compressor did not run for three, separate, prolonged winter periods. The leak may have been finally fixed in February 2013 judging by the observed compressor operation afterward and the relative decrease in auxiliary system heating. The house balance point is about 66 °F (Figure 67) and the occupants keep the set point in the mid 70°s F, so there is some amount of heating almost all year round (Figure 66). The "HP_in_2" label in the figure indicates that there is a second stage of auxiliary resistance heating metered separately from the first stage. Also, it appears the heat pump was not used at all for cooling at this site (based on a review of the vapor line temperature in summer months).

Figure 66. Heat Pump Site with Refrigerant Leak

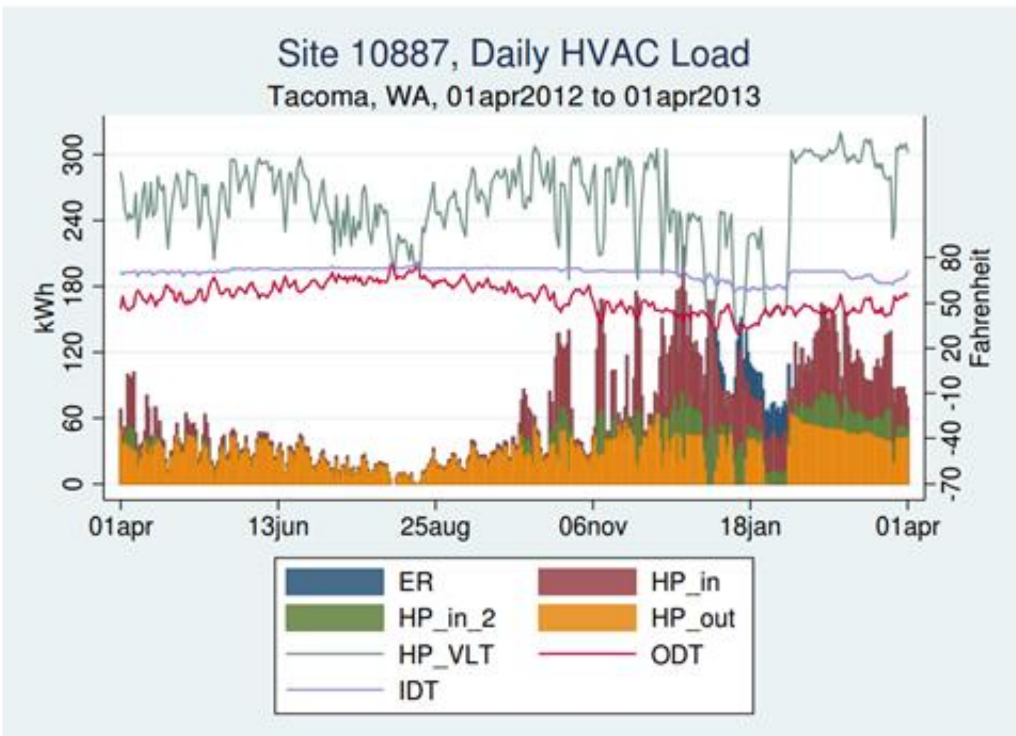
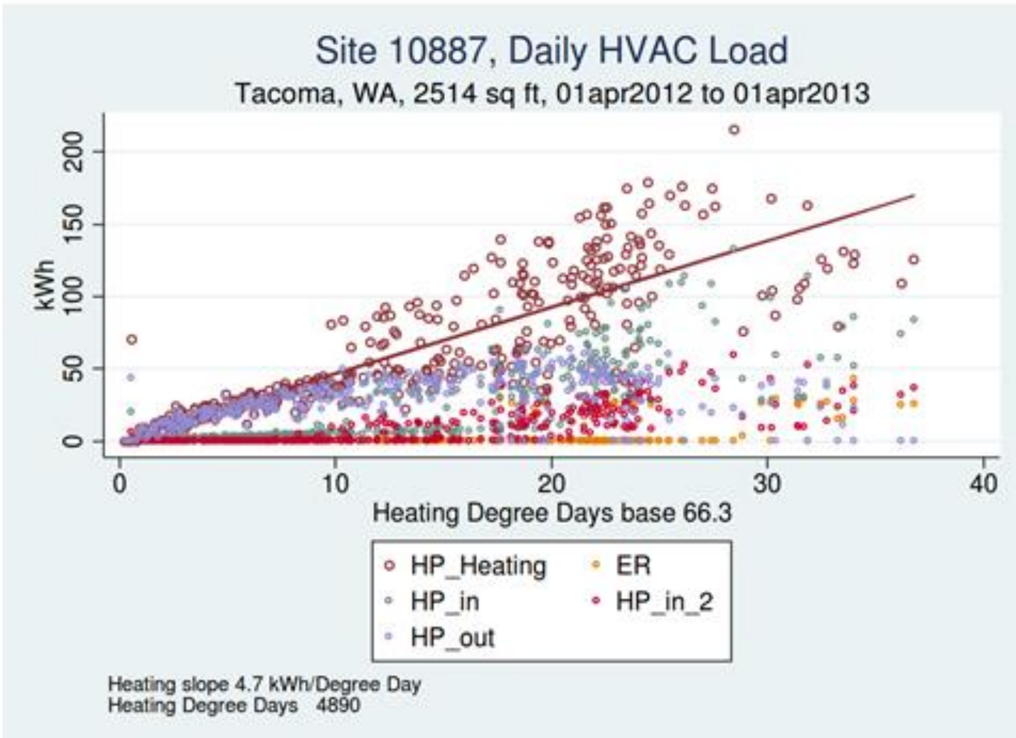


Figure 67. Site 10887 – Daily Heating Load Profile

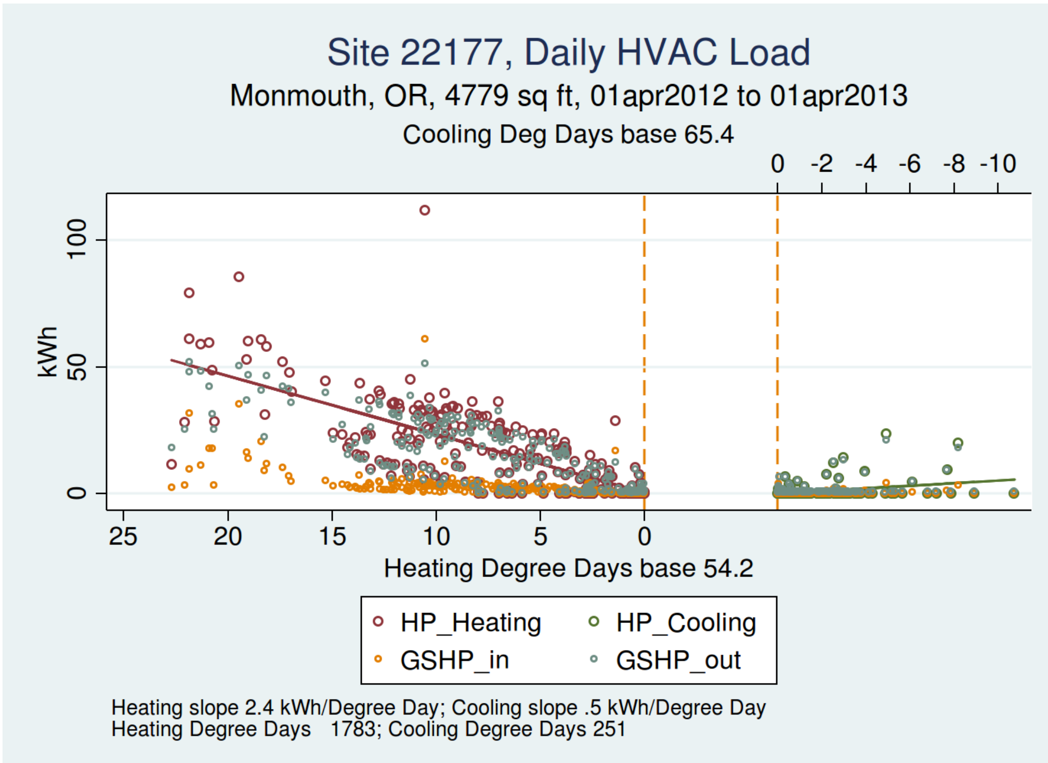


Ground Source Heat Pump

This section covers a ground source heat pump utilizing well water. The ground source heat pump is a small minority of all heat pumps in the Pacific Northwest primarily due to installation cost. The RBSA single family study turned up 10 GSHPs out of a total 1190 sites. Some consumers are interested in it because it does offer higher nominal efficiencies. Typically, though, the product will cost double that of a similarly-sized standard air source heat pump. The site in our sample is located south of Monmouth, Oregon in a 4,500+ square foot house, most of which was built in the early 1990s to Model Conservation Standards (Northwest Power and Conservation Council 2010).

This site is challenging to analyze because the occupancy pattern is erratic. The homeowners are gone a fair amount during the year, and the apparent heating setpoint varies. There is some added electric resistance usage, from the auxiliary heating system, when the outdoor temperatures dip below 35 °F. The summertime usage for cooling is limited, indicating the system is typically not programmed using a daily set point. Instead the cooling is operated manually on an as-needed basis. The final result, when one looks at the seasonal regression figure, is a noisy signal, especially on the cooling side (but the overall amount of cooling usage is limited, about 125 kWh).

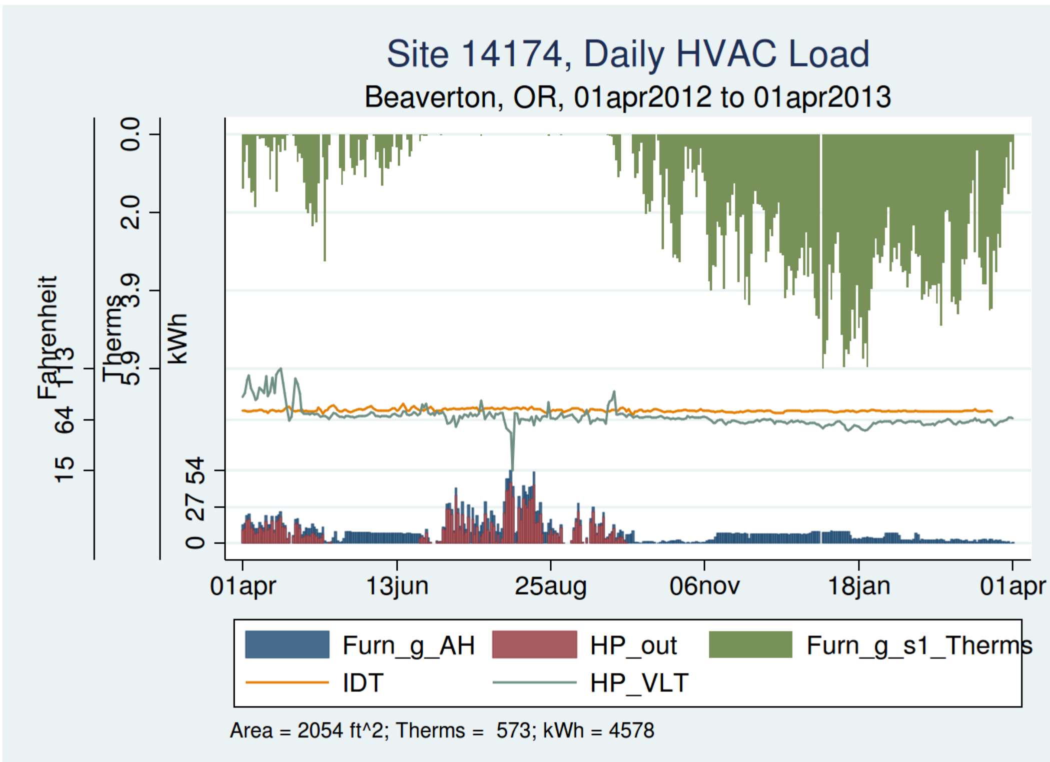
Figure 68. Ground Source Heat Pump Site



Dual Fuel Heat Pump

Dual-fuel heat pumps are air source heat pumps coupled with natural gas furnaces. The two dual-fuel sites also present challenges. The first is a site near Beaverton, Oregon. The site has a four ton heat pump and an 80,000 Btu/hr gas furnace, but Figure 69 clearly shows it is not using the heat pump during the winter. On the left side of the graph, there is a mixture of gas furnace usage, which is the green at the top, and the compressor, the red at the bottom. The amount of electricity used for heating via the heat pump is extremely limited (mostly just the air handler).

Figure 69. Dual Fuel Heat Pump Annual Usage

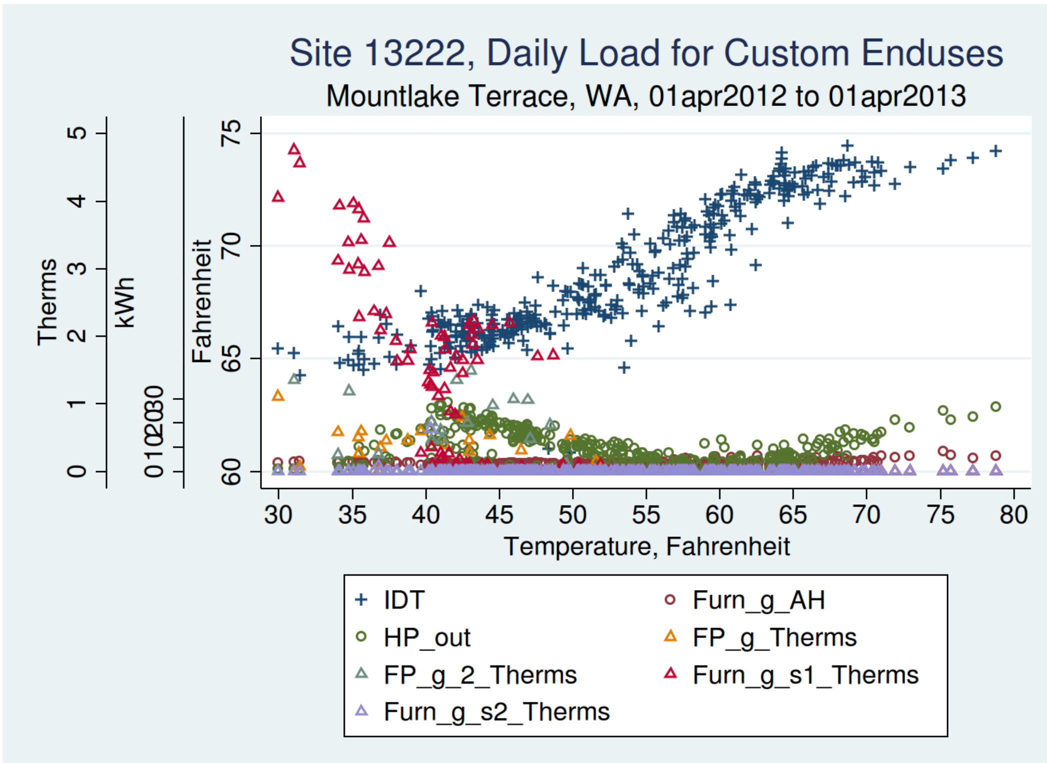


Furn_g_AH: Gas furnace air handler
Furn_g_s1_Therms: Gas furnace stage 1 therms

This system is operated effectively as a gas furnace in winter and an air conditioner in summer, but not as a dual-fuel heating system. The end of the first heating season (April 2012) shows some compressor heating, but the second season is all gas furnace heating. This is a good illustration of what can happen with a dual-fuel heat pump. For instance, factors such as the overall layout of the house, the price of natural gas versus electricity, and heat pump supply register delivery temperature versus gas can all affect the homeowner's decision on whether they rely more on their gas furnace or their heat pump to provide heating.

The second dual-fuel heat pump site, located near Seattle, shows more reliance on the heat pump, at least during certain parts of the year. Figure 70 shows consistent use of the compressor down to about 40 °F, which is indicated by the green circle. At that point, the first stage of the two-stage gas furnace starts to take on more of the load. Note, though, that the homeowner apparently also uses the furnace by itself some of the time even at outdoor temperatures warmer than 40 °F. This option would be available at the thermostat.

Figure 70. House with Dual Fuel Heat Pump and Two Gas Fireplaces



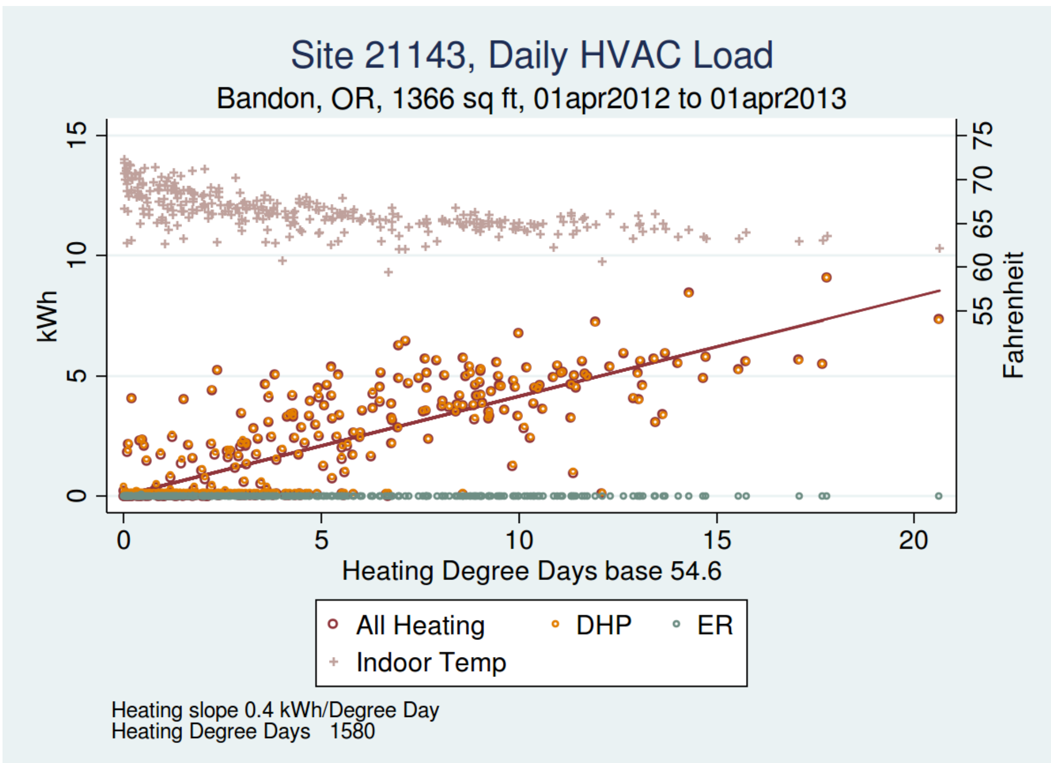
Furn_g_AH: Gas furnace air handler
FP_g_Therms: Gas fireplace therms
FP_g_2_Therms: Gas fireplace therms, second fireplace
Furn_g_s2_Therms: Gas furnace stage 2 therms

In addition to the gas furnace, there are two gas fireplaces at this site, shown in Figure 70 as FP_g_2_Therms and FP_g_Therms. Both of these fireplaces are used throughout the heating season. Overall the mixture of the different heat sources really puts this site into a different category from that implied by the “dual-fuel heat pump” label.

Ductless Heat Pump

Ductless heat pumps are the last category we will summarize. Three sites used a ductless heat pump; only one (21143) displayed a clear enough signal of usage to be generalizable. This site is located on the southern Oregon coast, is relatively small and well-insulated, and consequently has a modest heating slope, as shown in Figure 71. Note there is no cooling usage at this site and also that the heating degree days increase from left to right, in contrast to other "seasonal" regression graphics shown earlier in the report.

Figure 71. Ductless Heat Pump Seasonal Behavior



Appendix 7. Consumer Electronics Summary Tables

The tables in this appendix summarize power draw and energy use of different classes of consumer electronics devices across regions.

Table 107. Hourly Energy Use

	Watts				
	Puget Sound	Western Oregon	Eastern Region	All Regions	
End Use	Mean	Mean	Mean	Mean	n
Cable Box	16.0	23.0	19.2	18.3	23
Cable Box and DVR	21.2	28.6	32.2	28.9	13
CPU	47.5	30.6	22.4	37.9	49
Computer	16.3	12.9	31.3	24.0	56
Computer and Accessory	12.7	12.1	47.1	16.5	61
DVD	2.1	4.8	0.6	2.7	26
DVR	24.3	28.7	26.3	25.6	18
Game Consoles	12.8	6.7	10.1	10.3	39
Monitor	22.5	16.0	10.1	16.5	21
Stereo	—	7.1	14.2	9.8	8
TV	22.5	21.4	26.8	24.0	145

Table 108. Annual Energy Use

	Annual kWh				
	Puget Sound	Western Oregon	Eastern Region	All Regions	
End Use	Mean	Mean	Mean	Mean	n
Cable Box	140.1	201.5	168.5	160.5	23
Cable Box and DVR	185.6	250.9	282.5	253.0	13
CPU	415.9	268.1	196.1	331.7	49
Computer	143.1	113.3	274.5	210.0	56
Computer and Accessory	111.0	105.9	412.5	144.8	61
DVD	18.2	42.1	5.4	23.7	26
DVR	212.8	251.7	230.0	224.3	18
Game Consoles	112.3	58.4	88.8	90.5	39
Monitor	197.4	140.5	88.7	144.7	21
Stereo	—	62.6	124.5	85.8	8
TV	197.5	187.8	234.7	210.2	145

Table 109. Hourly Energy Use in High Power Mode

	High Power Mode Watts				
	Puget Sound	Western Oregon	Eastern Region	All Regions	
End Use	Mean	Mean	Mean	Mean	n
Cable Box[17]	-	-	-	-	23
Cable Box and DVR	29.6	28.6	64.4	43.6	13
CPU	87.3	66.3	61.6	76.3	49
Computer	58.1	41.8	69.6	61.5	56
Computer and Accessory	46.6	64.8	59.5	52.1	61
DVD	12.2	28.9	26.4	18.5	26
DVR	31.3	28.7	26.3	29.7	18
Game Consoles	76.1	51.4	46.4	60.7	39
Monitor	48.0	34.6	36.7	39.9	21
Stereo	-	26.2	19.3	23.6	8
TV	104.6	83.1	92.6	93.7	145

Table 110. Annual Energy Use in High Power Mode

	High Power Mode kWh/yr				
	Puget Sound	Western Oregon	Eastern Region	All Regions	
End Use	Mean	Mean	Mean	Mean	n
Cable Box	99.5	191.6	151.7	134.2	23
Cable Box and DVR	129.7	250.9	277.2	242.4	13
CPU	407.4	258.6	183.0	322.2	49
Computer	136.5	99.5	264.6	200.1	56
Computer and Accessory	82.8	83.9	396.2	118.9	61
DVD	17.2	41.7	5.4	22.9	26
DVR	212.8	251.7	230.0	224.3	18
Game Consoles	103.9	47.7	83.7	82.3	39
Monitor	194.8	130.6	87.0	139.6	21
Stereo	—	55.5	117.3	78.7	8
TV	193.5	183.9	230.6	206.2	145

[17] For most consumer electronics, a single mode threshold was set for a given type of device. However, when individual device power use profiles varied too widely, we could not assign one mode threshold to all the individual devices in a group. This was the case for set-top boxes. Mode thresholds were set on an individual basis. Although this method allows for accurate calculation of hours of use, it allows for the illusion that low power modes are greater than high power modes. This phenomenon arises because certain individual devices may have a higher low power mode than a similar device's high power mode. For this reason, we are unable to present a summary of low and high power mode energy draw for set-top boxes.

Table 111. Hourly Energy Use in Low Power Mode

	Low Power Mode Watts				
	Puget Sound	Western Oregon	Eastern Region	All Regions	
End Use	Mean	Mean	Mean	Mean	n
Cable Box	-	-	-	-	-
Cable Box and DVR	14.5	11.4	9.0	10.9	13
CPU	2.4	2.2	2.7	2.4	49
Computer	1.9	3.0	3.2	2.8	56
Computer and Accessory	4.5	5.8	4.8	4.7	61
DVD	0.4	0.6	0.3	0.4	26
DVR	0.0	0.0	0.0	0.0	18
Game Consoles	6.9	6.8	7.3	7.0	39
Monitor	1.6	2.2	2.5	2.1	21
Stereo	-	2.4	2.9	2.6	8
TV	1.6	2.2	1.6	1.8	145

Table 112. Annual Energy Use in Low Power Mode

	Low Power Mode kWh/yr				
	Puget Sound	Western Oregon	Eastern Region	All Regions	
End Use	Mean	Mean	Mean	Mean	n
Cable Box	40.6	9.9	16.8	26.3	23
Cable Box and DVR	55.9	0.0	5.3	10.6	13
CPU	8.5	9.5	13.1	9.6	49
Computer	6.6	13.8	10.0	9.9	56
Computer and Accessory	28.3	22.1	16.3	25.9	61
DVD	1.0	0.4	0.0	0.8	26
DVR	0.0	0.0	0.0	0.0	18
Game Consoles	8.4	10.7	5.1	8.1	39
Monitor	2.6	9.8	1.7	5.1	21
Stereo	—	7.0	7.2	7.1	8
TV	4.1	3.9	4.2	4.1	145

Appendix 8. Load Shapes

The figures in this appendix present monthly, daily, and hourly load shapes for most end uses metered. Where appropriate, a weekday versus weekend load shape is also presented.

Figure 72. Electric Water Heater Load Shapes

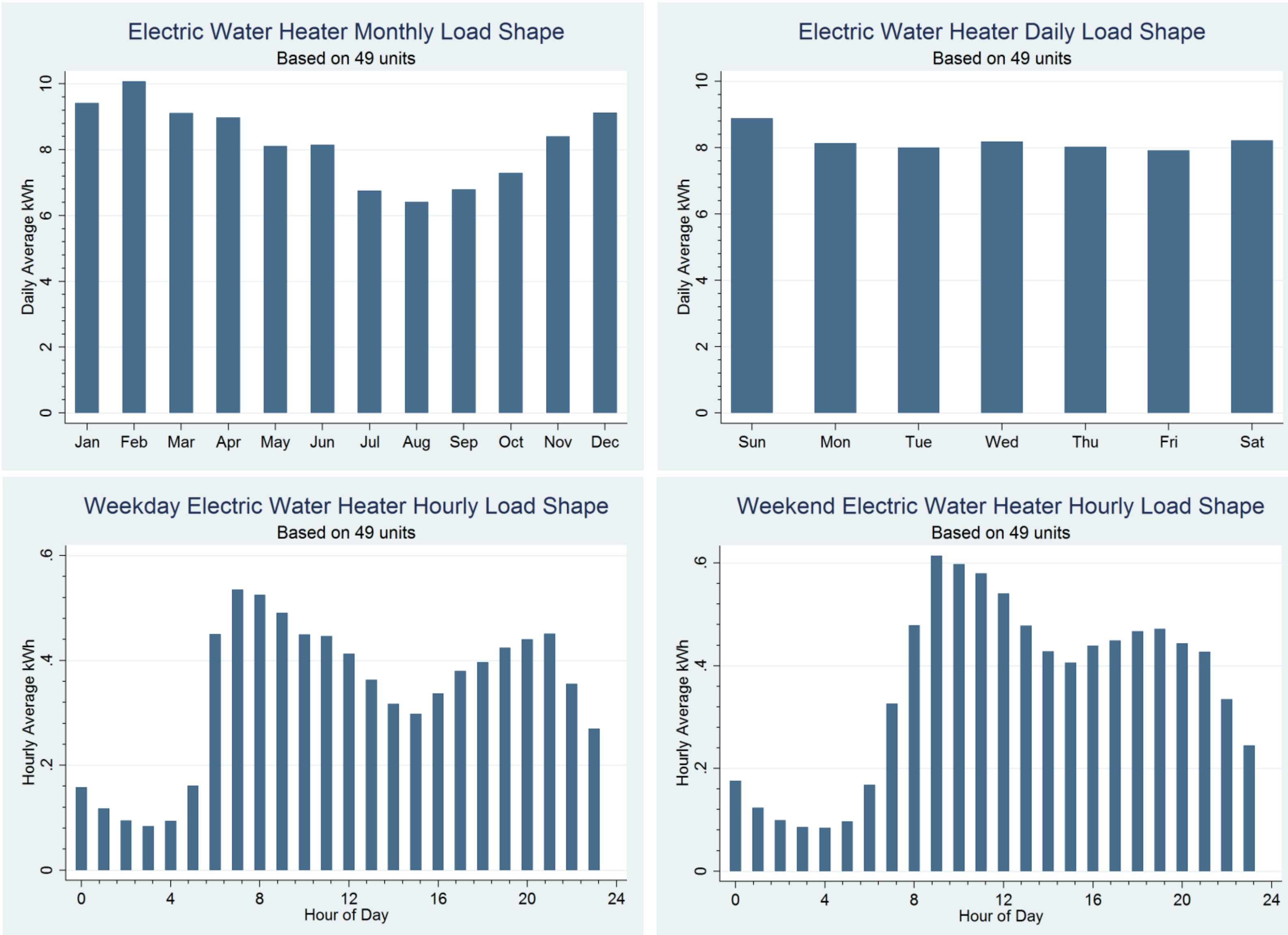


Figure 73. Gas Water Heater Load Shapes

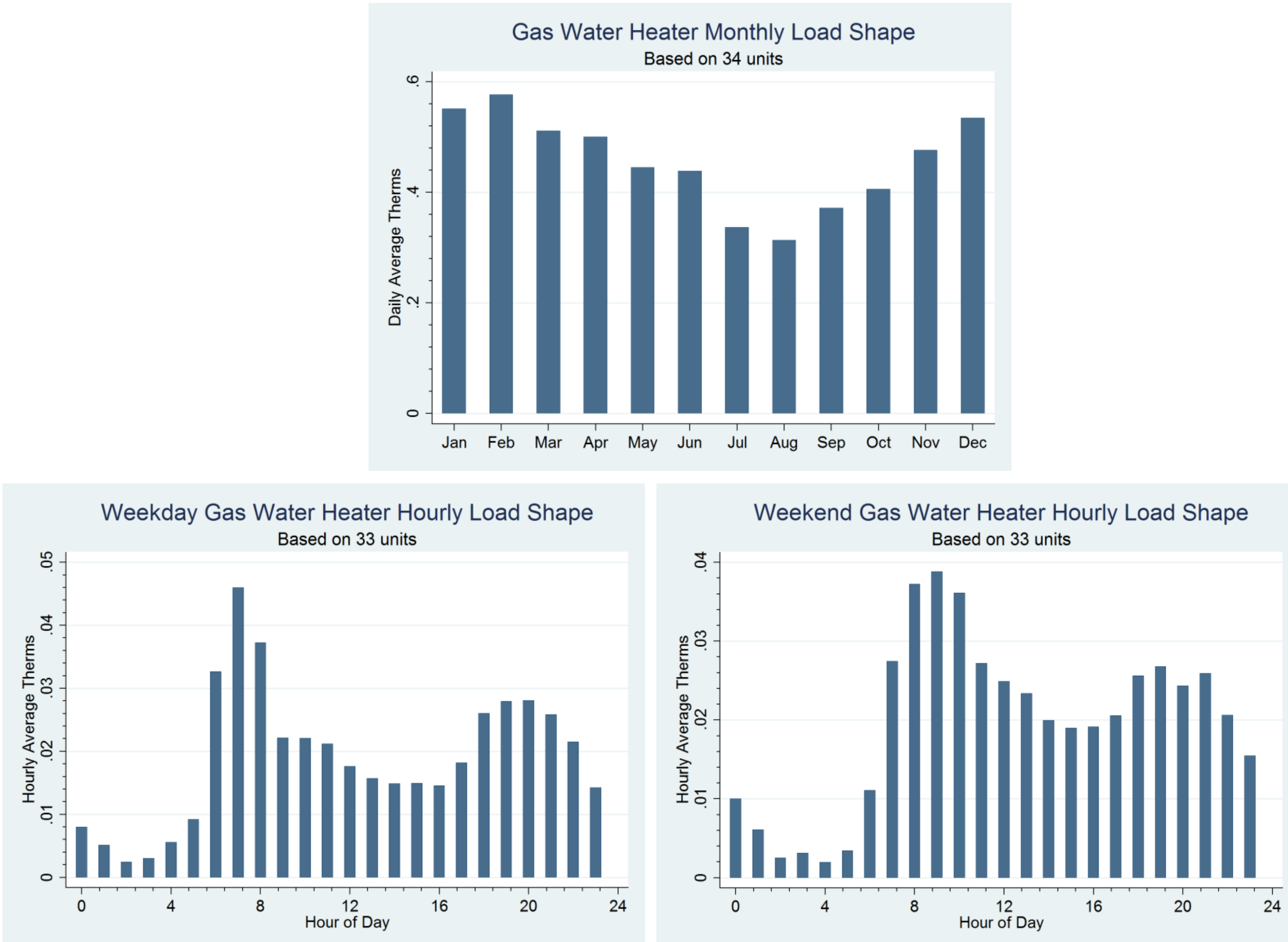


Figure 74. Refrigerator Load Shapes

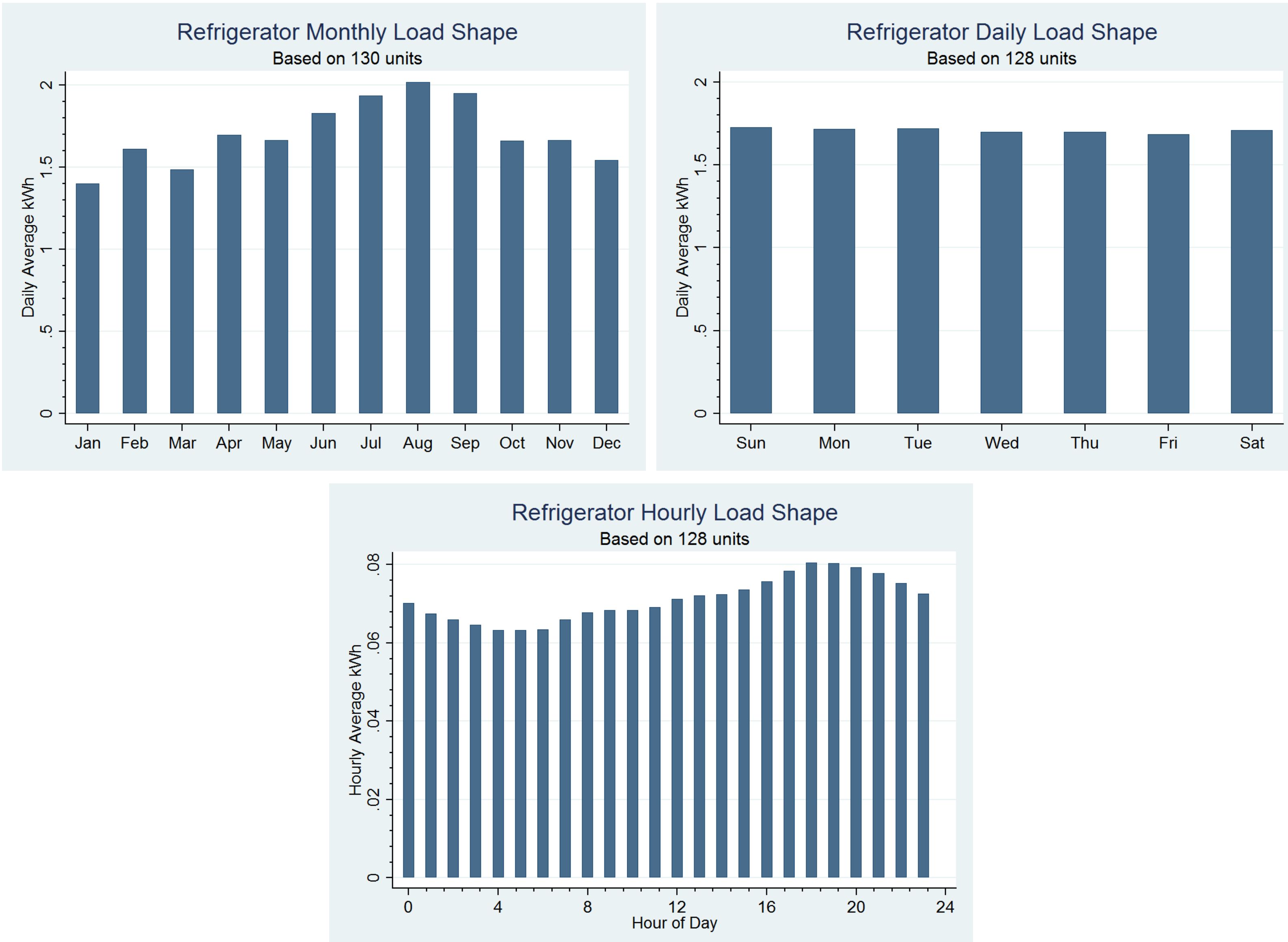


Figure 75. Freezer Load Shapes

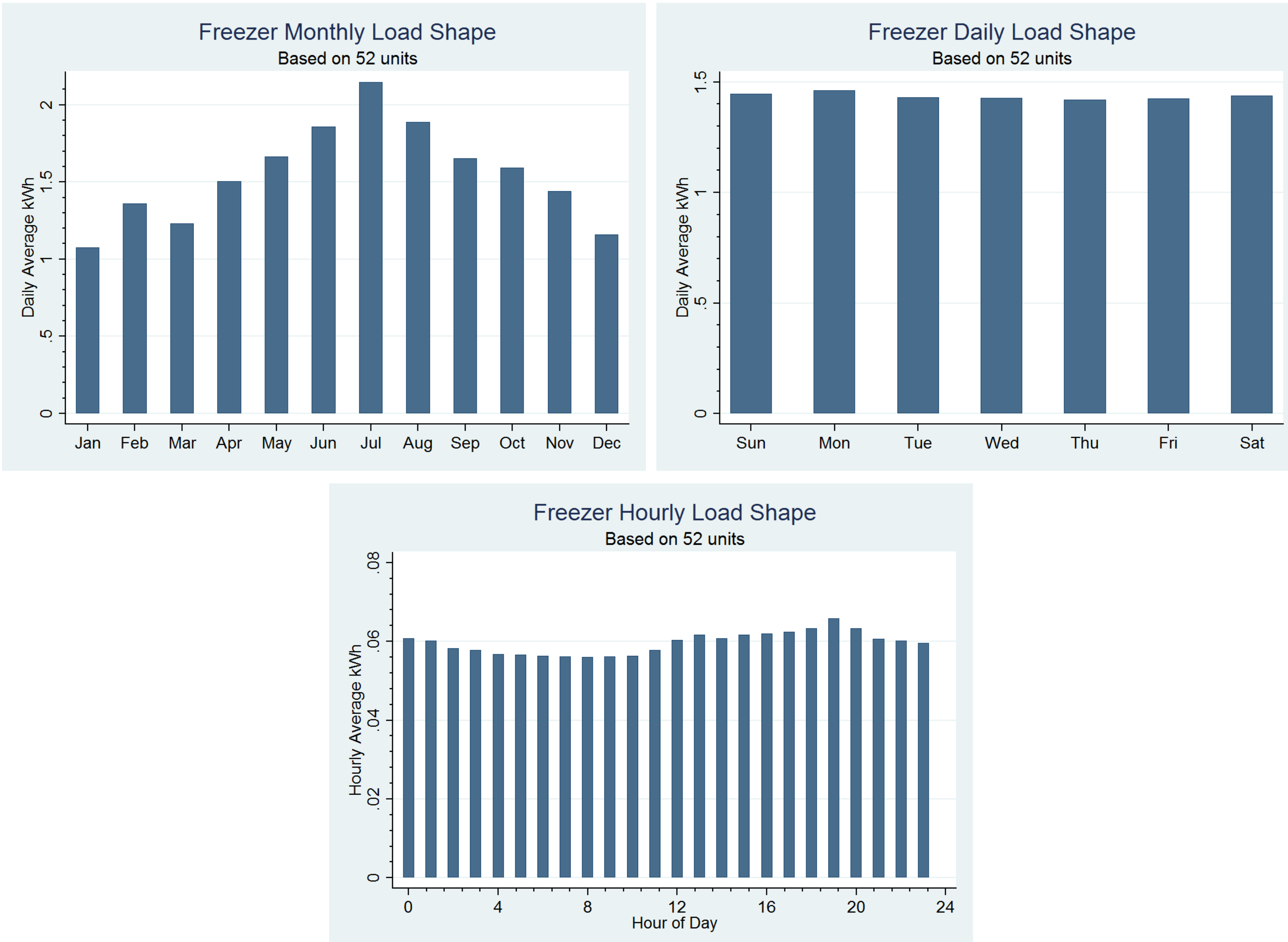


Figure 76. Dishwasher Load Shapes

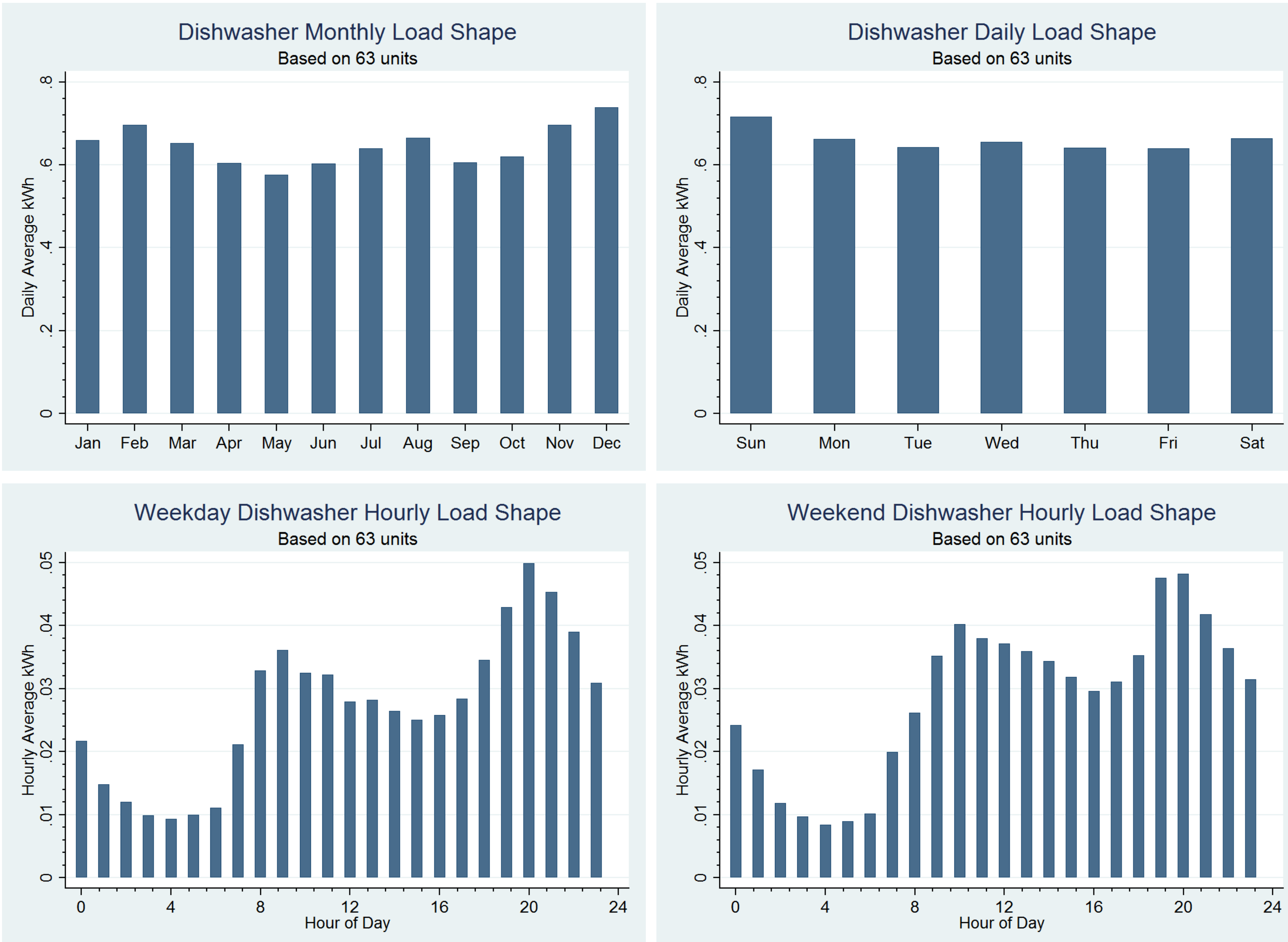


Figure 77. Clothes Washer Load Shapes

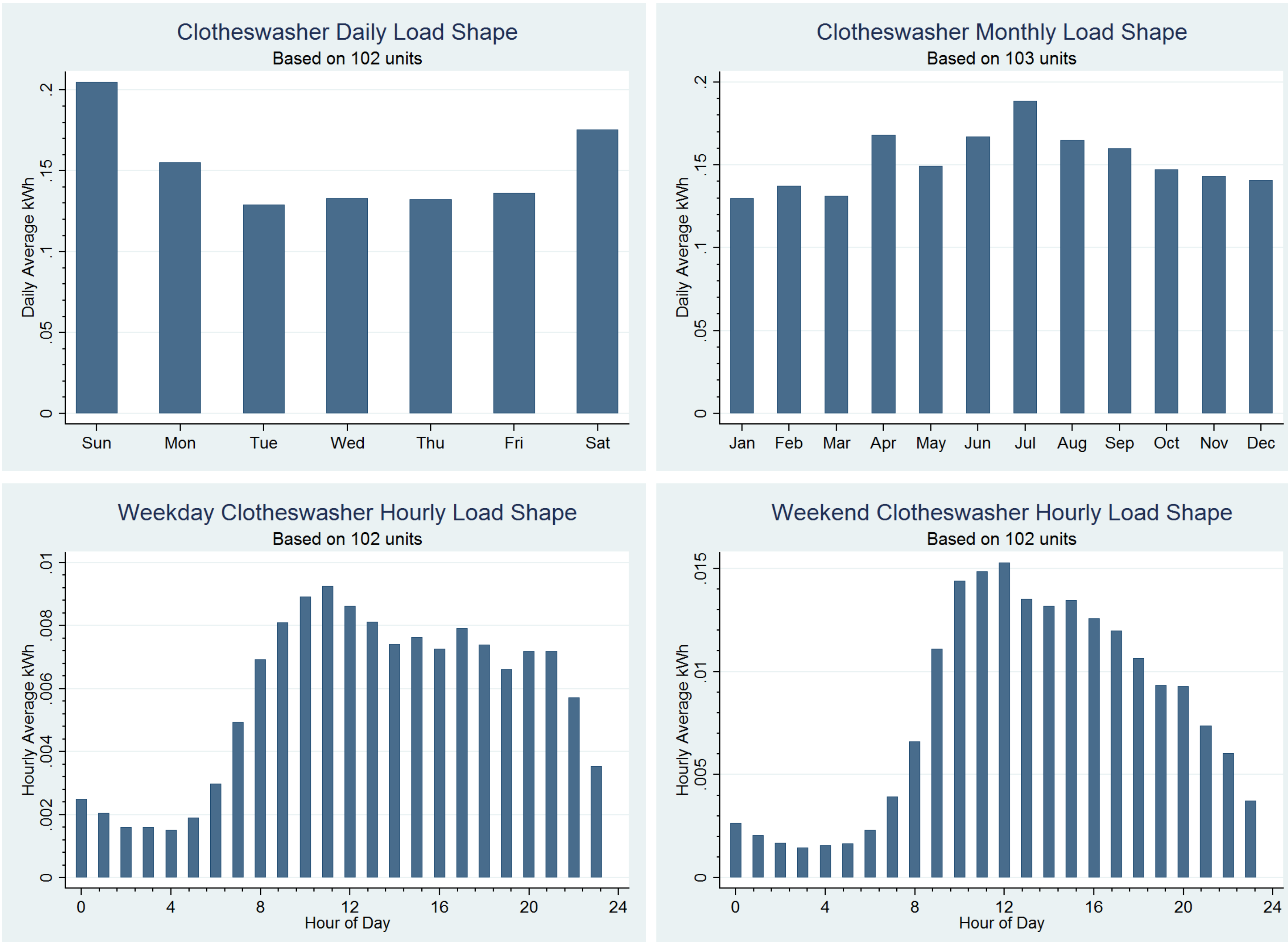


Figure 78. Dryer Load Shapes

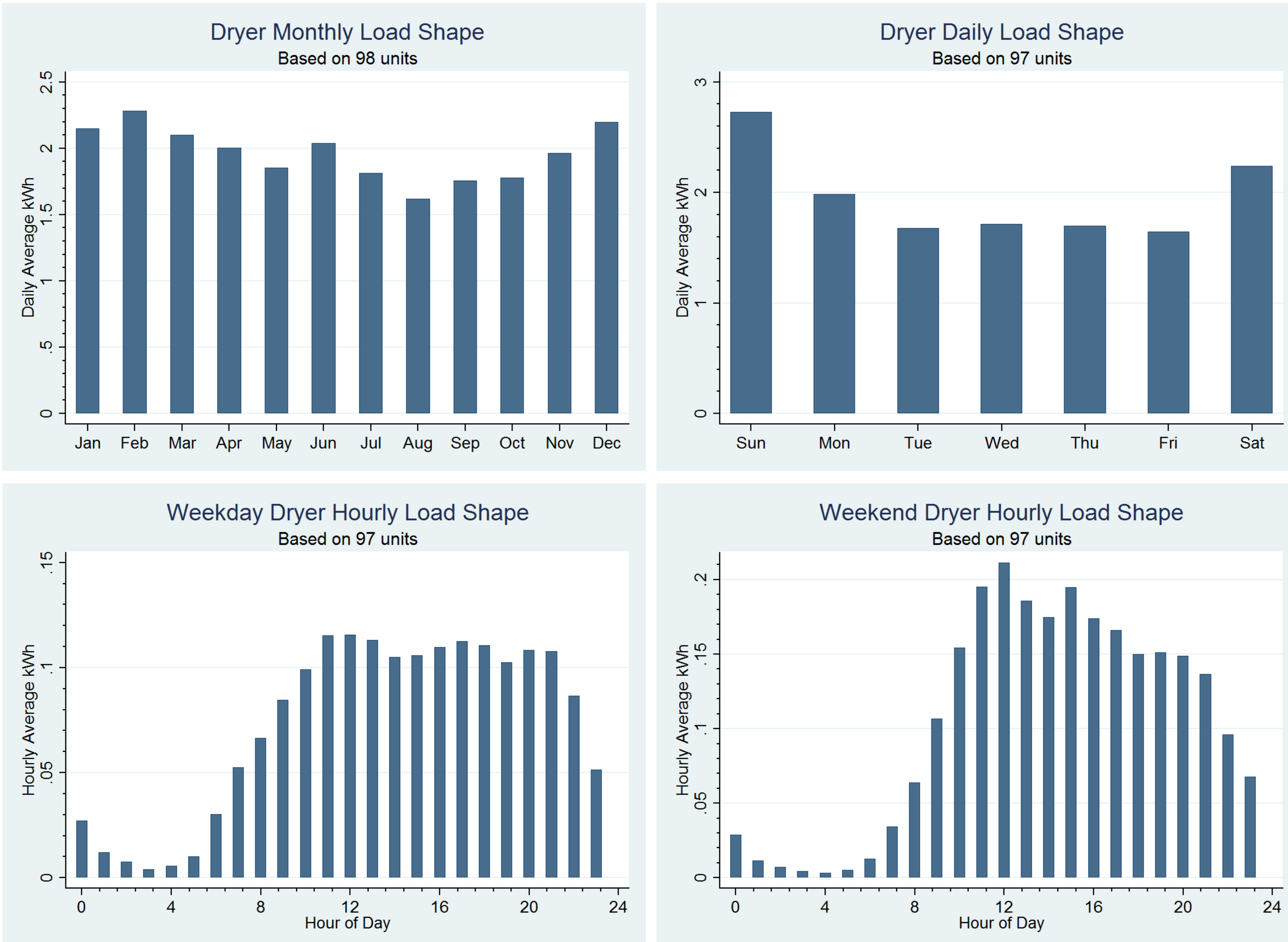


Figure 79. Oven Load Shapes

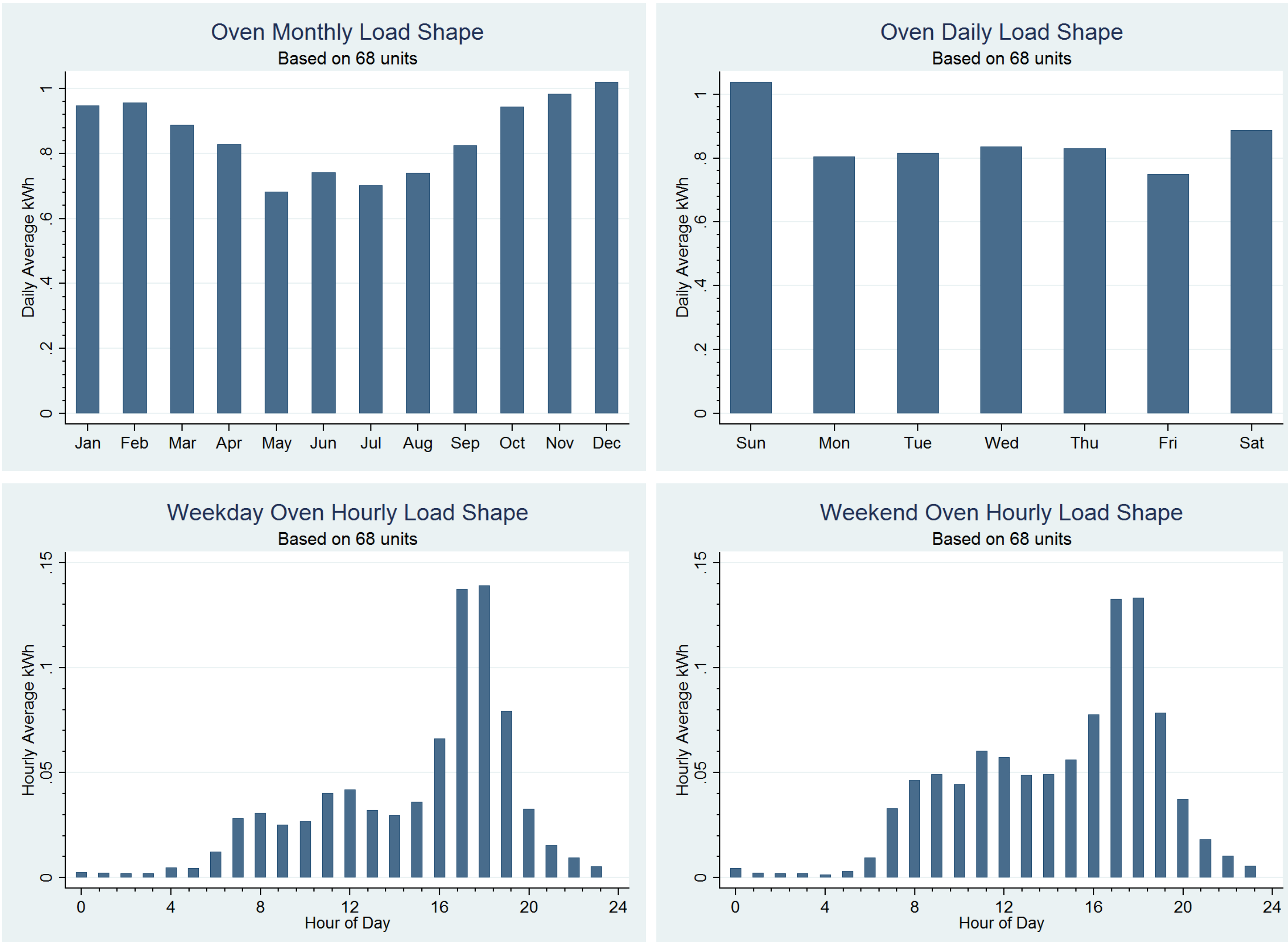


Figure 80. Television Load Shapes

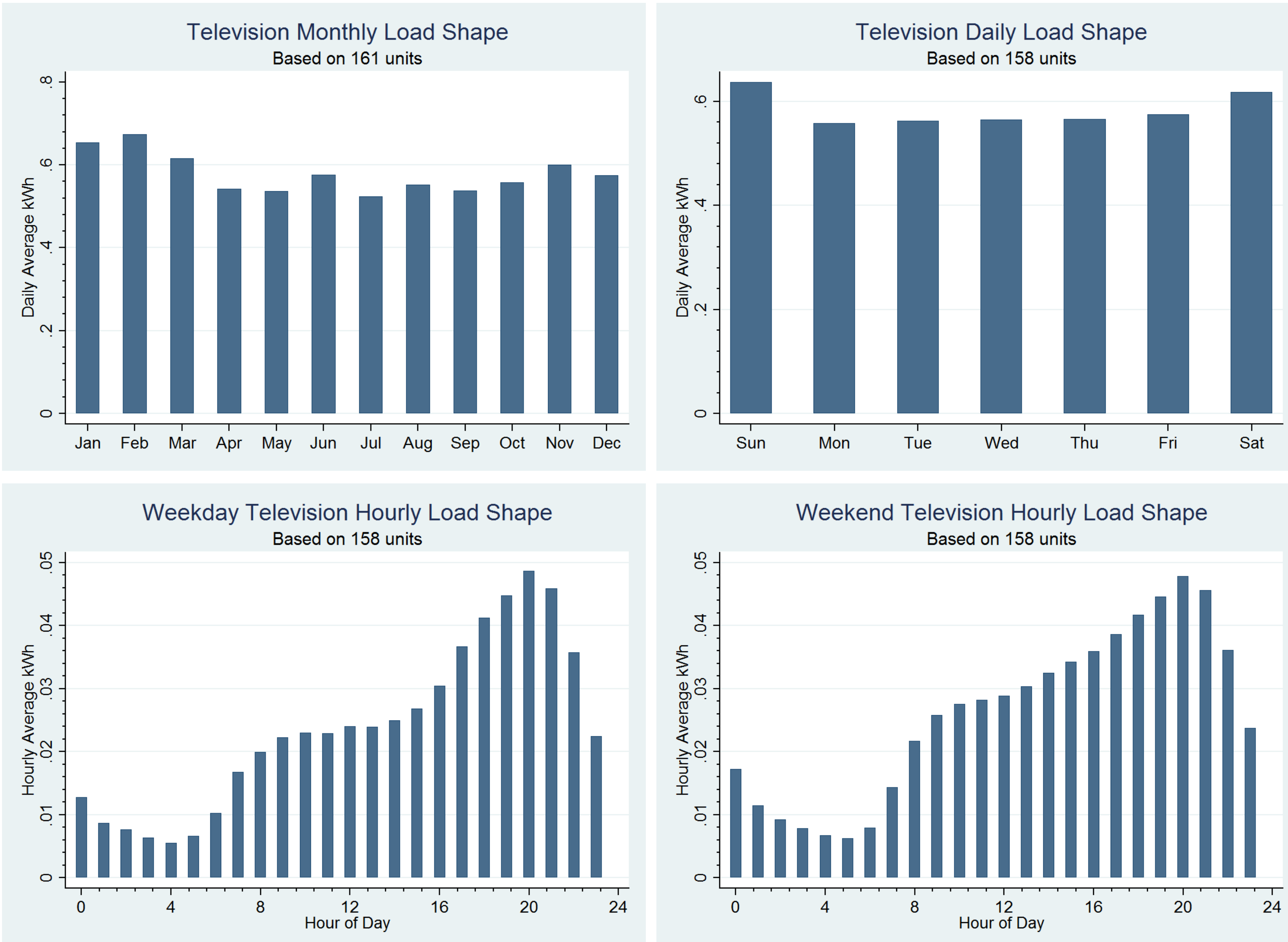


Figure 81. Cable Box and DVR Load Shapes

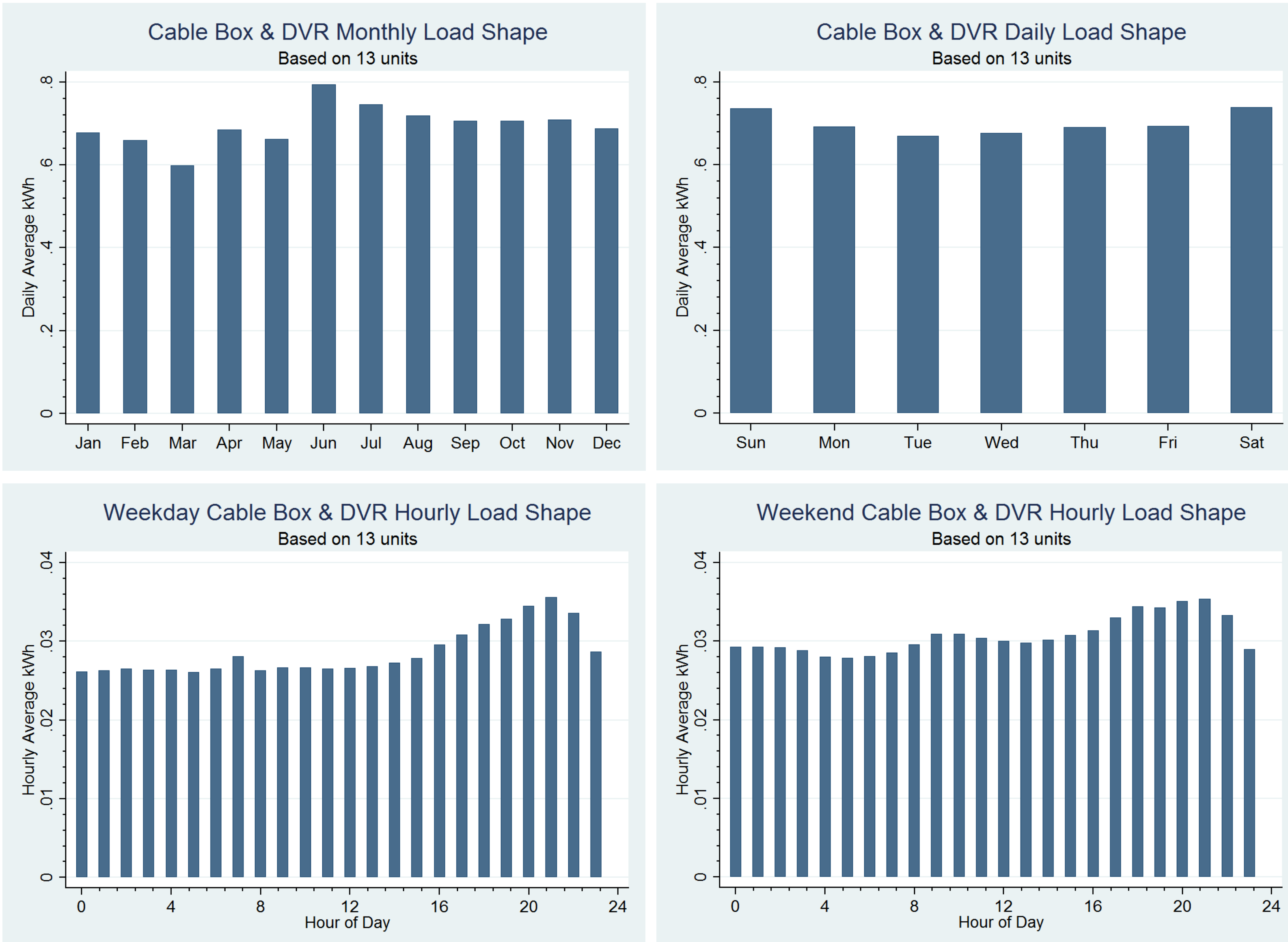


Figure 82. Cable Box Load Shapes

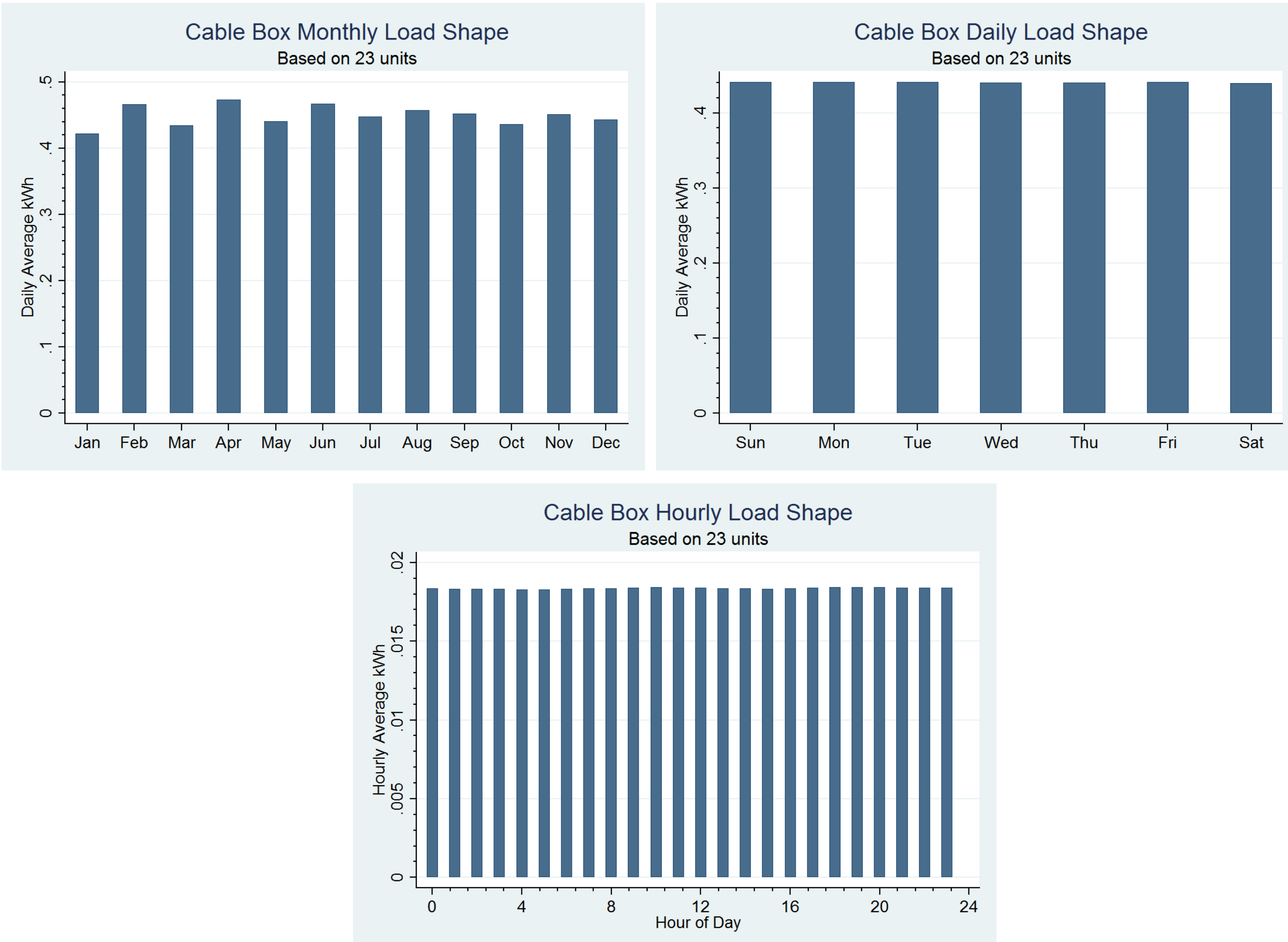


Figure 83. Gaming Console Load Shapes

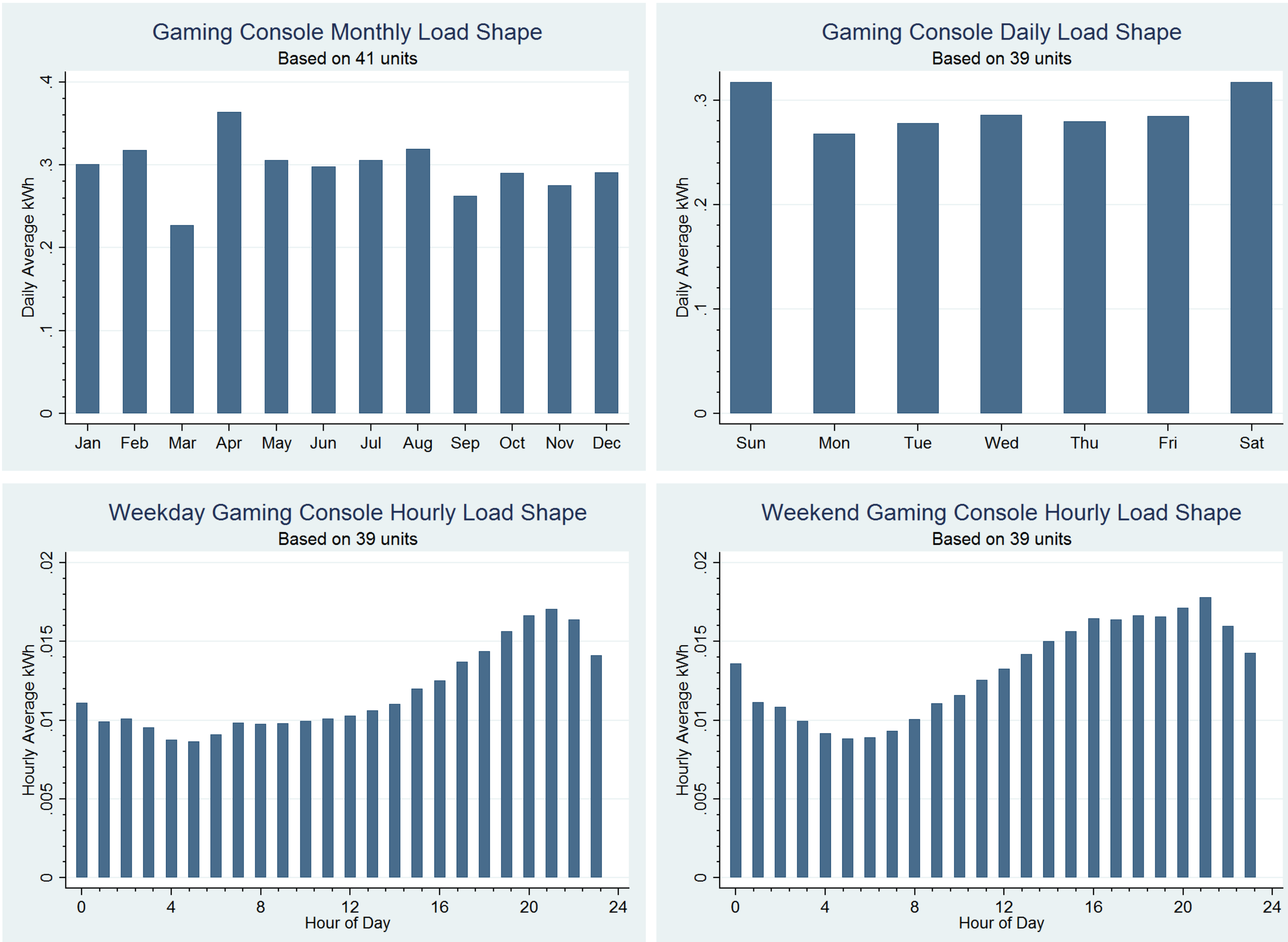


Figure 84. CPU Load Shapes

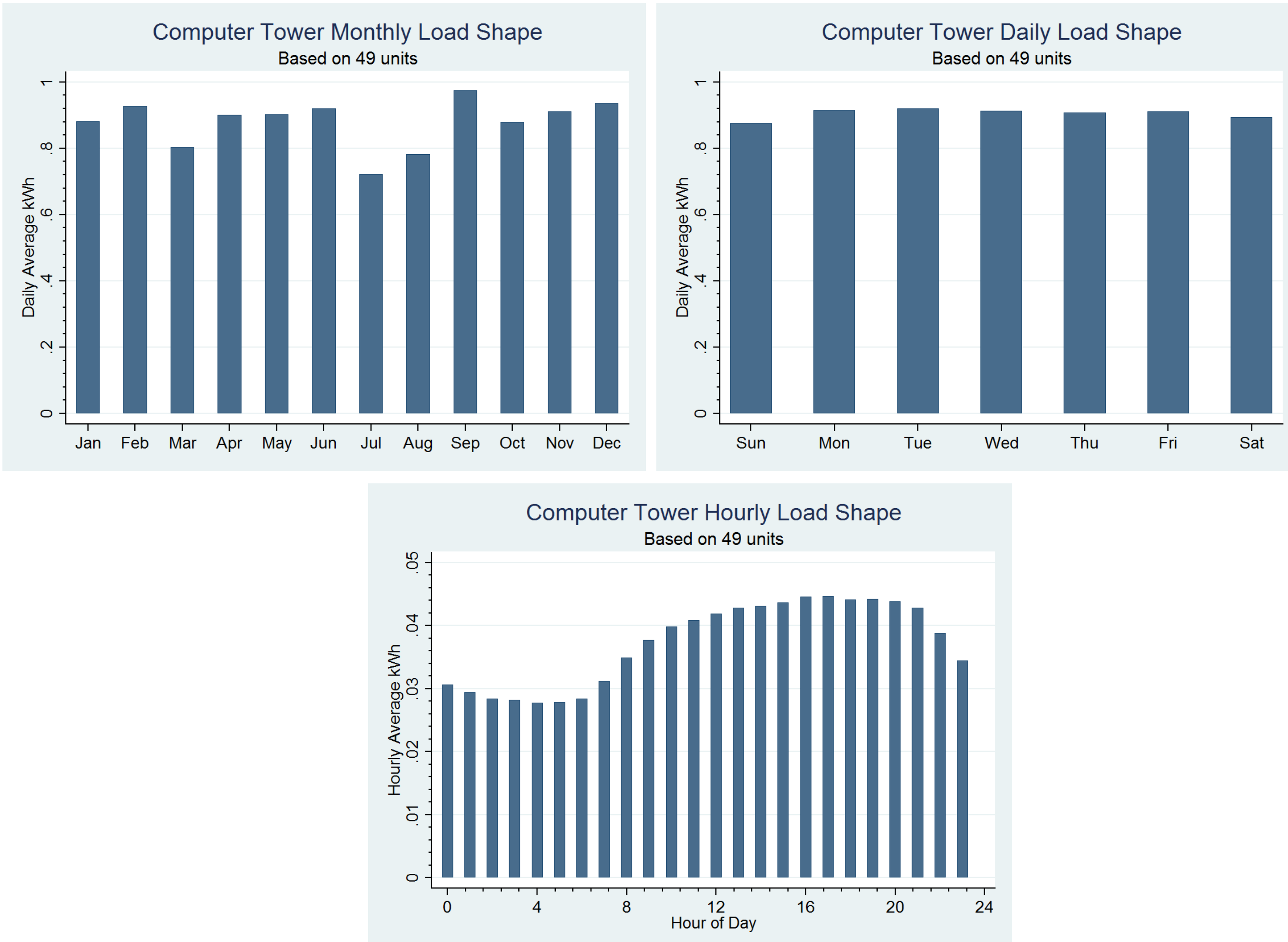


Figure 85. DVD Load Shapes

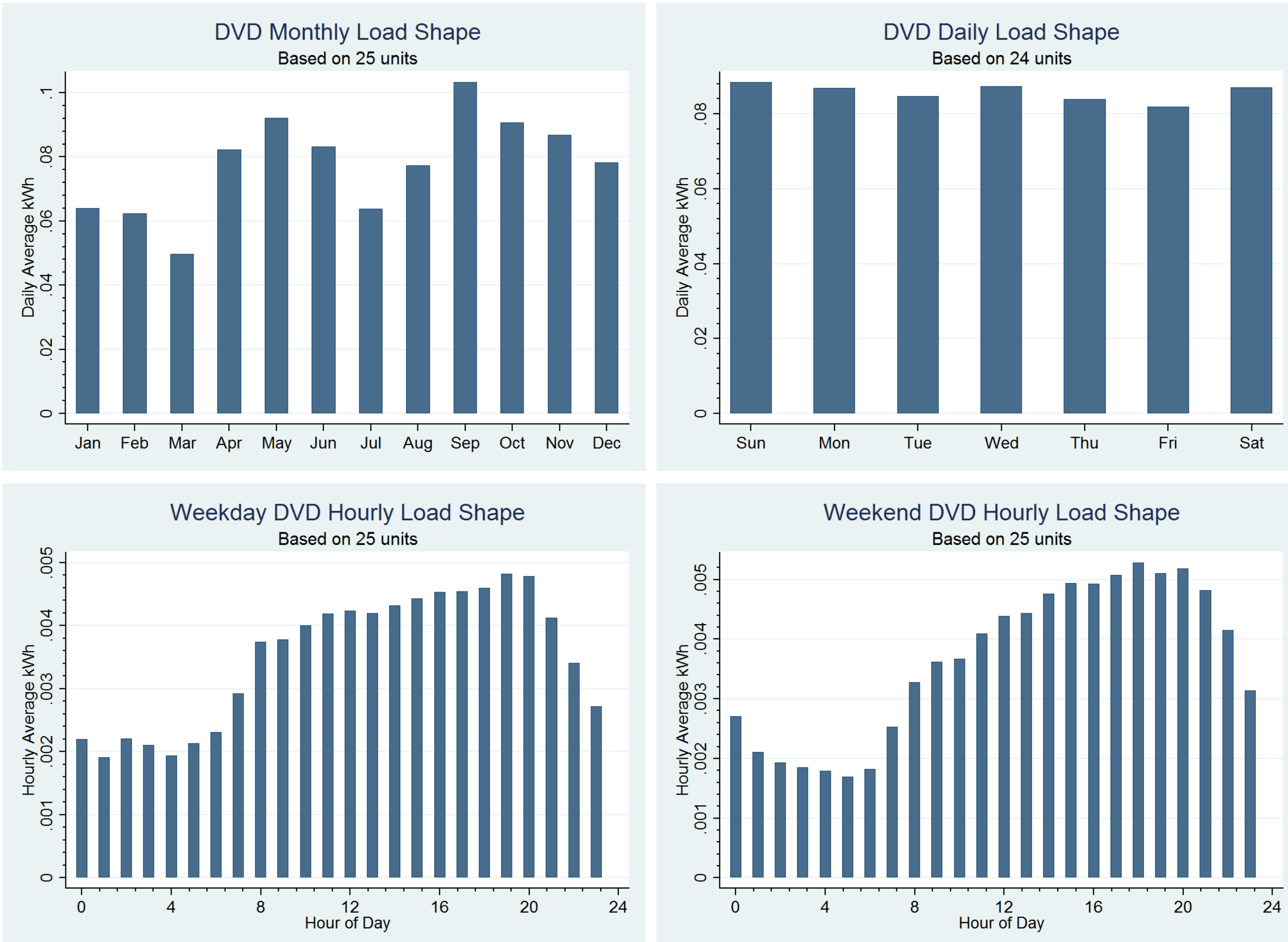


Figure 86: All Sites Total Service Load Shapes

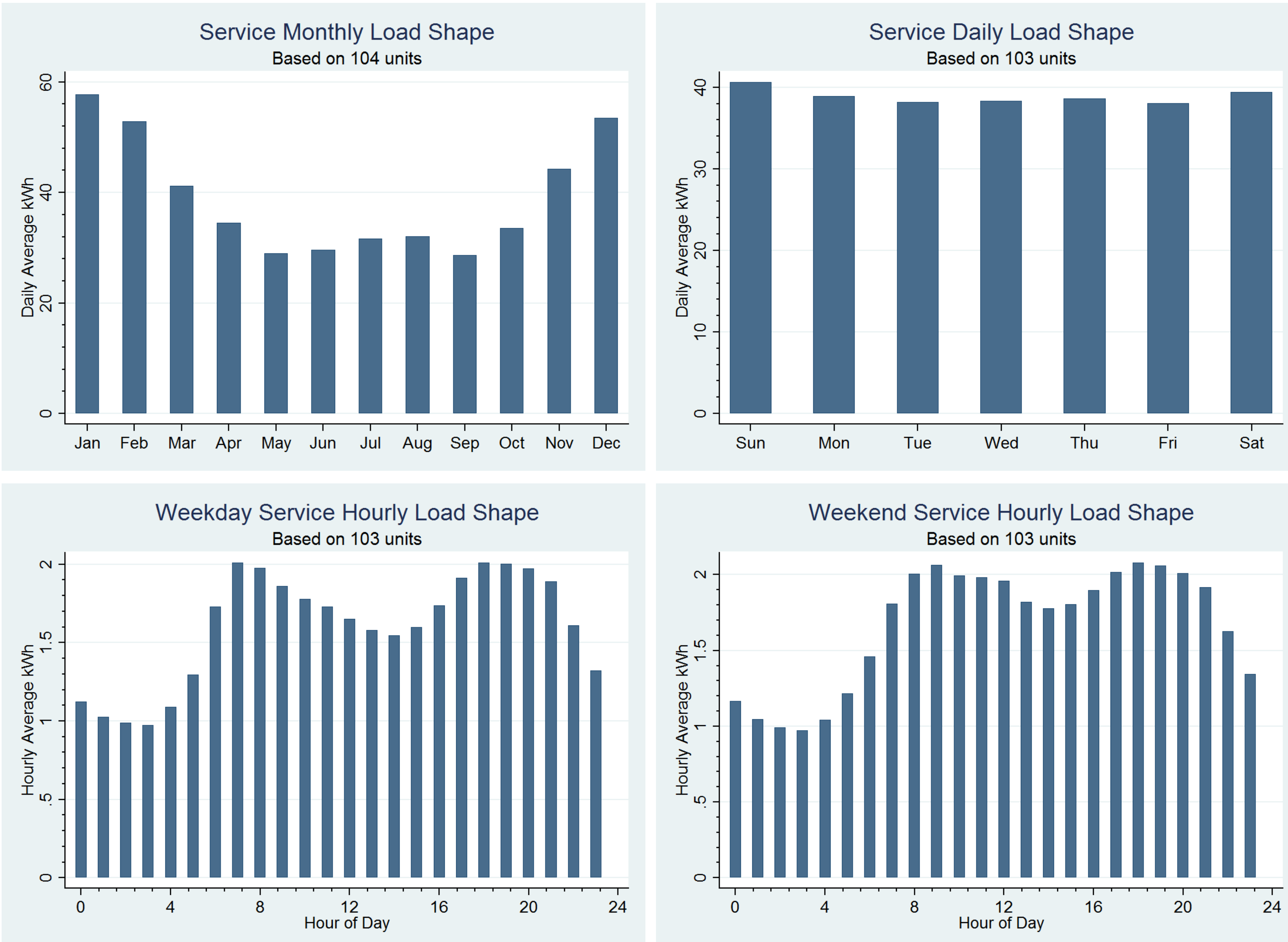


Figure 87: Non-Gas Sites Total Service Load Shapes

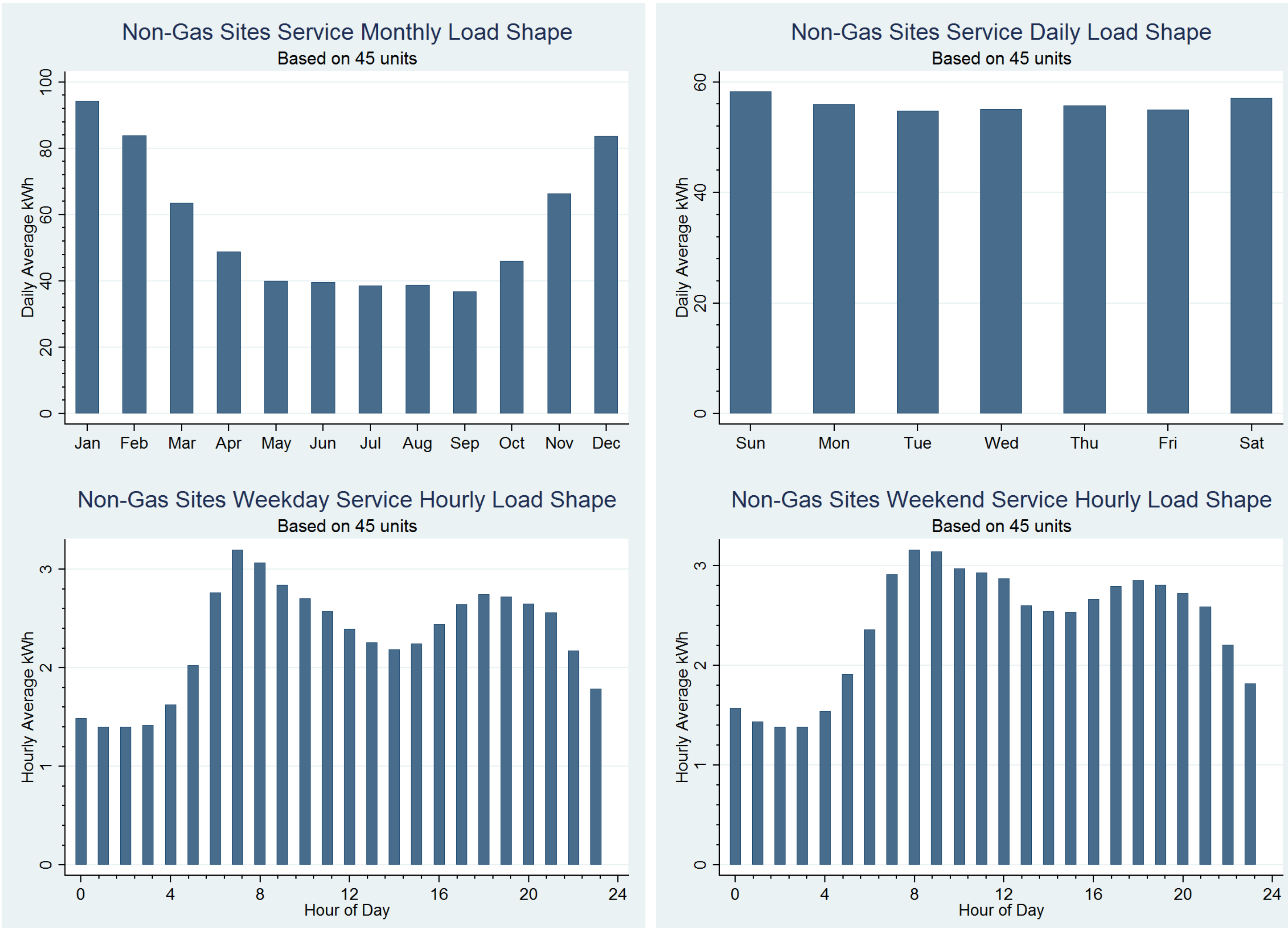


Figure 88: Natural Gas Sites Total Service Load Shapes