RES 1 BASELINE LOAD SHAPE STUDY

Prepared for:
The Electric and Gas Program Administrators of Massachusetts
Part of the Residential Evaluation Program Area

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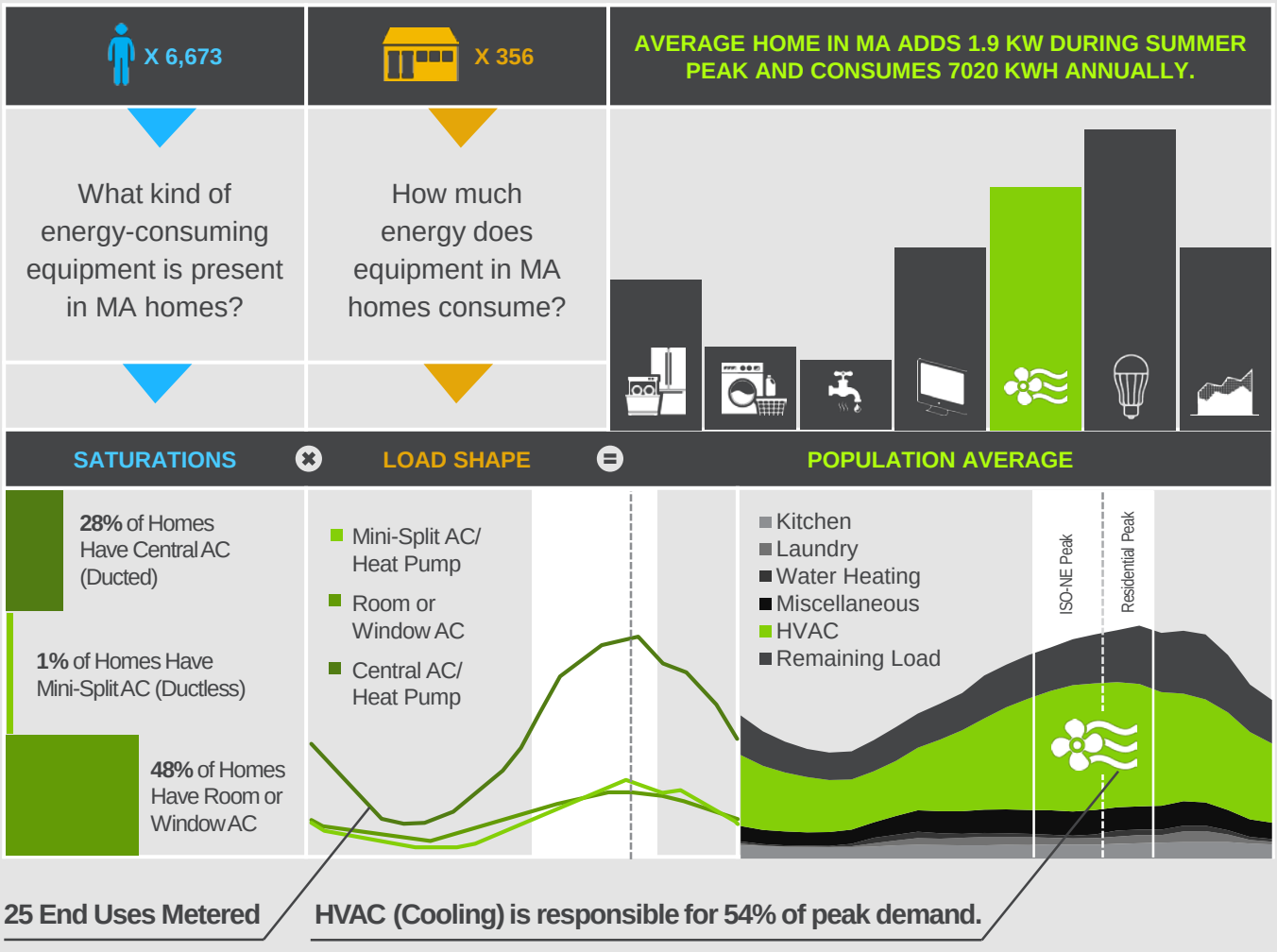
STUDY OVERVIEW

The primary goal of this study is to collect saturation, penetration, and usage behavior data for all major electric and gas appliances, mechanical equipment, and electronics in Massachusetts homes.

These data will support energy and peak demand savings calculations for program evaluation and design, as well as provide additional insight on the savings potential in the existing residential buildings market.

The research team surveyed 6,673 households, asking questions about household occupants and home equipment. Survey results were trued up and expanded upon with onsite metering of 25 end uses at 356 sites.



CONCLUSIONS

COOLING

Central air conditioners (AC) are the single most important end use driving summer peak demand.

Central AC should be the focus of efforts to reduce peak demands, but ductless heat pumps and room AC are also important to a comprehensive program offering.

HEATING

Hardwired electric heat, plug-in electric heat, ductless heat pumps, furnace fans, and boiler distribution systems all consume energy within the same order of magnitude, and are equally important as other prevalent non-HVAC end uses. Ductless heat pump saturation is increasing.

KITCHEN

Refrigerators are the second largest individual consumers of electricity. Peak impacts from kitchen equipment are negligible.

LIGHTING

Lighting consumes the most electricity of any single end use, but its energy intensity is falling quickly due to program interventions and federal standards.

WATER HEATING

Heat pump water heaters have about half of the energy consumption and peak demand of regular electric water heaters, providing potentially significant reductions in peak demand.

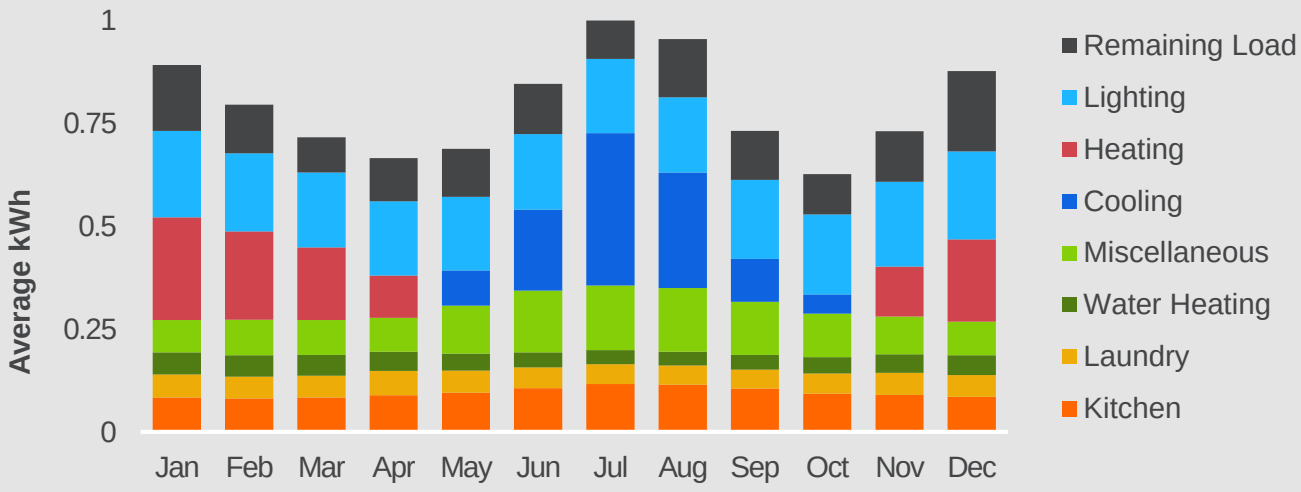
LAUNDRY

Some clothes dryers are used throughout the day, including during afternoon and evening peak.

MISCELLANEOUS

Pool pumps have the largest non-cooling summer peak demand of any metered end use.

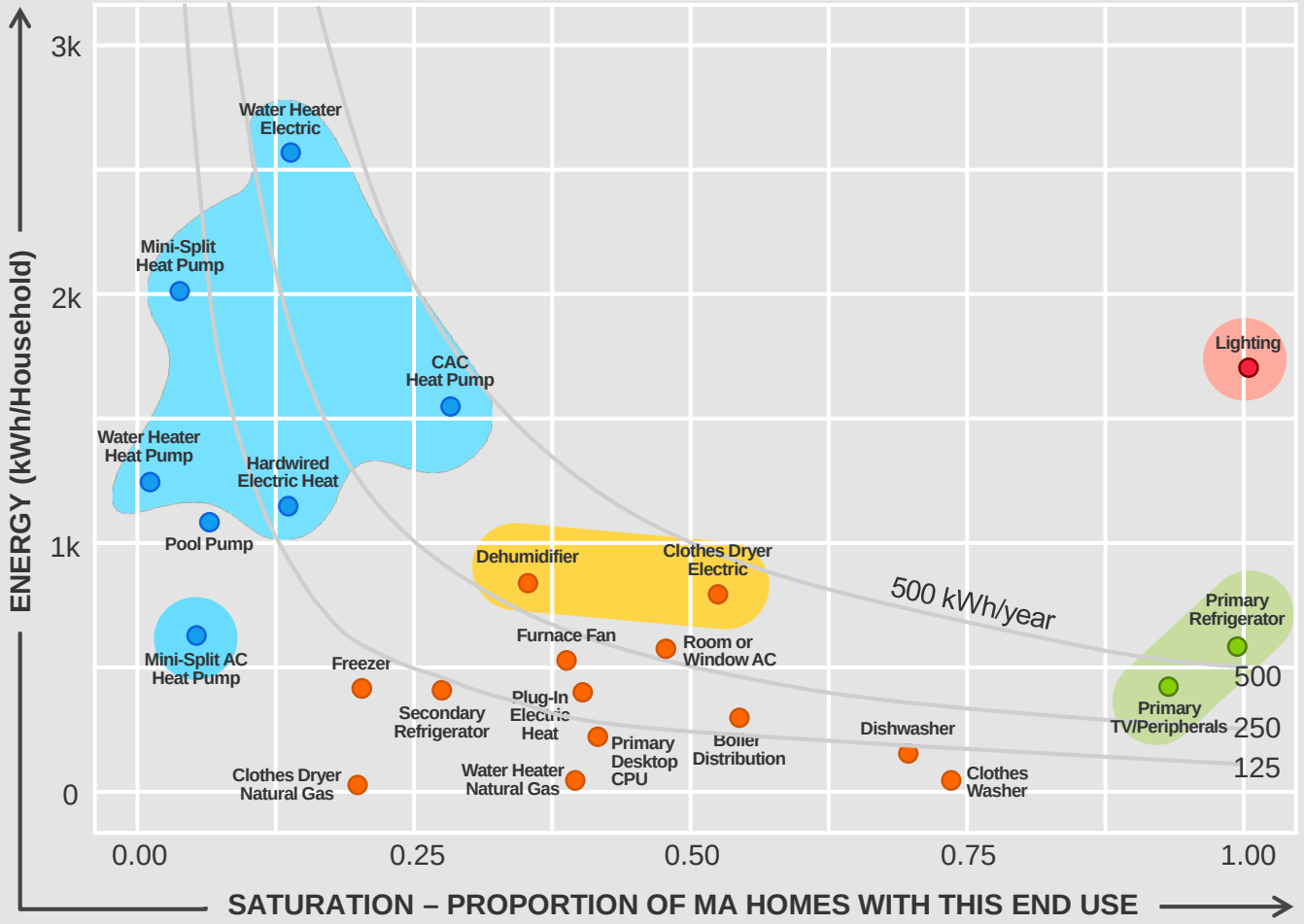
Program administrators should consider targeting dehumidifiers, clothes dryers, and pool pumps for additional peak demand savings with low customer impacts.



ANNUAL ENERGY CONSUMPTION

Electric HVAC and water heating on the move: Electric heating and hot water (including heat pumps) are anticipated to trend upward along with cooling. As saturations of these end uses go up, loads will increase.

Annual energy consumption for lighting is three times larger than any other single end use



Dryers and dehumidifiers are both medium energy consumers and present in many but not all homes.

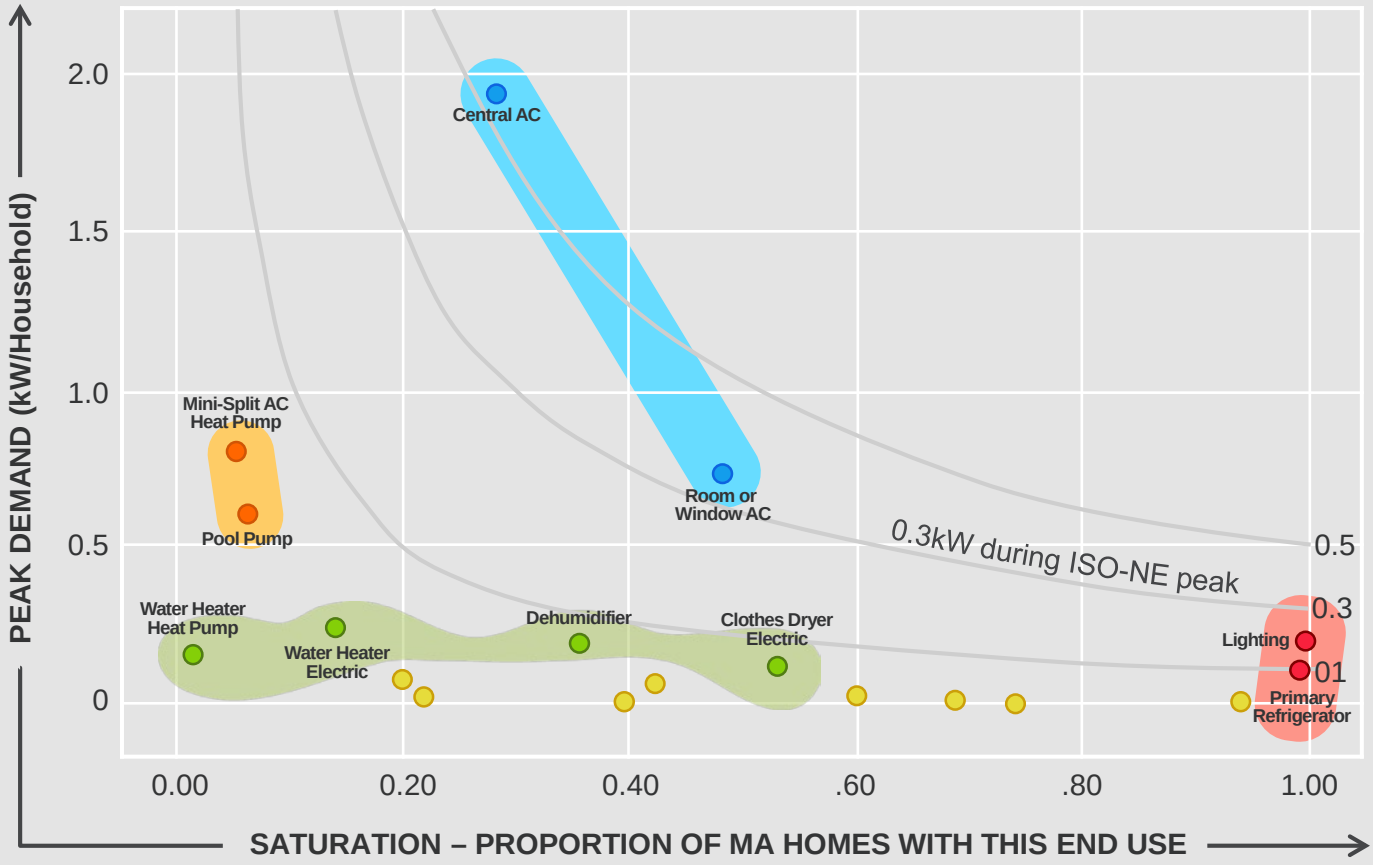
Everyone has a refrigerator; most people have TVs. These end uses are ripe for broad-based behavior or upstream/midstream programs to save energy.

Each point in this plot shows the household consumption and the fraction of households with a given end use. As you move up and to the right, the aggregate consumption per Massachusetts household goes up, as shone by the lines of constant aggregate Massachusetts consumption. For example, lighting is found in 100% of homes and has an annual consumption of 1680 kWh per home with a TV, so the statewide average is 1680 kWh per Massachusetts household, while Central AC is found in 28% of homes and has an annual consumption of 1530 kWh per home with a Central AC. This yields 434 kWh per Massachusetts household.

SUMMER PEAK DEMAND

Rare high quality opportunities for peak savings

Central air conditioners are the single most important end use driving summer peak demand, and their saturation is increasing. Room ACs are the next largest contributor. These two end uses are the best opportunity for near-term peak demand savings



Some households with these end uses have good opportunities for demand savings, but not all.

Ubiquitous end uses like refrigerators and lighting are candidates for behavior-based DR, or upstream/midstream programs.

Each point in this plot shows the household demand and the fraction of households with a given end use. As you move up and to the right, the aggregate demand per Massachusetts household goes up, as shone by the lines of constant demand. For example, lighting is found in 100% of homes and accounts for 0.19 kW per home, so the statewide average is 0.19 kW per household. Central AC is found in 28% of homes and has an average demand of 1.96 kW per home with a central AC. This yields 0.56 kW per Massachusetts household.

TABLE OF CONTENTS

1. Introduction 9

1.1 Study Goals 9
1.2 Summary of Research Activities 9
1.3 Terminology 11
1.4 Abbreviations 12

2. Results and Key Findings 13

2.1 Annual Energy Consumption 13
2.2 Peak Demand 20
2.2.1 Summer Peak Demand 21
2.2.2 Winter Peak Demand 29
2.3 End Use-Specific Findings 36
2.3.1 HVAC End Uses 36
2.3.2 Kitchen End Uses 44
2.3.3 Laundry End Uses 50
2.3.4 Water Heating End Uses 55
2.3.5 Miscellaneous End Uses 61

3. Overall Conclusions and Considerations 67

Appendix A. Methods A-1

A.1 Online Survey A-1
A.2 Onsite Sampling A-2
A.3 Onsite Metering A-0
A.4 Data Analysis A-1

Appendix B. Statistics B-1

Appendix C. Supporting Data C-1

LIST OF FIGURES

Figure 1. Study Approach for Determining End Use Load Shapes 10
Figure 2. Population Annual Energy Consumption by End Use Category 14
Figure 3. Population Annual Energy Consumption by End Use 15
Figure 4. Population Average Energy Consumption by Month and End Use Category 16
Figure 5. Average Annual Energy Consumption by End Use Category and Building/Occupancy Demographics 17
Figure 6. End Use Saturation and Annual Energy Consumption for Homes with End Use 18
Figure 7. Average Demand for Five Periods by End Use 21
Figure 8. Summer Peak Day End Use Category Load Shapes 22
Figure 9. Summer Peak Day End Use Load Shapes 23
Figure 10. ISO-NE Summer Peak Demand for Top 25% of Each Metered End Use's Users 24
Figure 11. Proportion of Homes with Average ISO-NE Summer Peak Demand Greater than 0.2 kW for Each Measured End Use 25
Figure 12. Summer ISO-NE Peak Demand by End Use Category and Building/Occupancy Demographics 26
Figure 13. End Use Saturation and Summer Demand for Homes with End Use 27
Figure 14. Winter Peak Day End Use Category Load Shapes 29
Figure 15. Winter Peak Day End Use Load Shapes 30
Figure 16. ISO-NE Winter Peak Demand for Top 25% of Each Metered End Use's Users 31
Figure 17. Proportion of Homes with Average ISO-NE Winter Peak Demand Greater than 0.2 kW for Each Measured End Use 32
Figure 18. Winter ISO-NE Peak Demand by End Use Category and Building/Occupancy Demographics 33
Figure 19. End Use Saturation and Winter Demand for Homes with End Use 34
Figure 20. HVAC Cooling Equipment Saturation and Penetration 37
Figure 21. HVAC Heating Equipment Saturation and Penetration 38
Figure 22. Population Annual End Use Energy Consumption – HVAC End Uses (kWh) 39
Figure 23. Summer Peak Day HVAC End Use Load Shapes for Homes with End Use 40
Figure 24. Cooling System Use 41
Figure 25. Winter Peak Day HVAC End Use Load Shapes for Homes with End Use 42
Figure 26. Secondary Heating Use 43
Figure 27. Rated vs. Measured Boiler Efficiency 44
Figure 28. Kitchen End Use Saturation and Penetration 45
Figure 29. Secondary Refrigerator Types 46
Figure 30. Population Annual End Use Energy Consumption – Kitchen End Uses (kWh) 47
Figure 31. Summer Peak Day Kitchen Load Shapes for Homes with End Use 48
Figure 32. Winter Peak Day Kitchen Load Shapes for Homes with End Use 49
Figure 33. Dishwasher Use 50
Figure 34. Laundry End Use Saturation and Penetration 51
Figure 35. Population Annual End Use Energy Consumption – Laundry End Uses (kWh) 52
Figure 36. Summer Peak Day Laundry Load Shapes for Homes with End Use 53
Figure 37. Winter Peak Day Laundry Load Shapes for Homes with End Use 54
Figure 38. Laundry Use 55
Figure 39. Water Heating End Use Saturation and Penetration 57
Figure 40. Population End Use Annual Energy Consumption – Water Heating End Uses (kWh) 58
Figure 41. Summer Peak Day Water Heating Load Shapes for Homes with End Use 59
Figure 42. Winter Peak Day Water Heating Load Shapes for Homes with End Use 60

Figure 43. Hot Water Use 61
Figure 44. Miscellaneous End Use Saturation and Penetration – Outdoor 62
Figure 45. Miscellaneous End Use Saturation and Penetration – Electronics 63
Figure 46. Population End Use Annual Energy Consumption – Miscellaneous End Uses 64
Figure 47. Summer Peak Day Miscellaneous Load Shapes for Homes with End Use 65
Figure 48. Winter Peak Day Miscellaneous Load Shapes for Homes with End Use....66

Figure A-1. eGauge Energy Metering Setup in Customer Homes....A-0
Figure A-2. Onset Plug Load Logger Used in Customer Homes....A-0
Figure A-3. Saturation and Load Shape Analysis Map....A-4
Figure A-4. Lighting and Remaining Load Comparison: January Weekday....A-6
Figure A-5. Lighting and Remaining Load Comparison: January Weekend....A-6
Figure A-6. Lighting and Remaining Load Comparison: June Weekday....A-7
Figure A-7. Lighting and Remaining Load Comparison: June Weekend....A-7
Figure A-8. Weather Normalization Test Results....A-9

LIST OF TABLES

Table 1. Measured End Uses by Category....11
Table 2. Annual Energy Consumption by End Use 19
Table 3. EFLH and CF by End Use 20
Table 4. Peak Period Definitions....21
Table 5. Summer Peak Demand by End Use....28
Table 6. Winter Peak Demand by End Use 35
Table 7. RASS Comparison – Heating Systems....36
Table 8. RASS Comparison – Cooling Systems....36
Table 9. RASS Comparison – Kitchen Appliances 44
Table 10. RASS Comparison – Laundry....50
Table 11. RASS Comparison – Water Heating Systems....56
Table 12. RASS Comparison – Miscellaneous....61

Table A-1. Survey Recruitment Summary A-2
Table A-2. Targeted Sampling Assumptions and Achieved Sample A-4
Table A-3. Combined End Uses for Load Shape Analysis A-3
Table A-4. Weather Years Used by Time Period....A-13
Table B-1. Comparison of Actual Relative Precision to Expected Relative Precision B-1
Table C-1. Appendix C Supporting Documents File Names and Contents....C-1

1. INTRODUCTION

Navigant Consulting, Inc. (Navigant), in collaboration with Bellomy Research and NMR Consulting, Inc., is conducting a large multiyear baseline saturation and load shape study in which data is collected via online survey, onsite validation, and long-term metering. This study and ongoing primary data collection effort strives to provide the Massachusetts Program Administrators (PAs) and Energy Efficiency Advisory Council (EEAC) consultants more granular data about the energy consumption of residential buildings and their occupants. The PAs and EEAC also want to learn more about relevant opportunities for reducing overall consumption and consumption during peak periods. The study began in January 2017 and will continue through at least the spring of 2019.[1]

1.1 Study Goals

The primary goal of the baseline study is to collect saturation, penetration, and usage behavior data for all major electric and gas appliances, mechanical equipment, and electronics in Massachusetts homes. These data will support energy and peak demand savings calculations for program evaluation and design and will provide additional insight into the savings potential in the existing residential buildings market. The secondary goal of this study is to support other research that the PAs are undertaking by providing comprehensive data for the sampled customers. These other research efforts include energy efficiency potential studies and market effects research, among others.

This report is intended to answer the primary research question stated in the study's Stage 3 Plan: "How and when are people using the electric equipment in their homes?" [2] We present key findings from the metered data that was collected between May 2017 and April 2018. The results and findings provided here may change in future updates to this report based on newly available or updated information.

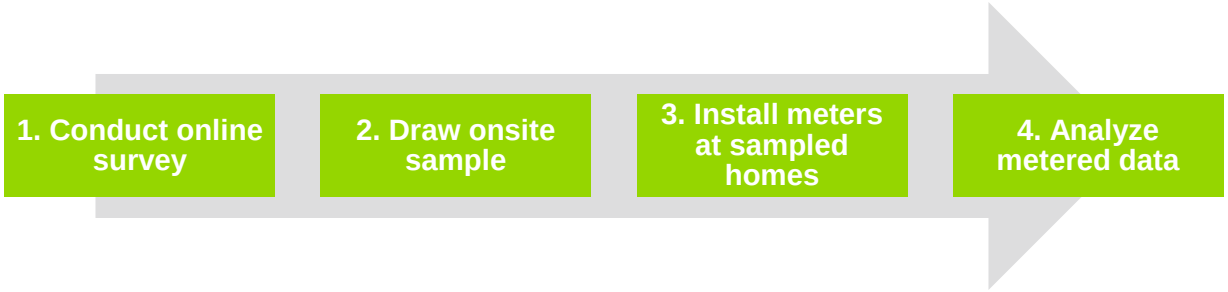
1.2 Summary of Research Activities

This study's research approach and activities followed the step-by-step process outlined in Figure 1. Information for each step is provided below the figure, and additional details on the study's methodology is contained in Appendix A.

[1] The originally scoped study was intended to last until the spring of 2018. However, the PAs and EEAC have decided to extend the study for at least 1 additional year. The Stage 3 Plan for the additional year of the study (Phase 3) was finalized in February 2018.

[2] This study has two primary research questions and three secondary research questions. All research questions can be found in the study's Stage 3 Plan.

Figure 1. Study Approach for Determining End Use Load Shapes



1. **Conduct online survey** to inventory saturation of several key end uses in Massachusetts residences, which serves as the population frame for the metered sample. The survey asked questions related to the respondents' demographics, home characteristics, and home appliances. Survey recruitment was completed via mailed postcards; most of the postcards were sent to households sampled randomly from the participating statewide utilities' customer bases. The research team received 6,673 total completed surveys, between February and June 2017.[3] The last 1,600 completes were obtained as part of a targeted recruitment effort based on geographies that had a higher saturation of underrepresented priority characteristics such as renter, low income, multifamily, and non-English speaking households.
2. **Draw onsite sample** to meet end use confidence and precision targets determined during the project's planning phase. The core sample was drawn to maintain several representativeness quotas. The oversample includes homes with specific under-sampled end uses, which ensures that all end uses meet the confidence and precision targets.
3. **Install meters** to measure all end uses at core sampled homes and the sampled end use for oversampled homes. Two kinds of meters were installed: meters installed in the panel that communicates remotely via power line carrier and non-communicating plug load meters installed at the end use. The initial 300 core site visits and 56 oversample site visits were completed between March and June 2017. The team downloaded the data from plug load meters for the heating season during revisits conducted in February and March 2018. The meters will remain in place for at least 1 more year.
4. **Analyze metered data** to determine typical year and peak year load shapes by end use.[4] Data from all meters were rigorously checked for quality and completeness before being aggregated to hourly granularity at each site. Site-level data were aggregated to generate per home average load shapes and peak period consumption for each end use. Saturations from survey data were used in conjunction with site-level metered data to generate aggregate (statewide) average load shapes and peak period results.

Table 1 shows the measured end uses for which Navigant is providing load shape results in this report. Most end uses on this list were identified during study planning as high priority end uses to measure. End uses that proved to be inconsequential to the overall load due to either small sample size or small load

[3] This does not include the additional 228 Cape Light Compact oversample completes.

[4] This report presents non-weather normalized results. Typical and peak year load shapes will need further weather normalization. Annual weather normalized results will be presented in the next report, which will be delivered in May/June 2018.

are combined as other heating and cooling,[5] other pumps,[6] and other miscellaneous metered loads.[7] Unmetered loads were calculated by subtracting the metered end use loads and a lighting load shape[8] from the metered whole premise loads.

Table 1. Measured End Uses by Category

End Use Category	Measured End Uses	
HVAC	• Central air conditioner/heat pump • Room air conditioner • Ductless air conditioner/heat pump* • Furnace fan	• Hardwired electric heat • Plug-in electric heat • Boiler distribution system • Ductless heat pump* • Other heating and cooling
Kitchen	• Dishwasher • Refrigerator	• Second refrigerator • Freezer
Laundry	• Electric clothes dryer • Gas clothes dryer*	• Electric washer
Water Heating	• Electric water heater • Heat pump water heater	• Gas water heater*
Miscellaneous	• Pool pumps • Other pumps • Primary TVs and peripherals*	• Dehumidifiers • Computers and peripherals* • Other miscellaneous metered loads

*End uses that the team had enough metered data to report on even though they were not identified as high priority end uses.

1.3 Terminology

Throughout this report, the research results are referenced with various terminology:

- **Population:** These results are scaled by saturation and show the overall impact to the system, on average, by home but do not represent the impact from an individual appliance.
- **For Homes with End Use:** These results only include homes with the relevant end use installed, irrespective of the saturation of that end use in the population.
- **Summer ISO-NE Peak:** For the purposes of this report, ISO-NE summer peak is approximated as 1-5 p.m. on the day with the highest summer ISO-NE system peak load. For the weather normalized data, peak demand was modeled for the previous 15 years, and the year that resulted in the median demand was chosen as typical.[9]

[5] All cooling-only end uses (room ACs, central ACs, ductless ACs), central heat pumps, whole house fans, and ground source heat pumps are combined as other heating and cooling.

[6] Pool pumps were the only type of pump found to have significant electricity consumption. All other pumps were combined into the other pumps group, which includes well pumps, booster pumps, sump pumps, and ejector pumps.

[7] The other miscellaneous metered loads group includes a long list of rare end uses that were metered but cannot be statistically extrapolated individually. These end uses include electric vehicle (EV) chargers, hot tubs, pool heaters, water beds, large battery chargers, and large fish tanks.

[8] While lighting results based on the previous Northeast Lighting Hours of Use Study are included in this report, lighting was not metered as part of the study, so the lighting results and unmetered loads may not align for small subgroups.

[9] Details on peak period dates are in Table A-4 in Appendix A.4.4.

- **Summer Residential Peak:** For the purposes of this report, residential summer peak is defined as a forward-looking evening peak, set for 5-7 p.m., using the same peak day that was chosen to represent the typical summer ISO-NE peak load.[9]
- **Summer Peak Days:** These results only include data from the peak day chosen to represent the typical summer ISO-NE peak load, as defined in Summer ISO-NE Peak above.[9]
- **Winter ISO-NE Peak:** For the purposes of this report, ISO-NE winter peak is approximated as 5-7 p.m. on the day with highest winter ISO-NE system peak load. For the weather normalized data, peak demand was modeled for the previous 15 years, and the year that resulted in the median demand was chosen as typical.[9]
- **Winter Expanded Peak:** For the purposes of this report, expanded winter peak is defined as 5-9 p.m., using the same dates that were chosen to represent the typical winter ISO-NE peak load.[9]
- **Winter Peak Days:** These results only include data from the peak day chosen to represent the typical winter ISO-NE peak load.[9]
- **Building Type:** Either single-family detached, single-family attached (2-4 units), or multifamily (5+ units).
- **Number of Occupants:** Number of permanent residents (adults and children) living in the home.
- **Top 25%:** Results are presented for homes that fall in the top 25% of energy consumers for a given end use.
- **Remaining Load:** This is the unmetered portion of the total household electricity use, composed of all of the end uses that did not get metered.

1.4 Abbreviations

Throughout this report, we have used several abbreviations as defined below:

- **AC:** Air Conditioner
- **ACS:** American Community Survey
- **CF:** Coincidence Factor
- **EEAC:** Energy Efficiency Advisory Council
- **EER:** Energy Efficiency Ratio
- **EFLH:** Equivalent Full Load Hours
- **EV:** Electric vehicle
- **HOU:** Hours of use
- **PA:** Program Administrators
- **SEER:** Seasonal Energy Efficiency Ratio
- **DHW:** Domestic Hot Water
- **HP:** Heat Pump
- **HVAC:** Heating, Ventilation, and Air Conditioning
- **ISO-NE:** ISO New England
- **TRM:** Technical Reference Manual

2. RESULTS AND KEY FINDINGS

This section contains weather normalized annual energy consumption (expressed as average power), summer peak demand and winter peak findings by end use category, and further end use-specific results. The full accompanying datasets, including additional charts and graphics, are provided as Appendix C to this report. Metered data were collected from March 2017 through May 2018 and adjusted according to the methodology laid out in Appendix A.4.

2.1 Annual Energy Consumption

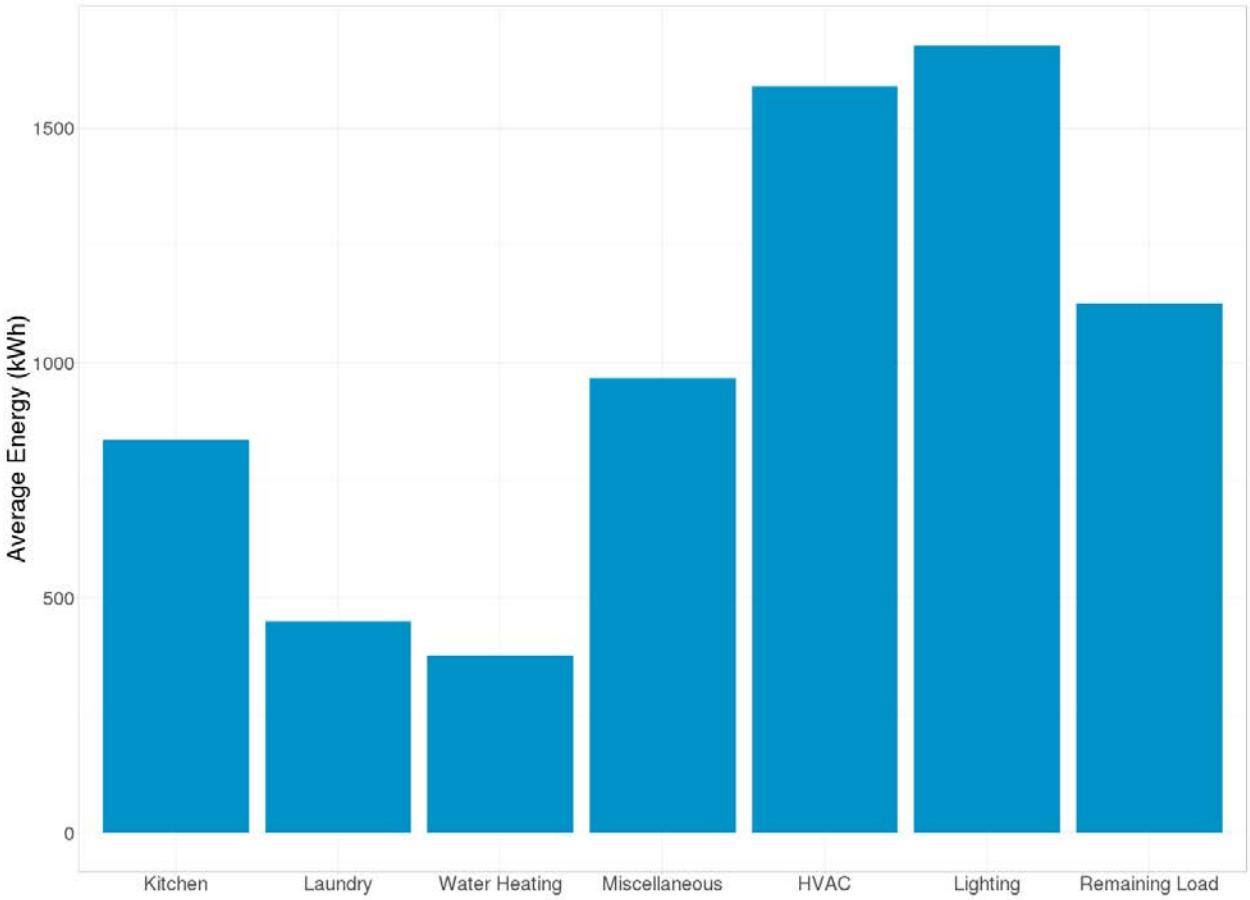
A wide variety of end uses contribute to overall residential energy consumption. End use saturation and average consumption for homes with end use is shown in Figure 6 and values are provided in Table 2.[10]

The energy consumption of each end use category is shown in Figure 2, and the consumption of each end use individually is shown in Figure 3. While 14 different ends uses consume at least 100 kWh per household, dehumidifiers may surprise people as having about the same annual consumption as electric water heaters or room ACs. Figure 4 shows that all end use categories have at least some seasonal variability, more than you might expect.

The number of occupants and weekday occupancy are highly correlated with overall energy usage, as shown in Figure 5. Owner-occupied homes and single-family detached homes also tended to have higher energy use. Further breakdowns of energy and demand by demographic and end use categories are available in Appendix C. Table 2 shows the energy consumption of individual metered end uses both for homes with the end use and averaged across the entire population of homes in Massachusetts.

[10] The saturations listed in the first column of the table were collected as part of this study and delivered to the PAs on July 17, 2017.

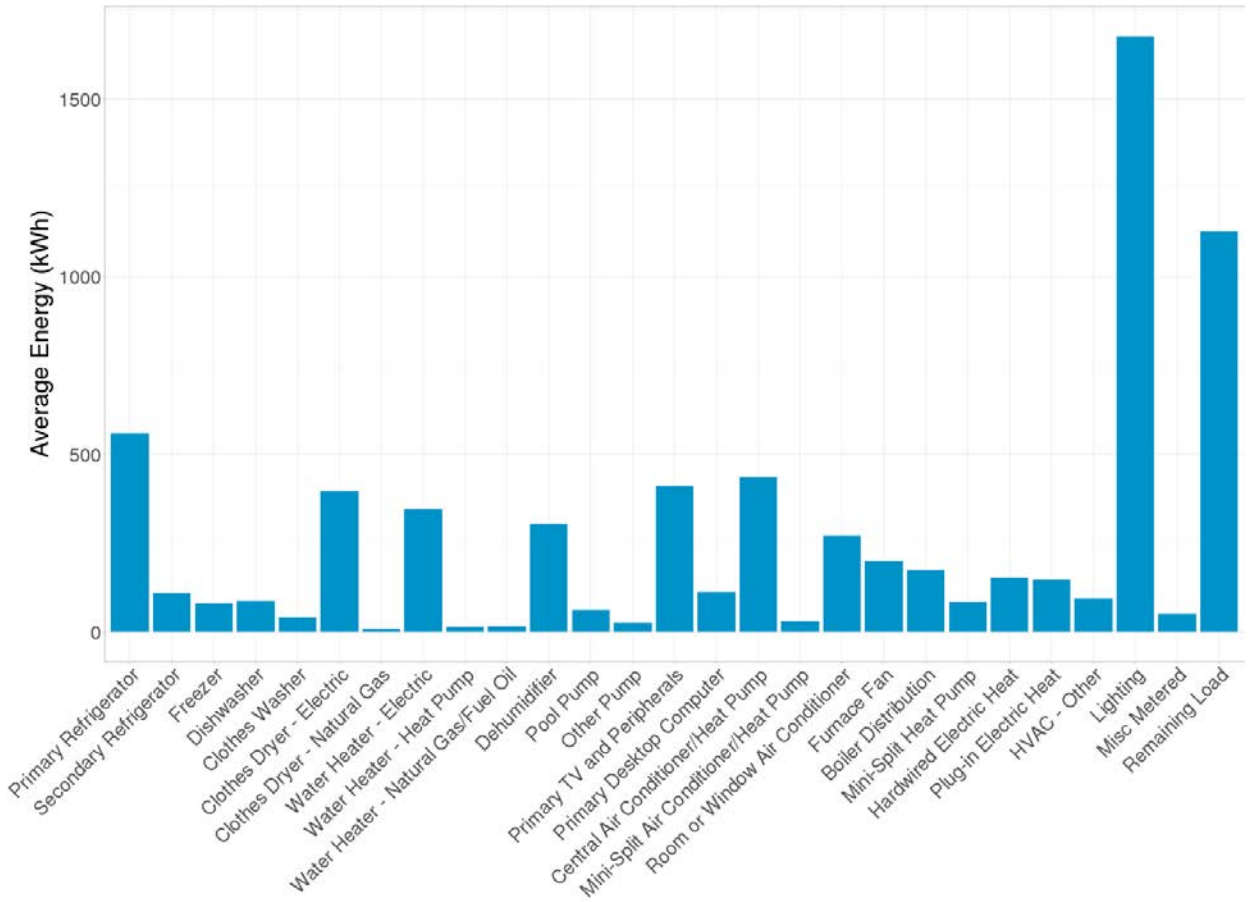
Figure 2. Population Annual Energy Consumption by End Use Category



Source: Navigant analysis

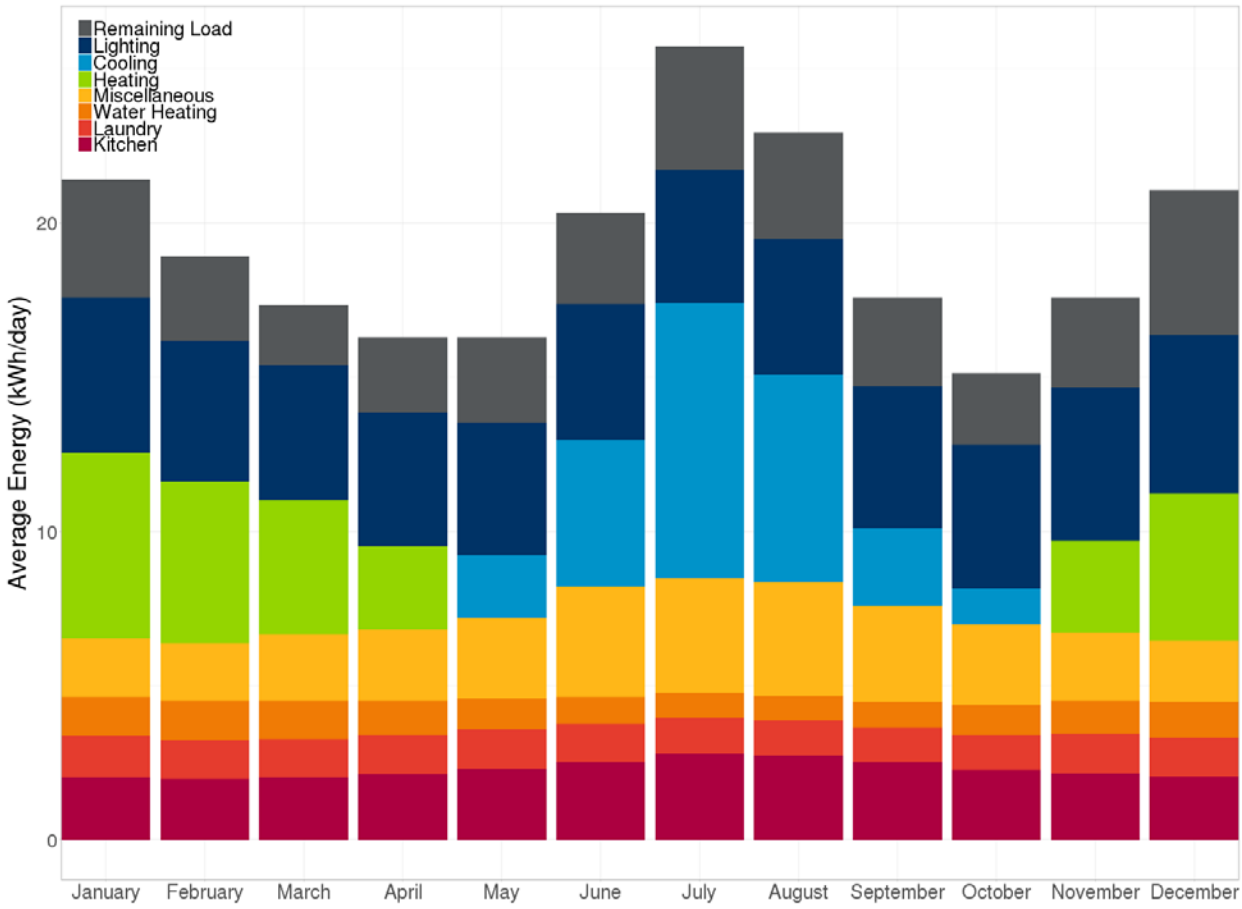
Key Finding: *Lighting and HVAC are the two largest end use categories.*

Figure 3. Population Annual Energy Consumption by End Use



Source: Navigant analysis

Figure 4. Population Average Energy Consumption by Month and End Use Category

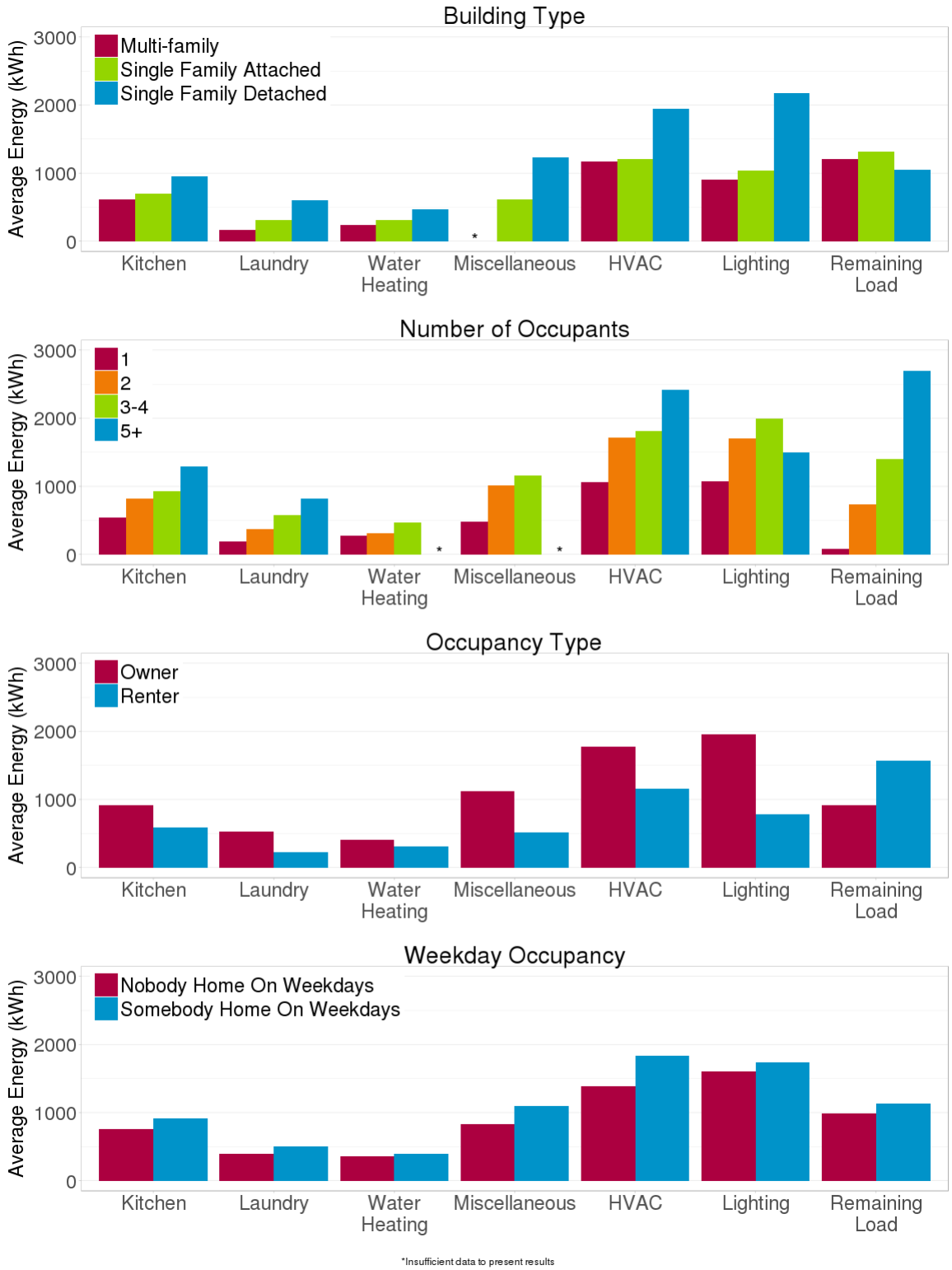


Source: Navigant analysis

Key Finding: *While HVAC is the most seasonally variable end use, refrigerators, hot water heaters, dehumidifiers, and pool pumps all contribute seasonal variation.*

Key Finding: *Household energy consumption for each end use correlates strongly with the number of occupants.*

Figure 5. Average Annual Energy Consumption by End Use Category and Building/Occupancy Demographics

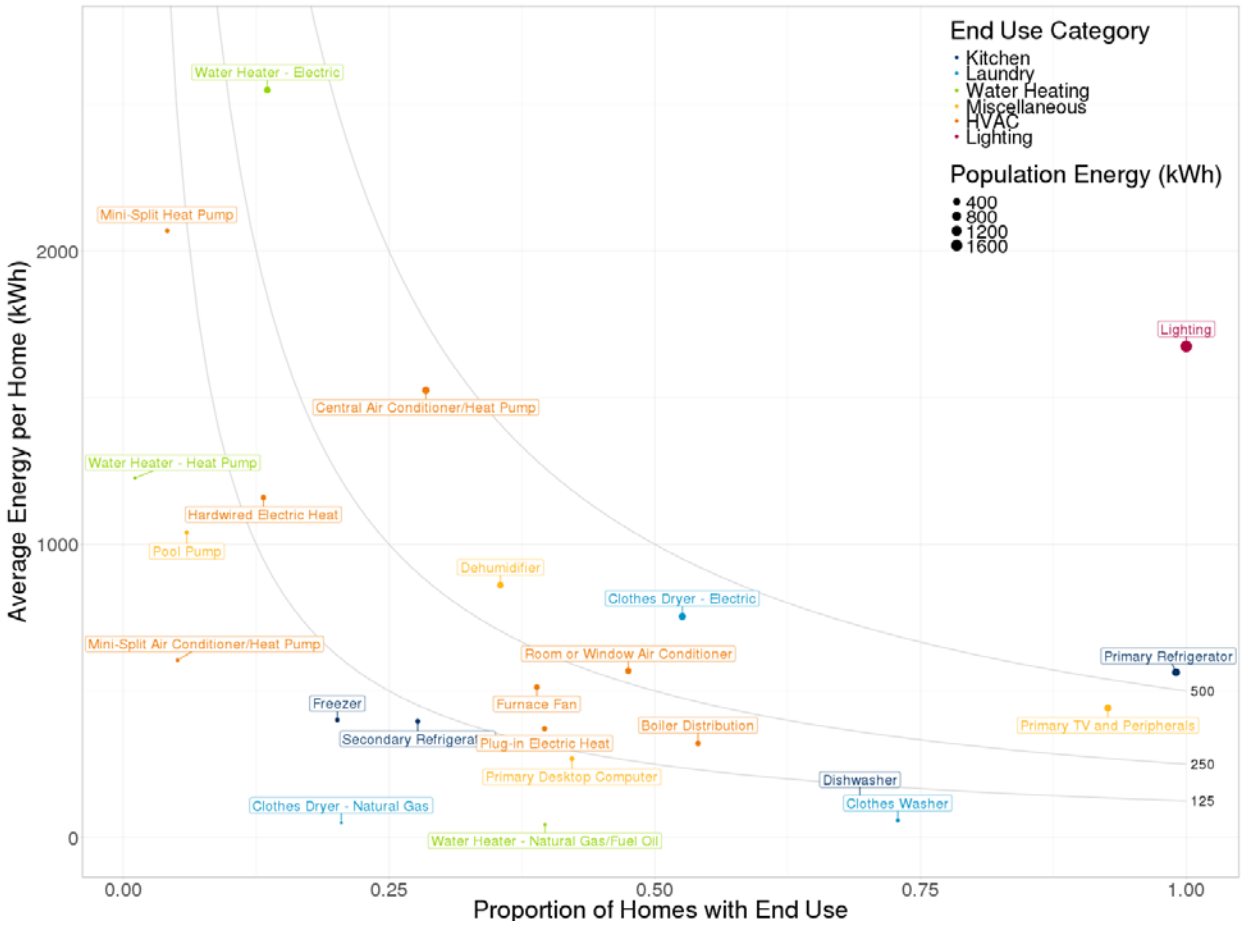


*Insufficient data to present results.

Source: Navigant analysis

Figure 6 illustrates the relationship between saturation, energy consumption per home with end use, and energy consumption for all homes. Saturation is shown on the x-axis, average energy consumption for homes that have a given end use is on the y-axis, and constant kWh lines are added to Figure 8 to show regions of equal household energy consumption across Massachusetts.

Figure 6. End Use Saturation and Annual Energy Consumption for Homes with End Use



Source: Navigant analysis

Key Finding: *Lighting consumes nearly 3 times more energy than any other single end use.*

Table 2. Annual Energy Consumption by End Use[11]

End Use Category	End Use	Saturation across MA Homes	Annual Energy per Home with End Use (kWh)	Population Annual Energy per Home (kWh)	Percentage of Annual Energy Load (%)
		[A]	[B]	[C = A x B]	[C/∑C]
HVAC	Central Air Conditioner (AC)/Heat Pump	0.28	1,530	434	6%
	Room or Window AC	0.48	569	270	4%
	Furnace Fan	0.39	513	200	3%
	Boiler Distribution	0.54	321	174	3%
	Hardwired Electric Heat	0.13	1,160	153	2%
	Plug-in Electric Heat	0.4	371	147	2%
	Mini-Split Heat Pump	0.041	2,070	86	1%
	Mini-Split AC/Heat Pump	0.051	605	31	< 0.5%
	HVAC - Other	1	N/A	95	1%
	HVAC Total	**N/A**	**N/A**	**1,590**	**23%**
Water Heating	Water Heater - Electric	0.14	2,550	345	5%
	Water Heater - Natural Gas/Fuel Oil	0.4	43	17	< 0.5%
	Water Heater - Heat Pump	0.011	1,230	14	< 0.5%
	Water Heating Total	**N/A**	**N/A**	**376**	**5%**
Kitchen	Primary Refrigerator	0.99	564	558	8%
	Secondary Refrigerator	0.28	396	110	2%
	Dishwasher	0.69	126	87	1%
	Freezer	0.2	401	81	1%
	Kitchen Total	**N/A**	**N/A**	**836**	**12%**
Laundry	Clothes Dryer - Electric	0.53	754	396	6%
	Clothes Washer	0.73	58	43	1%
	Clothes Dryer - Natural Gas	0.21	51	10	< 0.5%
	Laundry Total	**N/A**	**N/A**	**449**	**6%**
Miscellaneous	Primary TV	0.93	442	409	6%
	Dehumidifier	0.35	861	305	4%
	Primary Computer	0.42	269	113	2%
	Pool Pump	0.06	1,040	62	1%
	Other Pump	N/A	N/A	26	< 0.5%
	Misc. Metered	1	N/A	51	1%
	Miscellaneous Total	**N/A**	**N/A**	**967**	**14%**
	Remaining Load	1	1,680	1,680	24%

[11] Due to rounding, arithmetic with the values in Table 2 will not always work. Unrounded values are available in Appendix C.

End Use Category	End Use	Saturation across MA Homes	Annual Energy per Home with End Use (kWh)	Population Annual Energy per Home (kWh)	Percentage of Annual Energy Load (%)
		[A]	[B]	[C = A x B]	[C/∑C]
Remaining Load	**Remaining Load Total**	**N/A**	**N/A**	**1,680**	**24%**
Lighting	Lighting	**N/A**	**N/A**	**1,130**	**16%**
	Lighting Total	**N/A**	**N/A**	**1,130**	**16%**
All	**Total**	**N/A**	**N/A**	**7,020**	**100%**

Source: Navigant analysis

Equivalent Full Load Hours (EFLH) and Coincidence Factors (CF) for selected end uses are presented in Table 3. The team developed EFLH and CF numbers for end uses of interest that included both factors in their TRM equations, and where appropriate nameplate information was available for metered equipment. The values were calculated using the weather-normalized annual energy and peak demand measured in this study and the relevant name plate data (size and efficiency) from the measured equipment, as specified in the equations in The Massachusetts TRM[12]. Additional TRM inputs could be developed for non-EFLH end uses in this study, or the energy and demand can be used directly for measures using an energy and demand savings factor.

Table 3. EFLH and CF by End Use

End Use	EFLH	ISO Coincidence Factor (CF)	Utility Coincidence Factor (CF)
Dehumidifier	1282	0.27	0.28
Pool Pump	775	0.4	0.32
Central Air Conditioner/Heat Pump	419	0.48	0.5
Mini-Split Air Conditioner/Heat Pump	417	0.37	0.38
Room or Window Air Conditioner	348	0.44	0.46

Source: Navigant analysis

2.2 Peak Demand

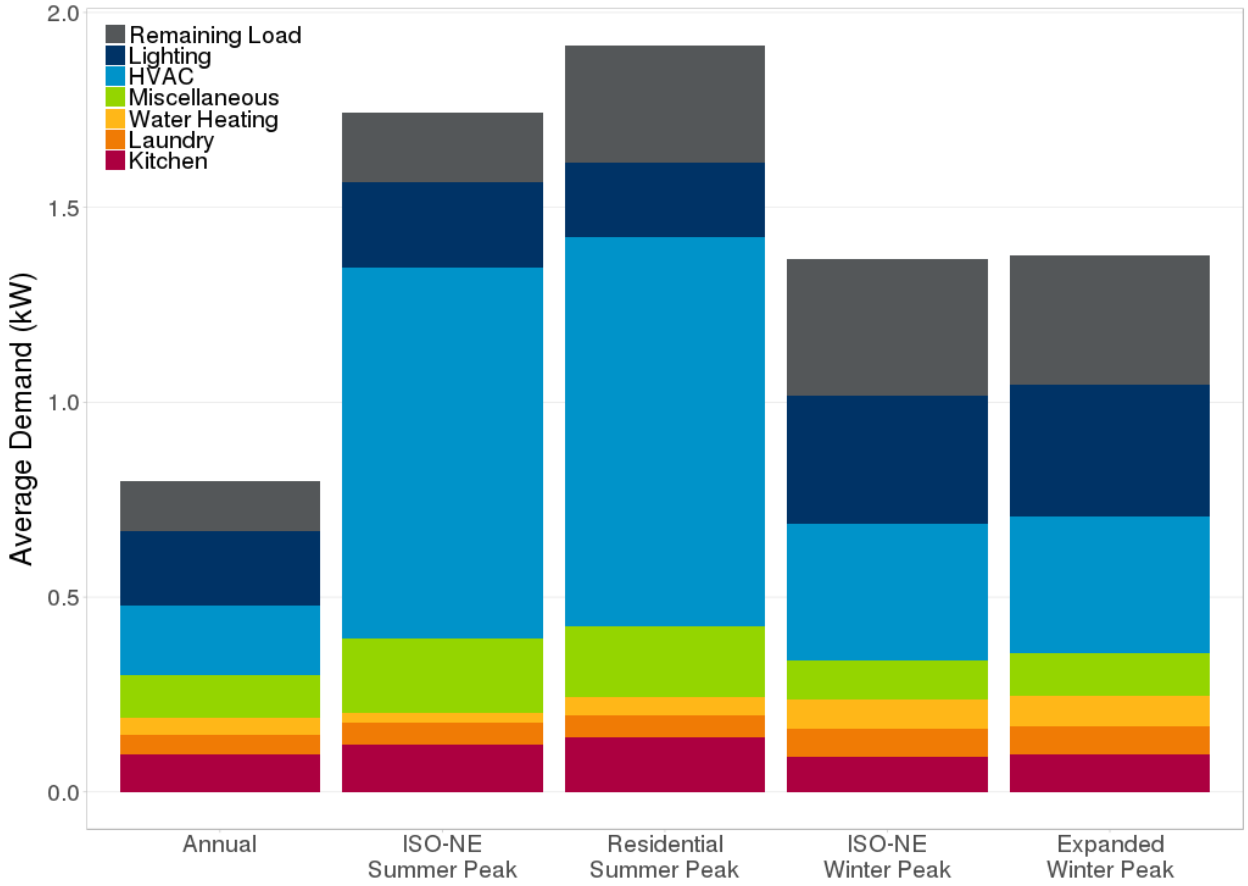
The average demand for five periods by end use category is shown in Figure 7. As laid out in the Terminology section, there are two summer peak periods and two winter peak periods defined, one ISO-NE and one longer peak period. Results are presented for each period.

12 Massachusetts Technical Reference Manual; 2016-2018 Program Years – Plan Version; October 2015 http://ma-eeac.org/wordpress/wp-content/uploads/2016-2018-Plan-1.pdf

Table 4. Peak Period Definitions

	Summer ISO-NE	Summer Residential	Winter ISO-NE	Winter Extended
Days	Non-holiday weekdays in June, July, August		Non-holiday weekdays in December, January, February	
Times	1 p.m.-5 p.m.	5 p.m.-7 p.m.	5 p.m.-7 p.m.	5 p.m.-9 p.m.

Figure 7. Average Demand for Five Periods by End Use



Source: Navigant analysis

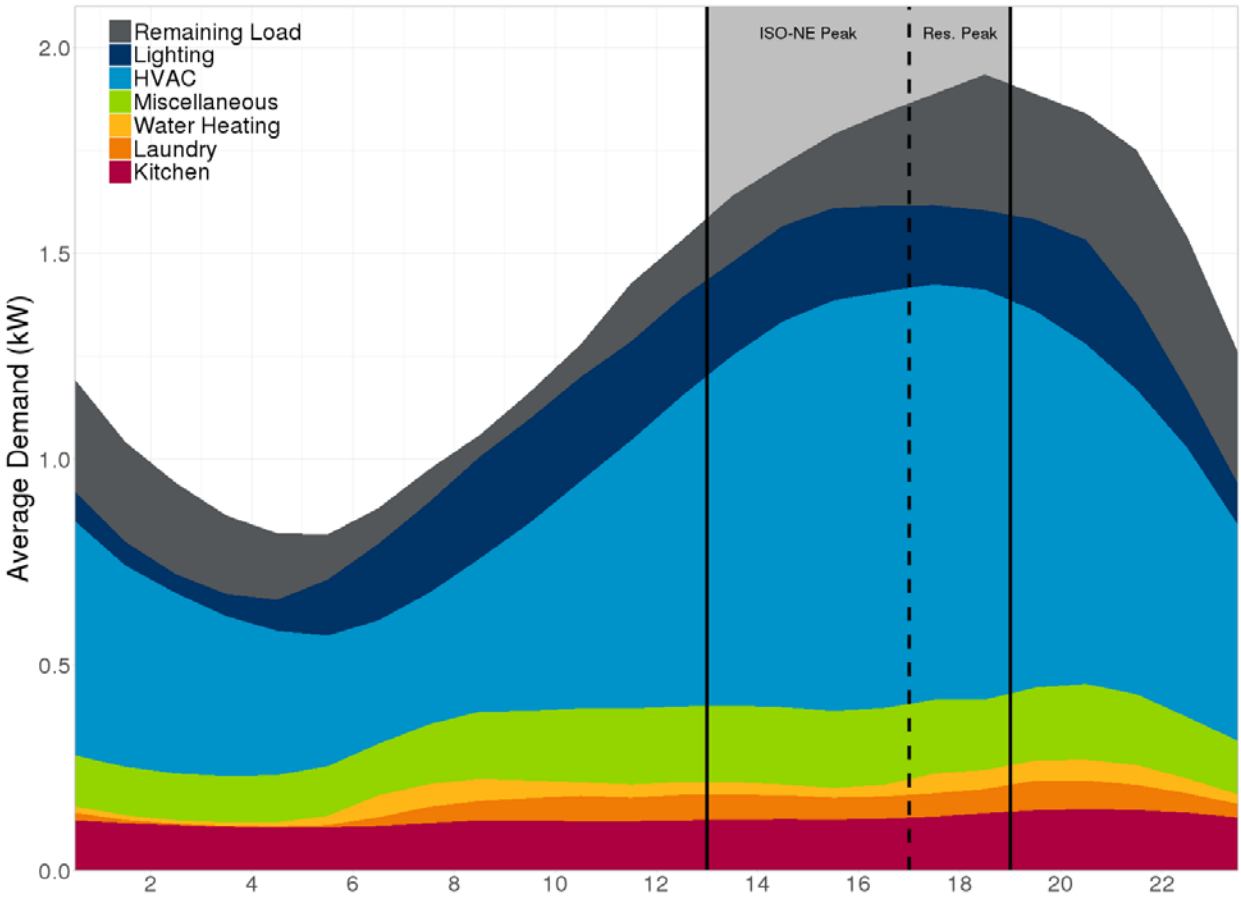
2.2.1 Summer Peak Demand

Peak demand per end use is plotted against saturation in Figure 12. Constant-kW average lines are added to Figure 8 to show regions of equal contribution to total demand across Massachusetts. High saturation but low demand end uses like primary refrigerators contribute roughly the same demand, on average, as end uses with low saturation and high demand like pool pumps.

The peak day load shapes by end use category with both peak periods highlighted are shown in Figure 8; it shows that both summer peak demand values are driven primarily by cooling (HVAC) loads. A more granular breakdown of end use load shapes is shown in Figure 9. The end use-specific average peak demand values for the ISO-NE summer peak period are shown with saturations in Table 5.

Figure 10 shows how the distribution of peak demands across households may influence the savings achievable through targeting high users. End uses with a bigger difference between the mean of the top 25% and the median of all users have peak demand more concentrated in a smaller number of houses, meaning they offer larger opportunities for targeting. Figure 11 shows the fraction of homes with an end use that have a peak demand higher than 200 W.

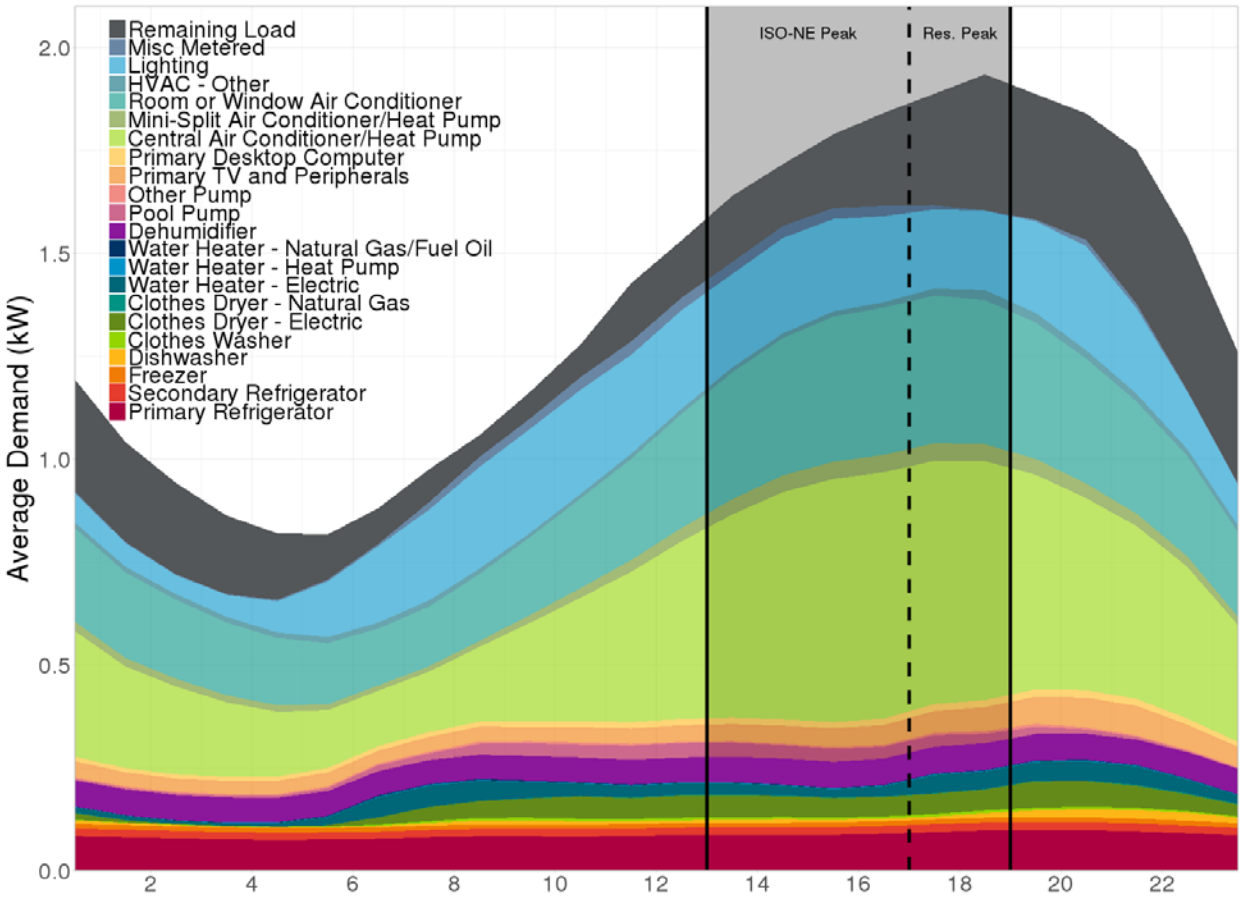
Figure 8. Summer Peak Day End Use Category Load Shapes



Source: Navigant analysis

Key Finding: *Cooling is responsible for half of peak demand.*

Figure 9. Summer Peak Day End Use Load Shapes

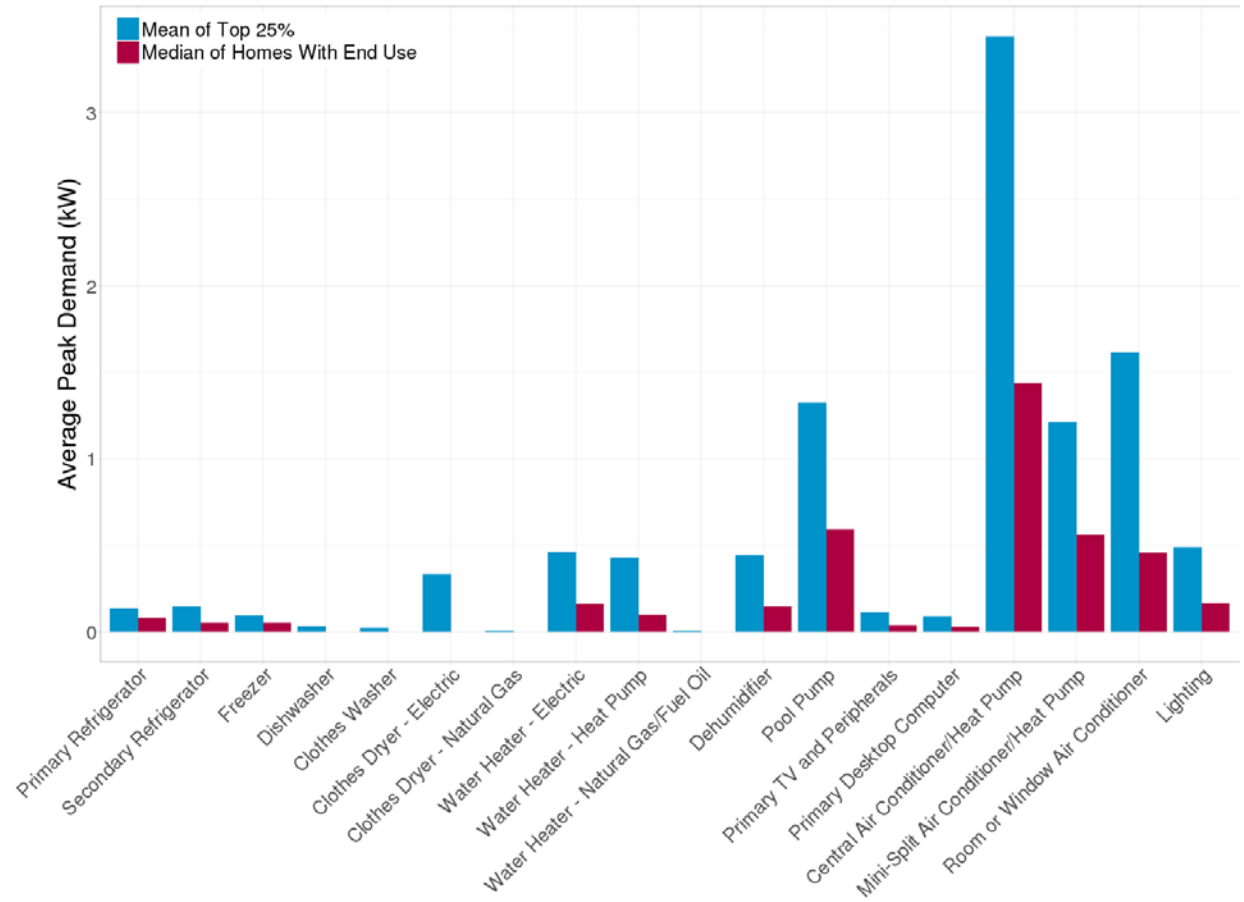


Source: Navigant analysis

Key Finding: *Refrigerators, dehumidifiers, clothes dryers, primary TVs and their peripherals, and pool pumps account for an additional 17% of the summer peak in Massachusetts.*

Figure 10 shows the ISO-NE summer peak demand for high users of each end use, which is much higher than the median for many end uses. Figure 11 shows the fraction of homes with the end use who consume more than a given threshold (0.2 kW) during ISO-NE summer peak hours.

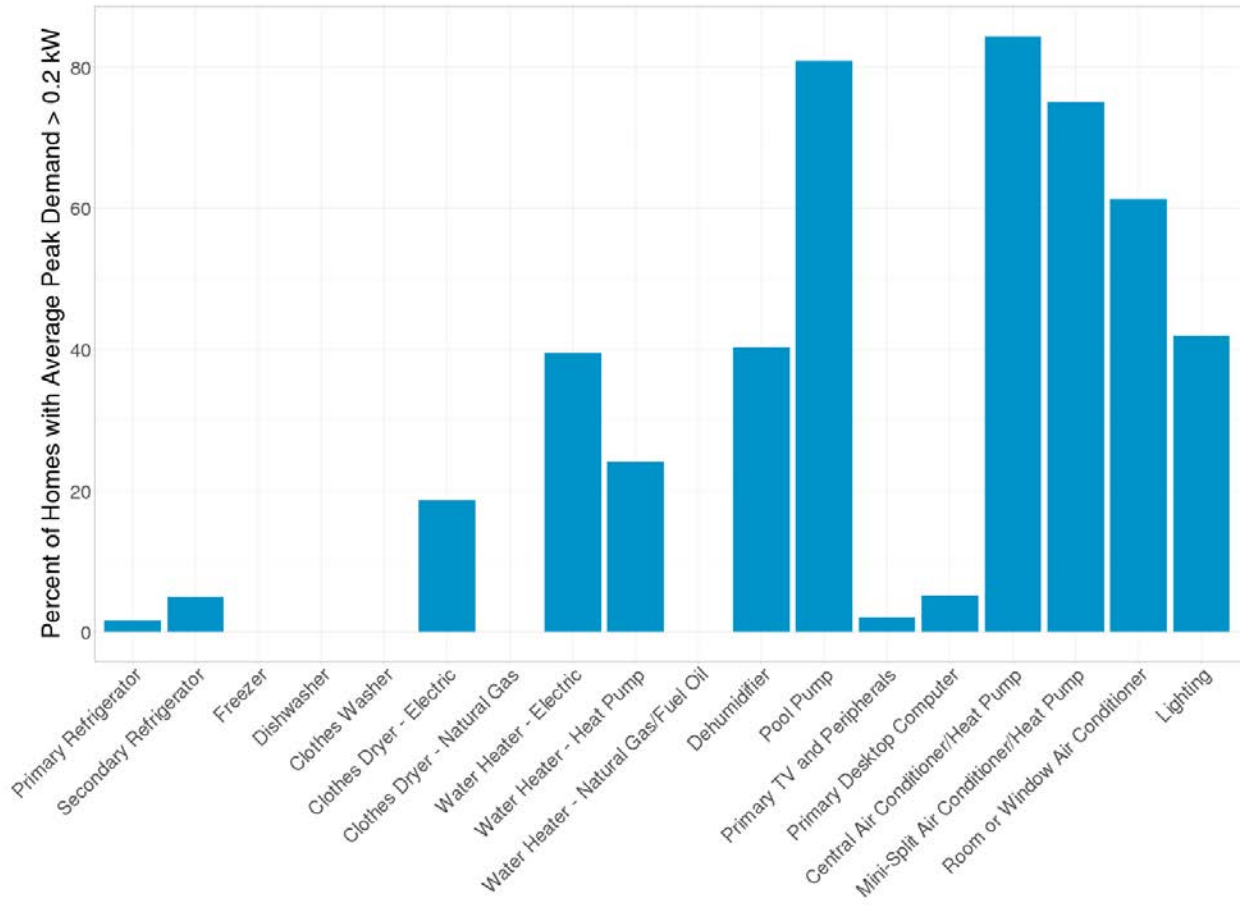
Figure 10. ISO-NE Summer Peak Demand for Top 25% of Each Metered End Use's Users



Source: Navigant analysis

Key Finding: *A small number of homes contributes all of the peak demand from clothes dryers.*

Figure 11. Proportion of Homes with Average ISO-NE Summer Peak Demand Greater than 0.2 kW for Each Measured End Use



Source: Navigant analysis

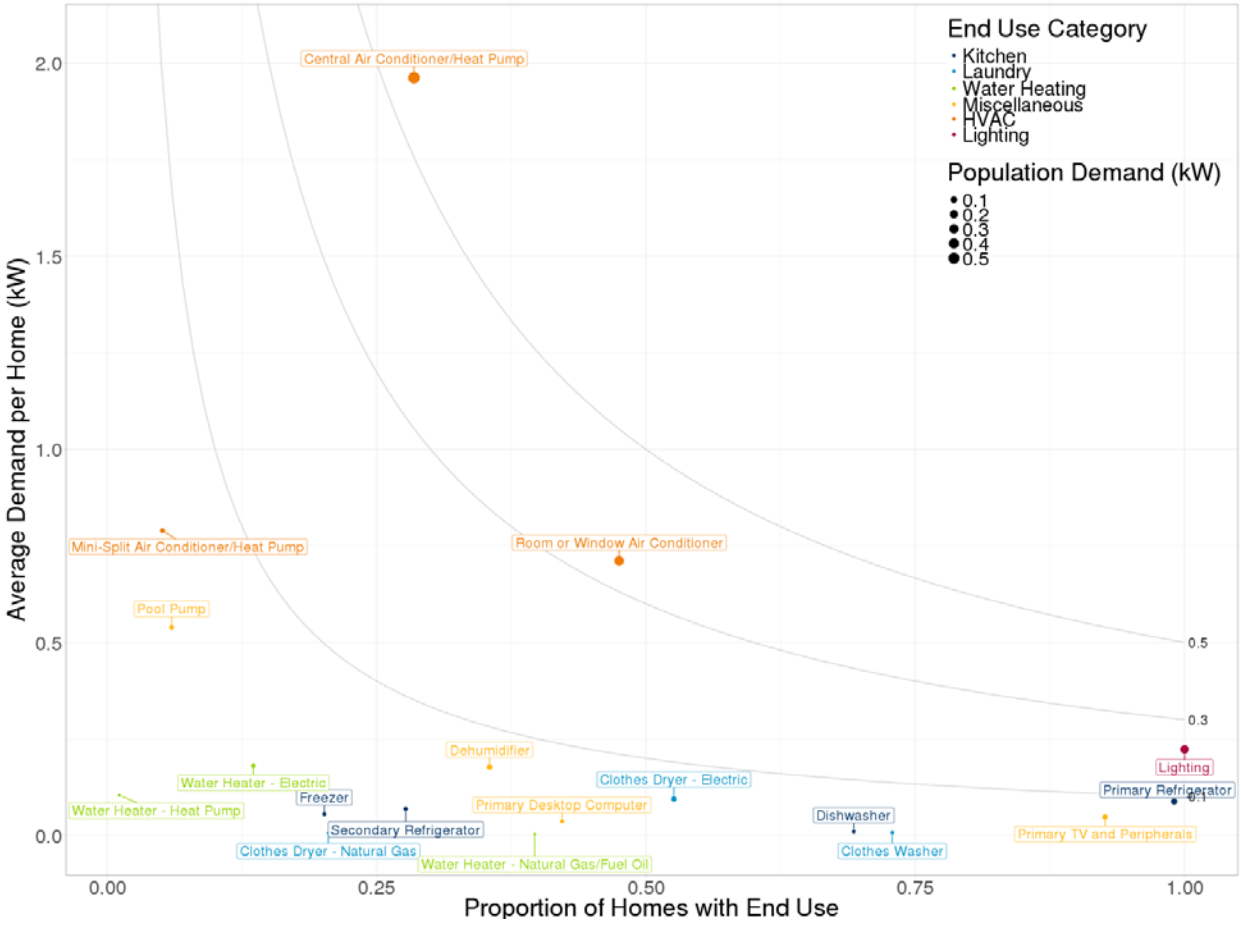
Figure 12. Summer ISO-NE Peak Demand by End Use Category and Building/Occupancy Demographics

*Insufficient data to present results.

Source: Navigant analysis

Key Finding: *Summer ISO-NE peak demand is highest in owner-occupied, single-family homes.*

Figure 13. End Use Saturation and Summer Demand for Homes with End Use



Source: Navigant analysis

Key Finding: *The top contributors to summer peak demand across all homes in Massachusetts are central ACs and room ACs.*

Table 5. Summer Peak Demand by End Use[11]

End Use Category	End Use	Saturation across MA Homes	ISO-NE Peak Demand for Homes with End Use (kW)	Residential Demand per Home (kW)	Average Population ISO-NE Peak Demand (kW)	Average Population Residential Demand (kW)	Percentage of System Average Residential Peak Load (%)
		[A]	[B]	[C]	[D = A x B]	[E = A x C]	E/∑E
HVAC	Central AC/Heat Pump	0.28	1.96	2.06	0.56	0.59	31%
	Room or Window AC	0.48	0.71	0.75	0.34	0.35	19%
	Mini-Split AC/Heat Pump	0.051	0.79	0.82	0.04	0.042	2%
	HVAC - Other	1	N/A	N/A	0.012	0.021	1%
	HVAC Total	**N/A**	**N/A**	**N/A**	**0.95**	**1**	**53%**
Water Heating	Water Heater - Electric	0.14	0.18	0.32	0.024	0.044	2%
	Water Heater - Natural Gas/Fuel Oil	0.4	0.0032	0.0035	0.0013	0.0014	< 0.5%
	Water Heater - Heat Pump	0.011	0.1	0.15	0.0012	0.0017	< 0.5%
	Water Heating Total	**N/A**	**N/A**	**N/A**	**0.027**	**0.047**	**3%**
Kitchen	Primary Refrigerator	0.99	0.088	0.097	0.087	0.096	5%
	Secondary Refrigerator	0.28	0.069	0.07	0.019	0.019	1%
	Freezer	0.2	0.056	0.057	0.011	0.011	1%
	Dishwasher	0.69	0.01	0.013	0.0071	0.0091	1%
	Kitchen Total	**N/A**	**N/A**	**N/A**	**0.12**	**0.14**	**7%**
Laundry	Clothes Dryer - Electric	0.53	0.095	0.095	0.05	0.05	3%
	Clothes Washer	0.73	0.0079	0.0088	0.0057	0.0064	< 0.5%
	Clothes Dryer - Natural Gas	0.21	0.0068	0.0049	0.0014	1.00E-03	< 0.5%
	Laundry Total	**N/A**	**N/A**	**N/A**	**0.057**	**0.058**	**3%**
Miscellaneous	Dehumidifier	0.35	0.18	0.18	0.063	0.065	3%
	Primary TV	0.93	0.048	0.06	0.045	0.056	3%
	Pool Pump	0.06	0.54	0.42	0.032	0.025	1%
	Primary Computer	0.42	0.037	0.04	0.016	0.017	1%
	Other Pump	N/A	N/A	N/A	0.0039	0.006	< 0.5%
	Misc. Metered	1	N/A	N/A	0.028	0.0058	< 0.5%
	Miscellaneous Total	**N/A**	**N/A**	**N/A**	**0.19**	**0.18**	**9%**
Lighting	**Lighting**	**1**	**0.22**	**0.19**	**0.22**	**0.19**	**10%**
Remaining Load	**Remaining Load**	**N/A**	**N/A**	**N/A**	**0.18**	**0.3**	**16%**
All	**Total All End Uses**	**N/A**	**N/A**	**N/A**	**1.75**	**1.91**	**100%**

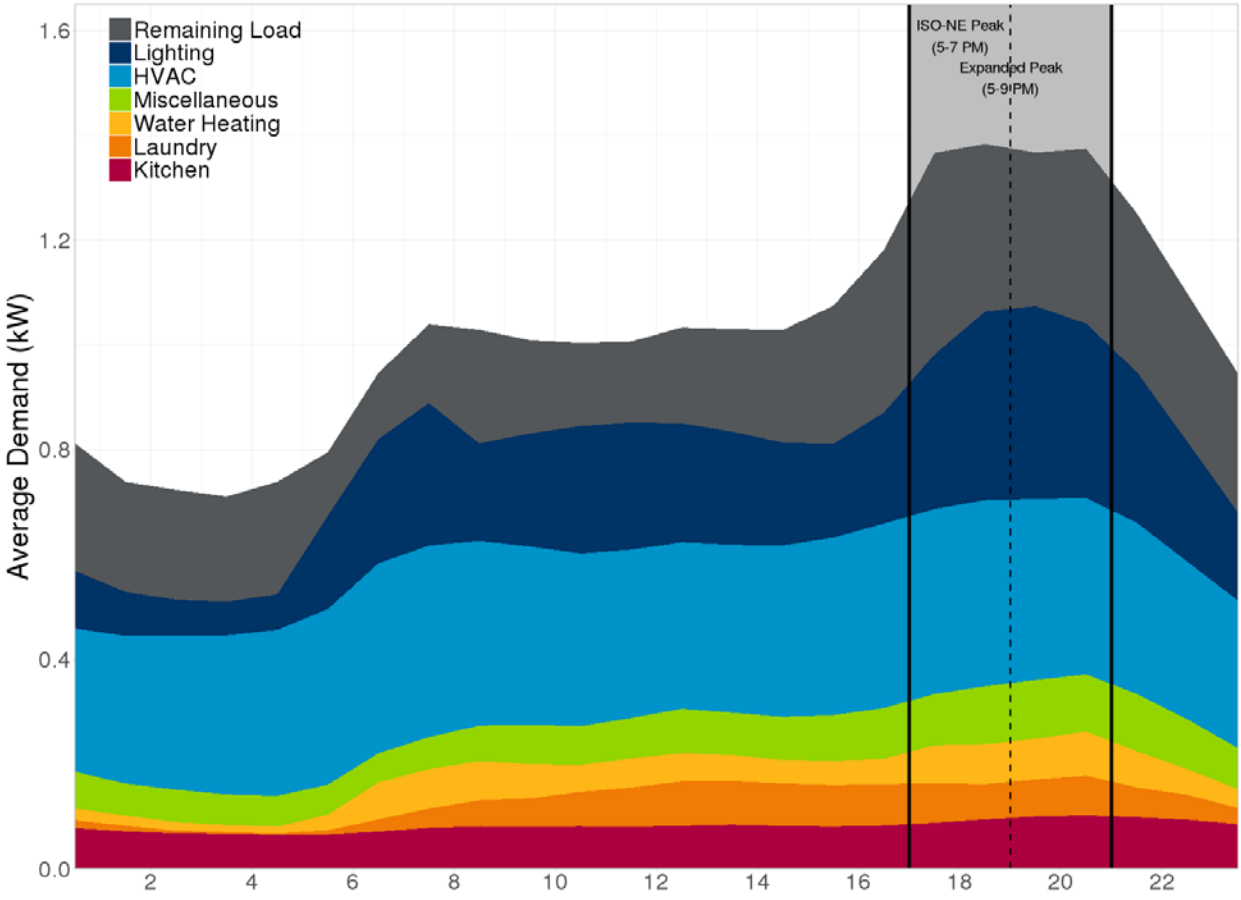
Source: Navigant analysis

2.2.2 Winter Peak Demand

Winter peak demand per end use is plotted against saturation in Figure 19. Constant-kW average lines are added to show regions of equal contribution to average demand across Massachusetts. High saturation but low demand end uses like primary TVs account for roughly the same winter demand, on average, as end uses with low saturation and high demand like electric water heaters.

The peak day load shapes by end use category with both peak periods highlighted are shown in Figure 14; this shows that both winter peak demand values are driven primarily by HVAC, lighting, and loads not individually metered in this study. A more granular breakdown of end use load shapes is shown in Figure 15. The end use-specific saturations and average peak demand values for the winter peak are shown in Table 6.

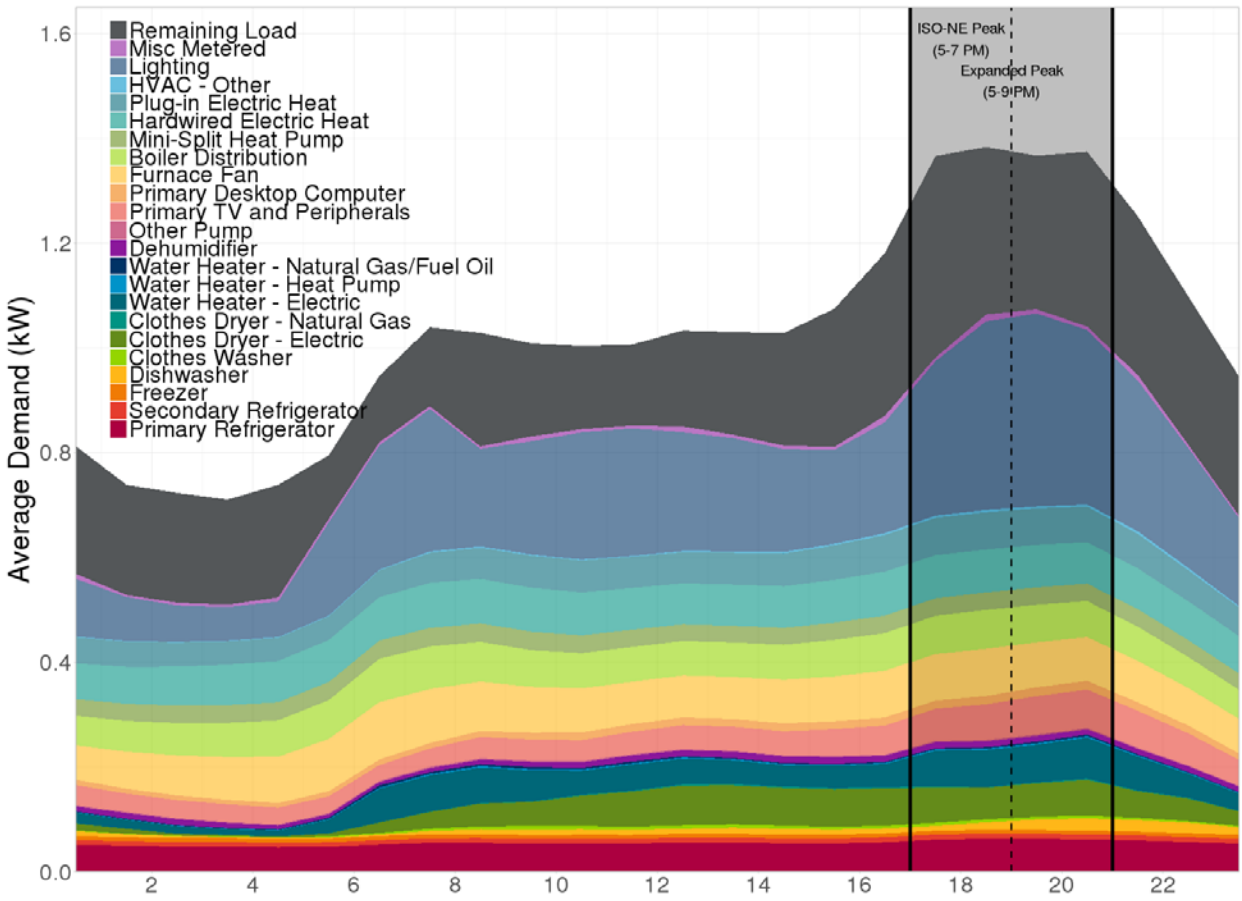
Figure 14. Winter Peak Day End Use Category Load Shapes



Source: Navigant analysis

Key Finding: *HVAC and lighting each account for one-fourth of winter peak demand.*

Figure 15. Winter Peak Day End Use Load Shapes

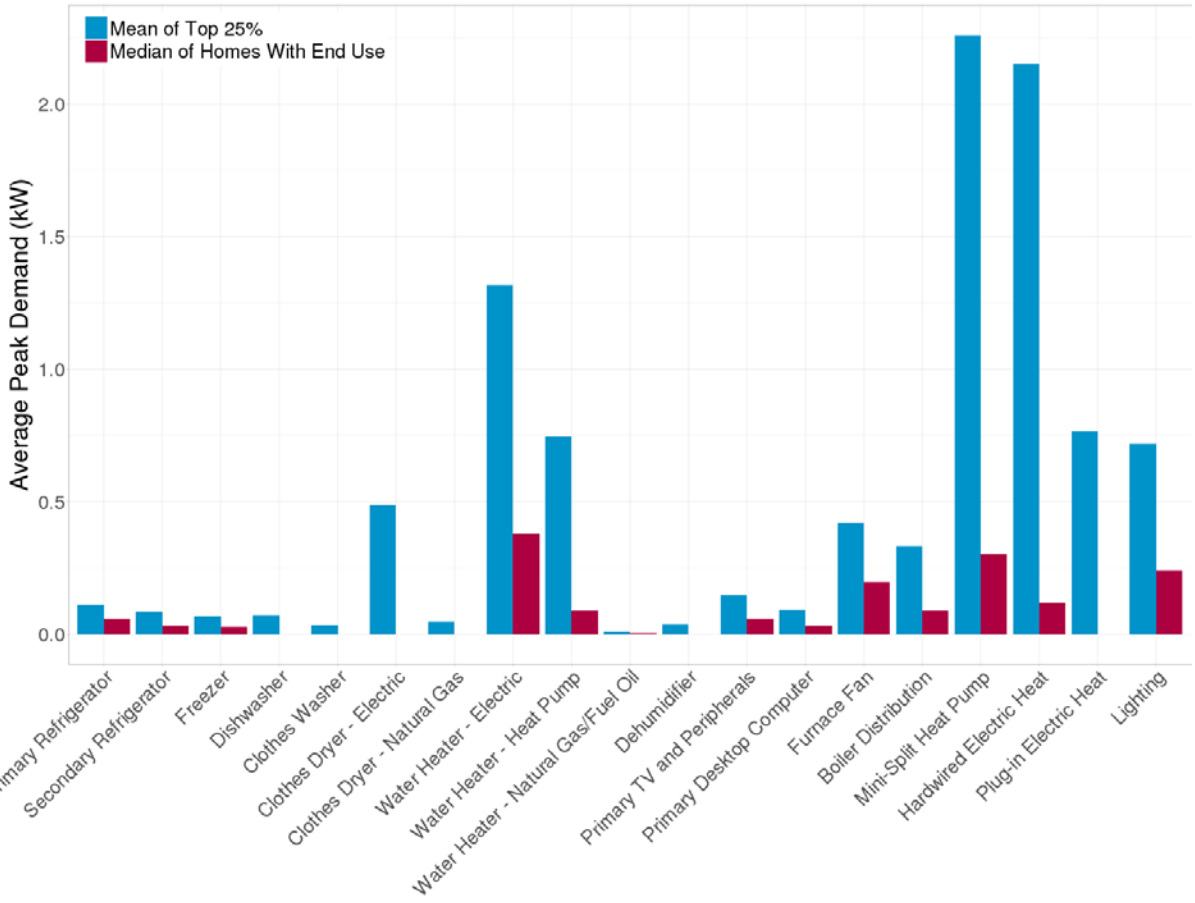


Source: Navigant analysis

Key Finding: *When the major end uses are disaggregated further, no single HVAC end use dominates winter peak demand, but the aggregate HVAC category presents significant savings opportunities.*

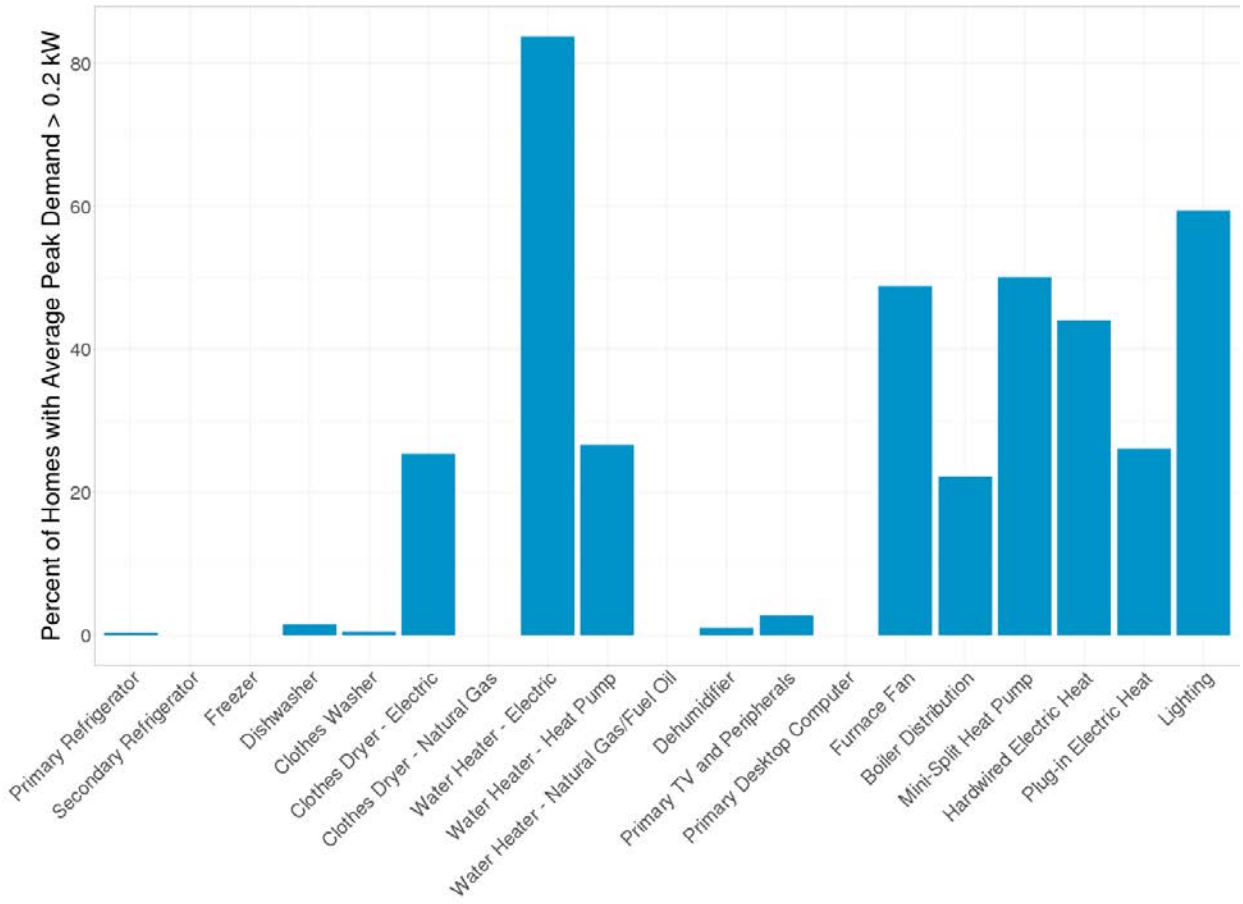
Figure 16 shows the peak demand for high users of each end use, which is much higher than the median for many end uses. Figure 17 shows the fraction of homes with the end use who consume more than a given threshold (0.2 kW) during peak. Winter peak demand is driven by a small number of homes and many households have very low usage during peak for HVAC end uses, less than 200W. Targeting will be important for increasing winter peak demand savings.

Figure 16. ISO-NE Winter Peak Demand for Top 25% of Each Metered End Use's Users



Source: Navigant analysis

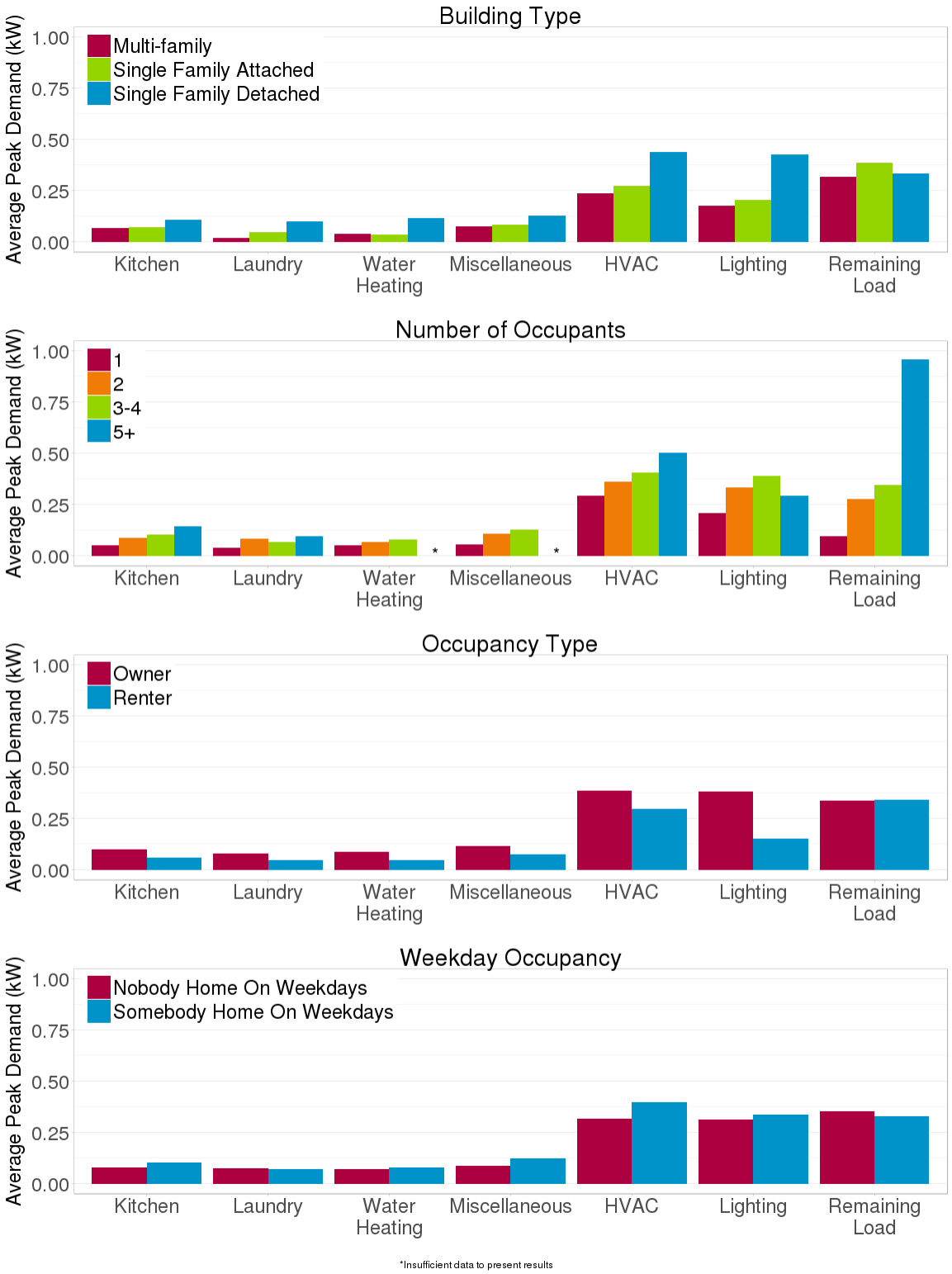
Figure 17. Proportion of Homes with Average ISO-NE Winter Peak Demand Greater than 0.2 kW for Each Measured End Use



Source: Navigant analysis

Figure 18 shows that the same building and occupancy demographics that drive the summer peak also drive the winter peak. Demand is highest for owner-occupied, single-family homes and is highest when there are more occupants or any occupant is home on weekdays.

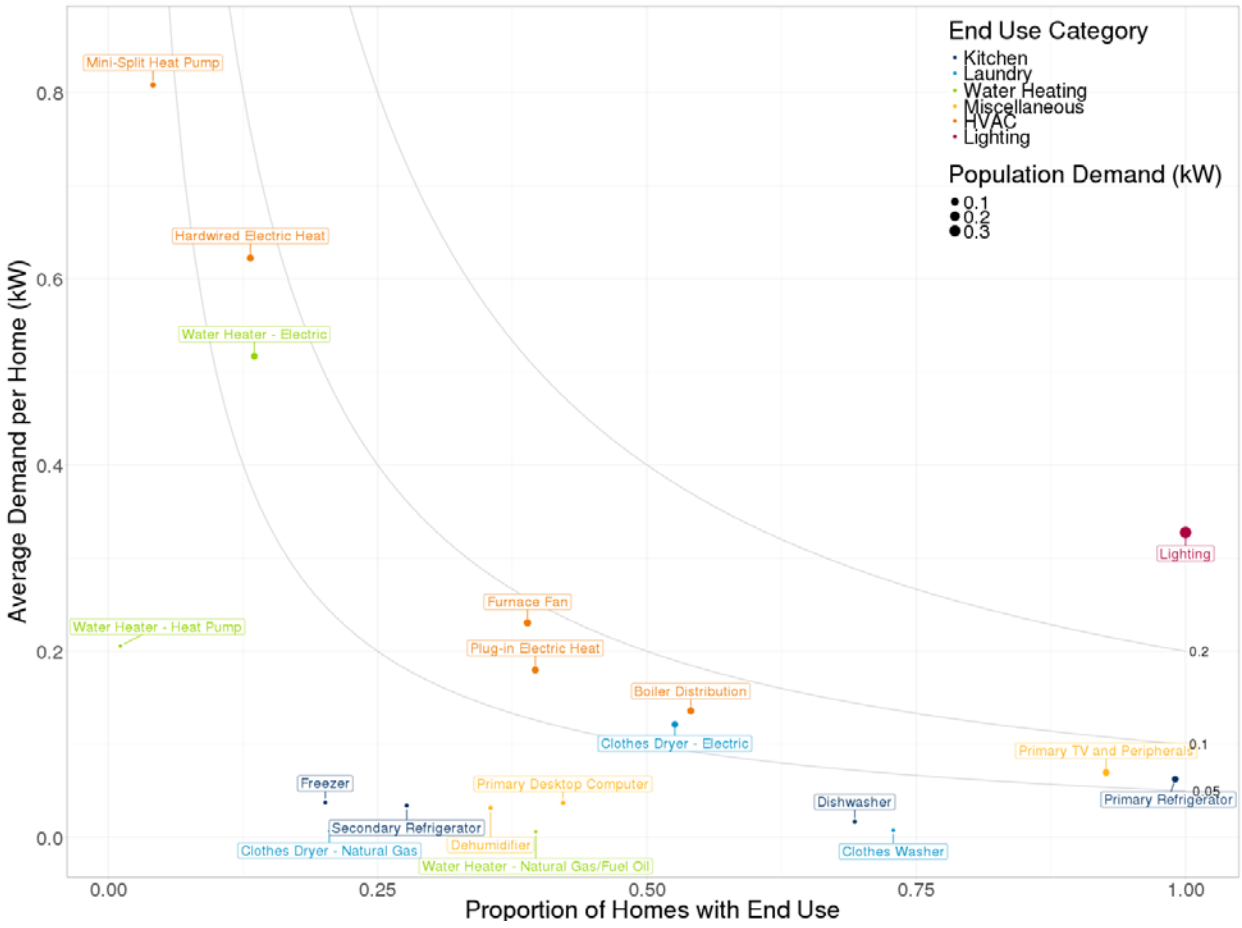
Figure 18. Winter ISO-NE Peak Demand by End Use Category and Building/Occupancy Demographics



*Insufficient data to present results.

Source: Navigant analysis

Figure 19. End Use Saturation and Winter Demand for Homes with End Use



Source: Navigant analysis

Table 6. Winter Peak Demand by End Use[11]

End Use Category	End Use	Saturation across MA Homes	ISO-NE Peak Demand for Homes with End Use (kW)	Expanded Demand per Home (kW)	Average Population ISO-NE Peak Demand (kW)	Average Population Expanded Demand (kW)	Percentage of System Average Expanded Peak Load (%)
		[A]	[B]	[C]	[D = A x B]	[E = A x C]	E/∑E
HVAC	Furnace Fan	0.39	0.23	0.22	0.09	0.087	6%
	Hardwired Electric Heat	0.13	0.62	0.61	0.082	0.081	6%
	Boiler Distribution	0.54	0.14	0.13	0.074	0.072	5%
	Plug-In Electric Heat	0.4	0.18	0.18	0.071	0.07	5%
	Mini-Split Heat Pump	0.041	0.81	0.81	0.033	0.033	2%
	HVAC - Other	1	N/A	N/A	0.0043	0.0042	< 0.5%
	HVAC Total	**N/A**	**N/A**	**N/A**	**0.35**	**0.35**	**0.25**
Water Heating	Water Heater - Electric	0.14	0.52	0.54	0.07	0.073	5%
	Water Heater - Natural Gas/Fuel Oil	0.4	0.0064	0.0072	0.0025	0.0029	< 0.5%
	Water Heater - Heat Pump	0.011	0.21	0.21	0.0023	0.0024	< 0.5%
	Water Heating Total	**N/A**	**N/A**	**N/A**	**0.075**	**0.078**	**6%**
Kitchen	Primary Refrigerator	0.99	0.063	0.063	0.062	0.062	5%
	Dishwasher	0.69	0.017	0.024	0.012	0.017	1%
	Secondary Refrigerator	0.28	0.034	0.034	0.0095	0.0094	1%
	Freezer	0.2	0.038	0.038	0.0076	0.0076	0.01
	Kitchen Total	**N/A**	**N/A**	**N/A**	**0.091**	**0.096**	**7%**
Laundry	Clothes Dryer - Electric	0.53	0.12	0.12	0.064	0.065	5%
	Clothes Washer	0.73	0.0078	0.0074	0.0057	0.0054	< 0.5%
	Clothes Dryer - Natural Gas	0.21	0.0069	0.0077	1.40E-03	0.0016	< 0.5%
	Laundry Total	**N/A**	**N/A**	**N/A**	**0.071**	**0.072**	**5%**
Miscellaneous	Primary TV and Peripherals	0.93	0.07	0.074	0.065	0.069	5%
	Primary Desktop Computer	0.42	0.037	0.038	0.016	0.016	1%
	Dehumidifier	0.35	0.032	0.031	0.011	0.011	1%
	Other Pump	N/A	N/A	N/A	0.0024	0.0025	< 0.5%
	Misc. Metered	1	N/A	N/A	0.01	0.0087	0.01
	Miscellaneous Total	**N/A**	**N/A**	**N/A**	**0.1**	**0.11**	**8%**
Lighting	**Lighting**	**1**	**0.33**	**0.34**	**0.33**	**0.34**	**25%**
Remaining Load	**Remaining Load**	**N/A**	**N/A**	**N/A**	**0.35**	**0.33**	**24%**
All	**Total All End Uses**	**N/A**	**N/A**	**N/A**	**1.37**	**1.37**	**100%**

Source: Navigant analysis

2.3 End Use-Specific Findings

This section provides plots and key findings by end use category to look at how each end use contributes to total energy consumption and peak demand.

2.3.1 HVAC End Uses

Space heating in Massachusetts is transitioning away from oil heat, primarily toward gas, but the saturation of electric heating equipment has gone up slightly in the last 8 years, as shown in Table 7. The table compares this study's results to the 2009 Massachusetts Residential Appliance Saturation Survey (RASS).[13]

Table 7. RASS Comparison – Heating Systems

End Use	All Homes		Single-Family Detached	
	2009 RASS Saturation	2017 Baseline Study Saturation	2009 RASS Saturation	2017 Baseline Study Saturation
Any Space Heating System	0.99	0.97	0.99	0.99
Natural Gas Heat	0.53	0.64	0.47	0.61
Oil Heat	0.36	0.24	0.44	0.31
Electric Heat	0.08	0.09	0.04	0.05

Sources: Navigant analysis, 2009 RASS

Table 8 shows that while the saturation of central cooling systems has gone up significantly in the last 8 years, room ACs have seen a decline, resulting in a modest increase for any cooling system across all homes.

Table 8. RASS Comparison – Cooling Systems

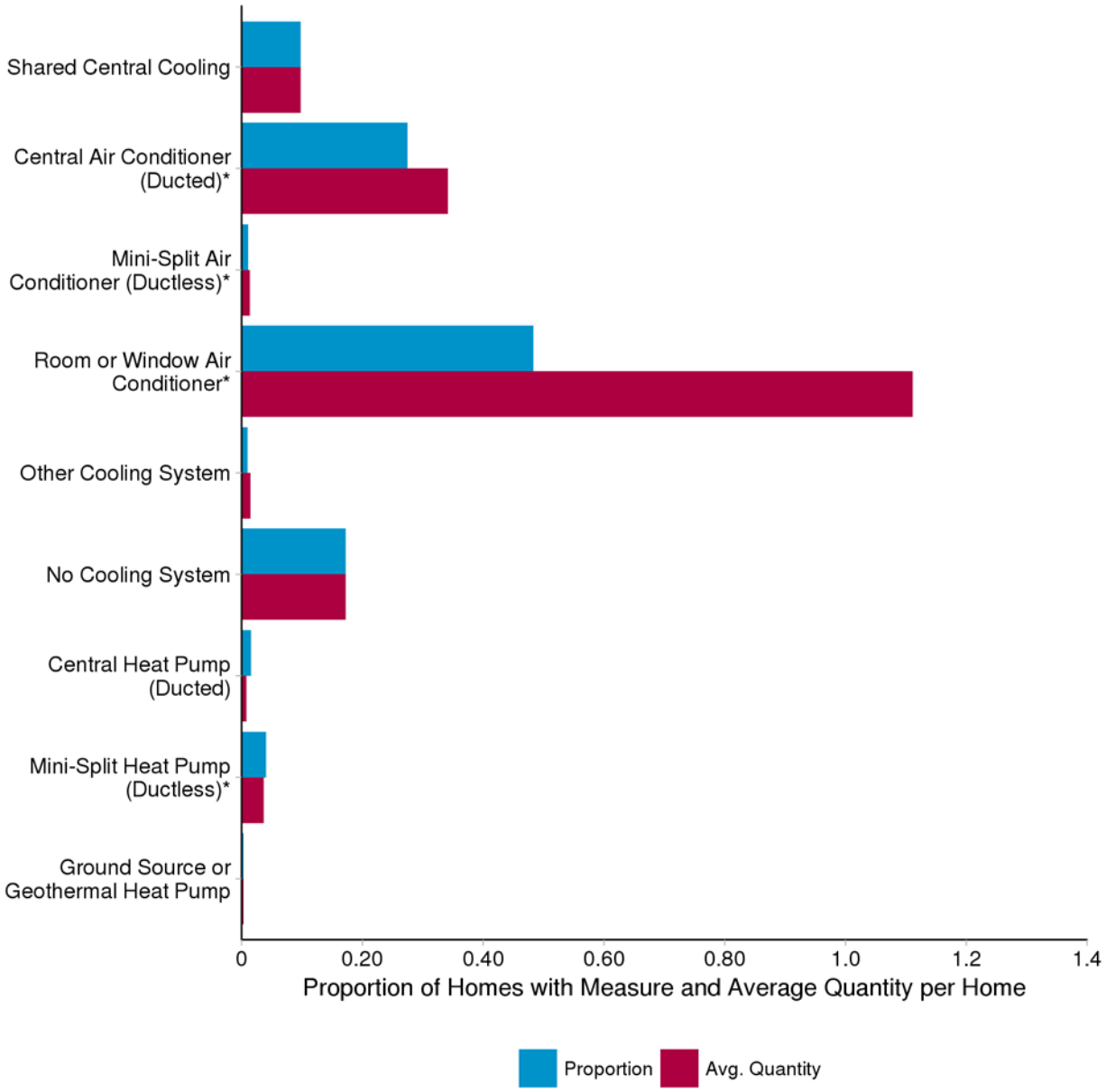
End Use	All Homes		Single-Family Detached	
	2009 RASS Saturation	2017 Baseline Study Saturation	2009 RASS Saturation	2017 Baseline Study Saturation
Any Space Cooling System	0.81	0.83	0.81	0.79
Central Cooling System*	0.29	0.35	0.30	0.40
Room or Window AC	0.64	0.48	0.6	0.47

* Includes central AC/HP and ductless mini-split AC/HP

Sources: Navigant analysis, 2009 RASS

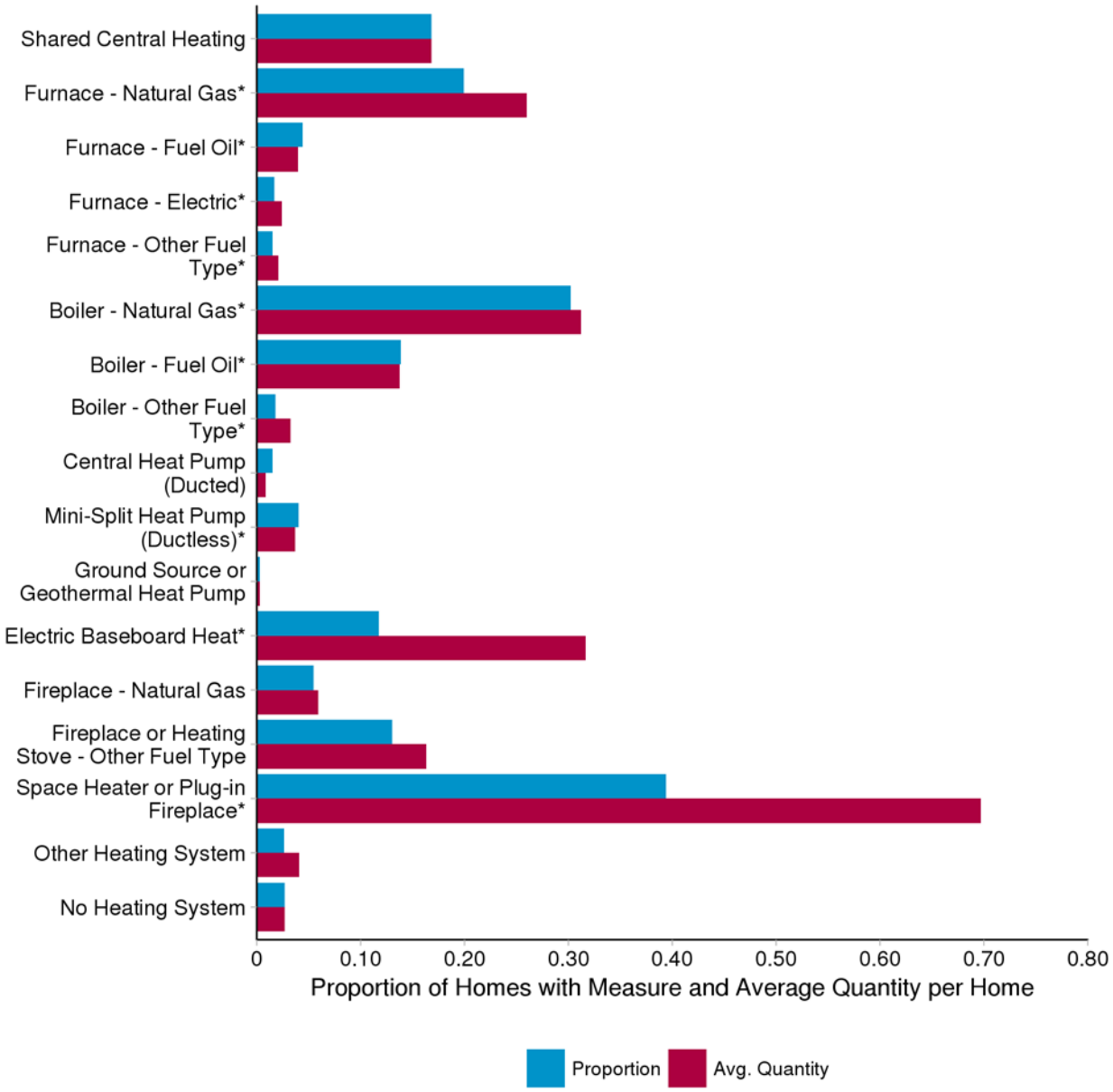
[13] http://ma-eeac.org/wordpress/wp-content/uploads/11_MA-Residential-Appliance-Saturation-Survey_Vol_1.pdf

Figure 20. HVAC Cooling Equipment Saturation and Penetration



Source: Navigant analysis

Figure 21. HVAC Heating Equipment Saturation and Penetration

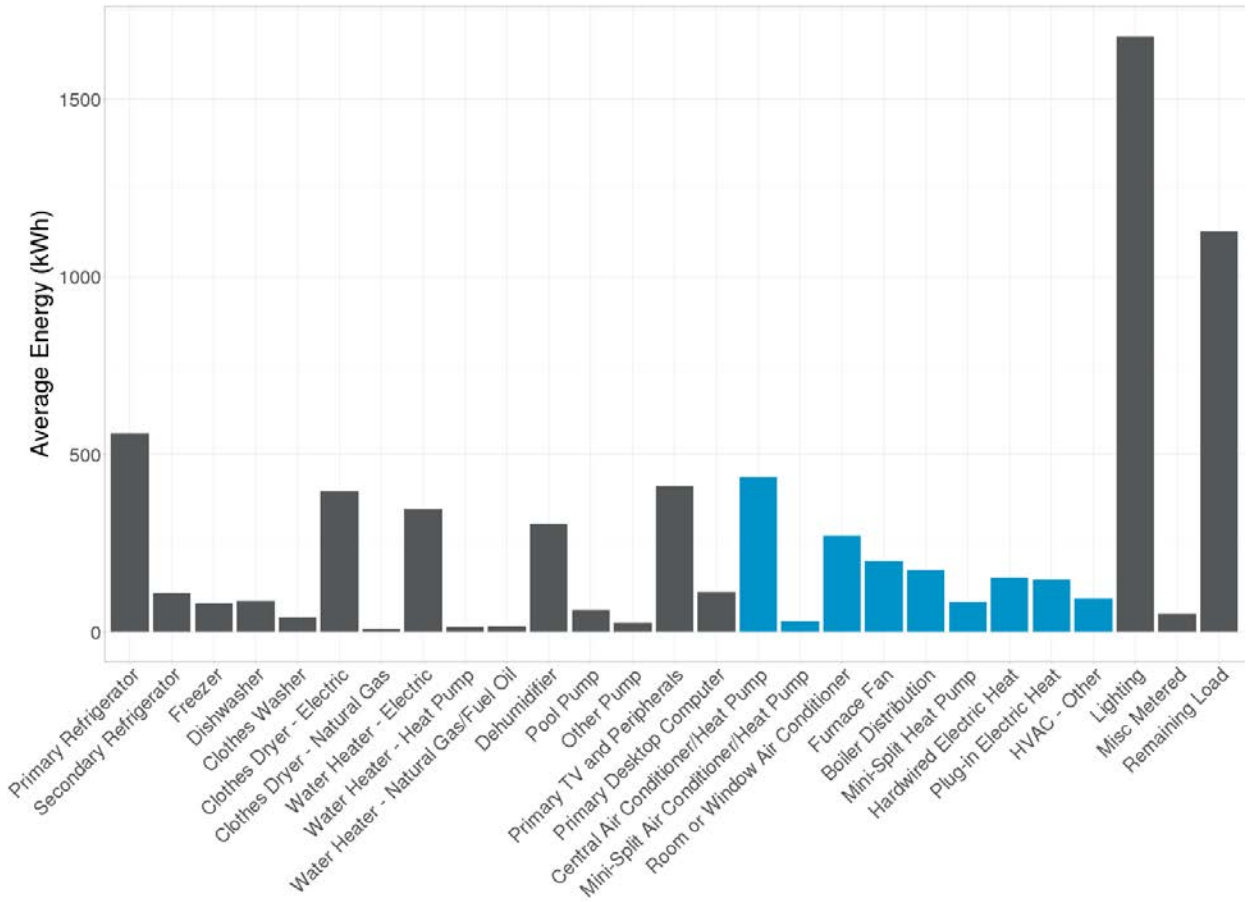


Notes: Saturation results were derived using data from all survey respondents (n = 6,673). Because some homes have multiple HVAC systems, totals may add up to more than 1.0.

Source: Navigant analysis

The saturations of heating HVAC systems are inversely related to their average consumption per household. Therefore, hardwired electric heat, plug-in electric heat, ductless heat pumps, furnace fans, and boiler distribution systems all consume energy within the same order of magnitude and are equally important as other prevalent non-HVAC end uses.

Figure 22. Population Annual End Use Energy Consumption – HVAC End Uses (kWh)

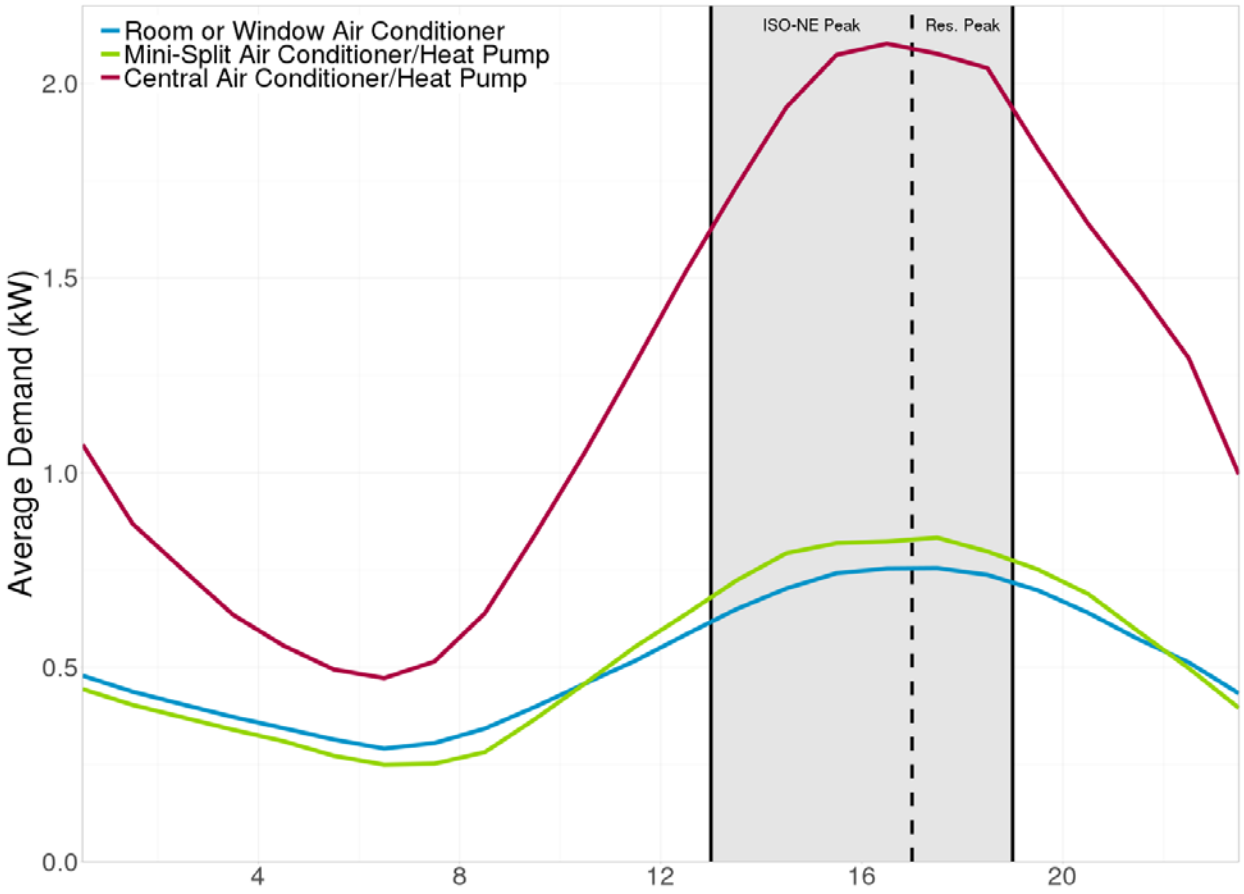


Source: Navigant analysis

As shown in Figure 22, central AC and room AC are the two largest individual HVAC end uses; each is larger than any single heating end use. Note that some homes are cooled by a combination of central AC and room AC, which pulls the average consumption for homes with room AC down. Homes cooled entirely with room ACs would have higher room AC demands and energy use than homes partially cooled by room ACs.

Cooling season HVAC end uses are the primary driver of summer peak loads. As shown in Figure 23, central AC demand peaks between 3 p.m. and 7 p.m. on the hottest days. Room AC demand per household is much lower and extends later than central AC load.

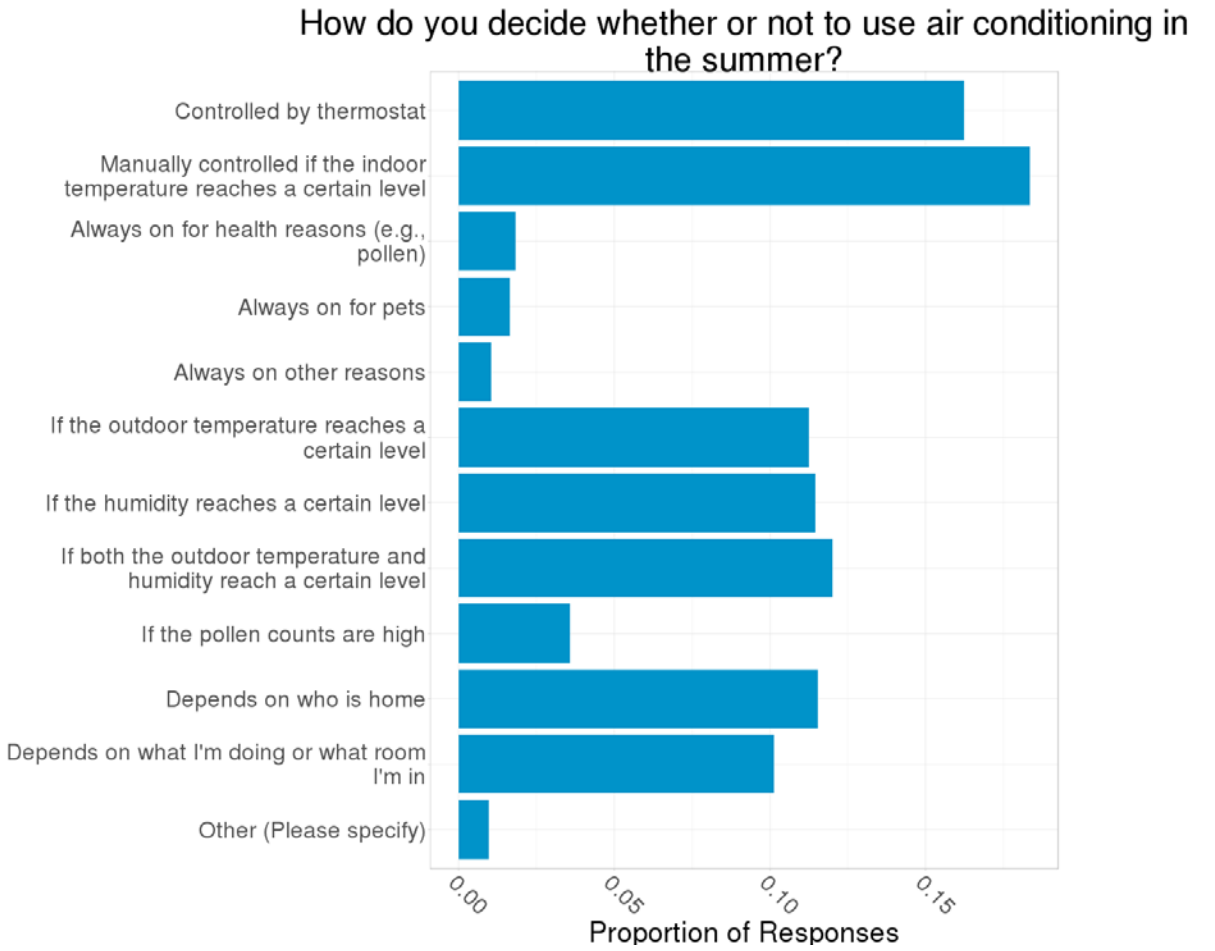
Figure 23. Summer Peak Day HVAC End Use Load Shapes for Homes with End Use



Source: Navigant analysis

Key Finding: *Central ACs are the single most important end use driving summer peak demand. The central AC peak load is greater than the total peak load for households without central AC.*

Figure 24. Cooling System Use

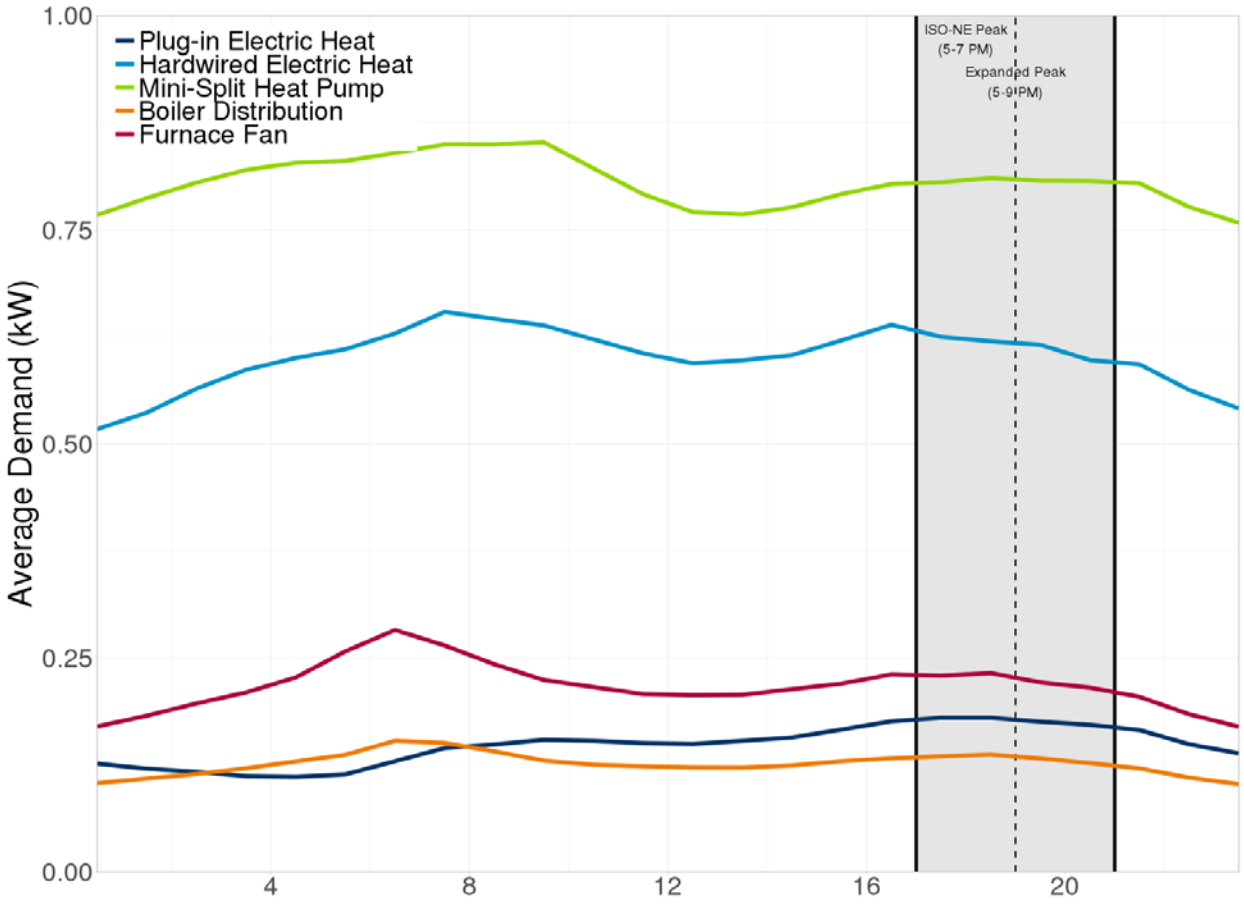


Source: Navigant analysis

Figure 24 demonstrates the wide variety of motivations driving central AC use. This suggests that attempts to change AC behavior on peak days may need to use a variety of tailored messaging to get the desired effect.

As shown in Figure 25, during the winter, hardwired electric heat and mini-split heat pumps are the two end uses with the highest demand in households where they are present. The hardwired electric heat peak day load shape is surprisingly flat compared to existing electric heat load shapes, such as those from simulation tools that follow a setback schedule.

Figure 25. Winter Peak Day HVAC End Use Load Shapes for Homes with End Use

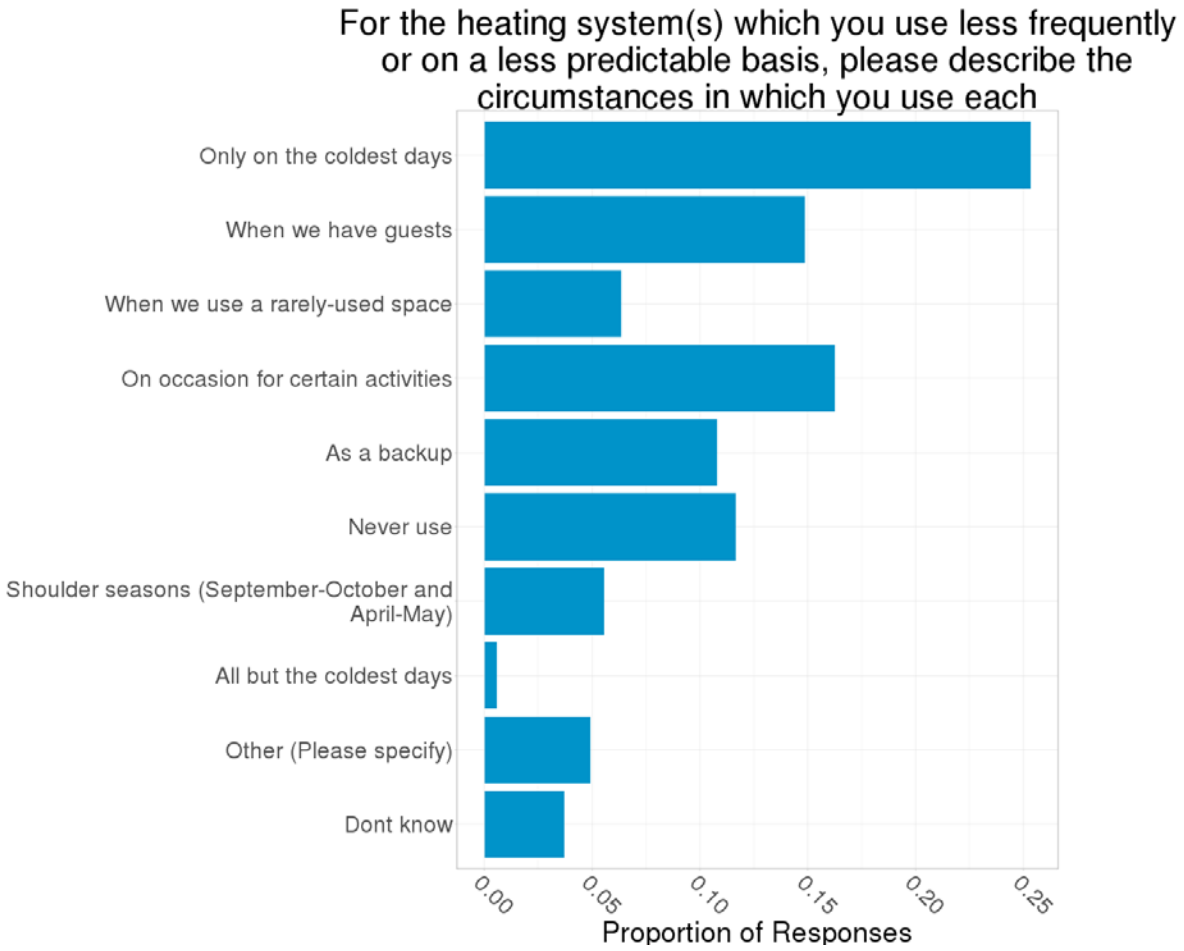


Source: Navigant analysis

Key Finding: *Winter peak day load shapes for electric heating are essentially flat.*

Figure 26 shows what drives the use of secondary heat, which may be what is driving the flat load shape for electric heat. Over one-third of people report using their secondary heating systems only on the coldest days or for backup heat. This is consistent with the observed trend (the hourly load shape is relatively flat), but usage on the coldest days is much higher than on other days during the winter.

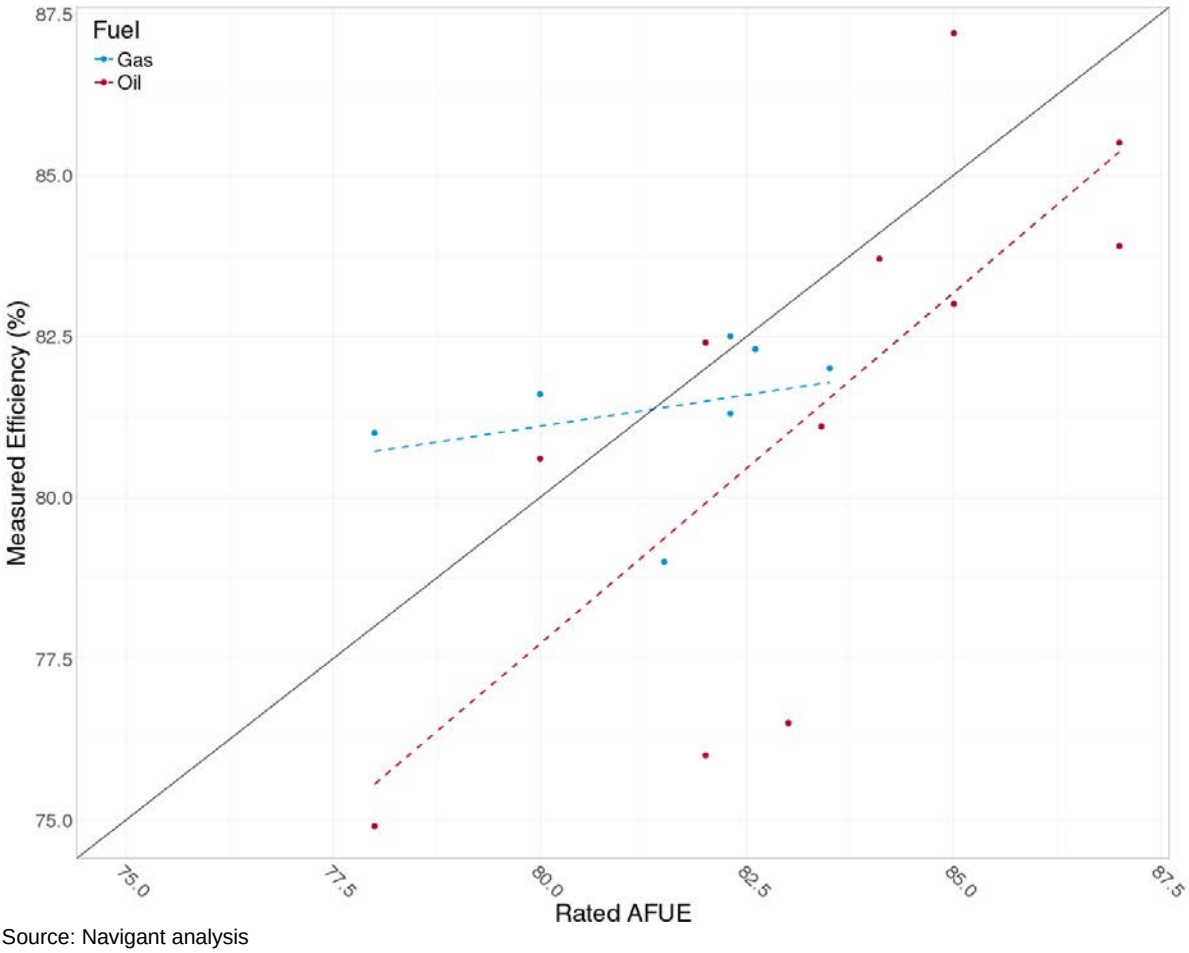
Figure 26. Secondary Heating Use



Source: Navigant analysis

Figure 27 shows a comparison of measured and rated efficiency for gas and oil boilers. The small sample of equipment measured does not provide statistically significant results; however, the trend in the data indicates that oil-fired boilers operate roughly 2% less efficient than their rating.

Figure 27. Rated vs. Measured Boiler Efficiency



Source: Navigant analysis

2.3.2 Kitchen End Uses

Since the 2009 RASS was conducted, there have likely been modest increases in Freezer and Secondary Refrigerator saturation.

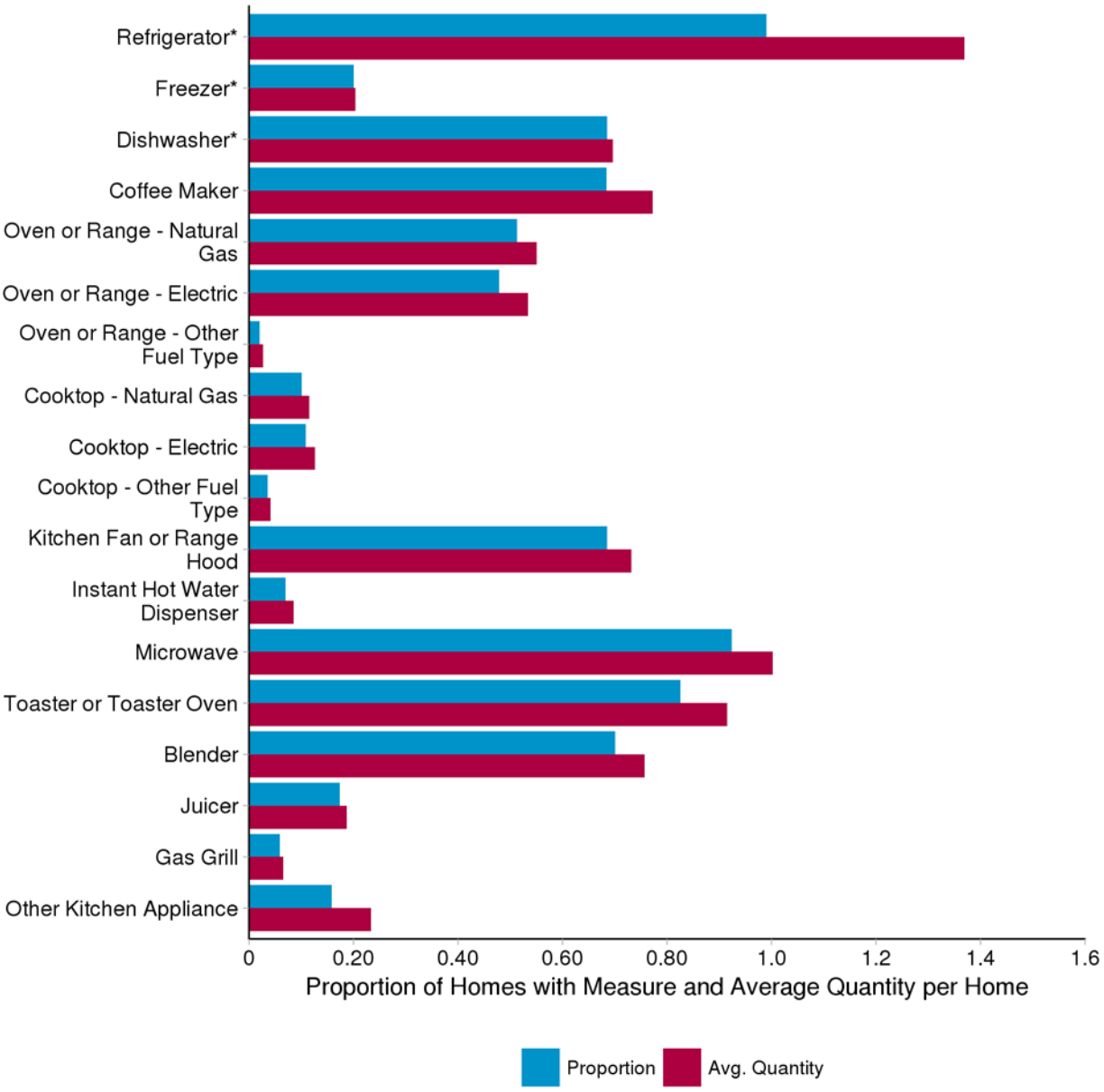
Table 9. RASS Comparison – Kitchen Appliances

End Use	All Homes		Single-Family Detached	
	2009 RASS Saturation	2017 Baseline Study Saturation	2009 RASS Saturation	2017 Baseline Study Saturation
Microwave	0.95	0.92	0.97	0.94
Dishwasher	0.71	0.69	0.77	0.78
Primary Refrigerator	1	0.99	1	1
Freezer	0.13	0.2	0.17	0.24
Secondary Refrigerator	0.28	0.36	0.35	0.45

Sources: Navigant analysis, 2009 RASS

Figure 28 shows that refrigerators are the only kitchen end use with an average quantity per home that is significantly higher than 1. Figure 29 shows that refrigerators with a top freezer are the most common type of secondary refrigerator.

Figure 28. Kitchen End Use Saturation and Penetration

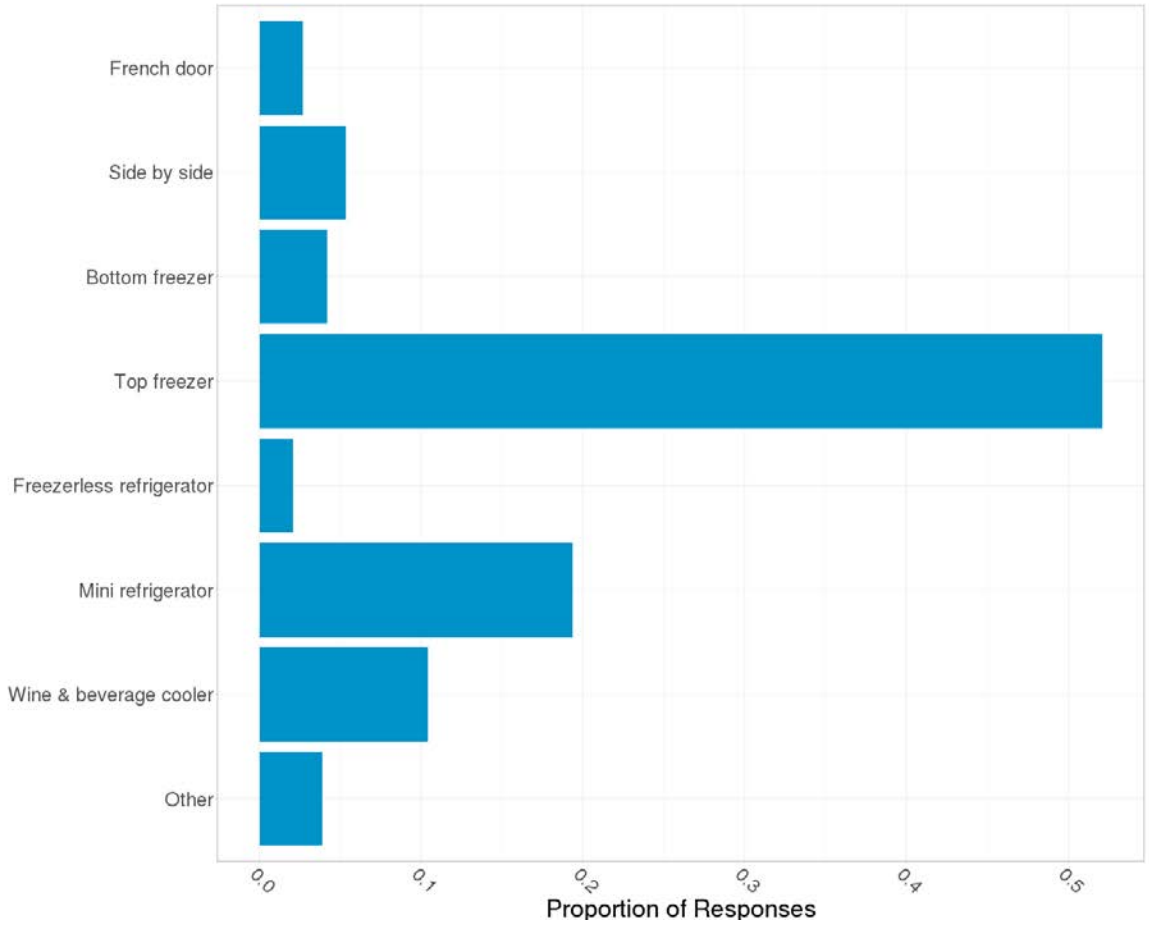


*Metered end use

Note: The refrigerator category includes mini fridges and wine coolers. Of the secondary refrigerators, 69% were full-size refrigerators (comparable to the refrigerators category in the 2009 RASS), while the remaining 31% were mini fridges and wine coolers.

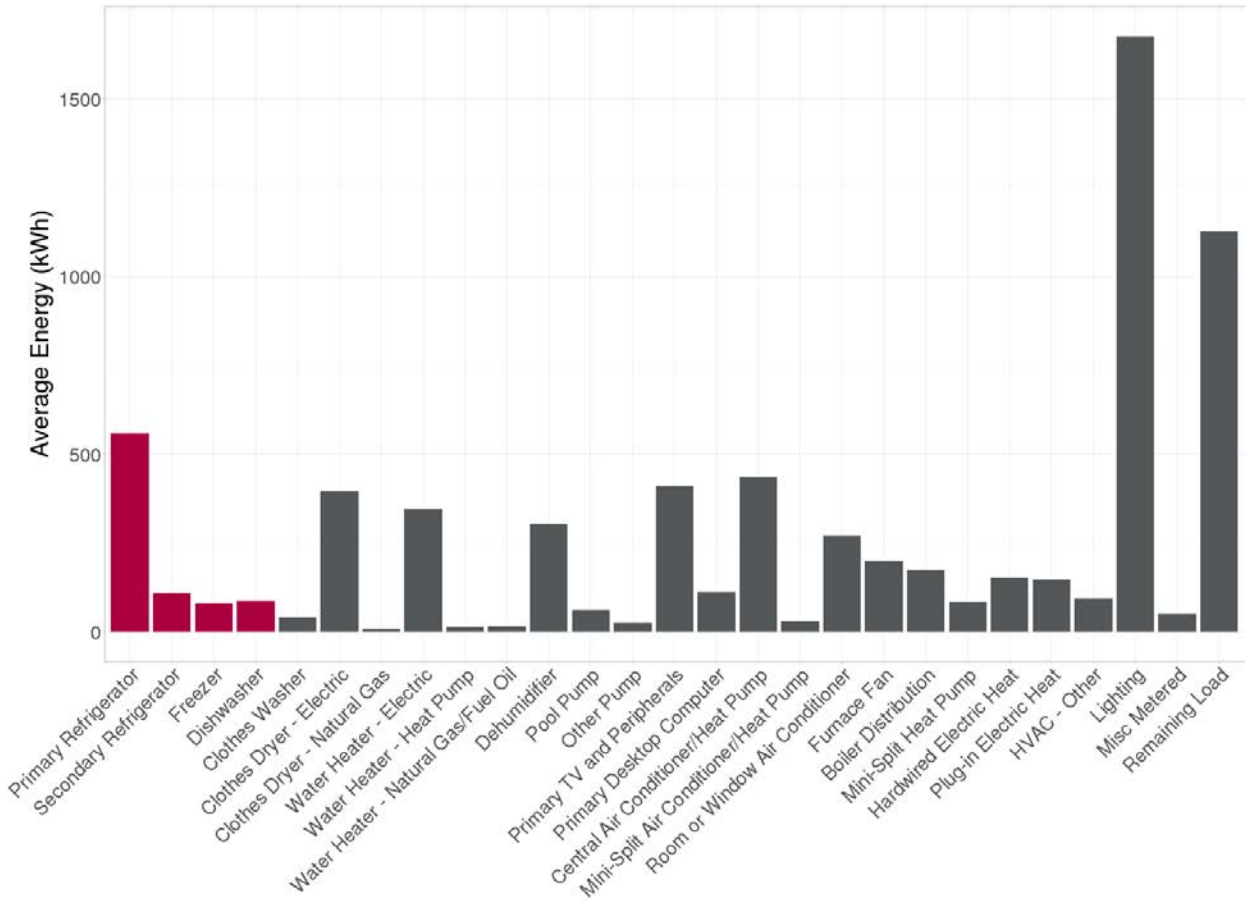
Source: Navigant analysis

Figure 29. Secondary Refrigerator Types



Source: Navigant analysis

Figure 30. Population Annual End Use Energy Consumption – Kitchen End Uses (kWh)

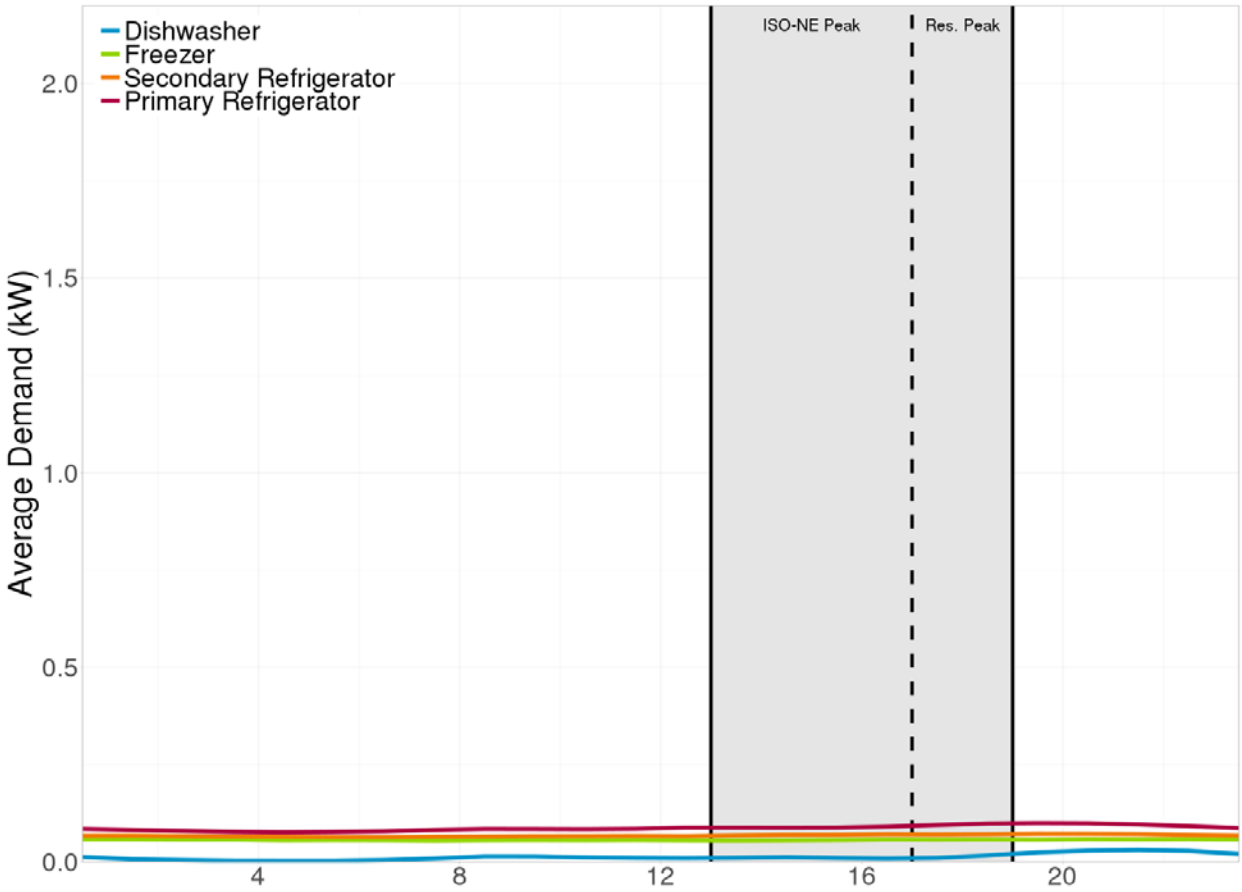


Source: Navigant analysis

Because refrigerators are in almost all homes and in use 24/7, they show up as one of the largest energy consumers in Figure 30. Refrigerator and freezer energy consumption varies seasonally, with higher consumption in the middle of summer. (See monthly energy consumption plots in Appendix C).

Figure 31 and Figure 32 appear to be almost blank, but this is because dishwashers, primary refrigerators, secondary refrigerators, and freezers have low peak demands compared with central AC and other large peak loads.

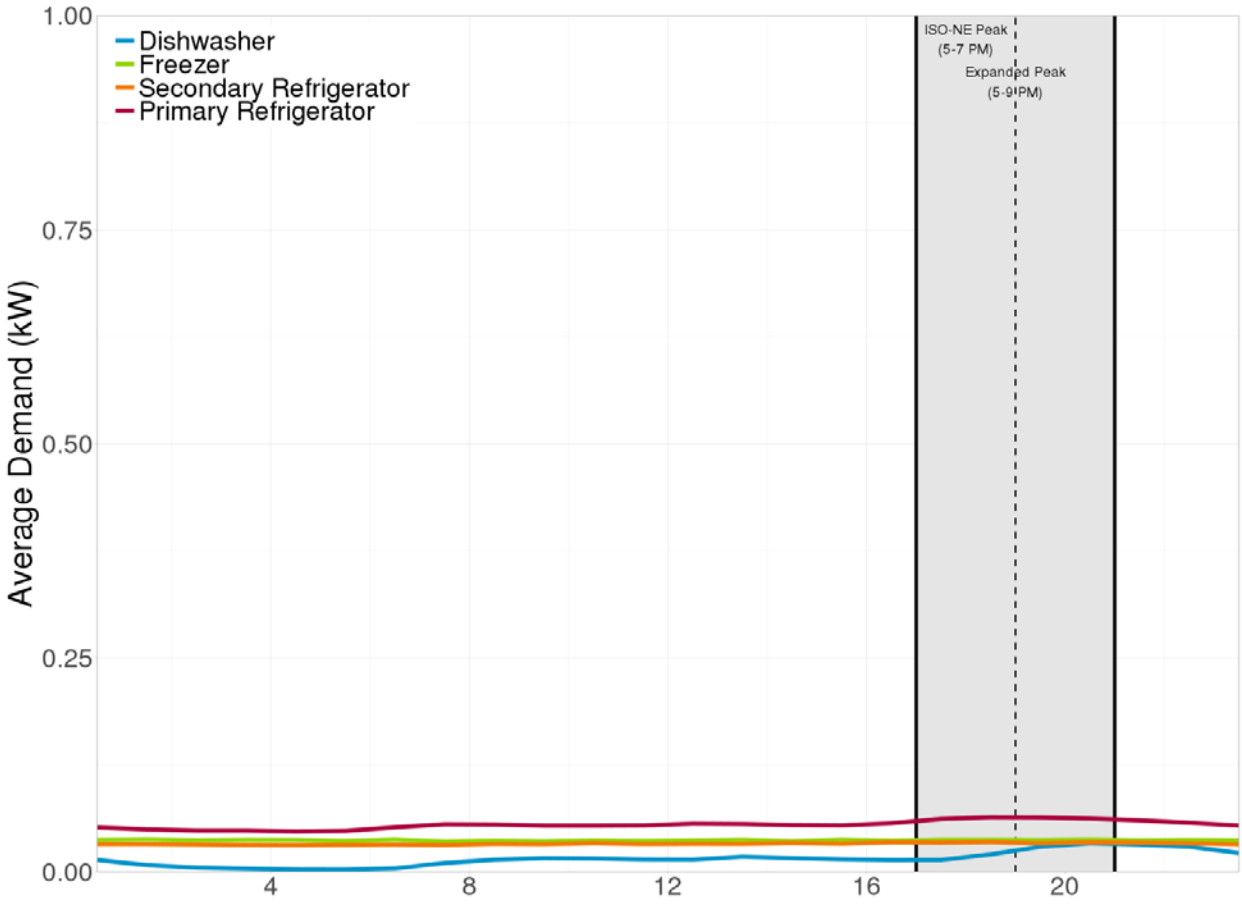
Figure 31. Summer Peak Day Kitchen Load Shapes for Homes with End Use



Source: Navigant analysis

Figure 33 confirms what is shown in Figure 31 and Figure 32—there are not typical schedules for running dishwashers in Massachusetts households.

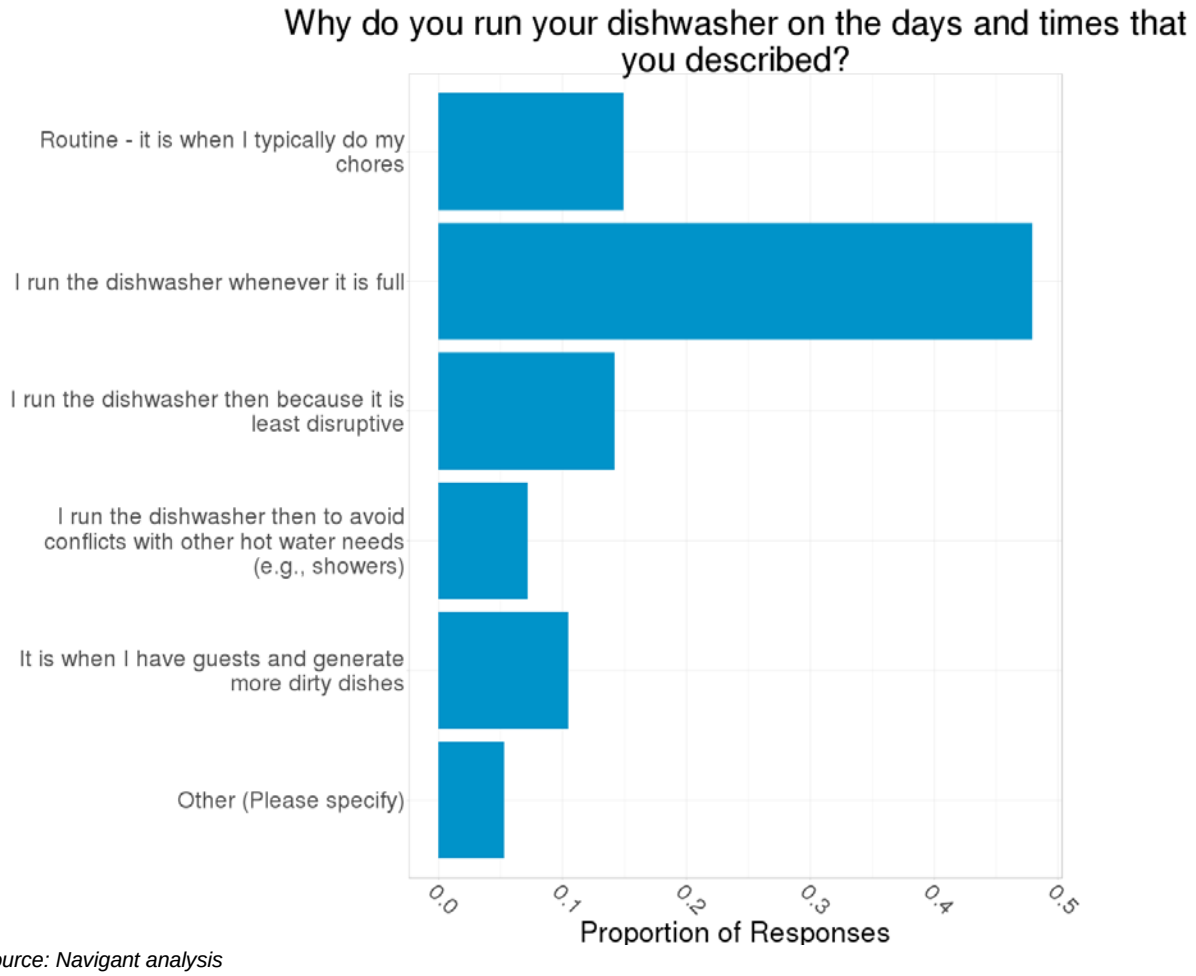
Figure 32. Winter Peak Day Kitchen Load Shapes for Homes with End Use



Source: Navigant analysis

Key Finding: *Kitchen end uses add no significant summer or winter peak load to the system, but refrigerators' energy consumption is significant across the entire population because of their high saturation.*

Figure 33. Dishwasher Use



Source: Navigant analysis

2.3.3 Laundry End Uses

Table 10 shows that not all single-family detached homes have individual laundry equipment. Differences in question wording and population may explain part of the apparent decline in laundry equipment saturation.

Table 10. RASS Comparison – Laundry

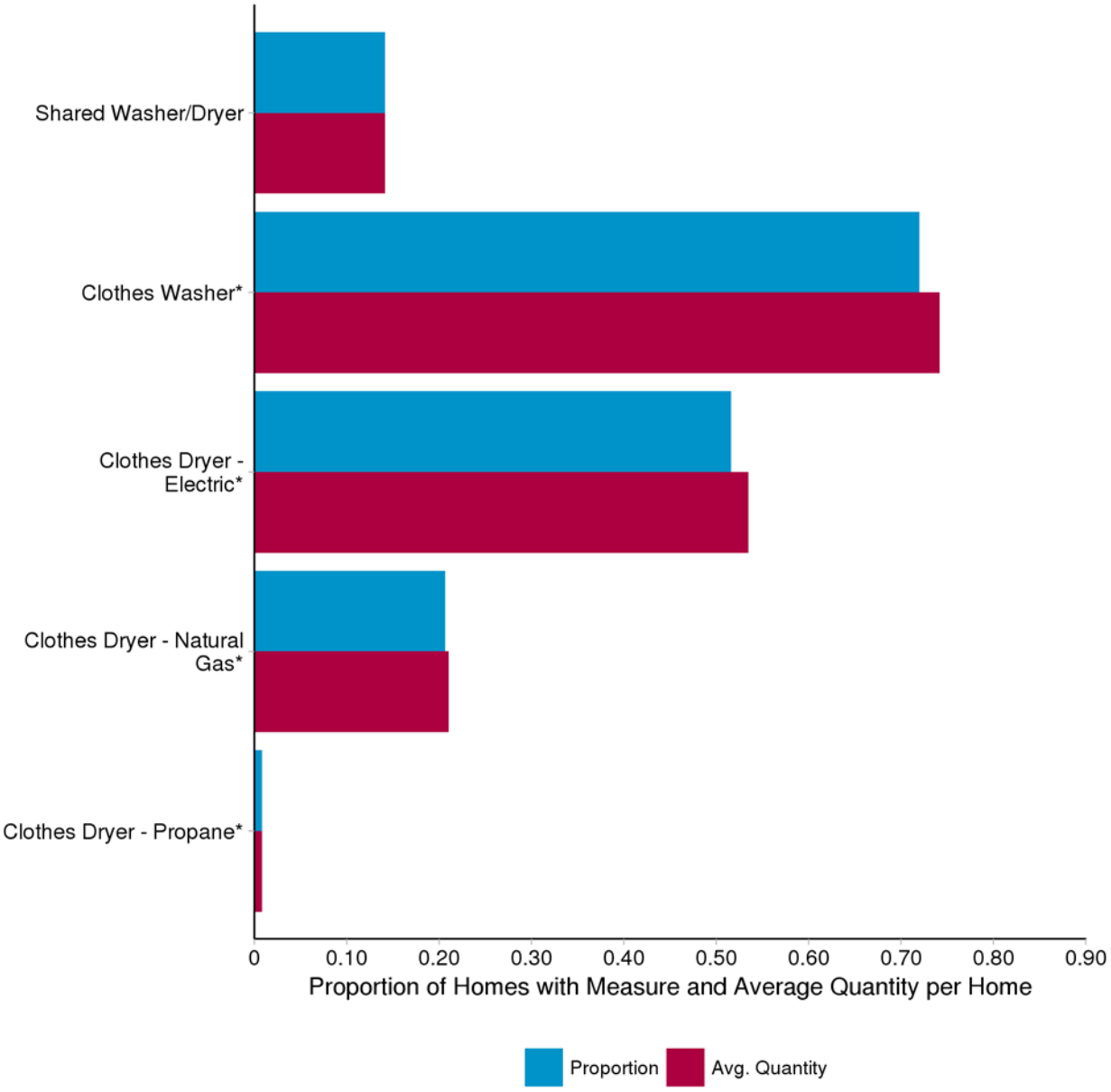
End Use	All Homes		Single-Family Detached	
	2009 RASS Saturation	2017 Baseline Study Saturation	2009 RASS Saturation	2017 Baseline Study Saturation
Clothes Washer (Private Use)	86%	72%	94%	90%
Clothes Dryer (Private Use)*	83%	73%	93%	92%

*Includes electric, natural gas, and propane clothes dryers.

Sources: Navigant analysis, 2009 RASS

Figure 34 shows the distribution of laundry equipment in Massachusetts homes; electric dryers are in half of homes, and natural gas is the dominant dryer fuel in remaining one fifth of homes with dryers.

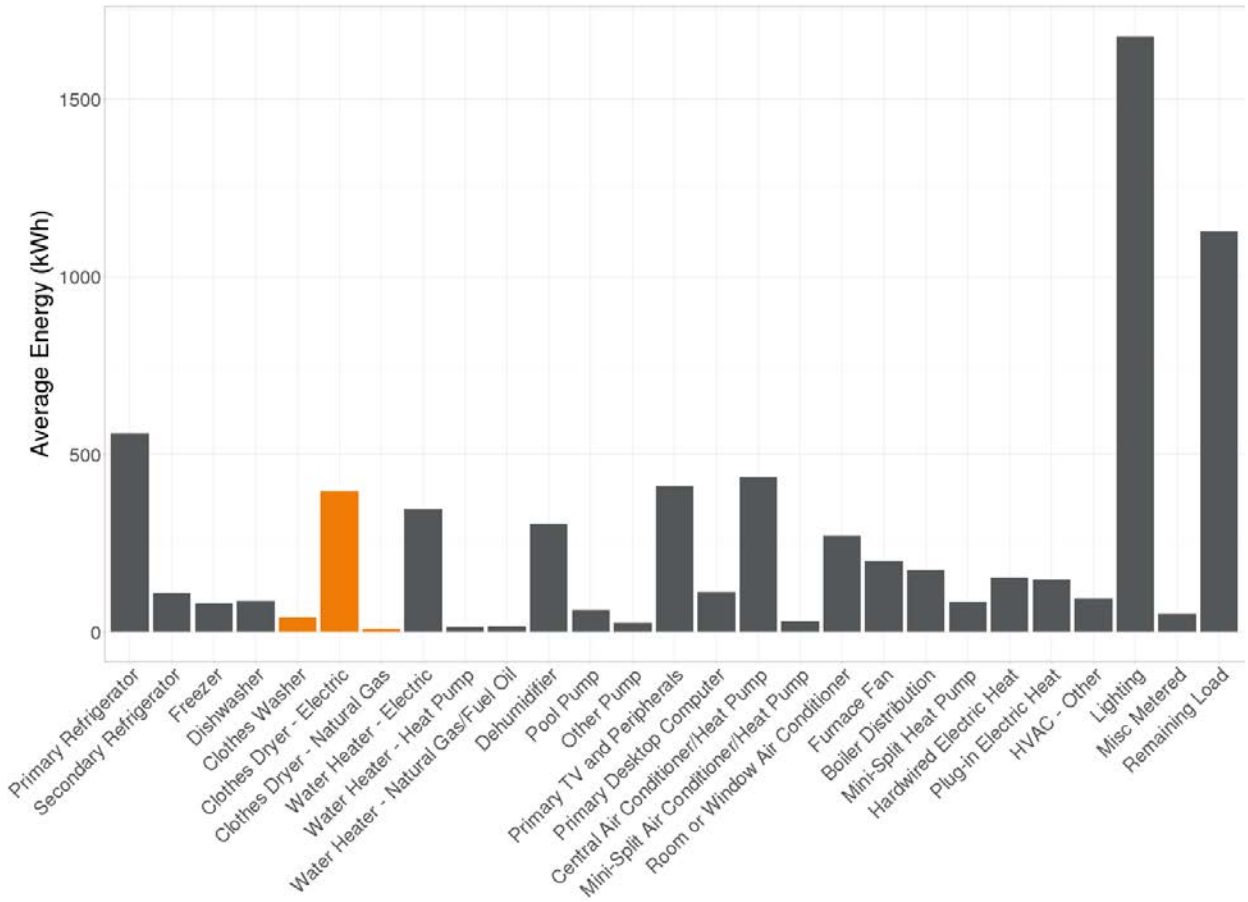
Figure 34. Laundry End Use Saturation and Penetration



Source: Navigant analysis

Figure 35 compares laundry end use consumption to energy consumption for all end uses. While clothes dryers have significant energy consumption (fourth largest of all end uses) and clothes washers appear to be low consumers, the energy saved by high efficiency clothes washers shows up primarily as reduced clothes dryer energy consumption and secondarily as reduced water heating consumption. Therefore, the savings potential for clothes dryers should be considered in conjunction with high efficiency clothes washers.

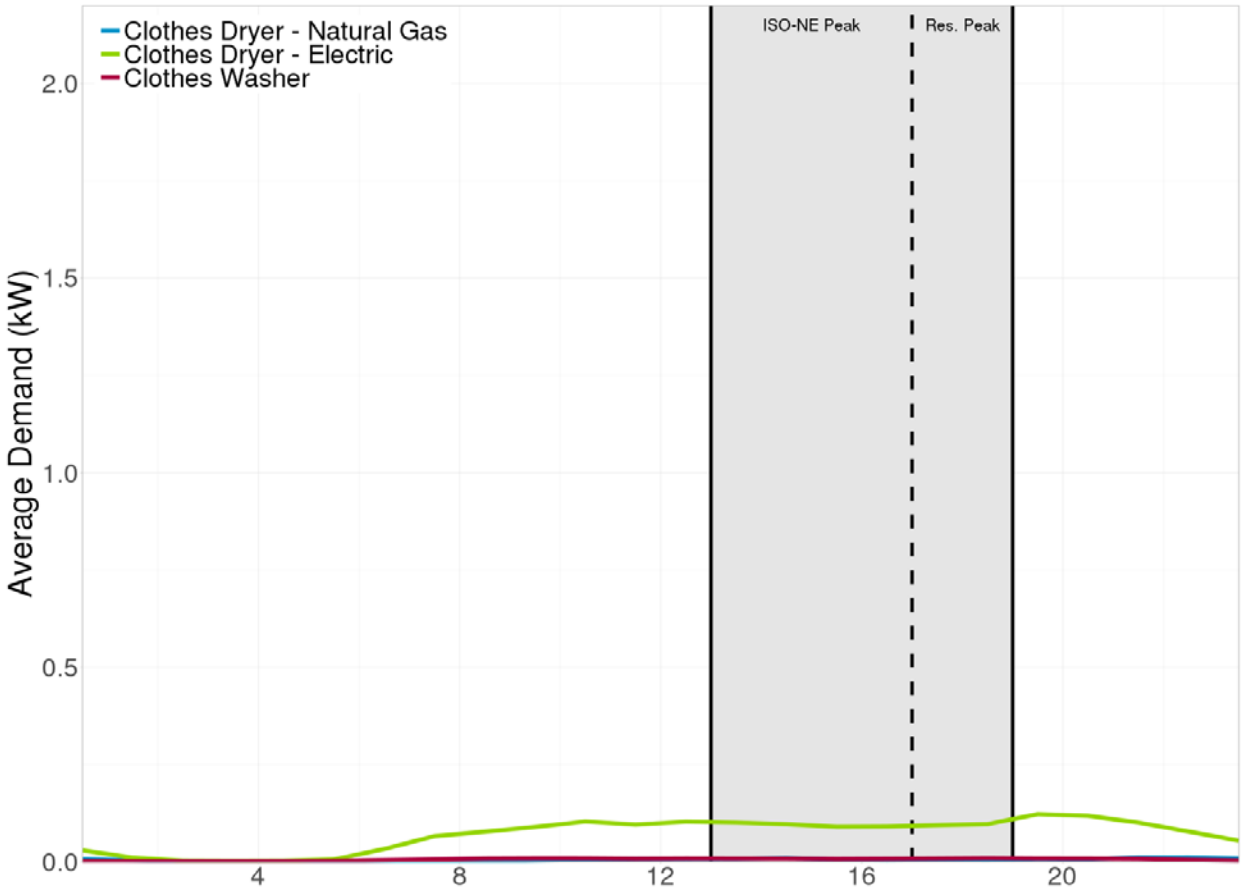
Figure 35. Population Annual End Use Energy Consumption – Laundry End Uses (kWh)



Source: Navigant analysis

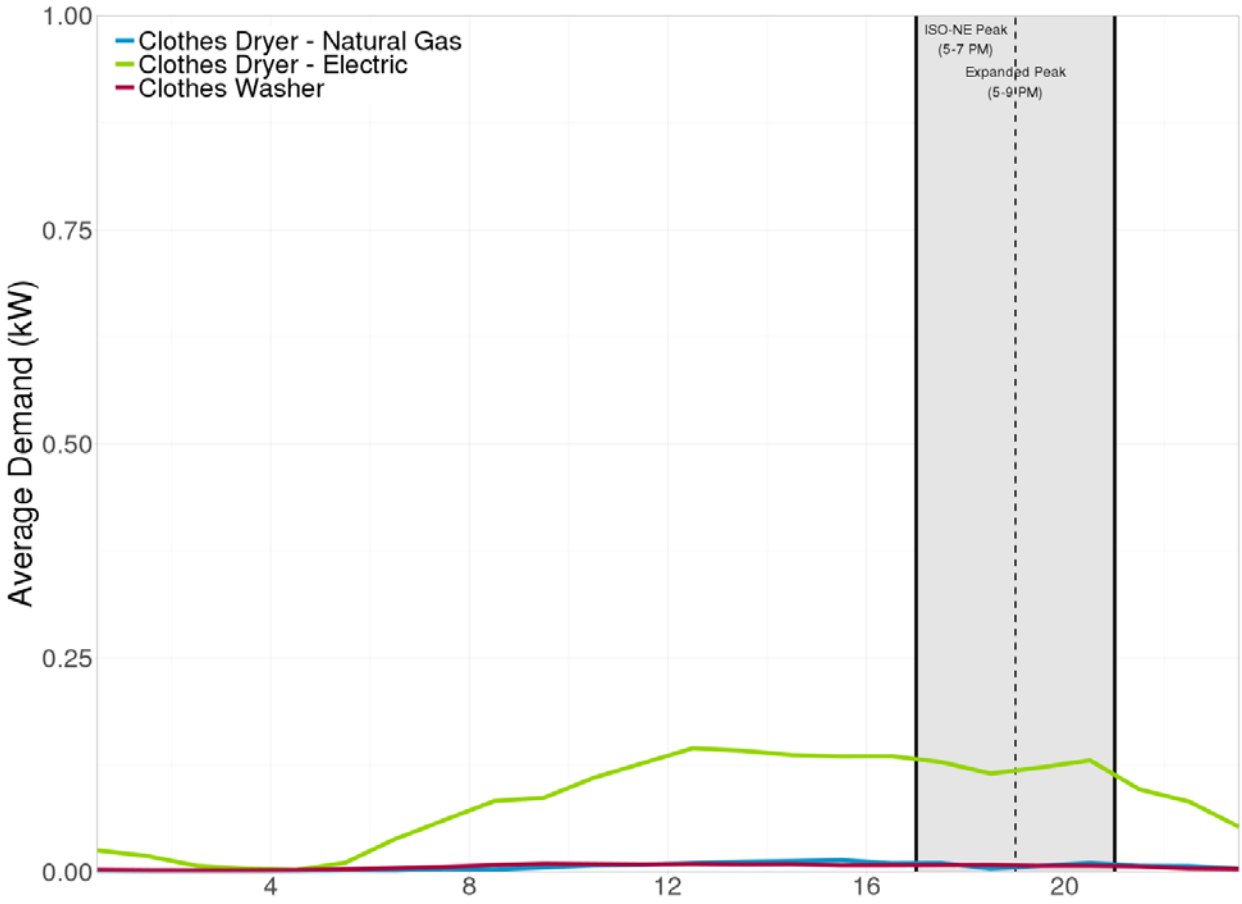
Figure 36 and Figure 37 show that while clothes dryer use peaks late in the day on summer peak days, there is some use throughout the day in all seasons. The other laundry end uses have near zero demand.

Figure 36. Summer Peak Day Laundry Load Shapes for Homes with End Use



Source: Navigant analysis

Figure 37. Winter Peak Day Laundry Load Shapes for Homes with End Use

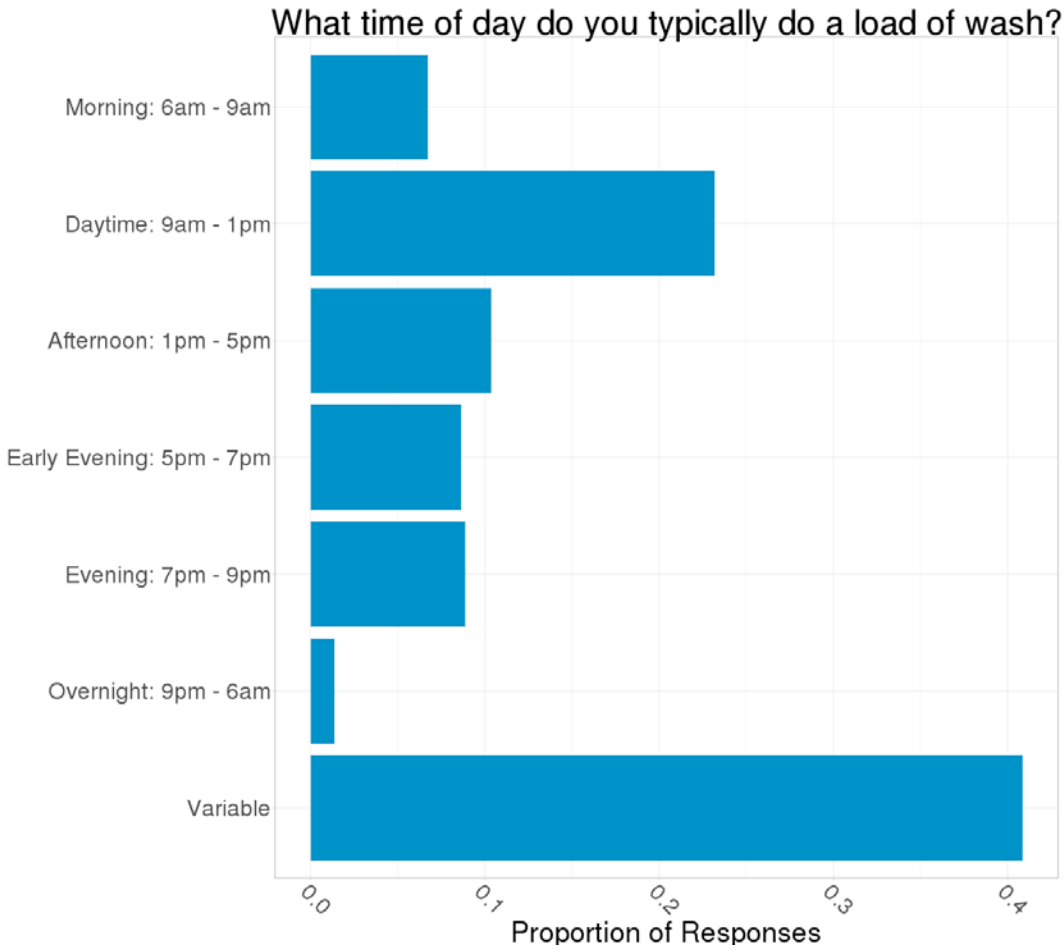


Source: Navigant analysis

Key Finding: *Some clothes dryers are used throughout the day, including during afternoon and evening peak in summer and winter.*

Figure 37Figure 38 confirms what is shown in Figure 36 and Figure 37—some households run laundry equipment between 9 a.m. and 1 p.m., but most households do laundry on a variable schedule throughout the day.

Figure 38. Laundry Use



Source: Navigant analysis

2.3.4 Water Heating End Uses

Overall, electric water heating is not a large energy consumer in Massachusetts at this time (Figure 40). Results from this study corroborate model estimates that show there is significant seasonality to water heating consumption, with higher consumption recorded in the winter and lower consumption in the summer. This is consistent with modeled loads using the mains temperature relationship from Christensen and Burch.[14] Over time, electric water heating may also become more important as people transition away from using oil boilers to supply space and water heating needs.

The study included both regular electric water heaters and an oversample of heat pump water heaters. As shown in Figure 41 and Figure 42, the summer and winter peak day load shapes for water heating have a modest double hump, with an initial peak in the morning followed by a second peak in the evening.

The shape for heat pump water heaters is based on a relatively small sample of 30 early adopters of the technology; this is indicative of how people use heat pump water heaters today but may not be

[14] Jay Burch and Craig Christensen, "Towards Development of an Algorithm for Mains Water Temperature." (paper presented at the ASES Annual Conference, Cleveland, Ohio, 2007).

representative of long-term adoption. Overall, heat pump water heaters appear to have demands that are about half of regular water heaters. This roughly corroborates the engineering savings estimates, but overall use of electric water heaters is lower than expected (2,540 kWh/year compared to the 3,330 kWh/yr in the value used for Navigant's 2017 Heat Pump Water Heater Impact Study[15] or the 4,622 kWh used by Energy Star[16] in the basis of the 2015 Massachusetts Technical Reference Manual[17]). This may be due to the fact that most electric water heaters in Massachusetts are found in multifamily residences with lower occupancy and lower consumption, while standard electric water heater assumptions are based on the hot water consumption of a family of four. However, the summer load shapes for electric water heaters and heat pump water heaters overlap at 4 p.m. during the peak period. Because of the small sample, it may be more appropriate to apply the water heating category load shape to use in calculating peak demand impacts from heat pump water heaters.

Table 11. RASS Comparison – Water Heating Systems

End Use	All Homes		Single-Family Detached	
	2009 RASS Saturation	2017 Baseline Study Saturation	2009 RASS Saturation	2017 Baseline Study Saturation
Any Water Heating System	0.98	1	0.97	1
Natural Gas Water Heating	0.57	0.37	0.55	0.42
Oil DHW	0.24	0.03	0.30	0.05
Electric DHW	0.16	0.16	0.14	0.18

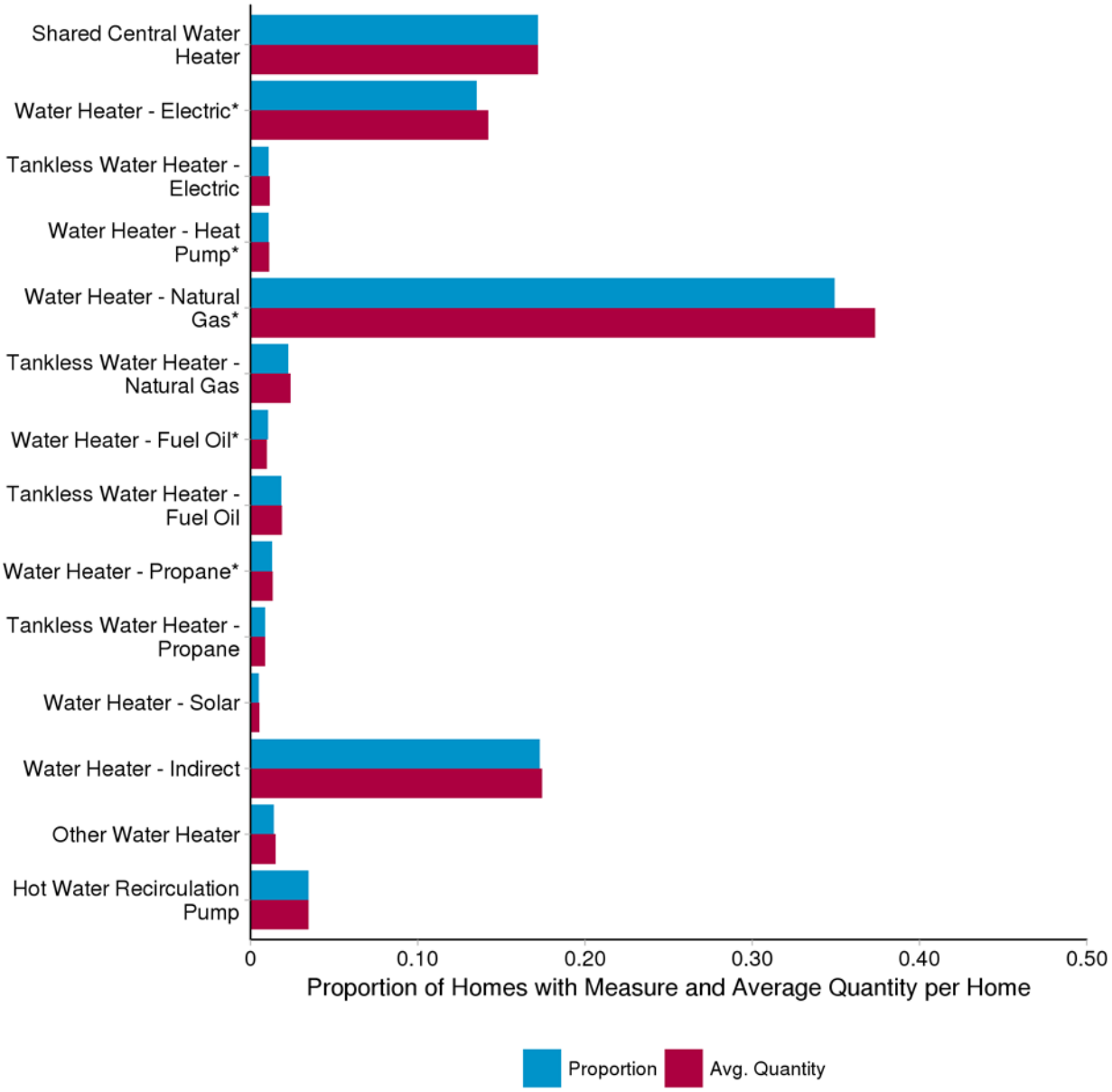
Sources: Navigant analysis, 2009 RASS

[15] See http://ma-eeac.org/wordpress/wp-content/uploads/Heat-Pump-Water-Heater-Impact-Study-Volume-1.pdf for the Navigant study, which was based on the 2012 Steven Winter Associates Study: http://ma-eeac.org/wordpress/wp-content/uploads/Heat-Pump-Water-heaters-Evaluation-of-Field-INstalled-Performance.pdf.

[16] https://www.energystar.gov/ia/partners/prod_development/new_specs/downloads/water_heaters/WaterHeaterAnalysis_Final.pdf

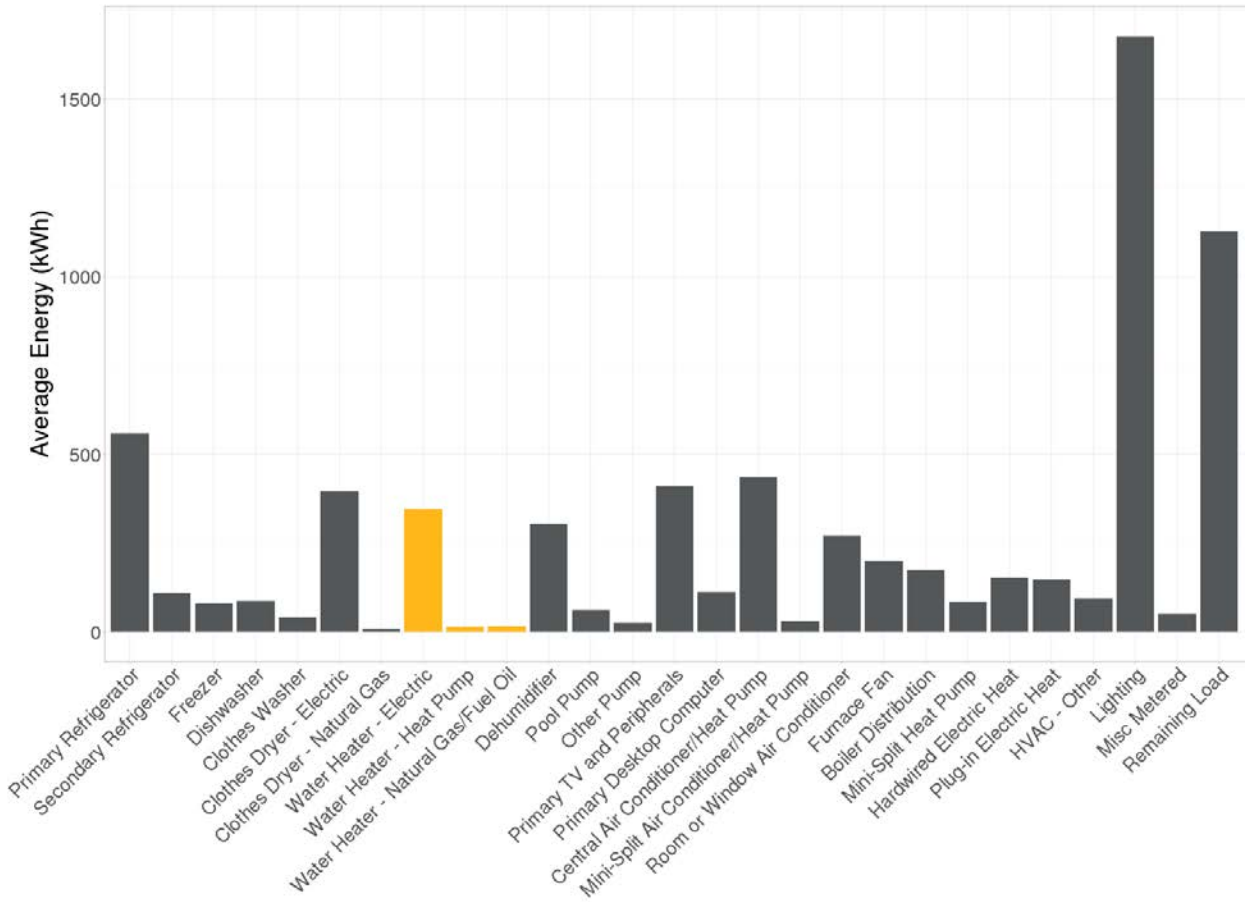
[17] http://ma-eeac.org/wordpress/wp-content/uploads/2016-2018-Plan-1.pdf

Figure 39. Water Heating End Use Saturation and Penetration



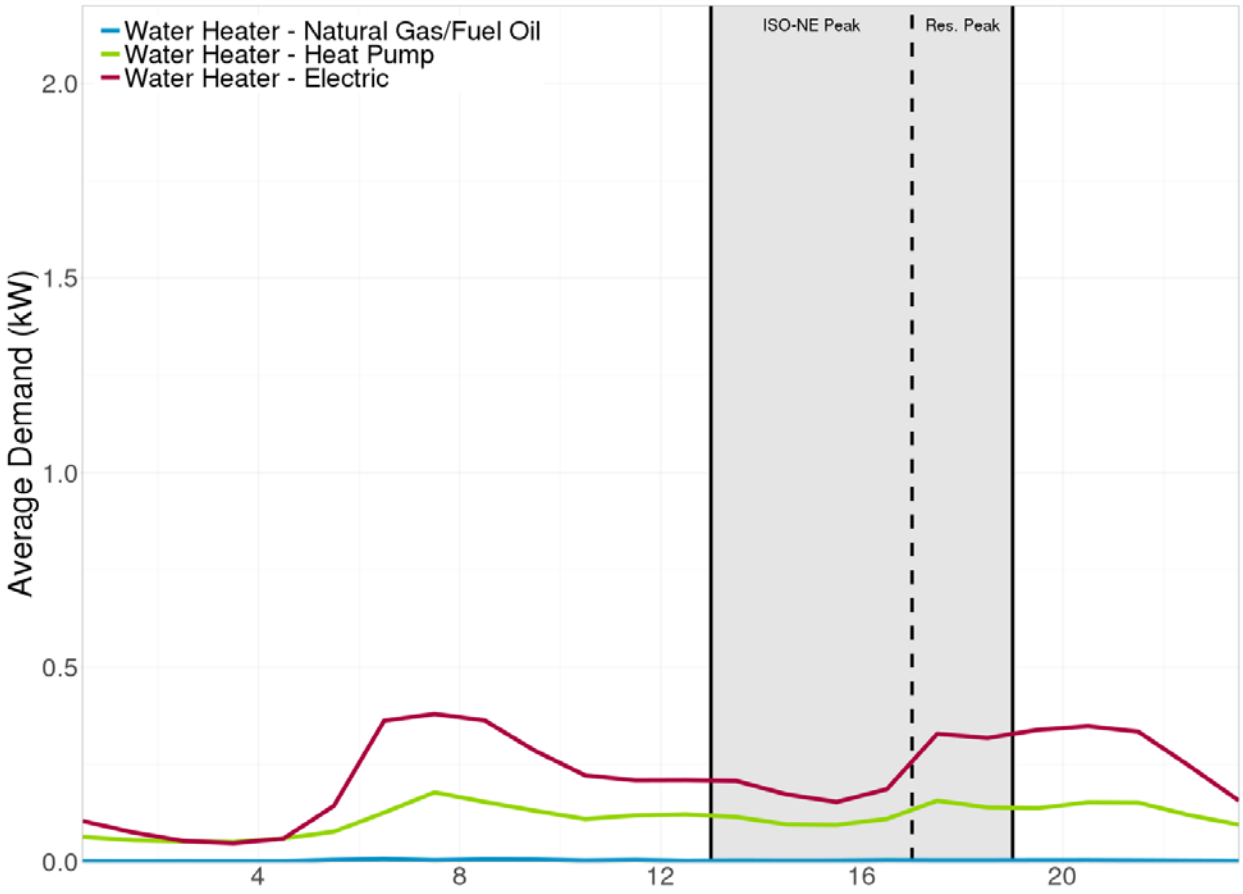
Source: Navigant analysis

Figure 40. Population End Use Annual Energy Consumption – Water Heating End Uses (kWh)



Source: Navigant analysis

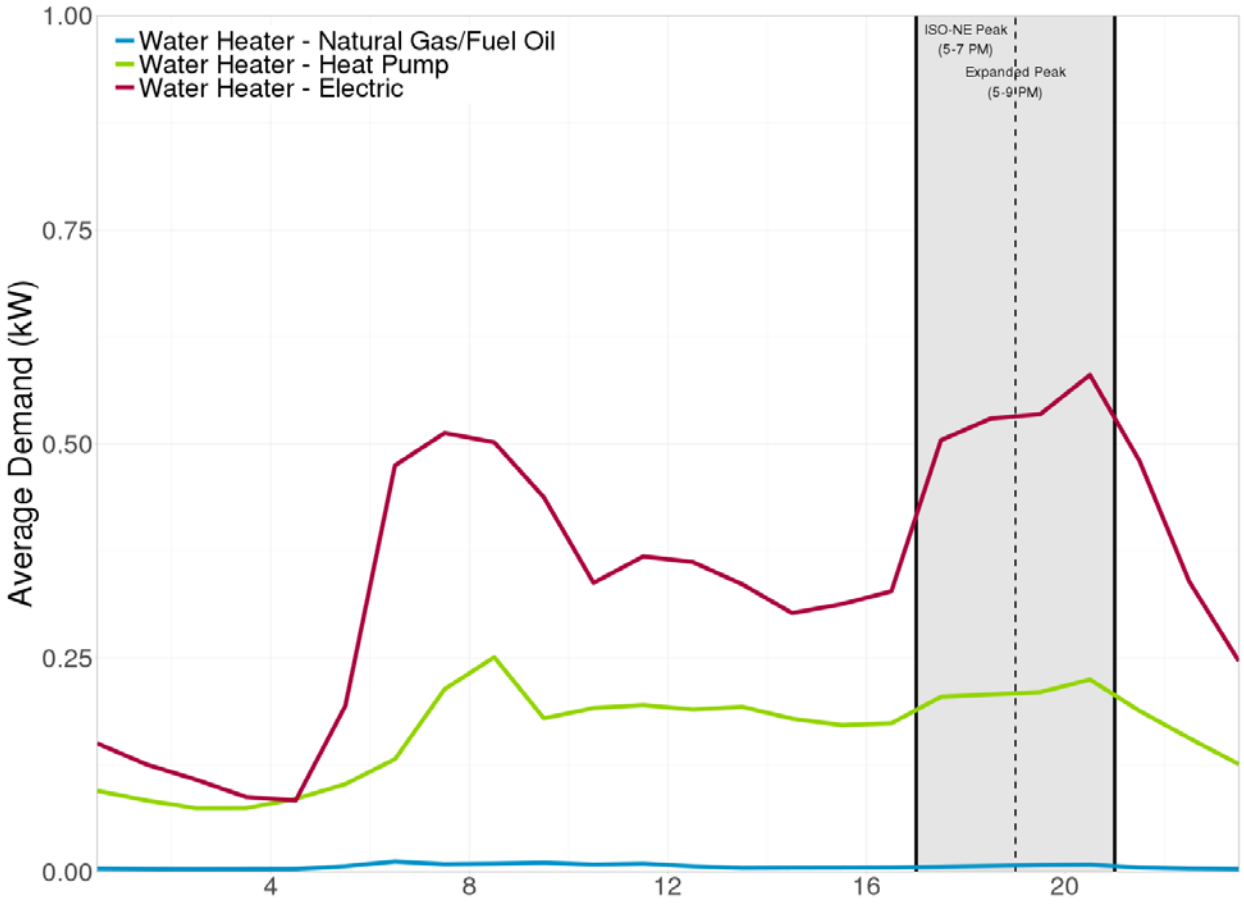
Figure 41. Summer Peak Day Water Heating Load Shapes for Homes with End Use



Source: Navigant analysis

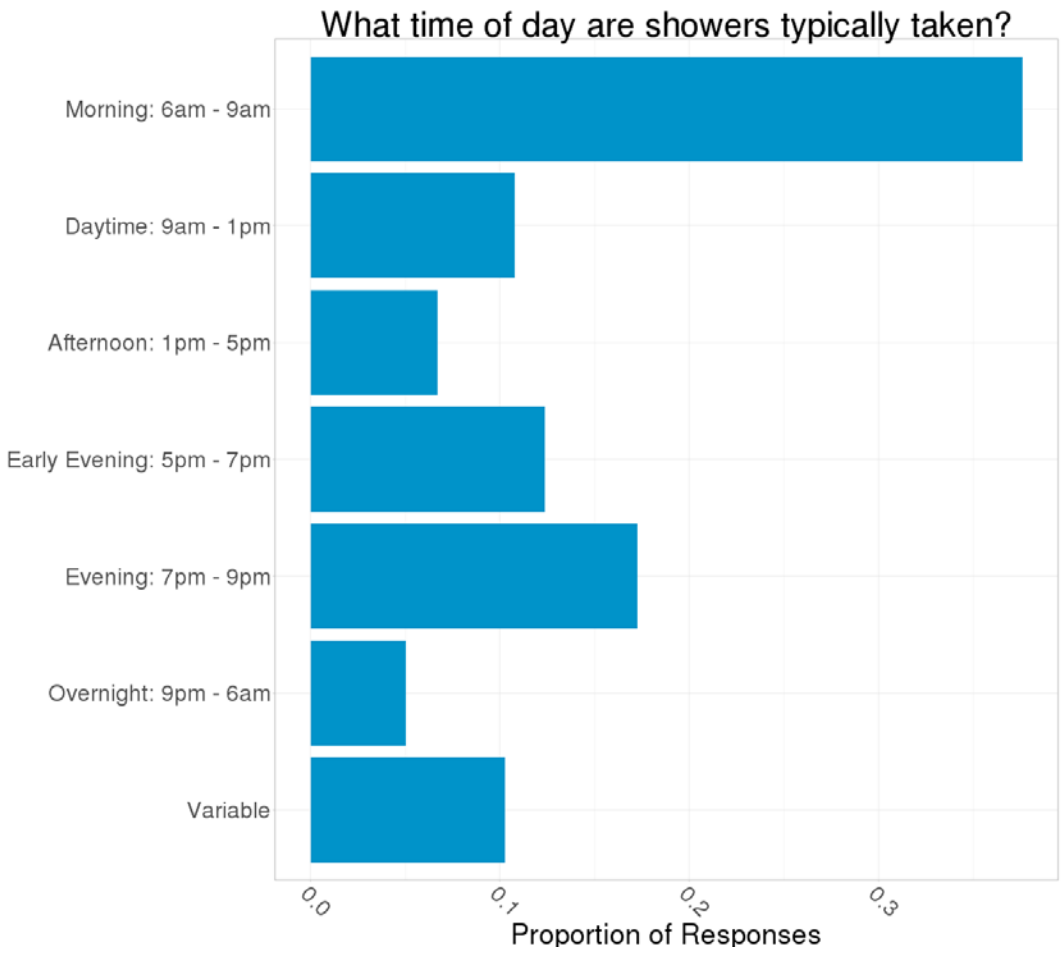
Key Finding: *Heat pump water heaters draw half as much power during peak hours as conventional electric water heaters in summer and winter. More heat pump water heaters in the population could lead to significant reductions in peak demand.*

Figure 42. Winter Peak Day Water Heating Load Shapes for Homes with End Use



Source: Navigant analysis

Figure 43. Hot Water Use



Source: Navigant analysis

Figure 43 shows that the morning peak in Figure 41 and Figure 42 may be driven primarily by showering, while the evening peak is likely a combination of showering, laundry, and dishwashing.

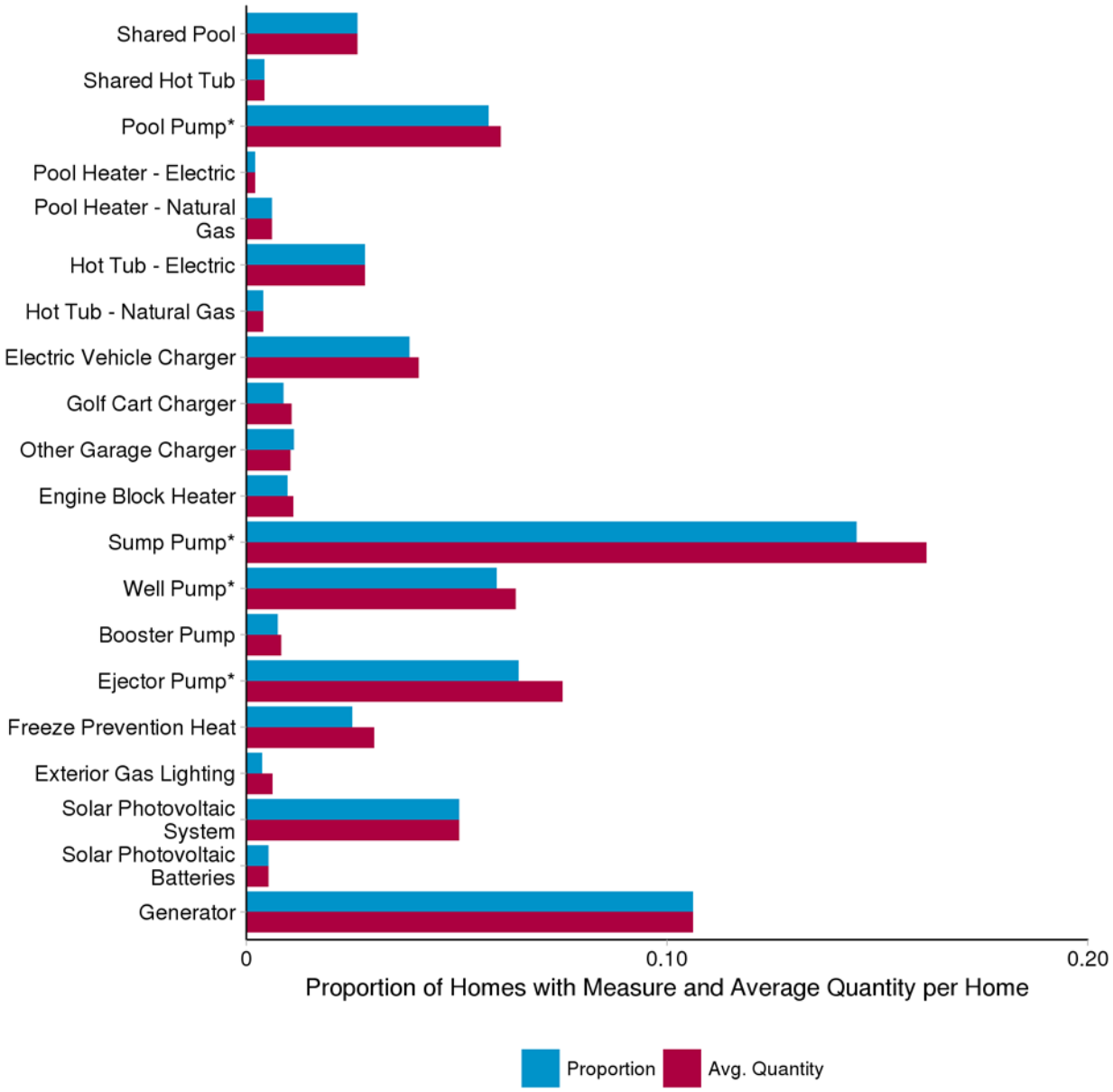
2.3.5 Miscellaneous End Uses

Table 12. RASS Comparison – Miscellaneous

End Use	All Homes		Single-Family Detached	
	2009 RASS Saturation	2017 Baseline Study Saturation	2009 RASS Saturation	2017 Baseline Study Saturation
Dehumidifier	0.50	0.34	0.65	0.48
Pond/well/pool pump	0.23	0.12	0.32	0.20

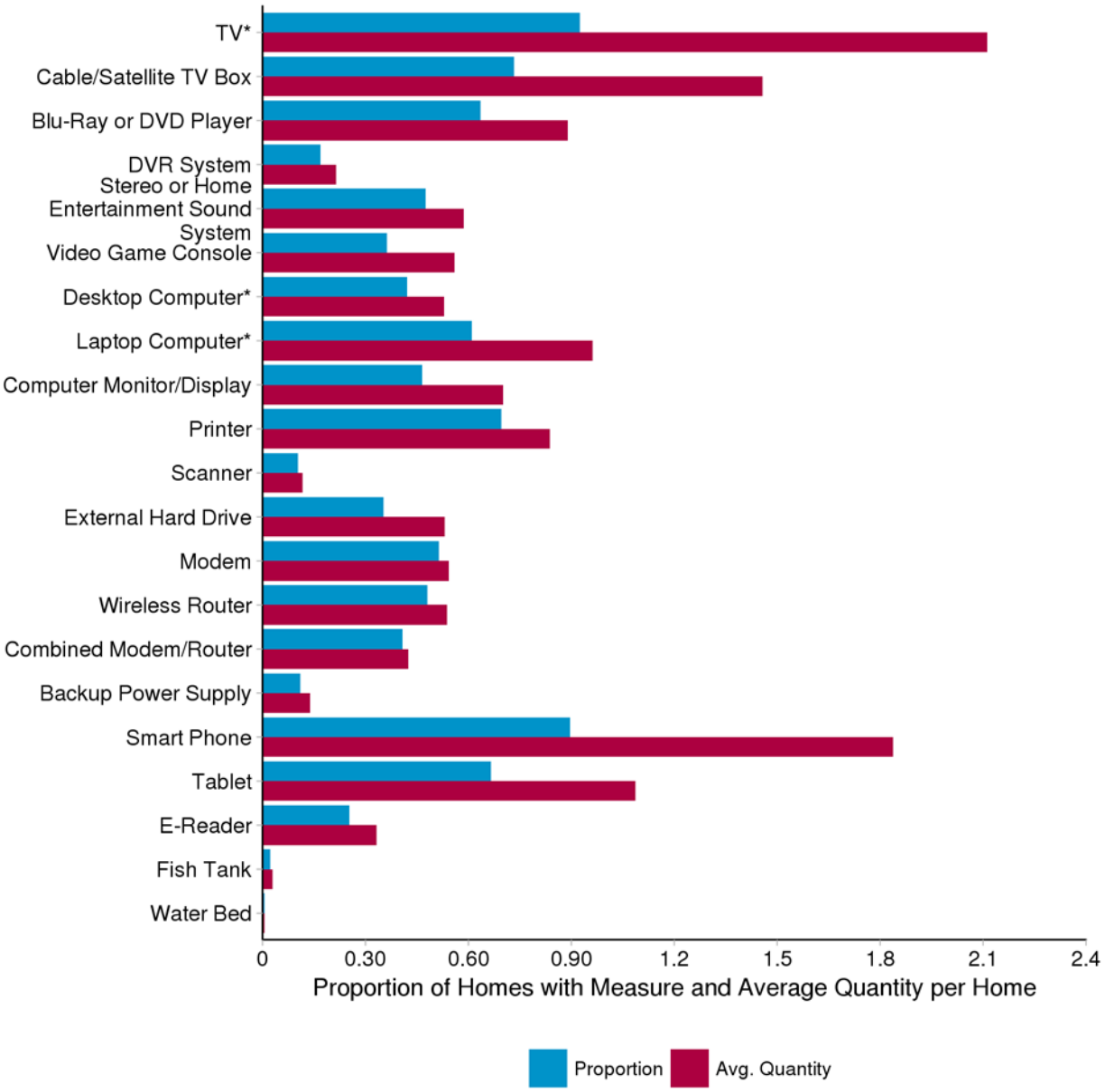
Sources: Navigant analysis, RASS

Figure 44. Miscellaneous End Use Saturation and Penetration – Outdoor



Source: Navigant analysis

Figure 45. Miscellaneous End Use Saturation and Penetration – Electronics



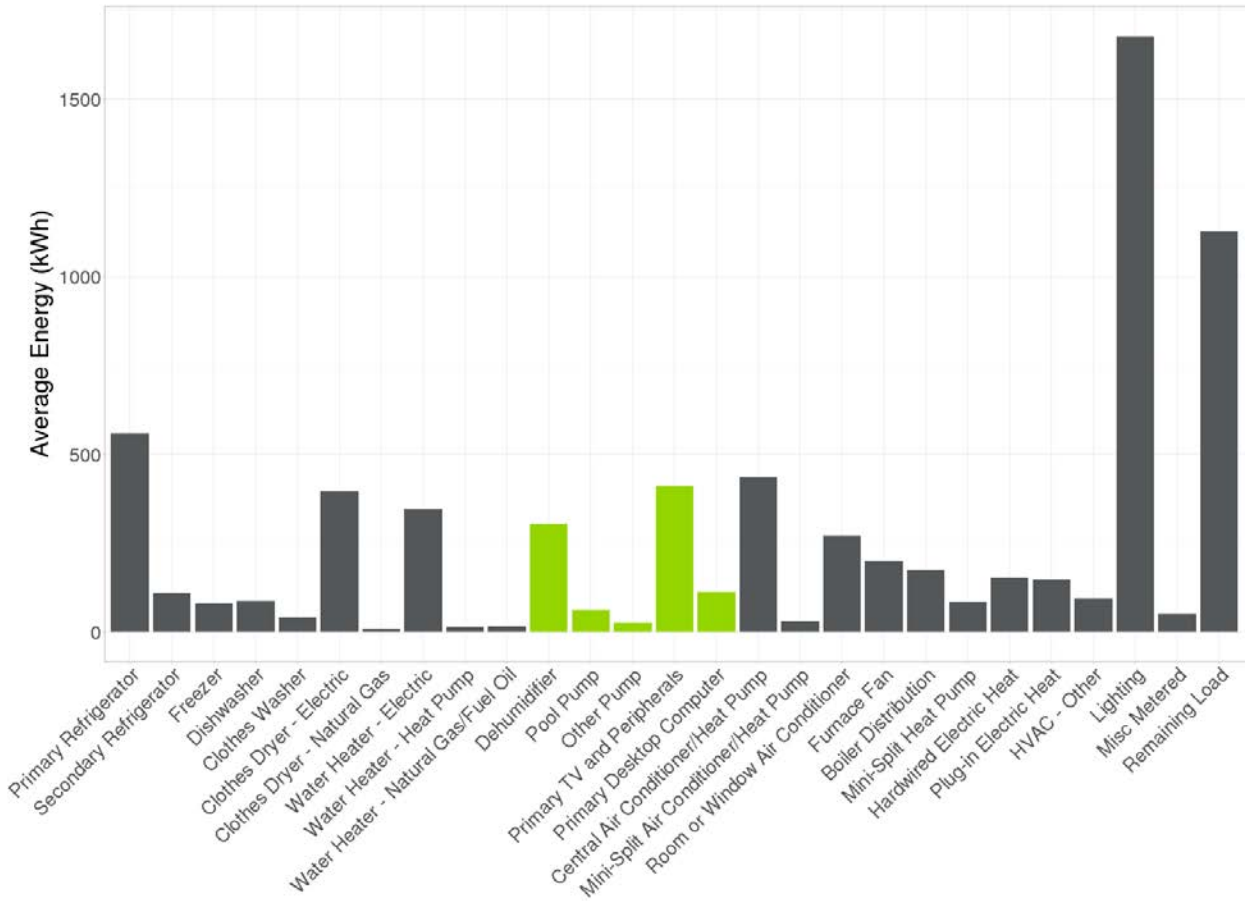
Source: Navigant analysis

The study targeted a handful of miscellaneous end uses for metering, including primary TV and accessories, primary computer and accessories, pool pumps, dehumidifiers, and a variety of other pumps.

Primary TVs, primary computers, and dehumidifiers all have significant annual energy consumption. Pool pumps contribute to summer energy consumption; however, none of the other pumps (including sump pumps and well pumps) use much energy in Massachusetts.

As shown in Figure 47, pool pumps are currently used primarily during the day and have large peak demands in the summer. Dehumidifiers also have significant demands on peak days. None of these end uses contribute significantly to winter peak load (Figure 48).

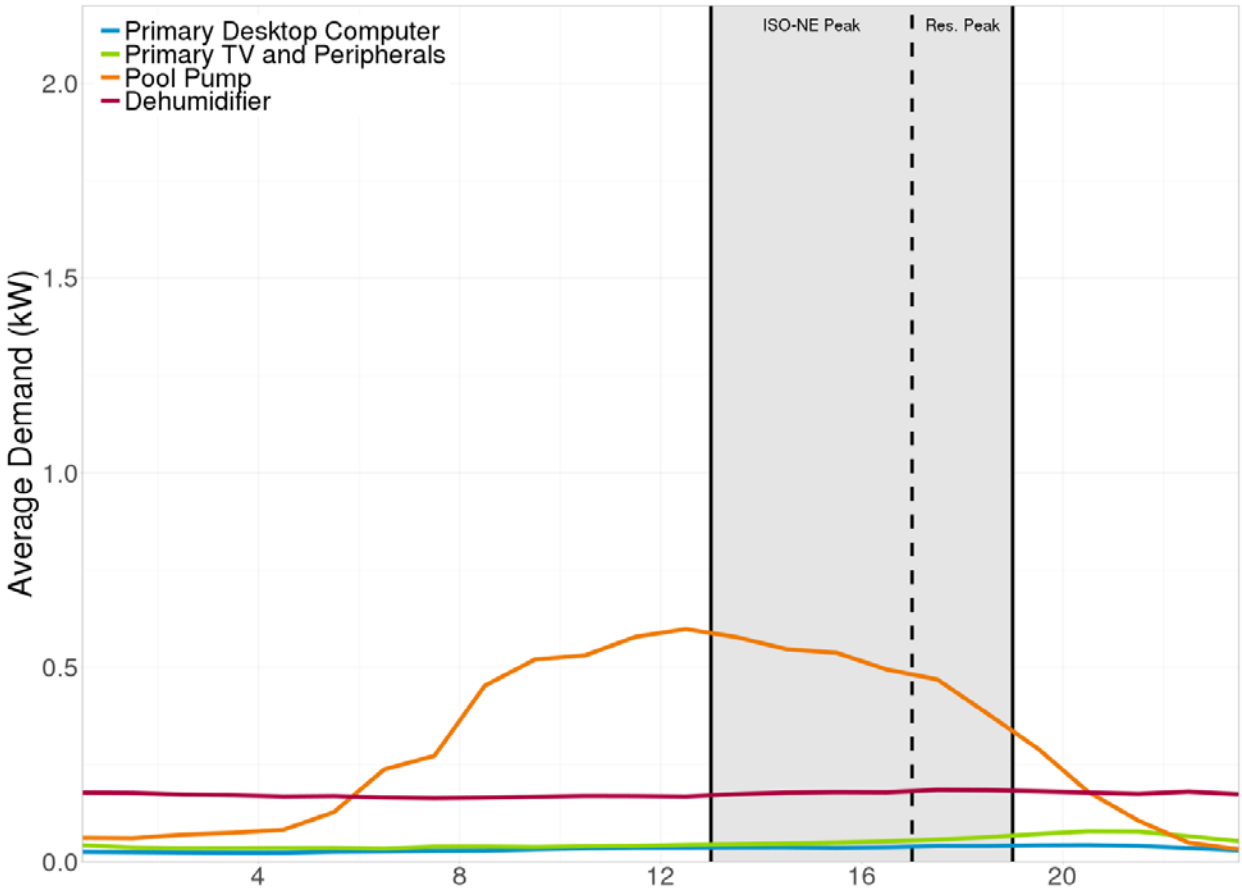
Figure 46. Population End Use Annual Energy Consumption – Miscellaneous End Uses



Source: Navigant analysis

Key Finding: *Primary TVs and accessories consume 6% of household electricity annually.*

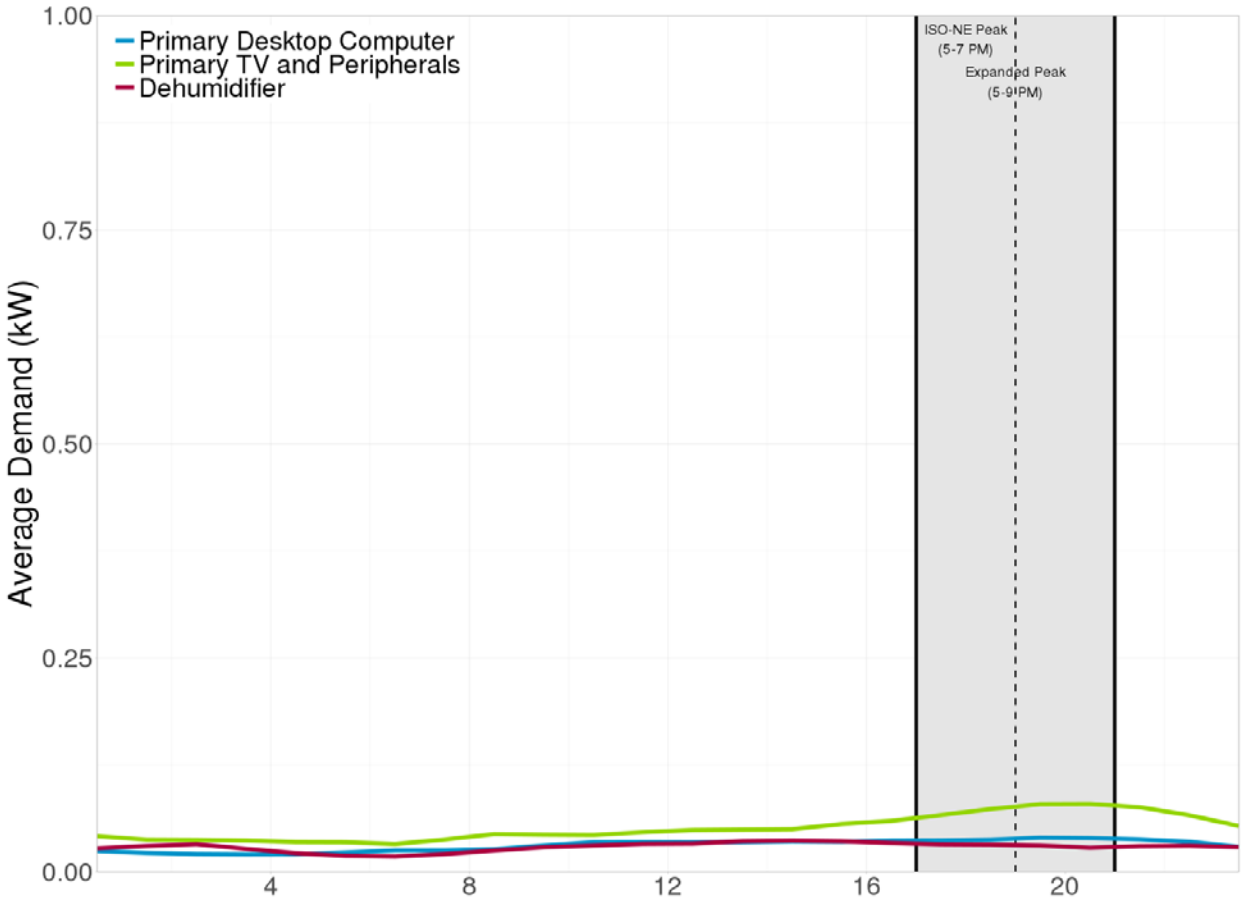
Figure 47. Summer Peak Day Miscellaneous Load Shapes for Homes with End Use



Source: Navigant analysis

Key Finding: *Pool pumps have the largest non-cooling summer peak demand of any metered end use.*

Figure 48. Winter Peak Day Miscellaneous Load Shapes for Homes with End Use



Source: Navigant analysis

Key Finding: *None of the miscellaneous end uses contribute significantly to winter peaks.*

3. OVERALL CONCLUSIONS AND CONSIDERATIONS

CONCLUSION 1: Across all homes in Massachusetts, central AC and room AC are by far the largest contributors to peak demand. Collectively, cooling makes up about half of total residential ISO-NE peak demand.

- Central AC loads averaged 1.7 kW during ISO-NE peak and room AC loads averaged 0.6 kW.
- Saturation of central cooling (including shared and individual household equipment) increased from 29% of households in 2008 to 45% in 2017, while room AC saturation is dropping (64% in 2008 down to 48% in 2017). The central cooling saturation increase is being driven primarily by increases in the prevalence of individual household ducted central AC and ductless heat pumps.

CONSIDERATION 1: Central AC should be the focus of efforts to reduce peak demands, but ductless heat pumps and room AC are also important to a comprehensive program offering.

- Because peak usage is driven as much by Energy Efficiency Ratio (EER) as by Seasonal Energy Efficiency Ratio (SEER), the PAs should consider including EER requirements in addition to SEER requirements to steer customers toward AC and HP offerings with higher peak demand savings.
- Massachusetts has significant opportunities for early central AC and HP retirement. Over 40% of central systems in Massachusetts have an EER of 9 or lower. This creates opportunities for approximately 0.7 kW of peak demand savings per system replaced with a new code-minimum efficiency system, in addition to significant energy savings. These low efficiency systems will generally be 12-25 years old during the 2019-2021 program period.

CONCLUSION 2: Across the remaining end uses, individual homes have a wide variety of significant end use loads during peak times.

- Electric clothes dryers are common (53% of homes), but they have large variability in use compared to other end uses. The bottom half of users did not use their dryers at all during peak times, while the top 25% of users have an average peak of greater than 0.3 kW.
- Dehumidifiers are relatively common (36% of homes). More than 25% of dehumidifiers were not in use at all during peak times, but the top 25% have a mean peak of greater than 0.4 kW.
- Electric water heaters are uncommon (14% of homes), but they have a mean of 0.2 kW during ISO-NE peak and the top 25% of users have a mean of 0.5 kW.
- Pool pumps are rare (6% of homes), but they have a mean ISO-NE peak demand of 0.6 kW.

CONSIDERATION 2: PAs should consider targeting homes with dehumidifiers, clothes dryers, and pool pumps for additional peak demand savings with low impacts on occupant comfort. Dehumidifiers (13% of all homes), clothes dryers (10% of homes), and pool pumps (5% of homes) all have opportunities for relatively easy peak savings of at least 0.2 kW without negatively affecting overall equipment performance or comfort.

CONCLUSION 3: Heat pump water heaters appear to use about half as much electricity as domestic water heaters, which corroborates much of the expected energy savings.

- Electric water heating load will become more important in the long run as more people switch from oil or propane heat sources to electricity.
- Once a home has a heat pump water heater, its water heating summer peak demand is relatively small. However, the increasing saturation of electric water heating in general and heat pump water heaters in particular means that peak demand savings opportunities remain.

CONSIDERATION 3: Energy efficiency program offerings should push heat pump water heaters for both energy and demand savings.

- Demand response offerings for heat pump water heaters will not have large effects during the summer or winter but may be worth targeting if higher peak users could be identified or influenced through behavior-based messaging.
- In other parts of the country, utilities are more interested in connected heat pump water heaters to increase demand during times of high renewables output than the ability to reduce demand during peaks.

CONCLUSION 4: Lighting is the end use with the largest contribution to total winter consumption and winter peak.

CONSIDERATION 4: Based on Conclusion 4, further improvements in installed lighting efficiency and controls—either induced by programs or the overall market—will cause significant reductions in peak loads.

- There are still significant opportunities for programs to cost-effectively reduce energy and peak consumption by inducing the early retirement of incandescent lamps and installing lighting controls. Particularly where individuals are waiting for infrequently used lamps to burn out before replacing them, there are significant lifetime savings available when replacing them early. Similarly, networked/connected LEDs offer additional energy and load shifting potential.

CONCLUSION 5: Electric resistance heat has a surprisingly flat hourly load shape on peak days, more like a refrigerator than an air conditioner on a peak day.

CONCLUSION 6: Electric resistance heating consumption is highly variable. The top 25% of households with electric resistance heat presently consume approximately 10 times as much as the median.

CONSIDERATION 5: Based on Conclusions 5 and 6, it may be difficult to generate winter electric HVAC peak demand or energy savings with program interventions. Targeting high users would help increase savings by a large amount. A bill-based electric resistance heating targeting algorithm could be developed and tested using this data.

CONCLUSION 7: Electric water heaters offer the largest non-HVAC, non-lighting opportunity for winter peak demand savings.

CONSIDERATION 6: If the PAs are looking for opportunities to reduce winter peak demand, they should consider electric water heater demand response opportunities.

APPENDIX A. METHODS

A.1 Online Survey

The online survey was distributed via postcard to 200,300 Massachusetts residents to achieve 6,901 completes. Postcards were mailed to utility account addresses with an invitation to participate in the online survey and a promise of a $10 gift card or check for participating. Reminder postcards were used to boost the representativeness of the sample by increasing the response rate of contacted residents. The invitation postcard also indicated that there would be another opportunity to participate in the metering study to earn $250 more. The primary goal of the survey questions was to understand end use saturation and penetration. The secondary goals of the survey questions were to understand residential customers' motivations for how they use energy and to understand where energy efficiency opportunities exist. Another explicit goal of the survey was to serve as a population frame for the onsite data collection effort.

The online survey was deployed in a modular way so not all survey recipients were asked to respond to all questions; rather, respondents answered questions about two of the end uses that they have indicated are present in their residence. This allowed the evaluation team to receive an adequate number of detailed survey modules while reducing the burden to the participant. The median survey response took 24 minutes. Bellomy Research programmed and administered the survey and managed the data collection process. The team thoroughly tested the final survey before implementing.

The survey asked questions about the following general areas:

- Premise occupant demographics such as number of occupants, age, work status, income, and homeowner versus renter
- Basic building characteristics such as building type (single or multifamily), age, window type, time since last significant renovation, and recent upgrades
- Presence and basic type of major end uses and appliances, including all those listed in Table 1.
- Detailed building characteristics (subset of homes with specific responses)
- Detailed appliance characteristics (including usage)

A summary of the survey recruitment effort and the response rate is shown in Table A-1.

Table A-1. Survey Recruitment Summary

Wave	Sampling Type	Residents Contacted	Postcards Sent	Complete Responses	Response Rate Per Resident
Pre-test	Random	1,000	1,000	62	6.2%
Wave 1	Random	50,000	150,000	3,364	6.7%
Wave 2	Random	30,000	60,000	978	3.3%
Wave 3	Random	38,000	76,000	1,231	3.2%
Wave 4	Targeted	73,000	73,000	1,038	1.4%
Oversample	Random	8,300	16,600	228	2.7%
Total		**200,300**	**376,600**	**6,901**	**3.4%**

Responses from the online survey informed the load shapes in the following ways:

- The online survey respondents formed the population frame from which the metered sites were sampled.
- The saturations calculated from the online survey responses and onsite visits were used to scale the load shapes to the population. More information about this process can be found in Appendix A.4.
- The binning variables used in the load shape calculations were determined through the online survey responses.
- Onsite end use targets were created based on saturations from online survey responses adjusted for onsite findings.

A.2 Onsite Sampling

The completed responses from the online survey served as the population frame from which the onsite sample was drawn. Having detailed information about each respondent's home and appliances allowed the team to thoughtfully select a sample capturing several different dimensions of the Massachusetts residential population that will help meet the objectives of the research.

The team used the following proportional quotas to ensure representativeness was maintained in the onsite sample:

- Occupant type: owner-occupied vs. renter-occupied
- Program interaction: previous program participation vs. no previous program participation
- Building type: single-family detached vs. single-family attached vs. multifamily
- Heating type: gas heat only vs. electric heat present vs. other heat
- Income: low income vs. non-low income
- Electric PA
- Gas PA
- Language spoken at home: English vs. language other than English
- Presence of end use

Navigant's initial goal for load shapes was to achieve results at the 90% confidence level with relative precisions ranging from 10% to 30% depending on the frequency of occurrence of the end use in the population and the interests of stakeholders in achieving various levels of rigor. Navigant found that data for some housing types and end uses was collected at a high rate in the survey data, while others that may be of interest to the PAs occurred infrequently. Therefore, Navigant implemented oversamples for certain end uses to ensure that sufficient data was collected to produce statistically significant findings at the population level. The oversampled end uses were hardwired electric heat, plug-in space heater/fireplace, electric hot water heaters, heat pump water heaters, and pool pumps.

Table A-2 shows Navigant's final sample for each end use of interest, including the targeted values on which the sample was designed. The precision values in the third through fifth columns of the table are the targeted relative precisions at 90% confidence based on the total number of sites in the last column. This includes the oversampled sites for the five end uses that have been flagged. Some end uses, including ground source heat pumps, tankless water heaters, aquaria, large battery chargers, well pumps, booster pumps, and electric vehicles (EVs), have been flagged as explicitly having no specific precision target due to the expense required to achieve the target. The field team metered these end uses when they showed up in the core sample but did not structure the sample to target them. Only anecdotal information from a handful of sites is likely to be derived from this study for these end uses, but the team analyzed these results if there were more than five sites with any given end use.

Table A-2. Targeted Sampling Assumptions and Achieved Sample

End Use	Assumed Saturation	Targeted End Use Precision – Energy	Targeted End Use Precision – Residential Peak	Targeted End Use Precision – ISO-NE Peak	Number of Core Sample Sites*	Targeted Number of Oversample Sites	Targeted Total Number of Sites
Central AC/Heat Pump	29%	9.0%	9.5%	6.9%	108	0	108
Room AC	64%	18.4%	23.7%	25.6%	142	0	142
Ground Source Heat Pump	1%	95.2%	100.6%	60.4%	3	0	3
Other Electric Heat	13%	20.1%	22.3%	19.8%	52	26	78
Space Heaters/Plug-in Fireplaces	39%	15.0%	36.8%	28.6%	112	11	123
Boiler Circulator Pump	51%	6.6%	10.2%	4.4%	156	0	156
Other Fuel Furnace Fan	53%	8.1%	2.4%	1.7%	104	0	104
Dishwasher	71%	8.4%	20.5%	22.1%	240	0	240
Freezer	13%	8.5%	6.6%	6.1%	66	0	66
Refrigerator	100%	3.0%	3.1%	2.1%	300	0	300
Second Refrigerator	28%	10.5%	9.7%	7.4%	86	0	86
Hot Water Heater	15%	9.8%	12.0%	11.7%	42	3	45
Tankless Hot Water Heater	0.6%	186.1%	289.8%	202.6%	2	0	2
Heat Pump Water Heater	2%	13.0%	20.3%	22.4%	3	28	31
Washer	86%	7.0%	22.1%	19.6%	262	0	262
Electric Dryer	68%	5.5%	45.1%	14.0%	195	0	195
Dehumidifier	50%	12.7%	12.8%	9.1%	116	0	116
Aquarium	2%	41.1%	41.1%	30.1%	6	0	6
Golf Cart/Large Battery Charger	5%	45.5%	45.5%	34.7%	15	0	15
Well Pump	12%	48.6%	51.8%	35.2%	36	0	36
Sump Pump	30%	36.6%	37.4%	28.7%	44	0	44
Booster Pump	5%	36.3%	2.9%	30.2%	15	0	15
Pool Pump	10%	18.2%	19.1%	15.6%	21	7	28
EV Charger	0.4%	N/A	N/A	N/A	1	0	1
Total					**300**	**76**	**376**

*The sum of core sampled sites is greater than the total because the team will collect data for more than one end use from each site.

Source: Navigant analysis

A.3 Onsite Metering

Navigant field technicians installed metering equipment on all applicable energy-consuming equipment to determine end use load consumption and load shape at customer homes. The full list of metered equipment and end uses of interest in this study are listed in Table 1.

Navigant installed two types of meters in customer homes:

1. **eGauge:** An energy monitoring system installed in residential electric panels[18]
2. **Onset UX-120 Plug Load Meters:** A meter installed directly between the end use equipment and the power outlet[19]

The eGuage and Onset meter setups are shown in Figure A-1 and Figure A-2.

Figure A-1. eGauge Energy Metering Setup in Customer Homes

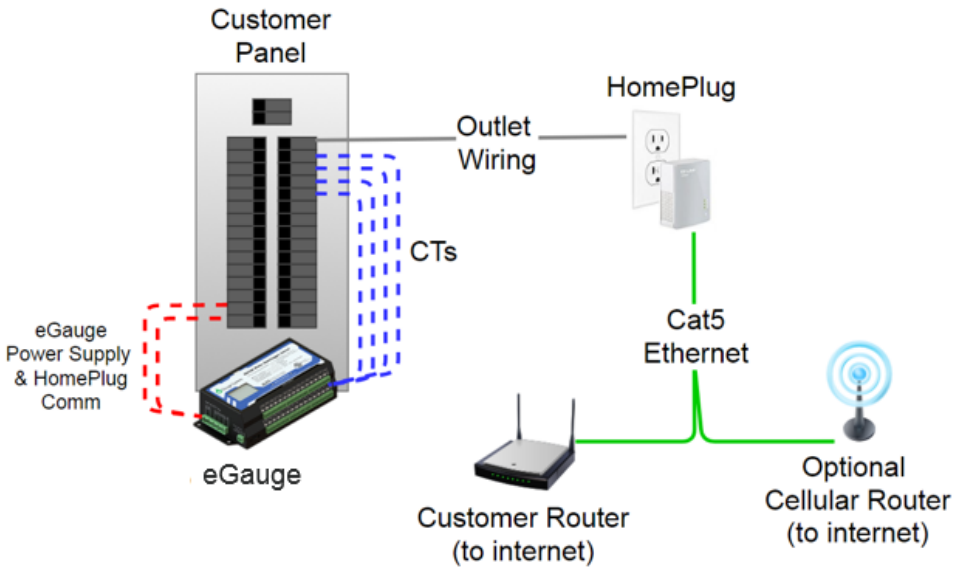


Figure A-2. Onset Plug Load Logger Used in Customer Homes

Navigant field technicians programmed both the eGauge and Onset plug load meters to measure the 1-minute power consumption of each piece of metered equipment. The meters were programmed to calculate an average energy consumption value for each minute of recording.

[18] For more information about eGauge meters, refer to http://www.egauge.net/products/EG3010/.

[19] For more information about Onset plug load meters, refer to http://www.onsetcomp.com/products/data-loggers/ux120-018.

For all metered equipment, Navigant technicians determined the optimal metering device to use based on several factors, including whether the equipment was installed on a dedicated circuit, if the power outlet was accessible, and customer preference. Whenever possible, Navigant used the eGauge to meter the equipment because it is able to connect remotely to secure eGauge proxy servers, allowing analysts to access the data in real time for analysis and quality control. To establish communication between the eGauge and the proxy server, Navigant used a Homeplug device, which transmits the eGauge data from the customer's electric panel to a router through powerline communication technology. Navigant used either the customer's personal internet router or a cellular modem/router to securely transmit the metered data to the eGauge servers. Throughout the metering period, Navigant monitored the eGauges remotely on a daily basis to ensure they maintained internet connection and high data quality.

The eGauge metering setup is not appropriate for equipment that is mobile or is not on dedicated electrical circuits, such as space heaters, room ACs, and primary televisions. For these equipment, Navigant used the Onset plug load logger, installing it directly between the equipment of interest and the electrical outlet. Navigant secured the meter to the appliance to ensure that it stayed with the appliance of interest, not at the outlet.

Navigant's meter installation period occurred between March and June 2017. Navigant revisited 319 sites in the fall of 2017 to download metered data from the Onset plug load loggers, install meters on newly purchased equipment, and collect characterization data on the equipment, if applicable. The resulting metered period for each logged equipment spanned 3-8 months for this phase of the analysis.

In collaboration with NMR, Navigant installed Tier 1 and Tier 2 smart strips on a sample of logged television and computer equipment in the study.[20] These equipment are logged with plug load meters, which will provide data to support deemed savings assumptions for smart strip equipment installed in customer homes. This pre/post metering study continued through February 2018, at which point Navigant revisited customer homes to download the plug load meter data. The data collected to date on these end uses is included in the results presented in this report.

A.4 Data Analysis

The saturation and load shape data analysis followed the steps listed in Appendix A.4.1 to A.4.4. The saturation data analysis is included because the saturation results played an important role in scaling the load shape results, as explained in Step 3 in Appendix A.4.2.

A.4.1 Saturation Data Analysis

The evaluation team cleaned and summarized data from the online portion of the survey for 6,901 respondents to generate saturations for all equipment types in residential homes in Massachusetts.

[20] Both Tier 1 and Tier 2 smart strips contain controlled outlets that switch on and off using smart sensors to reduce the power consumption of electronics not in use. Tier 1 smart strips use current sensing technology. When the control device (such as TV or PC) is turned on, the controlled equipment plugged into the controlled outlets are also turned on. When the control device is turned off, the accompanying equipment also turns off. Tier 2 smart strips use either a motion and/or remote control infrared activity sensor. In this study, the Tier 2 smart strips are only being used for TV and TV-related peripherals. The strip is programmed to turn the equipment off after a period of inactivity, typically 1 hour. Both smart strip types have a few "Always On" outlets used for equipment that must remain on at all times due to customer preference, such as internet routers.

Saturations were adjusted based on onsite verification and post-weighted based on the demographics of the survey respondents and the state of Massachusetts.

Step 1: Clean data:

- For values that appeared to be mistakes in the survey responses: quantities greater than 10 for most end uses or greater than 20 for sink faucets, showers, and gas lighting, values were changed to 1.
- For heating systems, boilers and furnaces were switched based on the distribution type that was indicated: where radiators were stated, the heating system was changed to boiler and where ducts were indicated, the system was changed to furnace.
- For ductless ACs where responses indicated the unit could also provide heat, AC was changed HP.

Step 2: Adjust raw survey data using onsite findings: Onsite data was used to adjust saturations using the ratio of the number of each type of equipment verified onsite to the number of each type of equipment claimed in the survey for each of the 300 sites visited for metering. Onsite adjustment factors were used for all end uses present in at least 10 sites.

Step 3: Apply post weights: In conjunction with the survey responses, a set of weights was developed using demographics information from the American Community Survey (ACS). The demographics selected for weighting results were education level (college degree vs. no college degree) and primary language spoken (English vs. non-English). These two demographics were selected because they had the largest effect on saturation results, they were the two demographics where the survey sample and Massachusetts population differed the most, and they were not highly correlated with each other.

Step 4: Calculate saturations: For each combination of two of the demographic slicing variables, and for each individual slicing variable, separate saturations and quantities were computed for the entire Massachusetts population of that demographic. Post weights were normalized for each combination of slicing variables to sum to 1, then the weighted proportion of homes with the end use and weighted mean quantity per home were calculated for each end use. Absolute precision was also computed at the 90% confidence level.

A.4.2 Load Shape Data Analysis

The load shape analysis consisted of five high level steps. First, 1-minute metered data from eGauge and Onset data loggers connected to all manner of equipment was cleaned and aggregated to create a dataset that has hourly data for each end use at each site. Second, the clean hourly data was summarized across sites for multiple time periods of interest to compute the energy consumption and demand for sites that have each end use. Finally, the estimates for homes with each end use were combined with saturations to compute consumption and demand of each end use for the Massachusetts population.

Step 1: Clean data: For the 1-minute data, eGauge and Onset Hobo logger data was checked for reasonableness and usability. Systematic checks for incorrect configuration were combined with engineering judgment to determine whether to keep or drop data from each source. Some data was excluded from the analysis, including where eGauges were logging multiple loads on a single register or considerable noise was observed in the data. In some cases, the data from hobo loggers could be

subtracted from eGauge registers to isolate an end use and for some end uses that were not logged because they are never used, data was filled in with zeros.

Step 2: Aggregate to Site, End Use, Hourly Granularity: First, for each logged piece of equipment, 1-minute data was aggregated to hourly data by computing the average kW observed in each hour. Next, hourly unit data was summed into end use totals at each site for each hour.

> **Adjustments:** For hours where not all units of a given end use were logged (e.g., only two out of three room ACs), data was scaled up using the ratio of total units to logged units.

Step 3: Calculate site-level end use load shapes: For each site, end use, time period (individual months, peak days, peak periods) and day type (weekdays, weekends, all days) of interest, the average kW was computed.

> **Exceptions:** Data was removed where a site and end use combo had less than half of the total hours in the period logged (e.g., for the ISO-NE peak, which covers 16 total hours, only sites with 8 or more hours of data for a given end use were included in the average).

> **Modifications:** Certain end uses were combined to broader categories, and data was summed across end uses to arrive at category (e.g., HVAC)-level average kW per period. Specific combinations are provided in Table A-3. A different set of categories may be appropriate for the winter metering and final results.

Table A-3. Combined End Uses for Load Shape Analysis

Category	End Uses Combined
Hardwired Electric Heat	Electric baseboard heat, electric furnace
HVAC – Misc.	Whole house fans, fireplace blowers, heat recovery ventilators, bathroom fan heaters, and ground source heat pumps
DHW – Gas/Oil	DHW – gas, DHW – gas tankless, DHW – oil, DHW – propane
Misc. Metered	Pool heaters, hot tubs, EV chargers, battery chargers, booster pumps, freeze prevention, fish tanks, water beds

Step 4: Calculate load shapes for homes with each end use: For each demographic slicing variable, end use, and time period, the average kW across sites was computed. Statistics (standard error and relative precision) were also computed at this level based on the variation in the site-level results.

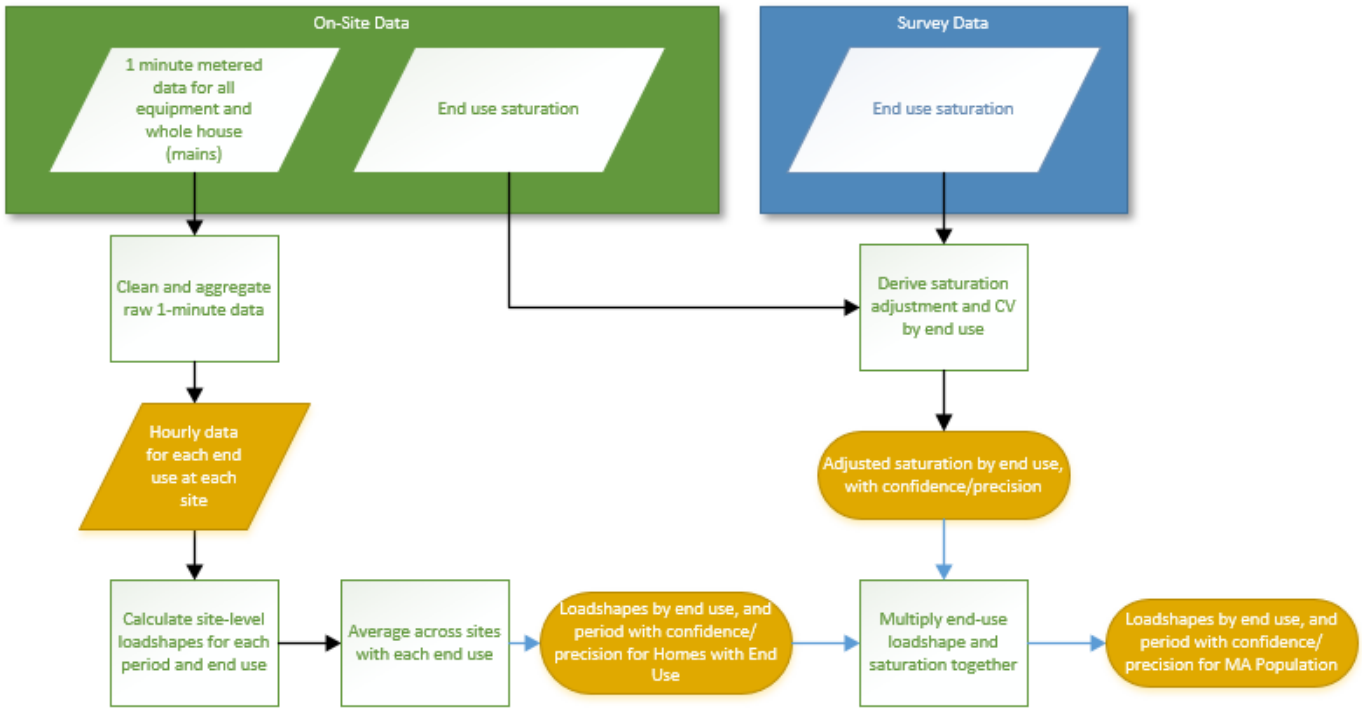
> **Exceptions:** Data was removed for demographic and end use combinations where there was data from less than five sites (e.g., for end use XXX and demographic YYY, there were only four sites, so no result was computed for that combination).

Step 5: Calculate load shapes for the Massachusetts population: The average kW per home, end use, category, and time period from the previous step was multiplied by the corresponding statewide saturation (for each end use and demographic) to compute statewide average kW for each end use across all homes.

> **Modifications:** The remaining load values were computed by subtracting all metered end use load shapes from whole home average consumption.

Figure A-3 is a schematic representation of the saturation and load shapes analysis.

Figure A-3. Saturation and Load Shape Analysis Map



A.4.3 Lighting Load Shape True Up

While the RES 1 Baseline Study included end use metering for a wide variety of end uses, the study did not include metering for lighting. Instead, the RES 1 Baseline Study relied on lighting load shape data captured as part of the *Northeast Residential Lighting Hours-of-Use Study*,[21] provided by NMR. The end use metering for the hours of use (HOU) study was conducted between 2012 and 2013, a period when the saturation of LEDs was only 1%-2%. The end use metering for the RES 1 Baseline Study was conducted between 2017 and 2018, a period during which LED saturation rose to nearly 27%.[22] In addition, the lighting load shapes were prepared using data from a separate sample of homes.

Given the differences in sample and the rapid changes observed in the residential lighting market over the past 5 years, it was necessary for NMR to reconfigure the 2014 HOU data to build new lighting load shapes weighted to the current sample and saturations.

The 2014 data was first inspected for erroneous data points, such as potential light pollution or incorrect measurements, that may have been missed during the original analysis (prior to manipulating the data so that the 2014 sample more accurately reflected the 2017 sample). This manipulation was accomplished by first adjusting the 2014 data with demographic weights so that the population demographics of the RES 1 study are accurately represented by the sample population.

[21] http://ma-eeac.org/wordpress/wp-content/uploads/Northeast-Residential-Lighting-Hours-of-Use-Study-Final-Report1.pdf

[22] http://ma-eeac.org/wordpress/wp-content/uploads/RLPNC_179_LtgMarketAssessment_28March2018_FINAL-1.pdf

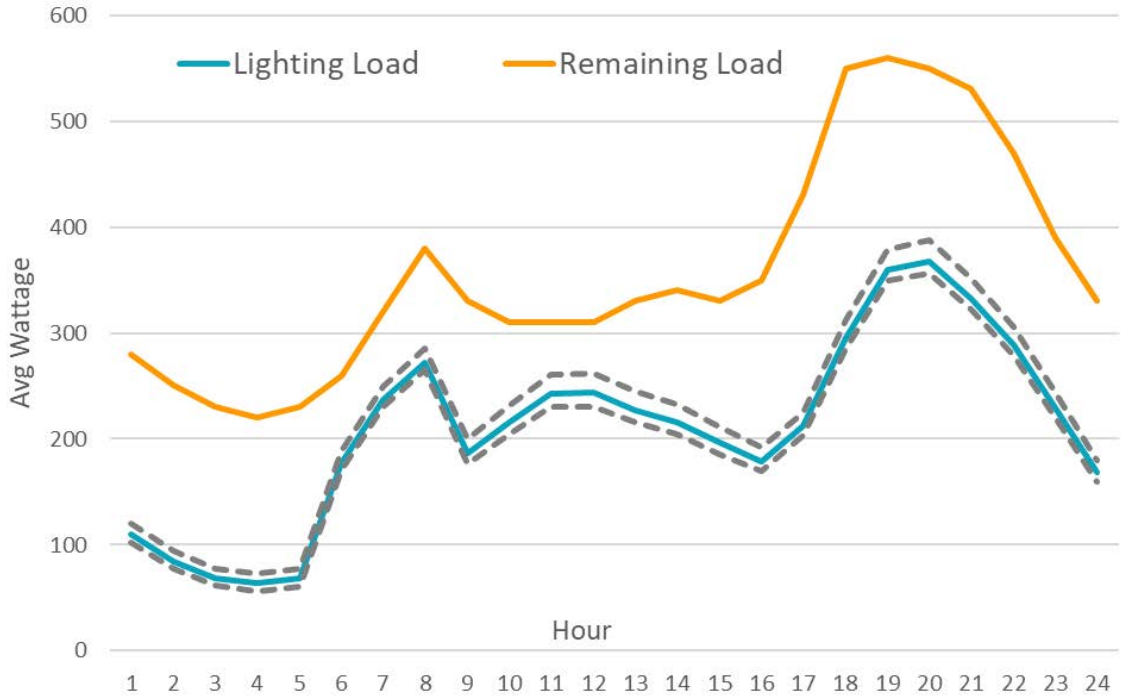
Next, the 2014 lighting data was collected at the per-room level of disaggregation, and, to update lighting saturation by room, lighting saturation data collected from RES 1 study participants was used to adjust bulb type saturation by room. These updates helped to make the 2014 HOU data consistent with the RES 1 household lighting usage. Average wattage by room from the RES 1 sample was applied to the 2014 HOU data.

The reweighted 2014 data was then aggregated to the household level by hour of the year for all bulbs and for efficient bulbs and inefficient bulbs separately. Lighting usage was then applied to the 2017 study bulb counts. Load shapes were constructed and compared to the remaining load shape from the RES 1 study.

The lighting load shape was not completely without issues. The lighting load displayed a later morning peak in the fall months. The fall months' data was based on data interpolated from periods with similar light per day but not by hour. To correct for this discrepancy, lighting usage in the early morning hours of the fall months was manipulated to reflect 2017 sunrise data.

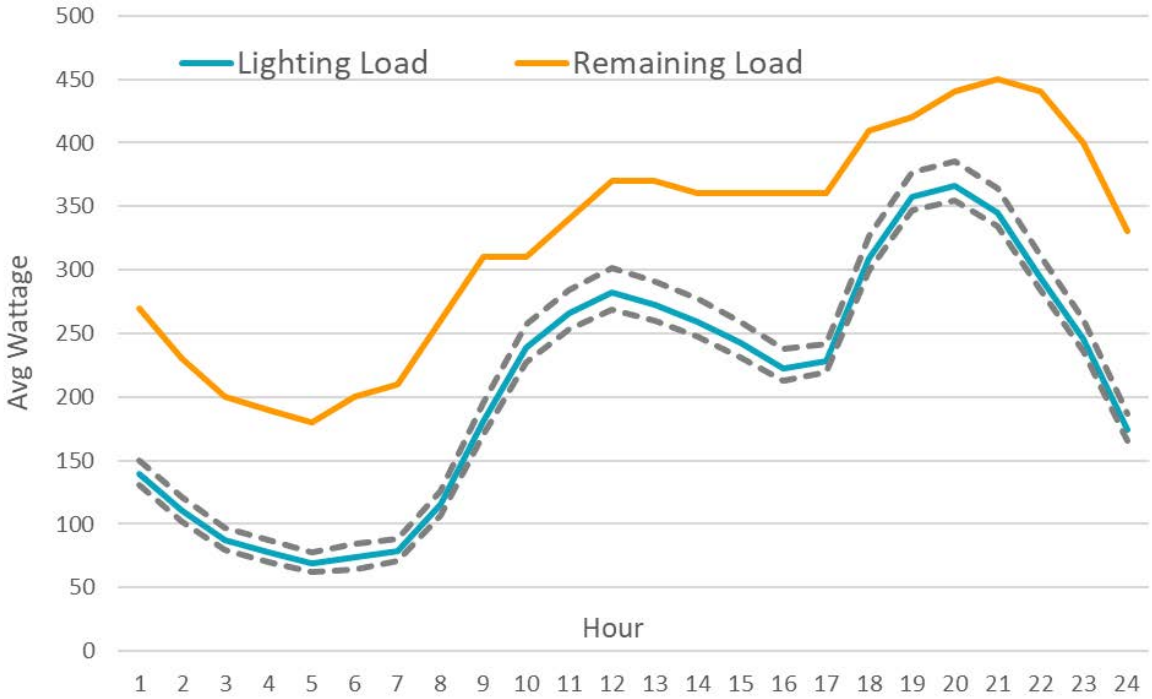
Figure A-4 through Figure A-7 display the load comparison for the months of January and June. Figure A-4 and Figure A-5 compare the lighting load for January (weekday and weekend). The January lighting load and remaining load peak at the same hours and have comparable shapes. Figure A-6 and Figure A-7 show the June loads. The June lighting load peaks later than the remaining load and slopes down dramatically during the evening hours, while the remaining load slopes up during the evening hours. The less comparable months could be adjusted manually so that the lighting slopes mimic the shape of the remaining load while preserving the lighting usage across the day. However, this adjustment exercise would likely be time-consuming and would not add value to the current study.

Figure A-4. Lighting and Remaining Load Comparison: January Weekday



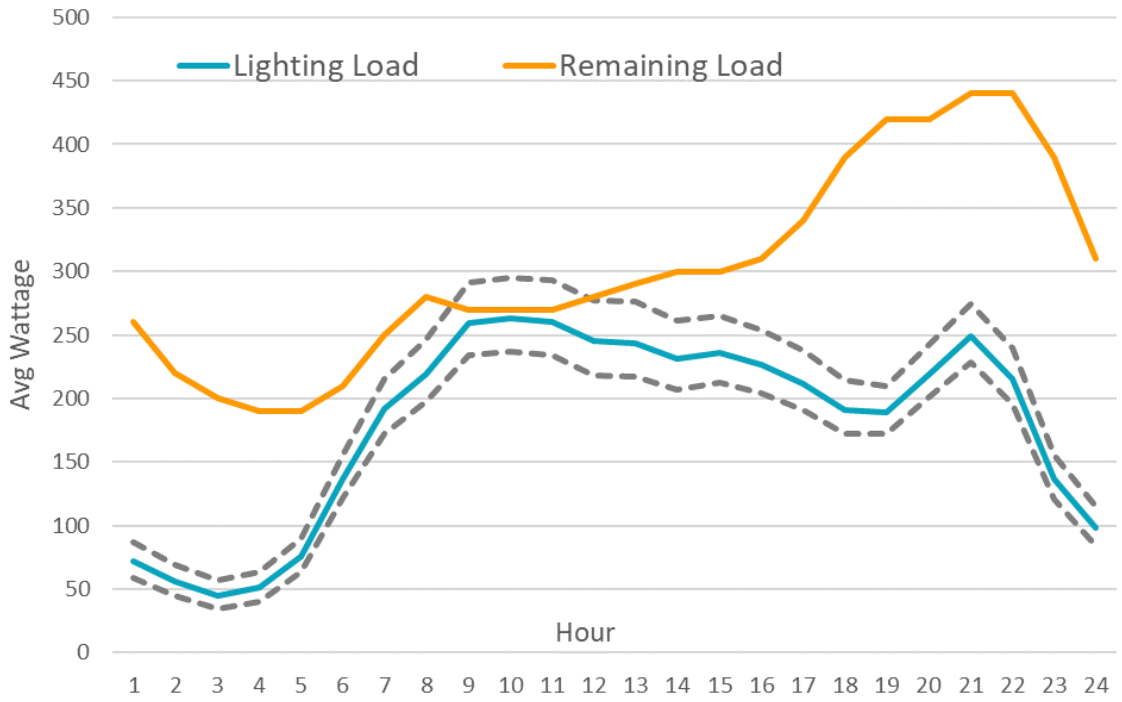
*Dashed lines indicate 80% confidence intervals.
Source: NMR analysis

Figure A-5. Lighting and Remaining Load Comparison: January Weekend



*Dashed lines indicate 80% confidence intervals.
Source: NMR analysis

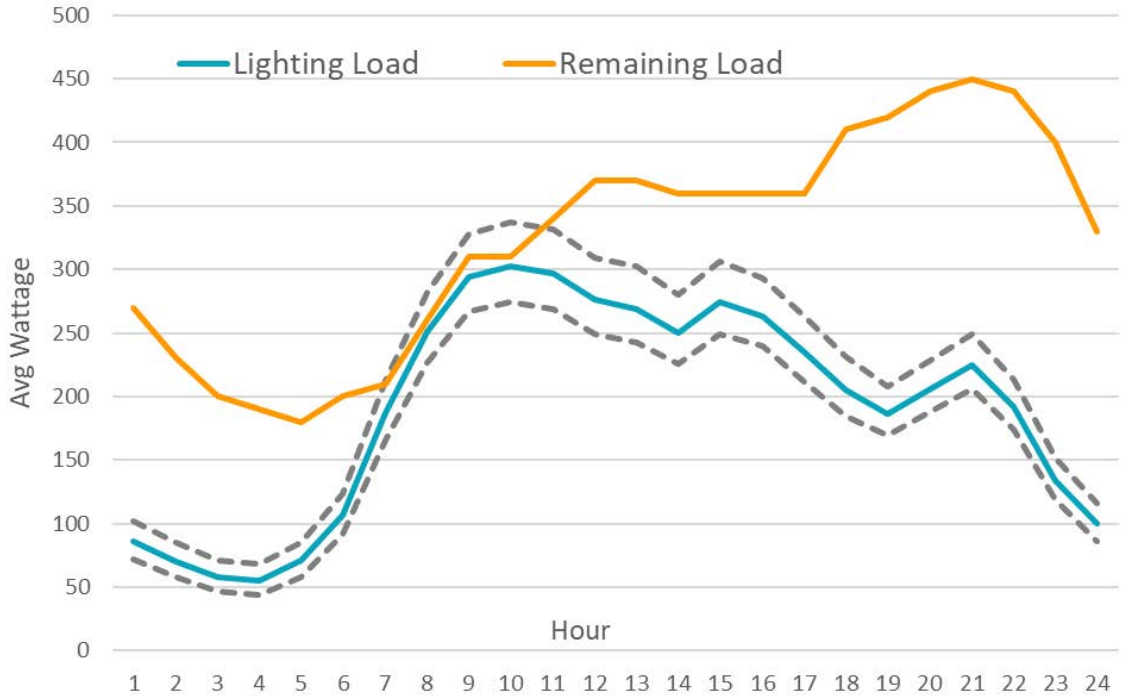
Figure A-6. Lighting and Remaining Load Comparison: June Weekday



*Dashed lines indicate 80% confidence intervals.

Source: NMR analysis

Figure A-7. Lighting and Remaining Load Comparison: June Weekend



*Dashed lines indicate 80% confidence intervals.

Source: NMR analysis

A.4.4 Weather Normalization

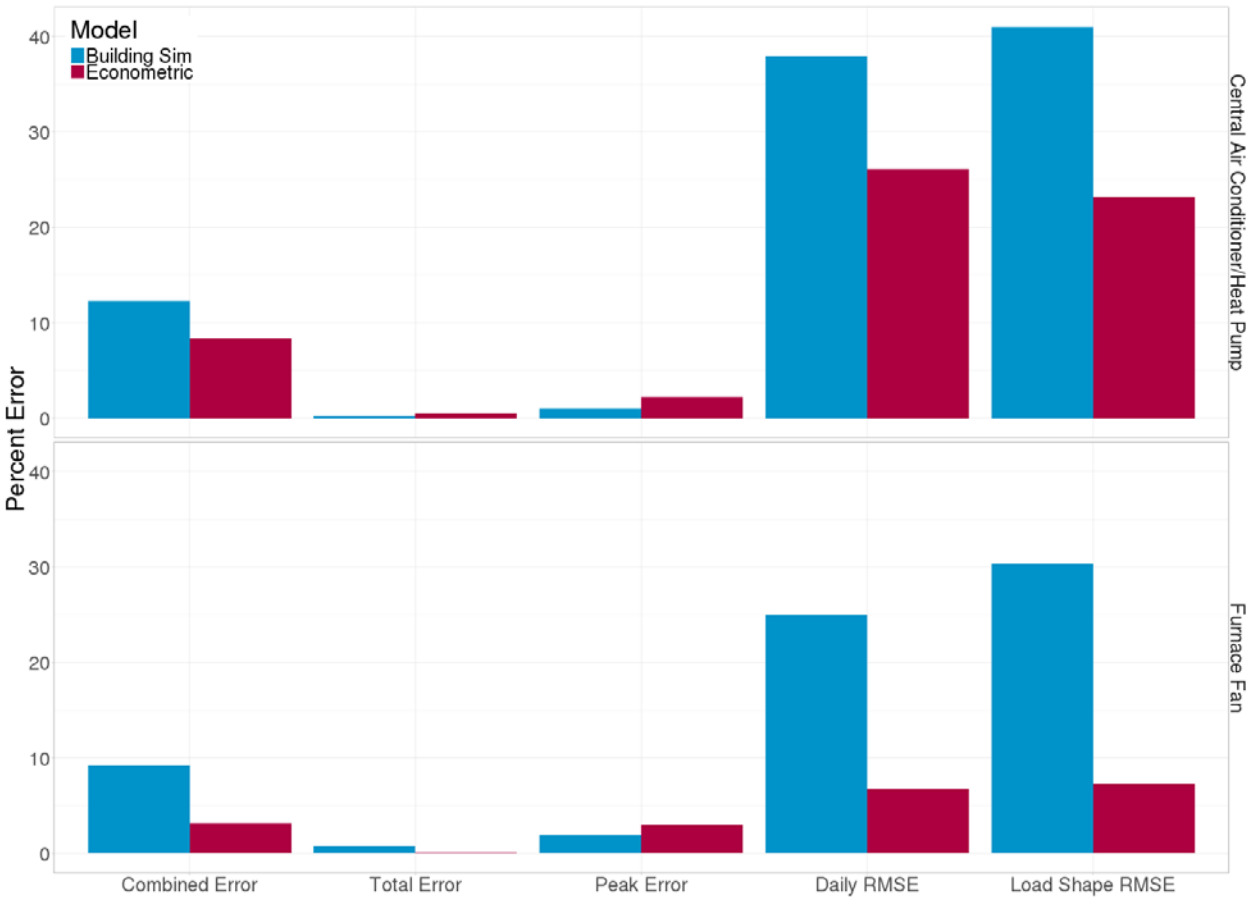
After calculating the end use load shapes for the metered period, the next step was to weather normalize the load shapes to estimate the usage in a typical weather year. The evaluation team tested two main methods for performing weather normalization: econometric regression analysis and building simulation modeling.

The evaluation team performed the regression analysis using the R statistical software package and building simulation using EnergyPlus. To test the performance of the two methods, the hourly metered data was first divided into a training set and a test set, split every other day. The team developed and calibrated models based on the data in the training set and evaluated them based on the test set to prevent over-fitting. The methods were tested on the two end uses that the team expected the building simulation model to perform best on (central AC and furnace fan); they were evaluated based on the following criteria:

1. Each model had to be within 5% of total energy use and peak demand.
2. Of the models that met the first criterion, the best model was selected based on a weighted average error:
    a. 35% error on total energy consumption
    b. 35% error on peak demand
    c. 15% root-mean-squared error (RMSE) on daily energy consumption
    d. 15% RMSE on average load shape by month, weekday/weekend, and hour of day

The results from the test are shown in Figure A-8.

Figure A-8. Weather Normalization Test Results



Source: Navigant analysis

For both end uses, the regression model performed significantly better than the building simulation model. Based on these results and that this was based on the end uses best suited to building simulation, the evaluation team decided to use the regression method to perform weather normalization for all end uses.

To determine the final regression model formulation for each end use, the team performed model selection using an iterative process based on 5-fold cross-validation to determine the best model while avoiding over-fitting. The method was as follows:

1. Add new predictor variables into the model one at a time based on the expected significance of the term from exploratory data analysis and engineering judgment. For numeric variables, try out polynomial terms up to the fourth degree.
2. Calculate the average error across all five cross-validation folds based on the weighted average error described above.
3. Keep the terms that result in a noticeable reduction in error, on average, across all folds.
4. Repeat Steps 1-3 for all relevant variables.

5. Check the resulting model coefficients and remove any terms that appear to be inconsistent with physical relationships (e.g., a negative coefficient on cooling degree hours in a cooling model)
6. Check the residuals plots of the final models to look for non-linearity, heteroskedasticity, outliers, and correlation over time.

After deciding on the optimal model formulation using cross-validation, the final models for each end use were re-run on the entire dataset. The team performed model selection by category for groups of similar end uses, but all model coefficients were calculated for each end use individually. The final model formulations by category were as follows.

Equation A-1. Cooling Model

$$y_t = \sum_{h=1}^{24} \beta_{1,h} \cdot Hr_{h,t} + \sum_{m=1}^{12} \beta_{2,m} \cdot Month_{m,t} + \sum_{b=1}^{3} \beta_{3,b} \cdot (NHBU_t)^b + \sum_{c=1}^{2} \beta_{4,c} \cdot (MA4_CDH_t)^c + \sum_{r=1}^{2} \beta_{5,r} \cdot (RH_t)^r + \sum_{h=1}^{24} \beta_{6,h} \cdot Hr_{h,t} \cdot NHBU_t + \sum_{m=1}^{12} \beta_{7,m} \cdot Month_{m,t} \cdot MA4_CDH_t$$

Equation A-2. Heating Model

$$y_t = \sum_{h=1}^{24} \beta_{1,h} \cdot Hr_{h,t} + \sum_{m=1}^{12} \beta_{2,m} \cdot Month_{m,t} + \sum_{d=1}^{2} \beta_{3,d} \cdot (MA4_HDH_t)^d + \beta_4 \cdot MA24_HDH_t + \beta_5 \cdot NHBU_t + \sum_{m=1}^{12} \beta_{6,m} \cdot Month_{m,t} \cdot NHBU_t$$

Equation A-3. Dehumidifier Model

$$y_t = \sum_{h=1}^{24} \beta_{1,h} \cdot Hr_{h,t} + \sum_{m=1}^{12} \beta_{2,m} \cdot Month_{m,t} + \beta_3 \cdot RH_t + \sum_{b=1}^{3} \beta_{4,b} \cdot (NHBU_t)^b + \beta_5 \cdot MA4_CDH_t + \beta_6 \cdot HDH_t + \sum_{m=1}^{12} \beta_{7,m} \cdot Month_{m,t} \cdot NHBU_t + \sum_{m=1}^{12} \beta_{8,m} \cdot Month_{m,t} \cdot HDH_t$$

Equation A-4. Pool Pump Model

$$y_t = \sum_{h=1}^{24} \beta_{1,h} \cdot Hr_{h,t} + \sum_{m=1}^{12} \beta_{2,m} \cdot Month_{m,t} + \beta_3 \cdot Day_Type_t + \sum_{b=1}^{3} \beta_{4,b} \cdot (NHBU_t)^b + \beta_5 \cdot MA4_CDH_t + \sum_{h=1}^{24} \sum_{m=1}^{12} \beta_{6,h,m} \cdot Hr_{h,t} \cdot Month_{m,t} + \sum_{h=1}^{24} \beta_{7,h} \cdot Hr_{h,t} \cdot Day_Type_t + \sum_{m=1}^{12} \sum_{b=1}^{3} \beta_{8,m,b} \cdot Month_{m,t} \cdot (NHBU_t)^b$$

Equation A-5. Refrigerator/Freezer Model

$$y_t = \sum_{h=1}^{24} \beta_{1,h} \cdot Hr_{h,t} + \sum_{m=1}^{12} \beta_{2,m} \cdot Month_{m,t} + \beta_3 \cdot Day_Type_t + \sum_{b=1}^{2} \beta_{4,b} \cdot (NHBU_t)^b + \sum_{c=1}^{2} \beta_{5,c} \cdot (MA4_CDH_t)^c + \sum_{h=1}^{24} \sum_{m=1}^{12} \beta_{6,h,m} \cdot Hr_{h,t} \cdot Month_{m,t} + \sum_{h=1}^{24} \beta_{7,h} \cdot Hr_{h,t} \cdot Day_Type_t$$

Equation A-6. Water Heating Model

$$y_t = \sum_{h=1}^{24} \beta_{1,h} \cdot Hr_{h,t} + \beta_2 \cdot DB_Ave_Month_t + \beta_3 \cdot Day_Type_t + \sum_{h=1}^{24} \beta_{4,h} \cdot Hr_{h,t} \cdot DB_Ave_Month_t + \sum_{h=1}^{24} \beta_{5,h} \cdot Hr_{h,t} \cdot Day_Type_t$$

Equation A-7. All Other End Uses Model

$$y_t = \sum_{h=1}^{24} \beta_{1,h} \cdot Hr_{h,t} + \sum_{m=1}^{12} \beta_{2,m} \cdot Month_{m,t} + \beta_3 \cdot Day_Type_t + \sum_{h=1}^{24} \sum_{m=1}^{12} \beta_{4,h,m} \cdot Hr_{h,t} \cdot Month_{m,t} + \sum_{h=1}^{24} \beta_{5,h} \cdot Hr_{h,t} \cdot Day_Type_t$$

Where:

y_t = Hourly consumption in hour *t*.

$Hr_{h,t}$ = A set of 24 flag variables corresponding to hour ending, where each flag is set to 1 if *h* is equal to the hour ending *t* falls in.

$Month_{m,t}$ = A set of 12 flag variables corresponding to month, where each flag is set to 1 if *m* is equal to the month *t* falls in.

Day_Type_t = A flag variable corresponding to day type, to 1 if *t* falls on a weekday, and 0 if it falls on a weekend or federal holiday.

$NHBU_t$ = The normalized heat buildup observed in hour ending *t*. Normalized heat buildup is calculated as follows:

$$NHBU = \frac{\sum_{t=1}^{72} (0.96)^t * (HeatIndex\ t\ hours\ prior)}{1{,}000}$$

CDH_t = The cooling degree hours observed in hour ending *t*. For this study CDH is defined as the greater of either the temperature in Fahrenheit less 65° or 0, whichever is greater. CDH with base temperatures of 70°F and 75°F were also tested, and it was determined that base 65°F produced the best fit.

$MA4_CDH_t$ = The 4-hour moving average of cooling degree hours (base 65°F) observed in hour ending *t*.

MA_24CDH_t	=	The 24-hour moving average of cooling degree hours (base 65°F) observed in hour ending *t*.
HDH_t	=	The heating degree hours observed in hour ending *t*. For this study HDH is defined as the greater of either 65°F less the temperature in Fahrenheit or 0, whichever is greater.
$MA4_HDH_t$	=	The 4-hour moving average of heating degree hours (base 65°F) observed in hour ending *t*.
MA_24HDH_t	=	The 24-hour moving average of heating degree hours (base 65°F) observed in hour ending *t*.
RH_t	=	The relative humidity in hour ending *t*, expressed as a percentage.
$DB_Ave_Month_t$	=	The 30-day moving average of outdoor dry bulb temperature observed in hour ending *t*, used as a proxy for the water main temperature (used in the water heating model).

To deal with the limitation of not having data for all months for some end uses, a second set of models was created for each end use, replacing the month terms with a season term (grouping Dec-Feb, Jun-Aug, and the remaining months). Model results from the monthly models were used where possible, and the missing months were filled in using the seasonal models.

To produce typical year results, the evaluation team ran the final models on 15 years of actual weather data from Worcester, Massachusetts (chosen as a representative weather station). Results were derived as follows:

1. Calculate average energy consumption for each end use in each month and peak period.
    a. For peak periods, determine the day of the system summer/winter peak for each year based on historical ISO-NE load data[23] and calculate the average consumption in the peak hours (1-5 p.m. in the summer, 5-7 p.m. in the winter) on those days.
2. Sum the modeled population energy consumption (per-home consumption x saturation) across all end uses to get the typical home consumption.
3. For each month and peak period, choose the weather year that resulted in the median typical home consumption across all end uses
4. Sum the data from the chosen months to derive the annual results

The years chosen are shown in Table A-4. .

[23] Historical ISO-NE data was pulled from the "Daily Summary of Hourly Data" files found on the ISO-NE website: https://www.iso-ne.com/isoexpress/web/reports/load-and-demand/-/tree/zone-info.

Table A-4. Weather Years Used by Time Period

Time Period	Weather Year
Summer Peak Days	2007
Winter Peak Days	2013
Summer Peak - ISO-NE	2007
Summer Peak - Residential	2007
Winter Peak - ISO-NE	2013
Winter Peak - Expanded	2013
January	2010
February	2013
March	2008
April	2011
May	2013
June	2012
July	2005
August	2015
September	2008
October	2010
November	2004
December	2004

APPENDIX B. STATISTICS

The study attained the confidence and precision shown in Table B-1. The study fell somewhat short of precision targets for both hardwired and plug-in electric heat due to the extremely high variability in electric heat consumption across homes. Similarly, pool pumps and heat pump water heaters had higher variability across homes than expected. Primary TVs and primary computers were added to the study later and had no original target. The energy values are expressed at a 90% confidence level, while the ISO-NE values are expressed at an 80% confidence level.

Table B-1. Comparison of Actual Relative Precision to Expected Relative Precision

End Use	Targeted Annual Energy Precision	Actual Annual Energy Precision	Targeted ISO-NE Peak Precision[24]	Actual ISO-NE Peak Precision
Central AC/Heat Pump	10.10%	11%	9.90%	8%
Room or Window AC	15.80%	18%	28.20%	12%
Ground Source Heat Pump	84.30%	N/A	93.60%	N/A
Hardwired Electric Heat	20.50%	33%	77.20%	24%
Plug-in Electric Heat	15.00%	30%	36.80%	23%
Boiler Distribution	6.70%	14%	5.80%	11%
Furnace Fan	6.60%	13%	1.70%	10%
Dishwasher	9.00%	11%	30.10%	21%
Freezer	11.20%	13%	10.40%	9%
Primary Refrigerator	3.00%	5%	2.70%	4%
Secondary Refrigerator	10.70%	16%	9.60%	12%
Water Heater - Electric	6.70%	12%	15.00%	16%
Tankless Water Heater	186.10%	N/A	415.60%	N/A
Water Heater - Heat Pump	13.00%	25%	29.10%	32%
Clothes Washer	7.00%	12%	25.40%	16%
Clothes Dryer - Electric	5.40%	9%	17.60%	16%
Dehumidifier	11.20%	19%	10.30%	13%
Aquarium	41.10%	N/A	41.10%	N/A
Golf Cart/Large Battery Charger	45.50%	N/A	45.50%	N/A

[24] All ISO-NE targeted/actual peak precisions are based on summer peak except for the 5 heating end uses, which are based on winter peak.

End Use	Targeted Annual Energy Precision	Actual Annual Energy Precision	Targeted ISO-NE Peak Precision[24]	Actual ISO-NE Peak Precision
Well Pump	48.60%	N/A	45.60%	N/A
Sump Pump	25.30%	N/A	25.60%	N/A
Booster Pump	36.30%	N/A	39.60%	N/A
Pool Pump	18.20%	25%	20.20%	22%
EV Charger	N/A	N/A	N/A	N/A
Primary TV	N/A	N/A	N/A	N/A
Primary Computer	N/A	N/A	N/A	N/A

Source: Navigant analysis

APPENDIX C. SUPPORTING DATA

The supporting data for all end use load shapes is included in the attached spreadsheets. The statistics for each value are also included within the spreadsheets.

Table C-1. Appendix C Supporting Documents File Names and Contents

File Name	File Type	Contents
Appendix C-1 Saturation Results Plots 2018-04-12	PDF	Detailed plots of saturation and quantity of all end uses by end use and demographic
Appendix C-2 Annual Results Plots 2018-07-27	PDF	Detailed plots of annual consumption, summer/winter peak demand, and load shapes by end use and demographic
Appendix C-3 All End Use Whole Period Results 2018-07-27	Excel	Total annual and monthly consumption and peak demand for each end use and time period with statistics
Appendix C-4-1 HVAC Load Shape Results 2018-07-27	Excel	Hourly load shapes by end use, demographics, time period, and day type with statistics
Appendix C-4-2 Water Heating Load Shape Results 2018-07-27	Excel	
Appendix C-4-3 Kitchen Load Shape Results 2018-07-27	Excel	
Appendix C-4-4 Laundry Load Shape Results 2018-07-27	Excel	
Appendix C-4-5 Miscellaneous Load Shape Results 2018-07-27	Excel	
Appendix C-4-6 Lighting Load Shape Results 2018-07-27	Excel	
Appendix C-4-7 Remaining Load Load Shape Results 2018-07-27	Excel	

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