Invisible No Longer: Cost-Effective Methods for Determining Gas End Use Load Shapes

Ryan Powanda, Chris Newton, Ken Seiden, and Jeremy Newberger, Guidehouse, Boulder, CO
Justin Spencer, Apex Analytics, Boulder, CO
Antonio Larson, National Grid, Waltham, MA
Robert Wirtshafter, Wirtshafter Associates, Inc., Chatham, MA

ABSTRACT

Low natural gas prices, population growth, and the desire to switch from delivered fuels to natural gas has led to dramatic increases in natural gas demand over the past decade. This trend has strained natural gas transmission and distribution capacity, leading some utilities to consider extensive system upgrades. Therefore, utilities are seeking to understand how customers use their gas appliances seasonally and on winter peak days to design effective energy efficiency and gas demand response programs. This information can be used to improve understanding of annual consumption of gas equipment and peak gas demand reductions associated with delivering gas energy efficiency programs.

This study presents a novel approach to measuring residential gas end-use loads where interval meters are unavailable, using emerging measuring equipment technologies and efficient, nested sampling. We installed new types of meters to collect high-frequency whole home gas readings on a large sample of homes in Massachusetts. For a subset of homes, the team piloted various end-use gas equipment proxy data collection.

The study team then used a combination of two methods to estimate gas end use annual, seasonal, peak day, and hourly consumption: a rigorous proxy-based disaggregation for the subset of homes with gas proxy meters, and a lower-cost non-intrusive load monitoring (NILM) disaggregation approach using only the whole home gas metered data for the larger sample of homes. We then used the results from the smaller sample of homes to true up the results from the larger sample to improve statistical rigor and minimize study cost. This study design and approach is applicable in other states, regions, and countries.

Background and Introduction

The overarching objective of the Massachusetts Building Use and Characterization Study[1] is to collect baseline equipment saturation, characterization, and consumption and peak demand[2] load shape data for all major electric and gas appliances, mechanical equipment, and electronics in Massachusetts homes. The data collected as part of the study provide an important input for updating the Massachusetts Technical Reference Manual (TRM), informing energy efficiency and demand response potential studies, and designing energy efficiency programs.

The study is designed as a panel study, wherein the research team fields an annual saturation and characterization survey to a sample of 6,300 homes and maintains an ongoing sub-sample of 300 homes across MA with both equipment characterization and end use consumption data collection. For these 300

[1] Formerly known as the Massachusetts Residential Baseline Study.

[2] For the gas peak day analysis, the team identified the coldest winter weekday during the metered period (based on average daily dry bulb outdoor air temperature). For this phase of the analysis, the gas peak day identified is January 20, 2020.

homes, the team collects high-resolution end use electric load shape data over time and characterizes annual, monthly, hourly, and peak day electric demand for all major electric equipment in the home, including Heating, Ventilation, and Air Conditioning (HVAC), kitchen, laundry, domestic hot water (DHW), and miscellaneous end uses.

In 2019, the team was tasked with characterizing load shapes for the major gas end uses in the home, including space heating, water heating, gas dryers, and kitchen and miscellaneous end uses. Historically, end use gas data collection has been expensive, requiring the use of expensive gas flow meters and installation from a trained professional. In this study we piloted novel data collection and analysis techniques to disaggregate end use consumption from cheaper, high-frequency whole home gas data collection using a Copper Labs wireless energy monitor.[3] Ever mindful of study costs, the team deployed a nested sampling strategy, wherein a larger sample of 68 homes included whole home gas data collection and a subset of 20 homes included additional gas end use proxy data collection using one or more of the following logger types: exhaust flue surface temperature loggers, gas solenoid valve loggers, and circuit-level and plug-in electrical meters. We also piloted multiple methods to disaggregate gas end use consumption from whole home consumption, detailed in this paper.

The following sections present the metering and analysis methodology deployed in the study and summarizes the resulting gas end use load shapes, including annual, peak day, and hourly load profiles for gas boilers, furnaces, water heaters, dryers, and other gas equipment. The conclusions provide considerations for industry professionals designing gas end use load shape studies using similar techniques.

Methodology for Gas Load Shape Metering and Analysis

The following section describes the methodology used by the team to collect whole home gas consumption and end use proxy equipment operation, as well as the analysis methods used to disaggregate gas end use consumption and derive typical gas end use consumption profiles, including annual, peak day, and hourly consumption.

Metering Methods

The team used a combination of whole home gas energy monitors and gas end use proxy loggers to collect gas equipment operation data for the analysis. We installed Copper Labs gas meters on all homes with eligible gas meter technology and the ability to connect to a Wi-Fi network. The Copper Labs device works on Type 12 automated meter reading (AMR) devices with bubble-up or always on broadcasting AMR modules. The Copper Labs meter collects medium frequency (1-minute interval) whole premise gas consumption by reading the AMR broadcasts from the connected gas meter and recording the readings on Copper Lab's servers.

Of the 171 homes with gas meters in 2019-2020 study sample, the team was able to successfully connect Copper Labs meters to 71 gas meters. The team experienced the following issues or constraints with the remaining 100 meters:

[3] https://www.copperlabs.com/
The Copper Labs loggers read signals from Automatic Meter Reading (AMR) style meters with "bubble up" or always broadcasting signals.

- Gas meter access constraints: The gas meters were in a remote area of the building and the AMR signal was out of range of the Copper Labs meter installed within the customer's residence. This was common in multifamily dwellings. Approximately 35 onsite customers with gas meters had this constraint (21% of homes with gas service).
- Incompatible gas meter: The Copper Labs meter only works with Type 12 AMR meters with always on broadcasting modules. Approximately 50 gas meters in the onsite sample were not compatible with the Copper Labs meter (37% of accessible gas meters).
- Internet connectivity constraints: Lack of reliable internet connectivity and other network constraints prevented the installation of the Copper Labs meters at approximately 20 sites (15% of accessible gas meters). The use of Wi-Fi extenders expanded internet access to several sites, but challenges still existed maintaining the reliability of the connection at other sites.

In addition to collecting whole home gas readings, we collected gas appliance readings for a subset of 20 homes with a working Copper Labs gas meter, with sites selected to achieve a broad representation of gas equipment types and combinations targeting gas furnaces, boilers, water heaters, clothes dryers, and fireplaces. Additionally, the team collected the following information to assist with the disaggregation of end use gas consumption from whole home metered consumption.

- **Proxy electric data -** The team used all available proxy electric data from the electric metering portion of the study to identify when electric components of the gas equipment are running.
- **Gas solenoid value logging -** We installed on-off loggers on all accessible gas solenoid valves to track gas consumption on each device of interest.
- **Exhaust duct temperature logging -** The team installed surface temperature loggers on exhaust ducts to determine the approximate timestamp of gas firing. The timing of the duct surface temperature increase or decrease is lagged (on the order of +/- 30 seconds per run time event) before or after the gas unit firing.

Table 1 shows the proxy data collection for each end use of interest in this study.

Table 1. Gas End Use Data Collection for Each Device of Interest

Gas End Use	Proxy Electric Data	Gas Solenoid Valve or Motor On/Off State Logging	Exhaust Duct Temperature Logging
Gas furnace	Furnace fan	Yes	Yes
Single speed gas boiler	Boiler circulator pump	Yes	Yes
Gas hot water heater	Exhaust fan		Yes
Gas dryer	Dryer operation		Yes
Gas fireplace	Blower fan		Yes

Data Quality and Availability

This section presents the data quality and availability of data for use in the analysis.

- **Whole home gas consumption -** of the 71 homes with gas whole home meter data collection via the Cooper Labs meters, 60 had sufficient data to be used in the analysis (no large data gaps). The primary failure mode for these meters was network connectivity issues. While the Copper labs meters provide data every minute, they only report the latest reading of the connected utility gas meter. Importantly, most utility gas meters in the study only provided readings in increments of 0.02 ccf (~2.1 kBtu), which significantly masks the minute-by-minute usage signals from smaller gas end uses. For example, a water heater running at 40 kBtu/h would need to run for 3.1 minutes before the meter would increment, while a clothes dryer at 20 kBtu/h would need to run for 6.2 minutes before the meter registered that usage. This presented a significant challenge for disaggregating this data, as discussed below.
- **Gas valve proxy meters -** of the installed gas valve proxy meters, three of the eight motor on/off meters and seven of the nine solenoid valve meters had useable data. The main failure mode for the motor on/off loggers was the fact that the motor loggers are very sensitive to the meter placement and may shift over time
- **Surface temperature -** of the temperature proxy meters, data was present for 43 of 49 meters. Six had no data at all, and another seven had less than 100 days of data, although we were still able to use the data in the analysis. Twelve of 20 sites had one or more meters drop offline before the end of the metering period. The main failure modes for these meters were batteries dying throughout the metered period, despite manufacturers claiming they would last far longer, and meters losing connection to the network.

Of the 20 sites with proxy data loggers installed, 15 sites had useable proxy data that were able to be used in the subsequent analysis. Four sites were missing data for one end use proxy (the proxy disaggregation method required proxies on all major end uses), and one site had only a single end use (boiler with indirect water heater, instead of separate boiler and water heater units) and so there was no disaggregation to perform.

Gas End Use Disaggregation Methods

We employed two different disaggregation methods in the analysis: a high-rigor method using the proxy meter data, and a lower rigor method using only the whole home gas data. The team used the results from the proxy disaggregation to develop adjustment factors to “true up” the whole home disaggregation results for the broader sample. This enabled us to improve the statistical precision on the final results by gathering a larger sample of sites with only whole home gas data and adjusting the results from those sites with a smaller sample of high-rigor proxy metered sites.

Disaggregation With Proxy Meters

In the proxy disaggregation, the team first processed the proxy metered data to identify the time periods when each piece of equipment was running. This was then used to identify which equipment was in use during each interval of whole home gas consumption. When multiple end uses operated during a given gas whole home consumption interval, we split the gas consumption based on the run time and the gas input rate of the equipment in use. First, the average input rate for each unit was determined from the whole home gas data for periods when only a single unit was running. The input rates were then multiplied by the run time to derive estimated unit consumption during each interval, and the whole home gas consumption for the interval was assigned proportionally based on the unit-level consumptions. Figure 1 below shows an example of whole home gas data collection at an example site, as well as the on/off values the team determined for each end use based on the unit-level electric consumption from the electric proxy meters, and the surface temperature reads from the space temperature loggers.

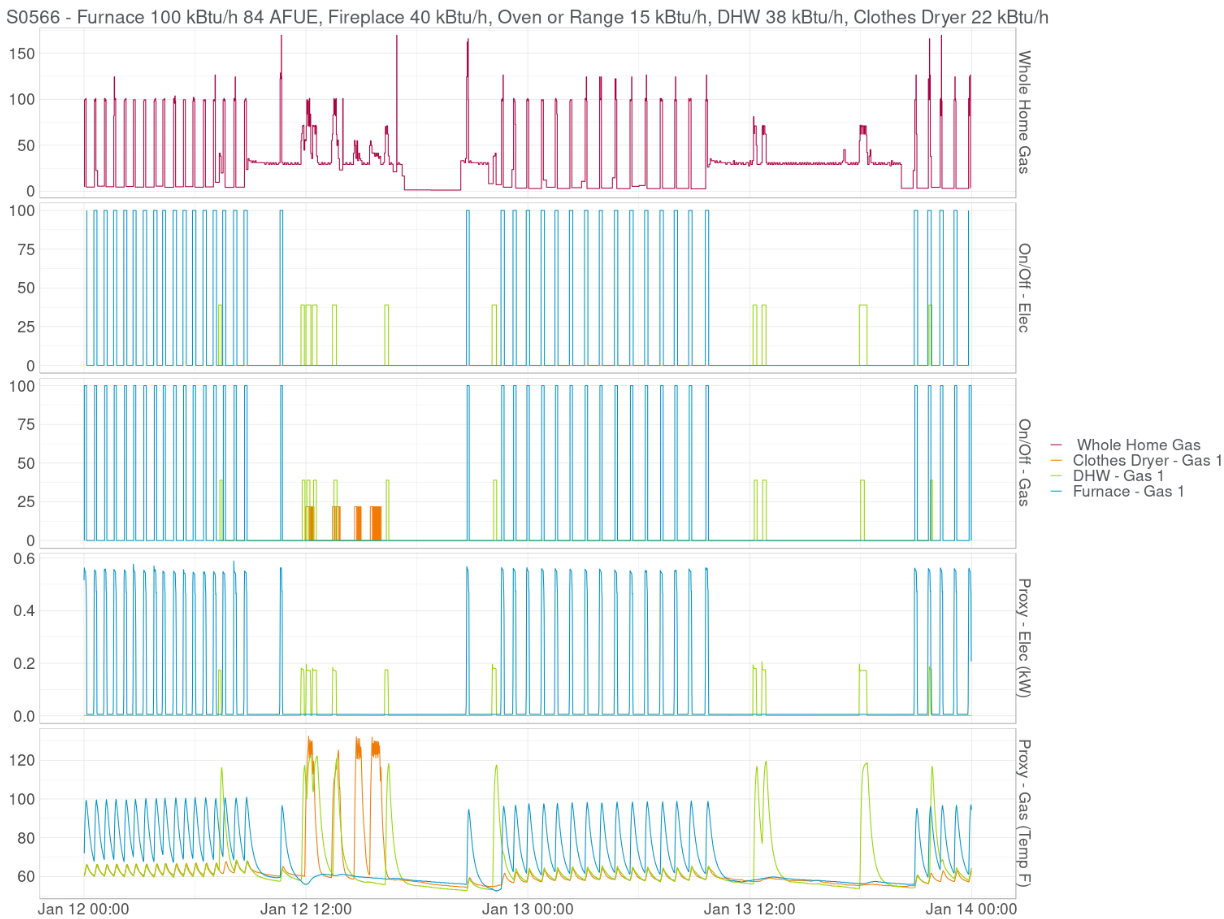

Figure 1. Example Whole Home Gas Consumption and End Use Proxy Data Collection with On/Off Period Identification

Unfortunately, the team was unable to accurately collect proxy usage data for gas cooking equipment (although future study phases are piloting methods to collect air temperature readings above the cooking surface).[4] However, we leveraged the electric cooking load shape from a previous, related study and developed an approximate gas load shape by converting electric energy consumption to gas energy consumption, using average efficiencies of electric (74%) and gas (40%) cooking equipment[5], and the conversion of kBtu/h per kW (3.412). The team then scaled down the proxy-disaggregated consumption values for non-cooking end uses by subtracting the assumed cooking consumption values. First, the cooking load shape for each day was adjusted so that all consumption fell during hours where there was whole home gas consumption, and then the cooking load was subtracted from the whole home total. All disaggregated end use loads were then adjusted by multiplying the ratio of the whole home load without cooking to the total whole home load.

[4] It is important to note that the gas cooking end use consumes a relatively small amount of total gas energy (less than 5% of annual consumption and less than 1% of winter peak day consumption). Due to the intermittent usage of gas cooking, and the relatively small gas consumption, it would be difficult to disaggregate gas cooking from total home gas consumption. The team will investigate methods for capturing gas cooking proxy data in future study phases.

[5] The team sources electric and gas cooking efficiency values from this paper: https://www.aceee.org/files/proceedings/2014/data/papers/9-702.pdf

We were unable to install proxy loggers on fireplaces for most sites due to the fact that the fireplaces were built into the wall and did not have an accessible exhaust duct.[6] In this case, the team again scaled down the consumption values from the other end uses using an approximate fireplace consumption value, derived from the one site that did have a fireplace proxy and other secondary sources. The method for adjusting for fireplace consumption was the same as the method described above for the cooking adjustments but applied only to sites with fireplaces present. This is not an ideal method; however, fireplace consumption is expected to be small relative to the total (1% for the one site with a proxy), therefore the team has confidence in the end use consumption estimates for the primary gas end uses – space heating and water heating, which make up approx. 95% of annual gas consumption and 99% of gas peak day consumption.[7]

Disaggregation Without Proxy Meters

For the 71 homes in the study sample with whole home gas loggers, the team used an engineering method to derive an estimate of the average load shape for each end use and time period of interest. First, we created an approximate gas load shape for clothes dryers and cooking equipment, using the metered electric dryer and cooking consumption from the broader study. Next, the team determined the summer water heating load shape by subtracting the dryer and cooking loads from the summer whole home data (when the heating equipment was not in use). We then scaled the water heating load shape to other months using differences in the water mains temperatures, sourced from Building America Benchmark data.[8] Finally, the team calculated the heating load by subtracting water heater, dryer, and cooking loads from the whole home gas consumption.

Disaggregation Adjustment Factors

The team then developed adjustment factors using results from the separate disaggregation analyses (with and without proxy meters). A simple linear model was fit for each end use and time period to predict the proxy value based on the non-proxy value. The models were used to apply adjustment factors to the results from the sites that did not have proxy meters, multiplying the predicted value by the modeled slope and adding the intercept term to calculate the adjusted value. An example of the adjustment factor linear models is shown in Figure 2 below for the winter peak day period for all sites with boilers, with the data points representing individual site consumption values, the blue line representing the modeled adjustment, and the black line representing the case where the actual consumption equals the predicted consumption. A good model fit is indicated by the points clustering close to the blue line, and the degree of adjustment applied is indicated by how far the blue line deviates from the black line.

[6] We are piloting methods to collect proxy data in future phases of the study, including placing air temperature loggers in close proximity to the fireplace. The ducts may also be accessible in the attic or on the roof, which pose their own challenges for onsite installations.

[7] The team will further investigate gas fireplace consumption in future study phases with a larger metered sample

[8] https://www.energy.gov/eere/buildings/building-america-analysis-spreadsheets

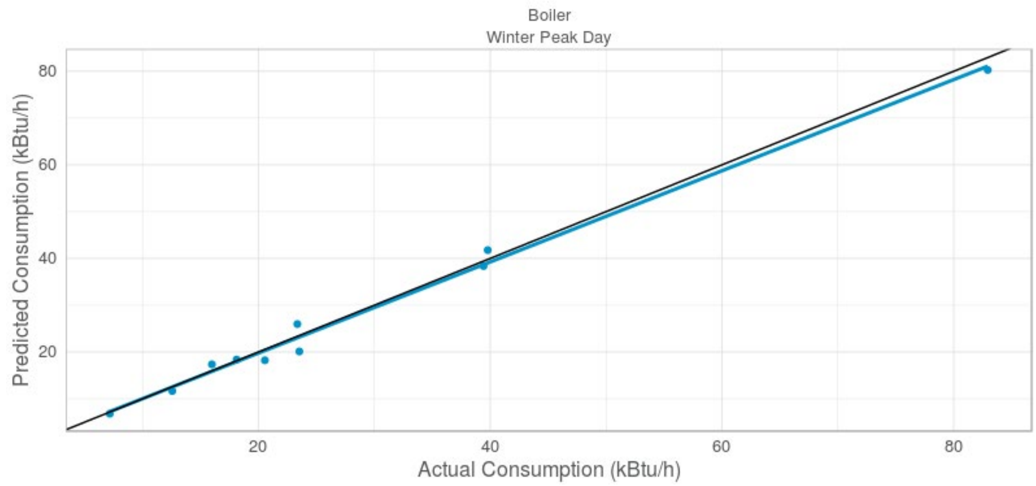

Figure 2. Disaggregation Adjustment Factor for Example Site, Boiler End Use

Figure 3 shows the average disaggregation adjustment factors for all end uses for the full sample of homes. The criteria used for evaluating the validity of the adjustment were how well the model fit (how close the individual points were to the line of best fit) and whether the slope of the modeled relationship was positive (indicating that higher predicted consumption was associated with higher actual consumption). The disaggregation adjustment worked well for heating end uses (boilers and furnaces), worked relatively well for water heaters, and poorly for clothes dryers. This is likely due to the fact that heating accounts for the vast majority of the gas load, so the whole home gas load was fairly similar to the heating load in the prior to disaggregation. The water heating loads were derived using actual data from the summer, adjusted for other times of the year based on water mains temperatures, so they were expected to be reasonably accurate as long as customer's water heating usage patterns didn't change too much throughout the year. The dryer values were expected to be the least accurate, since they were based on assumed electric dryer load shapes to begin with, and the timing of dryer usage is highly irregular even within a single site.

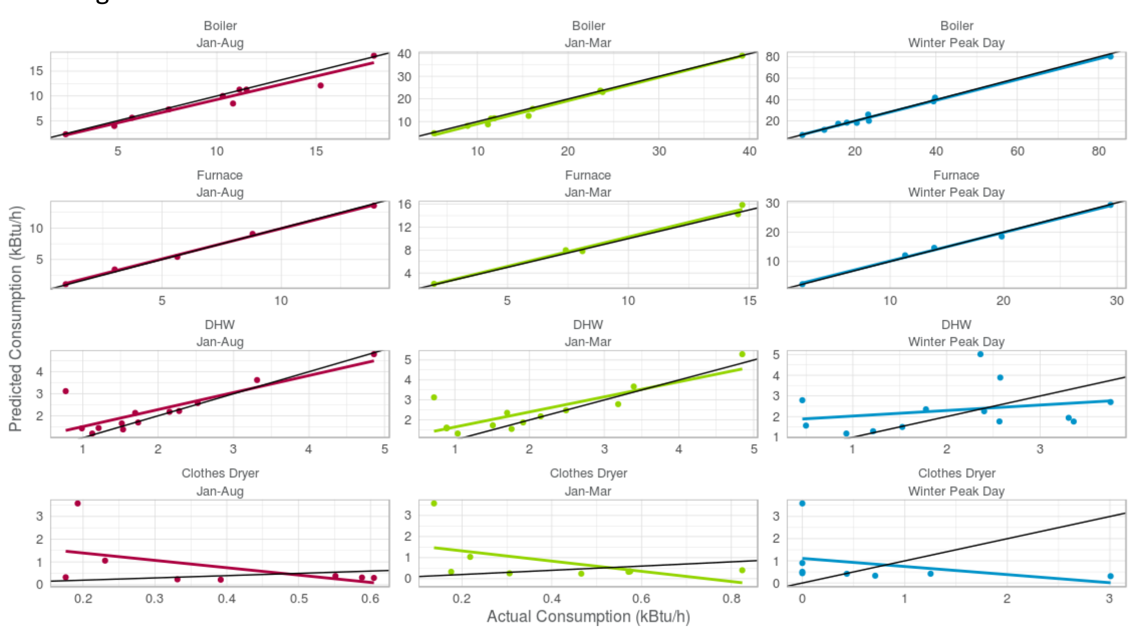

Figure 3. Average Disaggregation Adjustment Factors for Sites with the End Use

Weather Normalization Methods

The team used a regression-based approach to produce weather normalized consumption values from the metered end use consumption. First, each site was matched to hourly weather data from the nearest weather station, and predictor variables related to time (hour of day, month, weekday/weekend) and weather (heating degree hours (HDH), rolling average HDH, normalized heat build-up) were derived. We then ran preliminary piecewise linear models to determine site-specific base temperatures for the HDH calculations.

Next, the team fit models for each site and end use. The data was split 75%/25% into training and test sets by day, stratifying by month and peak days. A variety of model types (linear model, elastic net, random forest, extreme gradient boosting machine, support vector machine) were fit to the training set for each site and end use, using 5-fold cross validation to prevent overfitting. Models were evaluated using a blended error metric: 50% normalized root-mean-squared error (NRMSE) overall, 50% NRMSE on peak days.

Finally, we evaluated model performance on the test set, and chose the best model type and specification for each site and end use. The team then fit final models on the entire data set for each site and end use. The team then used these models to predict and normalize consumption using data from the past 15 weather years in Worcester, MA (2005-2019). For each time period of interest (months, peak days), the team determined the "typical" consumption by using the weather year that corresponded to the median consumption summed across all end uses.

Results

This section presents results from a variety of dimensions across the Massachusetts gas end use consumption analysis, including typical gas end use consumption at the annual, seasonal, peak day, and hourly levels. All results in this section are based on data collected from December 2019 through August 2020.[9]

Annual, Seasonal, and Peak Day Gas End Use Load Shapes

Figure 4 provides the typical annual, seasonal, and peak day gas consumption values for the average Massachusetts customer (with or without gas service).[10] The team calculated these values by multiplying the saturation of each end use in Massachusetts homes by the typical consumption in homes with the end use. Space heating consumption accounts for most of the natural gas used in Massachusetts homes (approx. 76% annually, 92% of winter peak). Gas water heaters are the next largest consumer of natural gas (approx. 19% annually, 7% of winter peak). Clothes dryer and other end use consumption (such as cooking) consumes approx. 5% of annual gas consumption (approx. 1% of winter peak day consumption).

[9] Data used to inform space heating end uses was collected "pre-COVID" (December 2019 through March 2020), while data used for water heating, dryer, and all other end uses were collected both before and during COVID (December 2019 through August 2021).

[10] Summary for average customer in Massachusetts, which includes a portion of customers with space heat provided by gas boilers or furnaces, and a portion of customers with non-gas space heat.

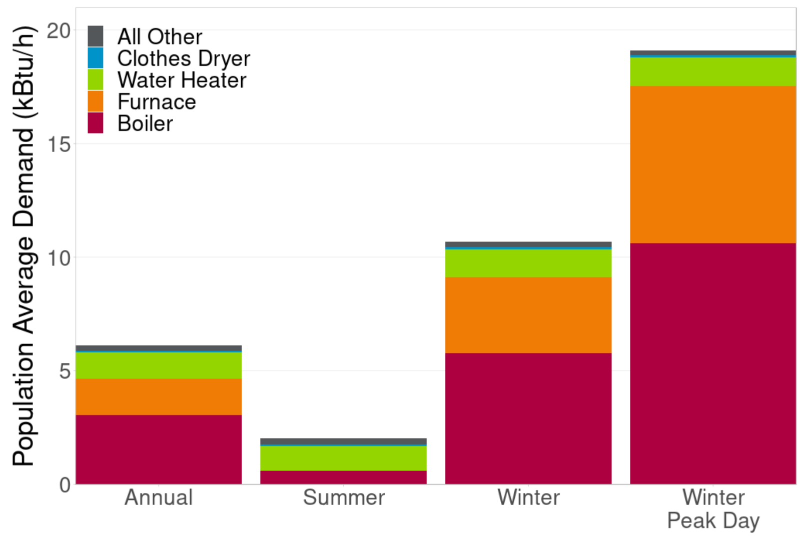

Figure 4. Population Average Gas End Use Consumption

Figure 5 provides the typical annual, seasonal, and winter peak day gas consumption for each end use. This plot summarizes the typical consumption values only for homes with the end use. Space heating end uses dominate gas consumption over the year, and especially during winter peak days. It is important to note that the boiler consumption includes some portion of hot water end use consumption, as a considerable portion of the boilers in Massachusetts are combination boilers providing both space heating and water heating functions.[11]

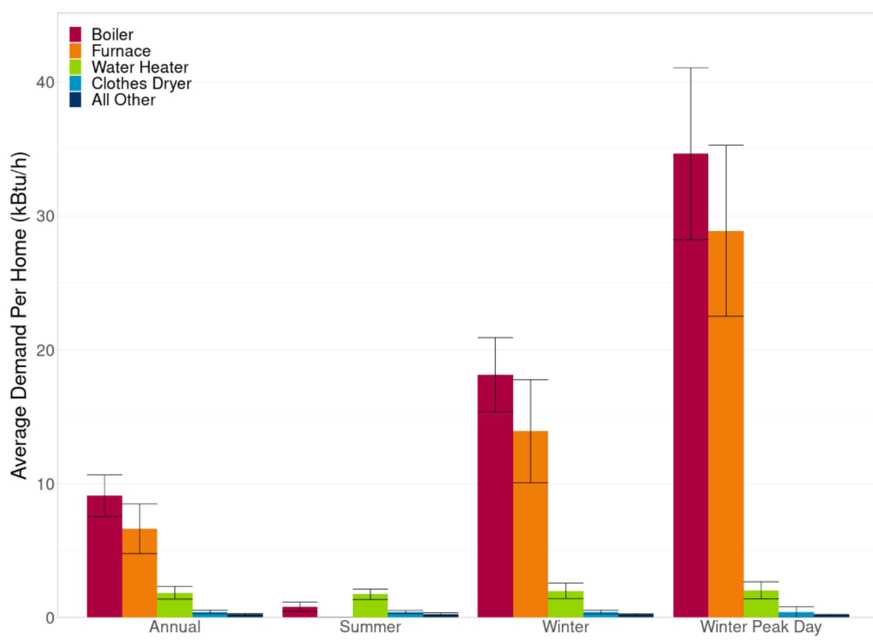

Figure 5. Typical Gas End Use Consumption for Homes with the End Use

[11] This is witnessed in the summer months where the average boiler consumption is approximately the same as the average hot water consumption for homes with the end use.

Table 2 shows the achieved relative precision for annual, seasonal (summer and winter), and winter peak day periods. The achieved relative precision at the annual level was reasonable for all end uses (approx. 30% and below). On the winter peak day, the achieved relative precision was also reasonable for all end uses with the exception of the clothes dryer due to its higher variability of usage.

Table 2. Achieved Relative Precision Values By End Use and Time Period

End Use	Annual Consumption Relative Precision	Summer Consumption Relative Precision	Winter Consumption Relative Precision	Winter Peak Day Consumption Relative Precision
Boiler	17%	43%	15%	19%
Furnace	28%	170%	28%	22%
Water Heater	26%	22%	29%	32%
Clothes Dryer	32%	29%	34%	98%
All Other	24%	35%	22%	13%

Hourly Gas End Use Load Shapes

Figure 6 provides the typical hourly gas demand by end use for the average Massachusetts customer (with or without gas service) on the average winter day and the winter peak day, respectively. The team calculated these values by multiplying the saturation of each end use in Massachusetts homes by the typical hourly demand profiles in homes with the end use. The peak in gas consumption occurs during the hours from 5-9AM, with a secondary peak from 5-9PM in both the average and peak winter days. The peak gas consumption on the winter peak day is approximately 60% higher than peak consumption on the average winter day. The morning and evening peaks are likely caused by setpoint recovery of the space heating system from a thermostat setback programmed during the nighttime and daytime hours for some customers, as well as additional usage of hot water, cooking, and laundry equipment when customers are awake and more likely to be at home.

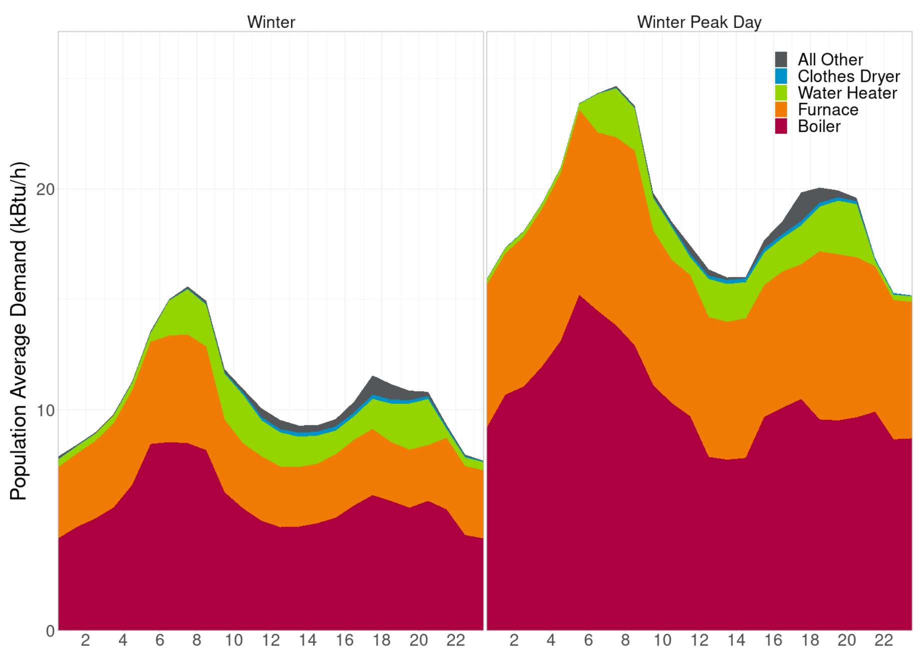

Figure 6. Population Average Hourly Gas Demand by End Use

Figure 7 provides the typical hourly gas end use consumption for the average winter day and winter peak days. This plot summarizes the typical consumption values only for homes with the end use. Space heating end uses peak during the hours from 5-9AM, with a secondary peak from 5-9PM, and is the primary driver for increased gas consumption during the winter peak day. Water heater consumption peaks from 7-9AM and again around 7-9PM, with a fairly flat consumption profile from 9AM-7PM Overnight gas consumption for water heaters is relatively low.

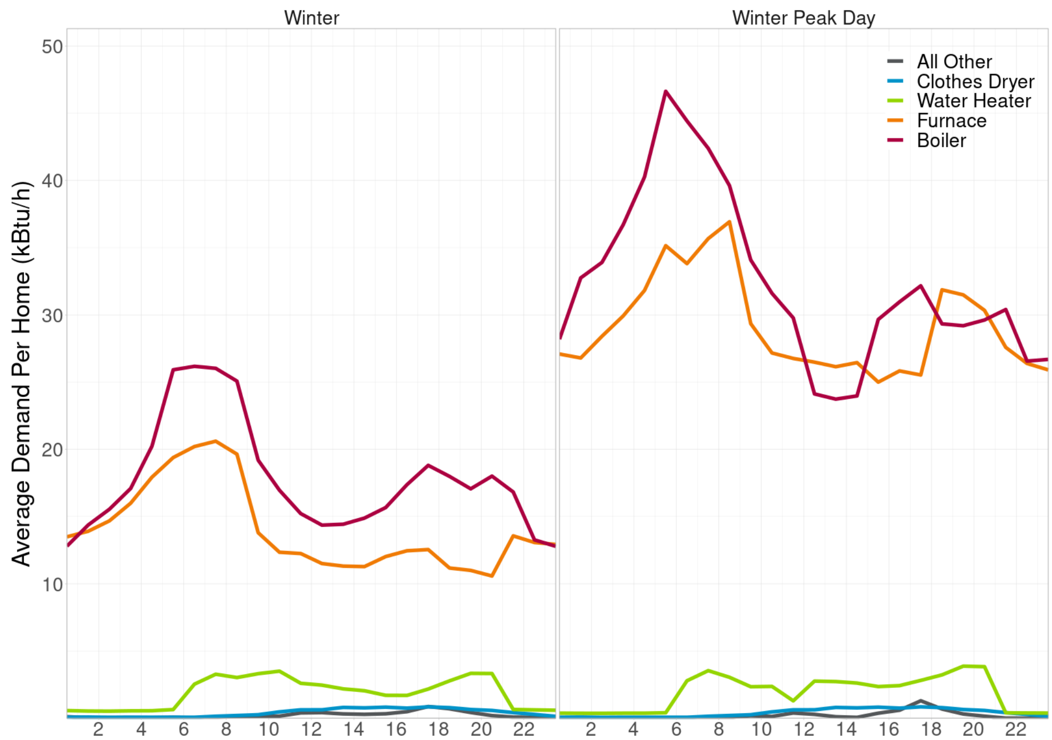

Figure 7. Average Winter Day and Winter Peak Day Hourly Gas End Use Consumption for Homes with the End Use

Conclusions

Based on the results of the study, space heating and water heating end uses offer the largest opportunity for peak demand savings and for gas demand response programs (92% and 7% of winter peak, respectively). While space heating obviously presents a large opportunity due to the relative contribution to peak day consumption, water heater consumption may also be relatively easy to shift consumption throughout the day with the use of water heater controls. Utilities should focus their programs around these two end uses and can de-prioritize gas clothes dryers and cooking which contribute only 1% to winter peak demand.

As part of the broader Massachusetts Building Use and Characterization Study, this gas end use consumption study was able to pilot and successfully disaggregate gas end use consumption from whole home gas data collection:

- We piloted several logger types to collect whole home gas consumption (Copper Labs meters) and gas end use operation proxies (electric meters, solenoid valve loggers, motor loggers, and surface temperature loggers). The Copper Labs meters work well to collect medium-frequency whole home gas consumption for homes without an interval gas meter. The proxy data loggers do an adequate job of collecting usage events for gas appliances.
- The team performed engineering-based end use disaggregation for a larger sample of homes without proxy data (NILM approach) and on a smaller subsample through use of the end use proxy data. The NILM approach worked reasonably well for this gas end use analysis and does better than similar analyses with electric end uses, as gas end uses are fewer in number than electric end uses in the home with large consumption signals for space and water heating.
- We successfully calculated adjustment factors between the analyses with and without proxy data to be able to extrapolate the results from the smaller sample to the larger metered sample, thus improving overall precision on the gas end use estimates.
- The team developed robust annual, seasonal, peak day, and hourly gas end use consumption estimates for space heating end uses (boilers and furnaces) and was able to achieve a reasonable relative precision on the water heating end use with the sample sizes attained in this study. The laundry and other gas end uses would benefit from a larger metered sample; the team plans to increase the sample of homes with proxy data collection in future project phases.

The metering methods presented in this paper offer a reasonably low cost strategy for gas end use data collection: the Copper Labs loggers can be configured and then mailed to customers for self-installation to eliminate onsite visits for the group of customers that only receive whole home gas data collection, minimizing study costs. Further, the surface temperature proxy logger used in this study can be installed by a field technician, forgoing the need for professional installation with a plumber or gas pipefitter.

The study team recommends that program administrators and evaluators strongly consider conducing similar jurisdiction-specific metering and disaggregation analyses if high-rigor gas end use consumption estimates are desired for evaluation or planning purposes.

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