High Efficiency Heating Equipment Impact Evaluation

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

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Executive Summary

Program Background and Objectives

The Massachusetts High-Efficiency Heating Equipment Rebate Program (HEHE) offers prescriptive rebates of up to $1,600 for the installation of new high-efficiency natural gas heating and water heating equipment. The objective of this evaluation was to determine gross energy savings for gas furnaces and boilers installed through the HEHE program, and refine the estimates of baseline efficiency and heating consumption. The evaluation sought to answer the following researchable questions:

- How much energy is being saved for the average installation of efficient space heating equipment through the Massachusetts HEHE program?
- How does the *in situ* efficiency of standard efficiency furnaces and boilers that are installed outside of the program compare to their rated efficiency?
- How does the *in situ* efficiency of existing equipment that is retired early compare to its rated efficiency?
- How are condensing boilers being installed and controlled, as it relates to their potential savings? [1]

Methodology

The team sought to assess home heating (and boiler hot water) consumption and annual heating loads for all types of installations, the efficiency of baseline space heating equipment, and the efficiency of new space heating equipment promoted through the program. With this in mind, the evaluation team designed the field portion of the study with two main components:

1. **Spot measurement of baseline and new equipment *in situ* efficiency**. This task provided efficiency estimates to reduce the uncertainty around new, early retirement and standard baseline furnace and boiler performance, including oil units. Additionally, spot measurements of baseline equipment provided an opportunity to better estimate fuel switching savings.[2]
2. **Long-term metering of post-retrofit high efficiency equipment** (majority of 2013-2014 heating season). This task refined estimates of annual heating load for furnaces and boilers. Logging of operating parameters was particularly important for condensing boilers where efficiency is dependent on return water temperature. The team minimized costs and uncertainty by conducting a preliminary billing data disaggregation. The metering sites were selected from within the billing data disaggregation population in a nested sampling design.

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[1] The high efficiency of condensing boilers relies on a low boiler return water temperature, which means that differences in installation practices that impact return water temperature have a large impact on savings.

[2] For new high-efficiency boilers, long term metering data also informed efficiency estimates as efficiency varies with return water temperature on all condensing boilers. Oil measurements are relevant only for fuel conversion baselines; the evaluation did not calculate any oil savings.

Results

The following sections present savings for furnaces and boilers. All savings in this report are first-year savings.

Furnace Results: Replace on Failure

Table 1 summarizes the verified savings estimates for furnaces. The results were calculated using the new baseline of 85 percent AFUE that the PAs will use for replace-on-failure units from 2014 forward; this calculation does not include an evaluation adjustment since the baseline is a negotiated value. Results based on a rated baseline of 80 percent AFUE with the evaluation adjustment for actual unit performance can be found in Appendix E. The team found that on average, standard efficiency furnaces performed slightly better than their rated efficiencies.

Table 1. Furnace Savings Findings

Measure	AFUE Type	Efficient AFUE	Baseline AFUE	Verified ROF Therm Savings	2013 Report TRM ROF Therm Savings	Relative Precision at 90% Confidence
95% AFUE Furnace ROF Baseline	Rated	95.2%	Negotiated Baseline: 85%	75	147	8.7%
	Verified	95.4%				
97% AFUE Furnace ROF Baseline	Rated	97.0%		86	162	
	Verified	97.2%				

The primary driver for reduced furnace savings was the fact that typical furnace participant heating consumption was lower than assumed in the current savings methodology. This is likely because the current methodology uses an annual heat load estimate for all gas system types, and this evaluation found that the average participant high efficiency furnace home uses less gas than the average participant home in Massachusetts.[3] Furnace savings were also reduced because of changes to the deemed baseline efficiency.

Boiler Results: Replace on Failure

Table 2 and Table 3 summarize the verified savings for standard boilers and combination boilers.[4]

[3] The evaluation team conducted additional research to understand factors driving lower heating consumption in furnace homes; these findings can be found in Appendix D.

[4] Combination boilers are boilers that provide a combination of heating and hot water in one contained unit. By including a small insulated hot water tank inside the same box as the boiler, these units preclude the need to install a separate indirect hot water heater.

Table 2. Standard Boiler Verified Savings

Measure	AFUE Type	Efficient AFUE	Baseline AFUE	Verified ROF Therm Savings	2013 Report TRM ROF Therm Savings	Relative Precision at 90% Confidence
90% AFUE Boiler ROF Baseline	Rated	92.7%	Rated: 82.0% Verified: 79.3%	110	104	9.9%
	Verified	87.2%				
95% AFUE Boiler ROF Baseline	Rated	95.0%		137	123	
	Verified	89.4%				
96% AFUE Boiler ROF Baseline	Rated	96.0%		148	131	
	Verified	90.3%				

The team found that although boilers serve larger loads than the deemed savings assumed,[5] verified savings estimates are similar to current deemed values because high-efficiency boilers are operating well below their rated efficiency. The average operating efficiency of the metering sample (standard and combination systems) was 88.4 percent, almost six percentage points below the average rated new efficiency of 94 percent. The team also found that baseline units operate below their rated AFUE, but not as significantly as high-efficiency equipment and for different reasons. The primary cause for lower efficiency in this group is that boilers are not fully utilizing available controls such as outdoor reset to keep supply and return water temperatures low enough to achieve condensing operation in most cases. The Boiler Results section includes additional detail on these findings.

[5] On average, boilers had both higher heating and higher hot water loads than were used in the deemed assumptions.

Table 3. Combination Boiler Verified Savings

Measure	AFUE Type	Assumed Efficient Case	Assumed Baseline Case	Verified ROF Therm Savings	Weighted Average Verified ROF Therm Savings	2013 Report TRM ROF Therm Savings	Relative Precision at 90% Confidence
≥90% AFUE Combination Boiler Indirect ROF Baseline	Rated	92.2% Combination	82% Boiler with Indirect	88	96	178	10.6%
	Verified	86.8% Combination	79.3% Boiler with Indirect				
≥90% AFUE Combination Boiler Standalone DHW ROF Baseline	Rated	92.2% Combination	82% Boiler 0.575 EF DHW	130			
	Verified	86.8% Combination	79.3% Boiler 0.575 EF DHW				
≥95% AFUE* Combination Boiler Indirect ROF Baseline	Rated	95% Combination	82% Boiler with Indirect	113	121	-	
	Verified	89.4% Combination	79.3% Boiler with Indirect				
≥95% AFUE* Combination Boiler Standalone DHW ROF Baseline	Rated	95% Combination	82% Boiler 0.575 EF DHW	155			
	Verified	89.4% Combination	79.3% Boiler 0.575 EF DHW				

*This is a new measure and thus there is no TRM savings estimate for comparison.

As with standard boilers, combination boilers operated well below their rated efficiency. Homes with combination systems also tended to serve smaller annual loads than homes with standard boilers, further reducing savings estimates. This could be due to a number of factors such as combination systems being installed in smaller, newer or better insulated homes. The team calculated savings for two baseline options: a boiler and a standalone domestic water heater, or a boiler with an indirect domestic water heater. Based on 2013 tracking data and on-site observations of the presence of indirect versus standalone water heaters, the team estimates that approximately 80 percent of standard (i.e. not combination) boilers have indirect water heaters. The weighted average savings values in Table 3 reflect this baseline share.

Early Retirement Results

The goal of this research was to understand the relationship between rated and actual performance of these units. Due to difficulty recruiting, the team only visited 38 sites across four equipment types and was not able to collect enough data to provide a statistically valid quantitative adjustment to early retirement baseline efficiency.

Although the team did not adjust the baseline with data from this portion of the study, the early retirement research did point to the following qualitative findings:

- There is not much difference in the ratios of actual to rated performance of old and new gas units. For the group of early retirement gas units less than 30 years old, the evaluation did not find evidence of significant degradation of efficiency.
- The results showed that the "early retirement" baseline of 72.5 percent AFUE may not be appropriate for units less than thirty years old and should be reviewed in future planning work. All but one sampled gas unit had rated and/or measured efficiencies above 75 percent AFUE.
- Oil units generally performed worse relative to their rated efficiencies than gas units.

Given these findings, the team estimated the early retirement baseline rated efficiency as the federal minimum efficiencies in place before the most recent standards came into effect. These efficiency standards have been in place since 1992, earlier than the installation of most early retirement units under 30 years old. Given the similarity in actual performance relative to efficiency ratings between the early retirement and standard new group and the small early retirement sample sizes, the team applied the standard new adjustment factors to the early retirement rated baselines as shown in Table 4.

Table 4. Early Retirement Baselines

Measure	Rated Baseline	Baseline Adjustment	Verified Baseline
Furnaces	78%	1.01	78.9%
Boilers	80%	0.97	77.4%

Overall Savings Results

The following tables present the evaluation team's recommended revised deemed savings values for each furnace and boiler measure. The team used the percentages of early retirement and replace on failure installations found in the 2012 HEHE and Cool Smart net-to-gross evaluation[6] to weight savings from each group into a single value for each measure. Furnace savings are calculated assuming 11.7 percent early retirement, boiler savings are calculated assuming 13.2 percent early retirement, and combination boiler savings assume 32.2 percent early retirement.

[6] "2012 Residential Heating, Water Heating and Cooling Equipment Evaluation: Net-to-Gross, Market Effects, and Equipment Replacement Timing." Cadmus Group, June 2013.

Table 5. Furnace Results, 85 Percent AFUE Baseline

Measure	Verified ROF Therm Savings	Verified ER Therm Savings	Verified Average Savings	2013 Report TRM Therm Savings
95% AFUE Furnace	75	127	81	159
97% AFUE Furnace	86	139	92	173

Table 6. Boiler Results

Measure	Verified ROF Therm Savings	Verified ER Therm Savings	Verified Average Savings	2013 Report TRM Therm Savings
90% AFUE Boiler	110	140	114	120
95% AFUE Boiler	137	167	141	139
96% AFUE Boiler	148	178	152	147

Note: Boiler savings include hot water loads from indirect water heaters.

Table 7. Combination Boiler Results

<table>
<tr><th>Measure</th><th>Baseline</th><th>Verified ROF Therm Savings</th><th>Verified ER Therm Savings</th><th>Verified Average Therm Savings</th><th>Weighted Average Verified Therm Savings</th><th>2013 Report TRM Therm Savings</th></tr>
<tr><td rowspan="2">90% AFUE Combination Boiler</td><td>Standalone Water Heater</td><td>130</td><td>159</td><td>139</td><td rowspan="2">104</td><td rowspan="2">238</td></tr>
<tr><td>Indirect Water Heater</td><td>88</td><td>111</td><td>95</td></tr>
<tr><td rowspan="2">95% AFUE Combination Boiler</td><td>Standalone Water Heater</td><td>155</td><td>184</td><td>164</td><td rowspan="2">129</td><td rowspan="2">-</td></tr>
<tr><td>Indirect Water Heater</td><td>113</td><td>136</td><td>120</td></tr>
</table>

Program Implications and Conclusions

This evaluation provided revised savings estimates for high-efficiency furnace and boiler replacements. In addition, the team noted several key findings:

- There are differences in annual heating load between equipment types: Average annual heating loads[7] for HEHE-installed furnaces and combination boilers were 26 percent and 19 percent

[7] The term "load" is used throughout this report to characterize heat delivered to the home by the furnace or boiler over the course of the year—i.e., the thermal "load" on the heating system. This is calculated as the actual consumption divided by the actual efficiency.

lower than the standard boilers, respectively. The team analyzed furnace and boiler home characteristics for over 180,000 homes in the Massachusetts Home Energy Services (HES) program and determined that these differences are largely due to the fact that boiler homes tend to be older, larger and less efficient than furnace homes.[8] Previous deemed savings used the same annual heating load for both furnaces and boilers.

- It is important to consider standby and cycling losses in addition to combustion efficiency when evaluating gravity-drafted equipment such as standard and early retirement boilers and furnaces. Older boilers in particular can have higher standby losses due to their large mass, especially when serving hot water loads year-round.
- High-efficiency boilers are not being installed to maximize potential savings. The PAs should consider ways to improve boiler operating efficiency through quality installation, and contractor and homeowner education. The Program Considerations and Conclusions section of this report discusses specific recommendations for further research in this area.
- Many older gas furnaces and boilers considered "early retirement" equipment have AFUEs of at least 75 percent, even when considering actual instead of rated performance. The PAs should use the revised early retirement baselines shown in Table 4 and broader research on early retirement units less than thirty years old may be needed if early retirement participation increases.
- Evaluation research suggests that as many as 80 percent of new combination systems are replacing boilers with indirect water heaters, but the TRM currently assumes a boiler and a standalone water heater as the baseline. Since the baseline system has a significant impact on savings, the PAs should consider conducting additional baseline research and/or requiring application information on what combination systems are replacing.

[8] There was not sufficient data to also make this comparison for combination systems, but the team believes these homes are also likely smaller and newer than standard boiler homes. Additional detail on the analysis of HES participants can be found in Appendix D.

Program Background and Objectives

The Massachusetts High-Efficiency Heating Equipment Initiative (HEHE) offers prescriptive rebates of up to $1,600 for the installation of new high-efficiency natural gas heating and water heating equipment. As shown in Table 8, this evaluation focused on high-efficiency furnaces and boilers with and without domestic hot water (DHW).

Table 8: Initiative Heating Equipment Measures

Equipment	Rebate	Evaluated in 2014
Furnace >=95% AFUE	$300	✓
Furnace >= 97% AFUE	$600	✓
Standalone Boiler >=90% AFUE	$1,000	✓
Standalone Boiler >=95% AFUE	$1,500	✓
Boiler with DHW >= 90% AFUE	$1,200	✓
Boiler with DHW >=95% AFUE	$1,600	✓
Heat Recovery Ventilator	$500	
After-Market Boiler Reset Controls	$225	

Source: GasNetworks

The objective of the evaluation was to determine gross energy savings for gas furnaces and boilers installed through the HEHE program and refine the estimates of baseline efficiency and heating consumption. The evaluation sought to answer the following researchable questions:

- How much energy is being saved for the average installation of efficient space heating equipment through the Massachusetts HEHE program?
- How does the *in situ* efficiency of standard efficiency furnaces and boilers that are installed outside of the program compare to their rated efficiency?
- How does the *in situ* efficiency of existing equipment that is retired early compare to its rated efficiency?
- How are condensing boilers being installed and controlled, as it relates to their potential savings?[9]

[9] The high efficiency of condensing boilers relies on a low boiler return water temperature, which means that differences in installation practices have a large impact on savings.

Methodology

For retrofit space heating equipment and combination heating and hot water equipment, there are three major parameters that determine energy savings:

- Annual home heating and combined heat and hot water load (for all types of replacements)
- Efficiency of the baseline space heating equipment*,* either existing equipment for early retirement and fuel switching participants or standard efficiency equipment for replacement on failure participants
- Efficiency of the new space heating equipment promoted through the program

In order to assess these major parameters, the evaluation team designed the field portion of the study with two main components:

1. **Spot measurement of baseline and new equipment *in situ* (measured) efficiency**. This task provided efficiency estimates to reduce the uncertainty around new, early retirement and standard baseline furnace and boiler performance, including oil units. Additionally, spot measurements of baseline equipment provided an opportunity to better estimate fuel switching savings.[10]
2. **Long-term metering of post-retrofit high efficiency equipment** (majority of 2013-2014 heating season). This task refined estimates of annual heating load for furnaces and boilers. Logging of operating parameters was particularly important for condensing where efficiency is dependent on return water temperature. The team minimized costs and uncertainty by conducting a preliminary billing data disaggregation and using a nested sampling approach.

The metering sites were selected from within the billing data disaggregation population in a nested sampling design. Table 9 describes the scope of and rationale for each evaluation activity.

[10] For new high-efficiency boilers, long term metering data also informs efficiency estimates as efficiency varies with return water temperature on all condensing boilers.

Table 9. Evaluation Activities

Activity	Rationale	Target Sample
Early Retirement Gas and Oil Boiler and Furnace Spot Measurements of Efficiency	Determine the ratio of *in situ* operating efficiency to nameplate efficiency for furnaces and boilers replaced in early retirement situations.	30 Gas Furnaces 30 Gas Boilers 30 Oil Furnaces 30 Oil Boilers
Standard New Gas Boiler and Furnace Spot Measurements of Efficiency	Determine the ratio of *in situ* operating efficiency to nameplate efficiency for new, standard efficiency furnaces and boilers.	30 Gas Boilers 30 Gas Furnaces
New Efficient Gas Boiler and Furnace Spot Measurements of Efficiency *	Determine the ratio of *in situ* operating efficiency to nameplate efficiency for new, high efficiency furnaces and boilers.	70 Gas Boilers 35 Gas Furnaces
New Efficient Gas Furnace Metering	Determine the operating hours associated with natural gas furnaces in Massachusetts.	35 Gas Furnaces
New Efficient Gas Boiler Metering	Determine the operating hours associated with natural gas boilers in Massachusetts and refine estimates of operating efficiency for condensing and modulating boilers.	70 Gas Boilers
Analysis of Furnace Participant Billing Data	Extrapolate furnace metering sub-sample results to determine average operating hours and associated savings for all participants.	1000 Furnace Participants
Analysis of Boiler Participant Billing Data	Extrapolate boiler metering sub-sample results to determine average operating hours and associated savings for all participants.	1000 Boiler Participants

* These units are the same as the new efficient gas furnace and boiler metering samples.

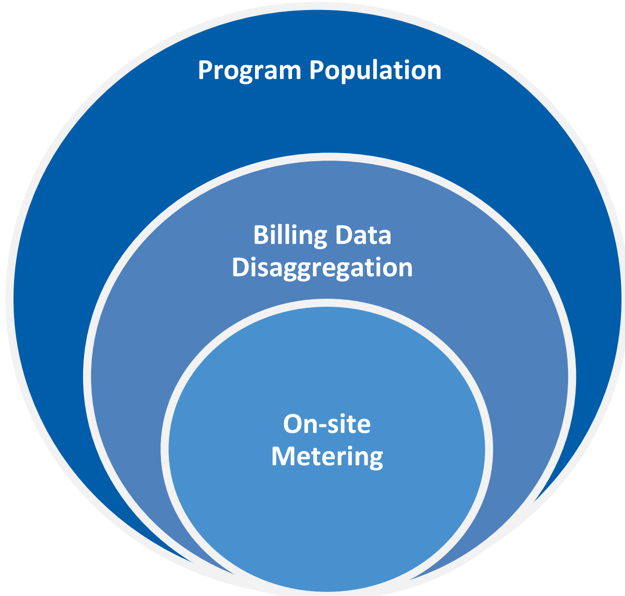
Overview of Approach

The team used a nested sampling approach in order to maximize the precision of results while keeping on-site sample sizes and associated costs low. This approach began with a “first phase” low cost-per-participant billing data disaggregation analysis.[11]

The first phase sample sizes were large and encompassed a wide range of participant behaviors, allowing for a smaller on-site sample. Figure 1 illustrates this concept.

[11] See Spencer et al., *Revisiting Double Ratio Estimation for Mitigating Risk in High Rigor Evaluation,* 2013 IEPEC.

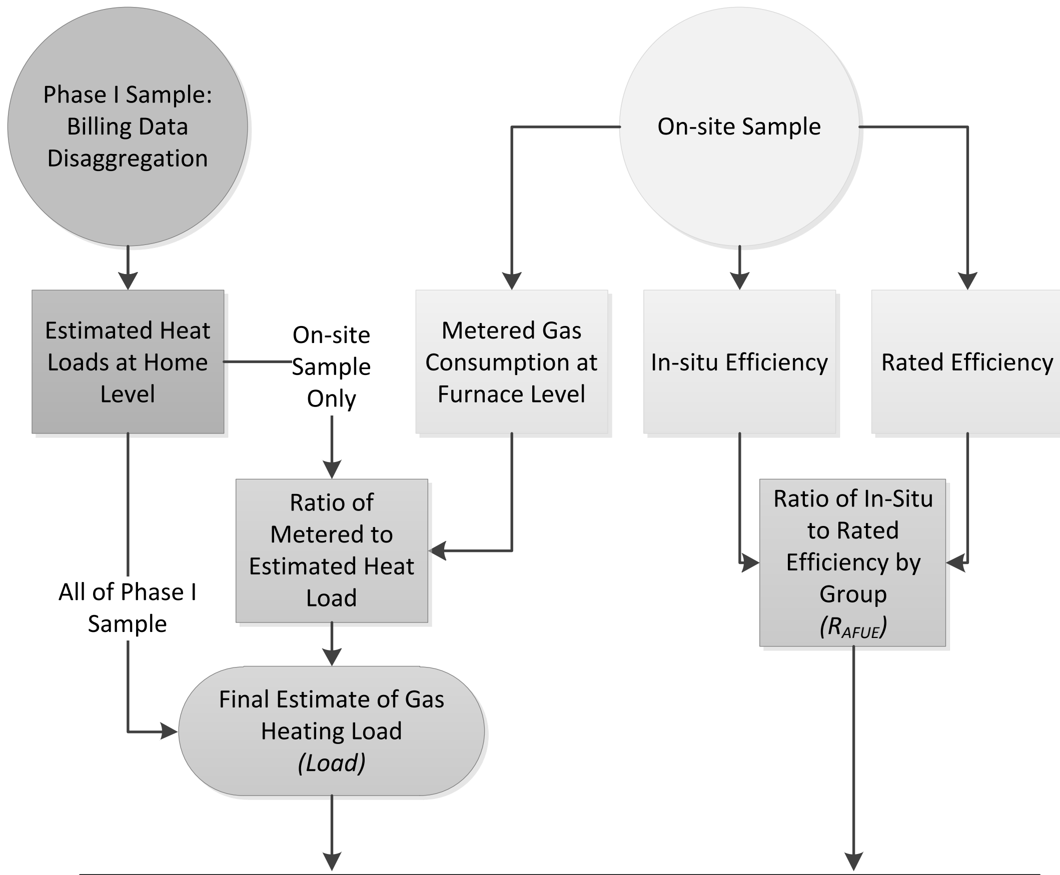
Figure 1. Nested Sampling Approach



We obtained the first phase estimate of annual heating system consumption by disaggregating large samples of participant billing data in order to incorporate a wider range of participant home characteristics and behaviors in the final results and eliminate sample bias.

Figure 2 shows how the measured parameters from each of these analysis components were combined to calculate savings.

Figure 2. Savings Calculation for Heating Equipment



$$Savings = Load \times \left(\frac{1}{AFUE_{base} \times R_{AFUE,base}} - \frac{1}{AFUE_{ee} \times R_{AFUE,ee}} \right)$$

Metering Approach

Long-term Metering

The team reviewed and cleaned the metered data using visual quality control (QC) techniques. We then combined spot consumption measurements, consumption interval metering data, and run-time metering data to calculate estimated consumption per furnace and boiler for the duration of the metering period.

Furnaces

For furnaces, the team used the following equation to derive metered gas consumption estimates for single and dual stage furnaces. [12] Table 10 shows how each measurement flows into the equation.

[12] The team excluded modulating furnaces from the metering sample because they would require an alternative metering configuration. This should not create any bias because there is no reason why the ratio of the metered data to the billing data disaggregation should be different for modulating furnaces. Modulating furnaces were included in the billing data disaggregation sample.

$$Metered\ Gas\ Consumption\ (Btu) = \sum_{stages} Run\ Hours_{stage} \times Btu/hour_{stage}$$

Table 10. Furnace Measurements

Measurement	Output	Variable
State (on/off) loggers on gas valves	Run time for each stage of unit operation	$Run\ Hours_{stage}$
State loggers on blower motors	Back-up total run time	Used to calculate $Run\ Hours_{stage}$ in event of logger failure
Spot measurements of gas consumption at each stage using the utility gas meter	Rate of gas consumption for each stage	$Btu/hour_{stage}$

Boilers

The efficiency of condensing boilers varies with return water temperature and most condensing boilers fully modulate over a wide range of input and output. The team metered the return water temperature along with the supply temperature to monitor both the efficiency of the boiler and the temperature delta across the boiler. The team used the following equation and measurements to determine total gas consumption, assuming a constant flow of water through each boiler's primary loop.[13]

$$Metered\ Gas\ Consumption\ (Btu) = \sum_{i,GAS=ON} Btu/hour_i * dt_i$$

Where:

$$Btu/hour_i = \frac{\dot{m} C_p \Delta T_i}{\eta_i}$$

Table 11. Boiler Measurements and Definition of Variables

Measurement	Output	Variable
State (on/off) loggers on gas valves	Indicator of when boiler is on	$GAS = ON$
Interval metering of supply and return water temperature	Supply and return water temperature at interval *i*	ΔT_i
Synchronized spot measurements of efficiency, gas consumption, and supply and return temperature	Estimate of water mass flow rate in primary boiler loop (constant)	$\dot{m}$
	Rate of gas consumption for a given efficiency and ΔT	$Btu/hour_i, \eta_i$
n/a	Specific heat of water	C_p

[13] Condensing boilers are designed to operate with a constant flow rate and require an installation that isolates the primary boiler pump from varying flow rates in the secondary loops serving the house zones.

For additional detail on the measurement and calculation approaches for furnaces and boilers, see Appendix B. Metered Data Analysis.

Spot Measurements

The team performed combustion tests on high-efficiency, standard new and early retirement units to determine the ratio of actual performance to rated efficiency for each group. The team used one standard test protocol for high-efficiency furnaces and all standard new and early retirement equipment and a modified protocol for high-efficiency boilers.

Furnaces and Standard Efficiency Boilers

The team took a series of spot measurements on each furnace and standard efficiency boiler operating in steady state. At each site, field staff turned on the unit, waited five minutes for it to warm up, and recorded the efficiency reading from a combustion analyzer every 15 seconds for three minutes. The final result for each unit is the average of the three-minute test.

The analysis team observed that standard efficiency equipment, particularly furnaces, measured higher relative to its rated efficiency than high-efficiency equipment. Part of this is due to the fact that AFUE ratings include cycling losses, which are greater in standard equipment due to higher stack temperatures and heat loss. A combustion test only captures the actual combustion efficiency at the time of the test. The team applied a 2 percent downward adjustment to the standard efficiency measurements to account for this difference between combustion efficiency and AFUE.[14] The team also applied a downward adjustment to standard efficiency boilers and all early retirement measured efficiency values.

High-Efficiency Boilers

As described above, condensing boiler efficiency varies with return water temperature. This means that a single spot measurement is not an accurate measurement of the seasonal operating efficiency of a boiler: return water temperature varies constantly as the boiler heats up and cools down, and may differ depending on which zones in the home are being served and what the outdoor temperature is. The team took a series of efficiency spot measurements concurrent with measurements of return water temperature as described above. We then used the long-term metered return water temperature data and the observed relationship between return temperature and efficiency from the spot measurements to estimate seasonal efficiency for each boiler.

Baseline Equipment Spot Measurement Recruiting

The team used different approaches to recruit participants for "standard new" and "early retirement" equipment. For standard new units, the team recruited from public permit data, using screening calls to confirm new units had been installed at each home. For early retirement units, the team worked with the HEAT Loan program implementation contractor. The implementation contractor reviewed applications to determine whether a planned replacement would meet the needs of the evaluation: The existing unit had to be a functioning natural gas or oil furnace or boiler being replaced with new natural gas equipment. The team screened out older units by disqualifying any replacements eligible for the

[14] The team relied on internal experts to inform this value, which is based on a review of the components of the AFUE test procedure calculation method and the relative weight of cycling and steady-state efficiency.

Early Replacement program which was ongoing at the time of the evaluation and targeted units at least 30 years old.

Billing Data Disaggregation

Navigant used participant billing records and program data on furnace and boiler models installed to estimate heating consumption and savings for the participants in each analysis sample. For a complete description of the disaggregation methodology, please see Appendix A. Billing Data Disaggregation.

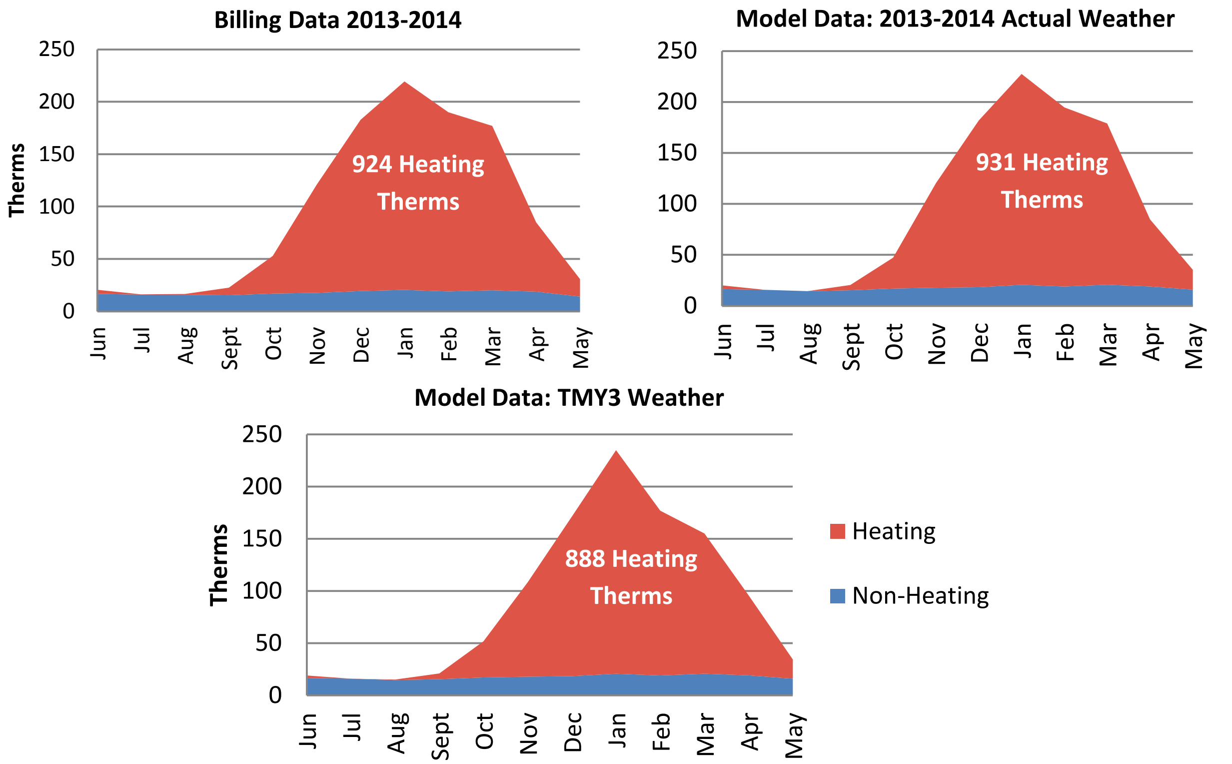
Calibrated Simulation

The evaluation team used home characteristics details collected from the on-site sample to build three energy models in the Building Energy Optimization (BEopt) software developed by the National Renewable Energy Laboratory (NREL).[15] The purpose of the modeling was to accurately extrapolate the billing data from the 2012-2013 heating season to a typical weather year. Navigant first built each model based on homes in the study and calibrated them such that the output aligned with the average consumption from the participant billing records when run with actual weather data from the recent heating season (to a difference of less than one percent).[16] Once the model was sufficiently calibrated, the analysis team ran the model using a Typical Meteorological Year (TMY3) file from Worcester, MA. TMY3 data represents typical weather patterns for the location. Figure 3 illustrates the alignment of the billing data and calibrated model. The lower value of the TMY3 model output indicates that 2013-2014 was a colder than average winter with higher heating usage.

[15] The evaluation team used the EnergyPlus engine with the BEopt software.

[16] The evaluation team used an actual weather file from Worcester for June 2013 – May 2014 to calibrate the model. The TMY3 file was also for Worcester. The TMY3 file reflects the average weather from 1991 to 2005 at a given location.

Figure 3. Calibrated Model Outputs for Standard Boilers: Annual Consumption



The team created three models in order to accurately model each equipment type. Standard boilers with and without indirect water heaters were grouped together. Table 12 shows the results of the calibration for each model.

Table 12. Model Calibration by Equipment Type, 2013-2014 Heating Season

Model	Billing Data Heating Therms	Model Heating Therms	Percent Difference
Furnace	729	728	0.03%
Standard Boiler	924	931	-0.85%
Combination Boiler	757	758	-0.14%

Furnace Results

The team met or exceeded sample size targets for the billing disaggregation and high-efficiency spot measurements. As shown in Table 13 and Table 14, there was some attrition for both long-term metering data and standard new efficiency spot measurements.

Table 13. Furnace Sample Dispositions

Group	Target	Achieved	Limitations
Long Term Metering	35	33	Unusable metered data (1) Unable to retrieve loggers (1)
High Efficiency Spot Measurements	35	35	n/a
Billing Data Disaggregation	1,000	1,678	n/a
Standard New Efficiency Spot Measurements	30	16	Efficiency >=95% AFUE (11) Unable to take measurements (3)

Table 14. Furnace Standard New Spot Measurement Sample Detail

Efficiency Group	Visited	Included	Attrition Notes
80-82% AFUE	14	11	Unable to take measurements
90-95% AFUE	5	5	-
≥95% AFUE	11	0	High-efficiency
Total	**30**	**16**	

Table 15 shows the results for average heating consumption for furnace participants. The final estimate of average typical year heating consumption is 606 therms. This is less than the 2013-2014 heating season estimate, indicating that the 2013-2014 heating season was colder than average. The ratio of metered to billed consumption estimates was 0.88, indicating that the billing data disaggregation slightly overestimated average heating consumption. This is partly due to the fact that some homes had multiple heating systems. The current Massachusetts TRM furnace savings estimates are based on an average annual heating load of 739 therms; the final estimate of average annual heating load for furnaces is 21 percent lower at 582 therms. The current TRM estimate may be higher because it is an average annual heat load for homes with both furnaces and boilers or because of other differences in household characteristics.

Table 15. Furnace Annual Heating Consumption Findings

Metric	Mean	n	Relative Precision at 90% Confidence	Description
2013 – 2014 Premise Heating Consumption, Billed	726	1,678	1.8%	Mean of site level 2013-2014 heating therms
Typical Year Premise Heating Consumption	693	-	-	Calibrated model heating therm output for a typical weather year
Ratio of Metered Unit Consumption to Billed Premise Heating Consumption	0.88	33	3.1%	Mean ratio of metered 2012-2013 heating therm use to disaggregated billing data heating therm use for the same period
Final Estimate of Typical Year Unit Heating *Consumption*	606	-	3.6%	Product of typical year heating consumption therms and mean ratio of metered to billed heating use
Final Estimate of Typical Year Annual Heating *Load*	584	-	-	Product of typical year heating consumption and average verified efficiency

*There are no statistical metrics for the step where the team extrapolated 2012-2013 data to a typical weather year; this is simply a weather adjustment to provide a result than can be used for annual savings across any given year.

Table 16 shows the final estimates of the ratio of in-situ to rated efficiency for each group of furnaces (early retirement equipment is covered in the Early Retirement Results section). On average, standard new furnaces performed one percent above their rated efficiencies. The team adjusted the standard new spot measurement combustion efficiencies downward by two percent to account for standby stack losses, which are the primary difference between measured combustion efficiency and the AFUE rating, which includes cycling tests as well as steady-state efficiency. The team did not make a similar adjustment to high-efficiency units because they operate at lower temperatures and use forced-draft instead of gravity-induced draft, making stack losses less significant.[17]

[17] The team believes that this adjustment would be very small, on the order of 1/10 of one percent, and elected not to make an adjustment

Table 16. Furnace Efficiency Findings

Efficiency Group	Mean AFUE Ratio	n	Relative Precision at 90% Confidence	Description
Standard New	1.01	16	1.1%	Ratio of efficiency spot measurements to rated AFUE for equipment rated <90% AFUE
High Efficiency	1.00	35	0.6%	Ratio of efficiency spot measurements to rated AFUE for equipment rated >=95% AFUE

Over the course of the evaluation the Massachusetts PAs implemented a new negotiated baseline of 85 percent. This baseline was determined with knowledge of the evaluation results, and thus the team did not apply the adjustment to this new baseline. Results of applying the adjustment factor to the former baseline of 80 percent AFUE can be found in Appendix E. Table 17 shows the calculated savings using the new deemed baseline of 85 percent AFUE.

Table 17. Furnace Savings Findings

Measure	AFUE Type	Efficient AFUE	Baseline AFUE	Verified ROF Therm Savings	2013 Report TRM ROF Therm Savings	Relative Precision at 90% Confidence
95% AFUE Furnace ROF Baseline	Rated	95.2%	Negotiated Baseline: 85%	75	147	8.7%
	Verified	95.4%				
97% AFUE Furnace ROF Baseline	Rated	97.0%		86	162	
	Verified	97.2%				

Boiler Results

As with the furnaces, the team exceeded the sample size target for the billing data disaggregation. The boiler long-term metering sites used a combination of several time-synchronized measurements. The team eliminated sites where either the long-term metered data was unusable due to logger failure or where the spot measurement data was unusable due to inconsistent operation of the boiler. For more detail on the quality control (QC) processes used to screen metered data, please see Appendix B. Metered Data Analysis. Unfortunately, there was no overlap between these two groups of excluded sites. Table 18 summarizes the attrition for each group.

Table 18. Boiler Sample Dispositions

Group	Target	Achieved	Limitations
Long Term Metering: Gas Consumption	70	42	Unusable metered data (16) Unusable spot measurements (12)
Long Term Metering: Efficiency	70	54	Unusable metered data (16)
Billing Data Disaggregation	1,000	1,688	n/a
Standard New Efficiency Spot Measurements	30 *(36 visited)*	28	Efficiency >=90% AFUE (6)* Unable to take measurements (3)* Unable to verify nameplate (1)

*Two of the units without spot measurements were also high-efficiency.

Table 19 shows the final results for average combined annual heating and water heating consumption and loads for both standard and combination boilers. The team chose to analyze combined annual heating and water heating consumption and loads for all boilers because field verification showed that 80 percent of standard boilers serve hot water loads. (Over half of the boilers listed as standalone systems in the program tracking data also served indirect water heaters.) The final ratio of metered to billing use for boilers of 1.01 demonstrates that the billing disaggregation predicted boiler combined heating and hot water consumption well. The results also showed that combination heating and hot water units tend to serve smaller annual heating and hot water loads than standalone boilers with or without indirect water heaters.

Table 19. Boiler Heating and Water Heating Consumption Findings

Metric	System Type	Mean	n	Relative Precision at 90% Confidence	Description
2013 – 2014 Heating and DHW Consumption, Billed	Standard	1,100	1,299	2.2%	Mean of site level 2013-2014 heating and hot water therms
	Combination	879	389	4.2%	
Typical Year Heating and DHW Consumption	Standard	1,071	-	-	Calibrated model therm consumption for a typical weather year
	Combination	847	-	-	
Ratio of Metered to Billed Use	All	1.01	38	4.2%	Mean ratio of metered 2012-2013 heating and hot water therm use to disaggregated billing data therm use for the same period
Final Estimate of Typical Year Heating and DHW *Consumption*	Standard	1,079	-	4.7%	Product of typical year heating consumption therms and mean ratio of metered to billed heating and hot water use
	Combination	853	-	5.9%	
Final Estimate of Typical Year Annual Heating and DHW *Load*	Standard	954	-	-	Product of typical year heating consumption and average verified efficiency
	Combination	755	-	-	

Table 20 shows the final adjusted ratios of in-situ to rated efficiency for standard new and high-efficiency boilers.

Table 20. Boiler Efficiency Findings

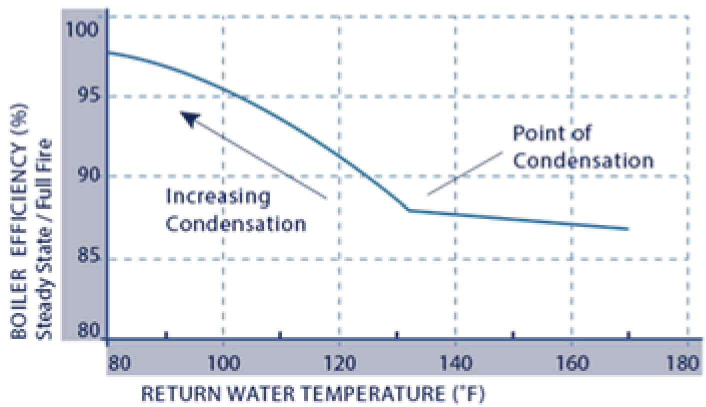
Metric	Mean	n	Relative Precision at 90% Confidence	Description
Ratio of Standard New In-situ to Rated Efficiency	0.97	25	5.5%	Adjusted ratio of efficiency spot measurements to rated AFUE for equipment rated <90% AFUE
Ratio of High Efficiency In-situ to Rated Efficiency*	0.94	42	-	Ratio of efficiency spot measurements to rated AFUE for equipment rated >=95% AFUE

*Since boiler efficiency was determined using long-term metering data, uncertainty for this parameter is included in the consumption findings. For details, see Appendix C. Uncertainty Calculations.

The team found that both standard and high-efficiency boilers performed below their rated efficiencies for two different reasons. The standard efficiency boiler spot measurement tests demonstrated combustion efficiencies equal to rated AFUE on average. As with standard furnaces, the team applied an adjustment factor to account for higher standby losses in gravity-vented equipment. Standby losses for standard efficiency boilers are greater than those for standard efficiency furnaces due to the combination of passive venting design and large thermal mass of the cast iron boilers with relatively high water capacity (as compared to high-efficiency boilers), which increases the passive stack losses in between active firing periods.[18] The team thus applied an estimated adjustment factor of 3 percent for boilers, greater than the 2 percent adjustment factor applied to standard efficiency furnaces. High efficiency boilers do not experience high passive stack losses because they have sealed combustion systems with combustion air blowers running only in conjunction with a firing event.

High-efficiency boilers also underperformed relative to their rated AFUE because they did not typically attain the return water temperature necessary (typically below 120-135°F) in order to achieve condensing of the water vapor in the flue gas which drives efficiencies above 90 percent. Figure 4 shows a typical efficiency versus return water temperature curve for a condensing boiler.

Figure 4. Condensing Boiler Efficiency[19]



Over the course of the winter, metered data showed that most systems spent the majority of heating hours operating with supply and return temperatures too high to achieve condensing. This is illustrated by the distribution of return water temperatures for each site: Figure 5 shows three examples.

[18] Some efficient boilers are designed with higher mass. If they are not passively vented, the mass may provide an efficiency benefit.

[19] Image source: Shen, Lester. Home Energy Pros, "High Efficiency Should Be a Drain: A Closer Look at Condensing Boilers." Blog post 10/29/13, Accessed 10/20/14. http://homeenergypros.lbl.gov/profiles/blogs/high-efficiency-should-be-a-drain-a-closer-look-at-condensing

Figure 5. Distribution of heating hours by return water temperature (RWT)

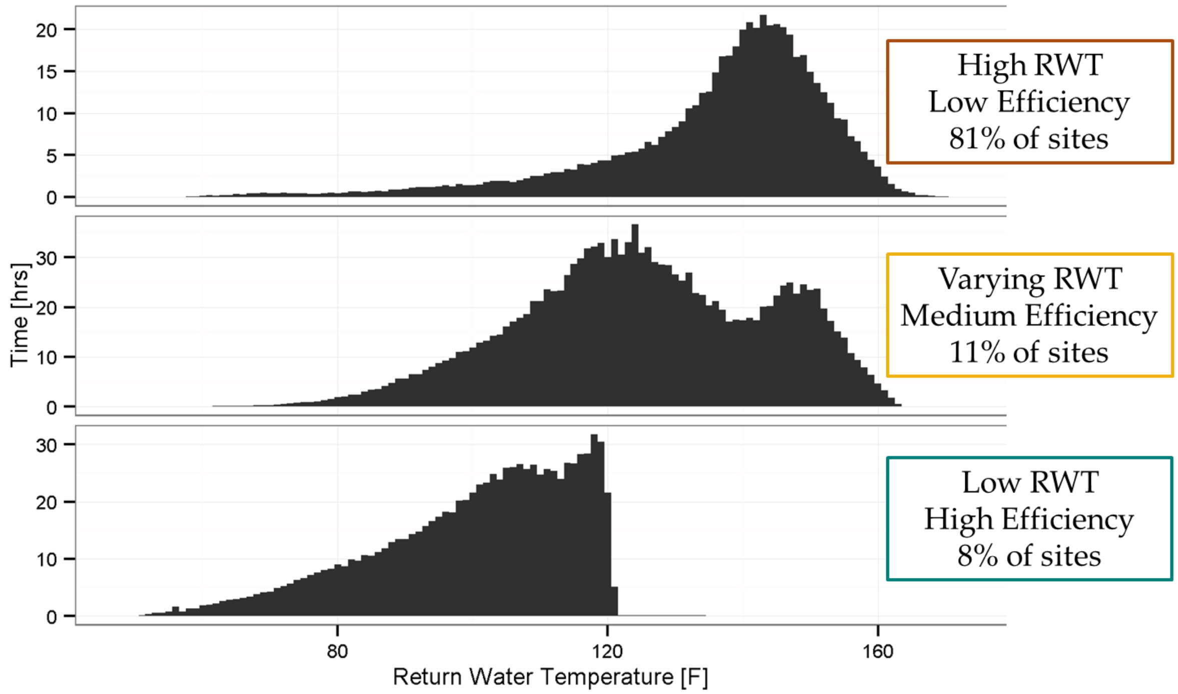


Table 21 and Table 22 show the final verified savings results for each boiler measure in the 2013 report TRM. Although the high-efficiency boilers performed below their rated AFUE, verified savings ranged from 106 - 113 percent of 2013 Report TRM savings values due to larger than assumed annual heating and hot water loads and below rated operating baseline efficiency. As previously noted, the verified boiler annual loads are higher than current assumptions because the annual loads account for the fact that the majority of standard boilers serve hot water as well as space heating.

Table 21. Standard Boiler Verified Savings

Measure	AFUE Type	Efficient AFUE	Baseline AFUE	Verified ROF Therm Savings	2013 Report TRM ROF Therm Savings	Relative Precision at 90% Confidence
90% AFUE Boiler ROF Baseline	Rated	92.7%	Rated: 82.0% Verified: 79.3%	110	104	10.0%
	Verified	87.2%				
95% AFUE Boiler ROF Baseline	Rated	95.0%		137	123	
	Verified	89.4%				
96% AFUE Boiler ROF Baseline	Rated	96.0%		148	131	
	Verified	90.3%				

For combination systems, the current baseline assumption is a boiler and a standard efficiency standalone water heater. The team also estimated savings for an alternative baseline of a boiler with an indirect water heater, which this evaluation found to be more common in Massachusetts.[20] The weighted average verified ROF savings use this evaluation finding and assume 80 percent of boiler homes have indirect water heaters and 20 percent have standalone water heaters.[21] The team assumed an average efficiency of 92.2 percent for the ≥90 percent AFUE efficient case and an efficiency of 95 percent for the ≥95 percent AFUE efficient case.

Table 22. Combination Boiler Verified Savings

Measure	AFUE Type	Assumed Efficient Case	Assumed Baseline Case	Verified ROF Therm Savings	Weighted Average Verified ROF Therm Savings	2013 Report TRM ROF Therm Savings	Relative Precision at 90% Confidence
≥90% AFUE Combination Boiler Indirect ROF Baseline	Rated	92.2% Combination	82% Boiler with Indirect	88	96	178	10.6%
	Verified	86.8% Combination	79.3% Boiler with Indirect				
≥90% AFUE Combination Boiler Standalone DHW ROF Baseline	Rated	92.2% Combination	82% Boiler 0.575 EF DHW	130			
	Verified	86.8% Combination	79.3% Boiler 0.575 EF DHW				
≥95% AFUE Combination Boiler Indirect ROF Baseline	Rated	95% Combination	82% Boiler with Indirect	112	121	-	
	Verified	89.4% Combination	79.3% Boiler with Indirect				
≥95% AFUE Combination Boiler Standalone DHW ROF Baseline	Rated	95% Combination	82% Boiler 0.575 EF DHW	155			
	Verified	89.4% Combination	79.3% Boiler 0.575 EF DHW				

[20] This estimate includes an engineering-based adjustment of eight therms of additional savings due to reduced standby losses from an indirect tank to a smaller combination tank.

[21] Based on indirect system prevalence in program tracking data (47 percent of non-combination systems) and percent of boilers tracked as standalone which on-site visits verified as actually serving indirect systems (58 percent).

Early Retirement Results

The evaluation team visited a total of 38 homes with early retirement units. Recruiting this particular group was a challenge, and this achieved total fell significantly short of the goal of 120 total visits (30 in each of the four groups). The team was able to convert the majority of leads that the HEAT Loan program identified, but there was not enough volume through this recruitment channel to meet the evaluation plan targets. The team also made several efforts to recruit directly through contractors, but as anticipated had difficulty getting leads even from those contractors who initially expressed interest. The evaluation offered customers $75 to participate and contractors $25 for each converted lead.

Table 23 shows the dispositions of the recruited sites. The team was not able to use all sites in the analysis of actual to rated performance due to inability to take spot measurements and missing or unverifiable nameplate data. The evaluation team relied on Preston's Guide, internet searches and direct calls to manufacturers to verify nameplate data. Gas boilers presented the greatest challenge for verifying nameplate data, as the consolidation of some boiler manufacturers resulted in loss of records for older model specifications.

Table 23. Early Retirement Site Disposition

Group	Total Sites Visited	Sites with Usable Measurements	Sites with Verified Rated AFUE	Total Usable Sites	Attrition Notes
Gas Boilers	11	11	6	6	Recent boiler manufacturer consolidation created gaps in nameplate data records
Gas Furnaces	10	7	8	5	Fan-vented flues prevented measurements at three sites; some illegible nameplates
Oil Boilers	9	9	9	9	-
Oil Furnaces	8	8	7	7	One unit with an illegible nameplate
Total	**38**	**35**	**30**	**27**	

Due to the small sample sizes and further attrition due to missing nameplate and measurement data, the team could not provide a statistically significant quantitative baseline adjustment for any group. As illustrated in Figure 6 and Figure 7, oil units generally performed worse relative to their nameplate efficiencies and gas equipment showed similar relative performance to the standard new group. This indicates that there may not be significant degradation of operating efficiency over the lifetime of these units. For both gas furnaces and boilers, the results also indicated that the average efficiency—rated and measured—of many units in this early retirement group may be higher than previously believed. The majority of the sampled equipment was measured and/or rated above 75 percent AFUE. The team also encountered a small number of furnaces above 90 percent AFUE: these units were all at least 15 years old.

Figure 6. Gas Equipment Rated and Measured AFUE by Age

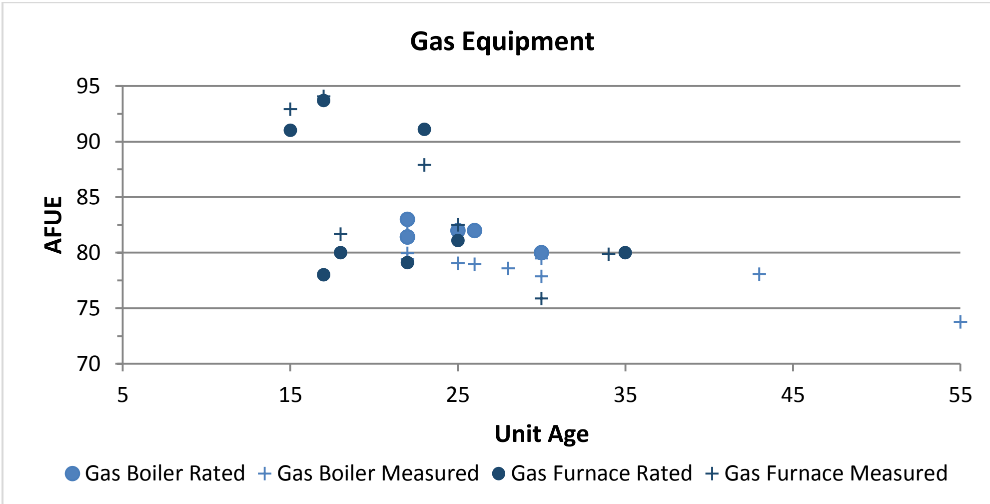
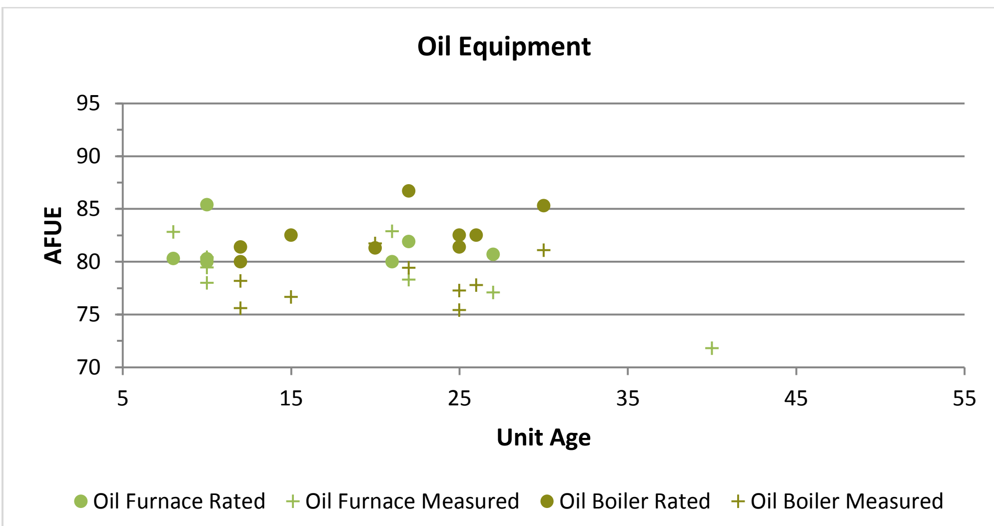


Figure 7. Oil Equipment Rated and Measured AFUE by Age



The distribution of efficiencies suggests that the current TRM baseline of 72.5 percent AFUE is too low for early retirement units less than 30 years of age. This assumption assumed more significant performance degradation, which this evaluation did not observe. Given this finding, the team estimated the early retirement baseline rated efficiency as the federal minimum efficiencies in place before the most recent standards came into effect. These efficiency standards have been in place since 1992, before the installation of many early retirement units under 30 years old. Given the similarity in actual performance relative to efficiency ratings between the early retirement and standard new group and the small early retirement sample sizes, the team applied the standard new adjustment factors to the early retirement rated baselines as shown in Table 24.

Table 24. Early Retirement Baselines

Measure	Rated Baseline	Baseline Adjustment	Verified Baseline
Furnaces	78%	1.01	78.9%
Boilers	80%	0.97	77.4%

Final Savings Results

The following tables present the evaluation team's recommended revised deemed savings values for each furnace[22] and boiler measure. The team used the percentages of early retirement and replace on failure installations found in the 2012 HEHE and Cool Smart net-to-gross evaluation[23] to weight savings from each group into a single value for each measure. Furnace savings are calculated assuming 11.7 percent early retirement, boiler savings are calculated assuming 13.2 percent early retirement, and combination boiler savings assume 32.2 percent early retirement.

Table 25. Furnace Results, 85 Percent AFUE Baseline

Measure	Verified ROF Therm Savings	Verified ER Therm Savings	Verified Average Savings	2013 Report TRM Therm Savings
95% AFUE Furnace	75	127	81	159
97% AFUE Furnace	86	139	92	173

Table 26. Boiler Results

Measure	Verified ROF Therm Savings	Verified ER Therm Savings	Verified Average Savings	2013 Report TRM Therm Savings
90% AFUE Boiler	110	140	114	120
95% AFUE Boiler	137	167	141	139
96% AFUE Boiler	148	178	152	147

Note: Savings include hot water loads from indirect water heaters.

[22] Furnace results using the previous TRM baseline of 80 percent AFUE may be found in Appendix E.
[23] "2012 Residential Heating, Water Heating and Cooling Equipment Evaluation: Net-to-Gross, Market Effects, and Equipment Replacement Timing." Cadmus Group, June 2013.

Table 27. Combination Boiler Results

Measure	Baseline	Verified ROF Therm Savings	Verified ER Therm Savings	Verified Average Therm Savings	Weighted Average Verified Therm Savings	2013 Report TRM Therm Savings
90% AFUE Combination Boiler	Standalone Water Heater	130	159	139	104	238
	Indirect Water Heater	88	111	95		
95% AFUE Combination Boiler	Standalone Water Heater	155	184	164	129	-
	Indirect Water Heater	113	136	120		

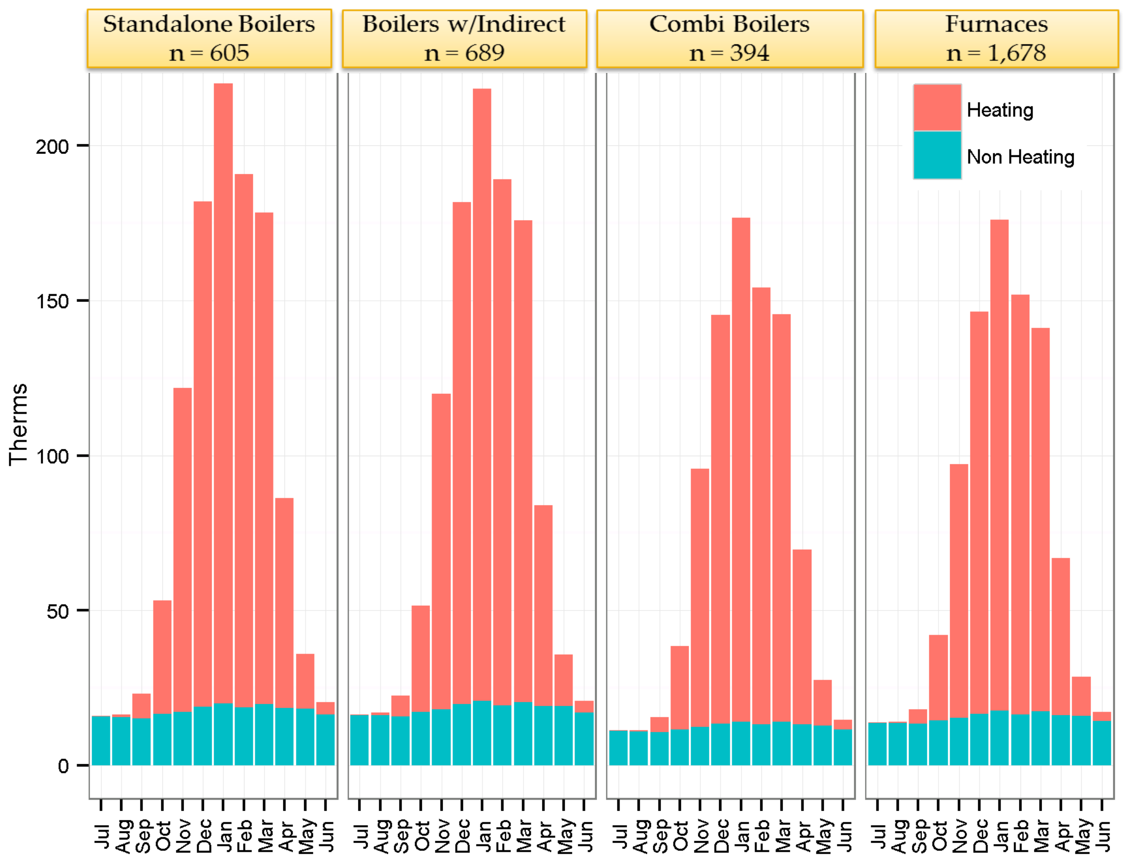
Program Considerations and Conclusions

Several findings from this study could have implications for the HEHE program. This section summarizes these findings and potential next steps for the program.

Heating Consumption Differs by Equipment Type

The billing data disaggregation and long-term metering analyses showed that on average, homes with furnaces and combination boiler systems use less gas for heating than homes with standalone boilers or boilers with indirect water heaters. This is summarized in Figure 8, which shows the average heating and non-heating consumption by equipment type. These discrepancies are likely a result of differences in housing stock: as shown with HES participant home characteristics data, furnaces are more likely to be in newer and/or smaller homes (See Appendix D for additional detail). The PAs should use updated deemed savings values that reflect these differences and keep these patterns in mind when planning HEHE and other programs.

Figure 8. Average Heating and Non-Heating Consumption by Equipment Type

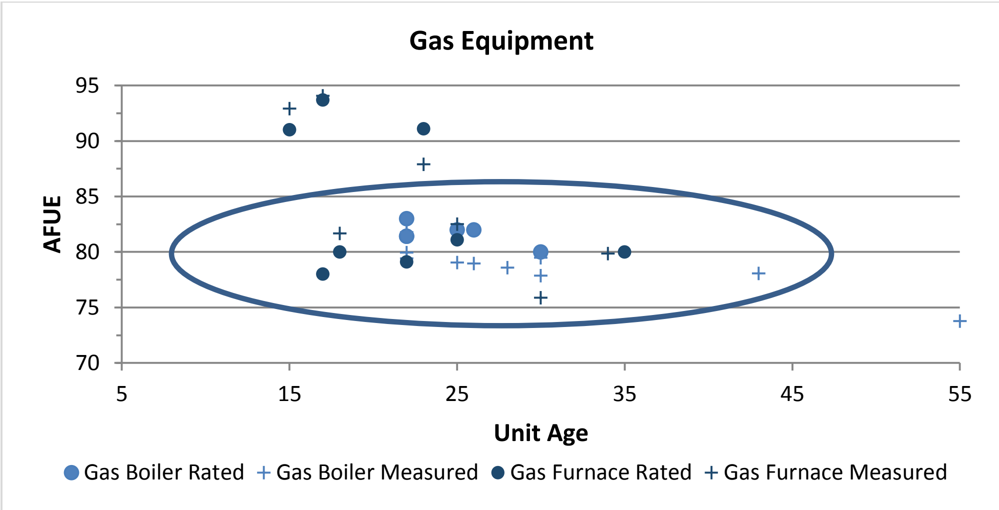


Early Retirement Baselines Should Be Updated

The target group for this research was still functioning units less than 30 years old which participants are choosing to replace early. For this group (though not for the very old units specifically targeted by early replacement programs), this evaluation's research suggests that the deemed baseline of 72.5 percent

AFUE is too low. As shown in Figure 9, the majority of sampled gas units have measured and/or rated AFUEs between 75 percent and 85 percent. The team used previous federal minimum efficiency standards (in place since 1992) to calculate savings and recommends implementing these baselines moving forward. If early retirement program participation increases in the future, the PAs may need to conduct broader research on early retirement units less than 30 years old.

Figure 9. Gas Equipment Rated and Measured AFUE by Age



Combination System Baseline Requires Updating

The evaluation team analyzed program tracking data and on-site system type data and found that the majority of "standard" boilers (i.e. not combination systems) in the program have indirect water heaters and not standalone water heaters. This suggests that the majority of combination systems are likely replacing boilers with indirect water heaters. The evaluation team used a weighted average of 80 percent indirect water heaters and 20 percent standalone water heaters based on the evaluation sample findings. Since the baseline system has a significant impact on savings, the PAs should consider conducting additional research and/or requiring application information on what combination systems are replacing.

High-Efficiency Boiler Installation Practices Leave Savings on the Table

This study demonstrated that most boilers operate well below their rated efficiency and operating efficiency could be improved through contractor and customer education. The main cause for low efficiency performance is a lack of aggressive outdoor air reset supply temperature curves: when high-efficiency boilers operate at supply temperatures above 140°F, return water temperatures often exceed the condensing range (~130°F and below) and efficiency begins to drop off significantly. Outdoor reset controls can reduce the time a boiler spends running at high supply and return temperatures by lowering supply temperature as outdoor air temperature increases and the home needs less heat. Over 50 percent of boilers in the metering sample showed no evidence of effectively programmed outdoor reset controls, and only 12 percent showed outdoor reset curves aggressive enough to demonstrate significant condensing. The team conducted a high-level analysis of optimal outdoor reset curves and estimates that in a best-case scenario, a boiler in Massachusetts with well-programmed outdoor reset controls could see an operating efficiency improvement of up to 3 to 4 percentage points from the average efficiency of 88.4 percent observed in this study.

The obvious programmatic solution to this problem is to improve contractor education on outdoor reset controls and enact a quality installation program component to push contractors to implement these controls more effectively. This is a simple, low-cost way to recoup some of the savings left on the table. However, this step alone will not fully capture boiler savings potential in all homes. In order to maintain effective outdoor reset schedules, two criteria must be met:

1) Distribution must be sized such that boilers can meet home loads at lower supply temperatures and/or have a large enough temperature differential to consistently deliver lower return water temperatures at higher supply temperatures.
2) Customers must understand what to expect from their systems and set thermostat schedules accordingly, or thermostats must be “smart” enough to adapt to condensing boilers’ capabilities (i.e., begin morning warm-up well in advance of scheduled morning temperature change)

The following sections describe the issues behind each of these criteria and potential options the program should consider to increase the number of installations meeting them.

Distribution Sizing and Design

Many heating distribution systems in Massachusetts were designed for older boilers which operated at high supply temperatures (180°F would be typical). When new high-efficiency systems are installed, best practice is to perform a Manual J calculation to determine the loads in each zone and whether the existing distribution can meet those loads at lower supply temperatures. In order for the boiler to condense for the majority of the heating season, the distribution system must be able to meet zone loads with 140°F supply water on all but the coldest “design days.” This supply temperature would typically ensure a low enough return water temperature for the boiler exhaust air to condense most of the time. Many homes may have zones which would require additional distribution in order to meet peak loads at lower supply temperatures.

One option for the program is to focus contractor education on understanding this issue and require distribution sizing analysis with each condensing boiler installation. This analysis would require:

1) Conducting a Manual J calculation for heating loads in each zone served by the new boiler
2) Calculating heat delivery for existing distribution at supply temperatures of 140°F or below
3) Installing additional distribution as needed to ensure loads can be met while returning water at temperatures in the condensing range

There are several options for adding distribution, such as high-efficiency panel radiators. Figure 10 illustrates two examples of panel radiators, which come in many sizes and styles.

Figure 10. Example Panel Radiators[24]

An alternative to adding distribution is reducing loads in homes with boilers. With measures like improved insulation, windows or air sealing, zone loads will decrease, meaning that the heating needs can be met with cooler supply water.

However, additional distribution and envelope improvements can both be costly upgrades. The evaluation team recommends conducting additional research on the costs and benefits of these options.

Homeowner Expectations

Homeowners who are accustomed to a standard boiler supplying 180°F to their radiators will need to adjust to lower supply temperatures. Lower supply set points and aggressive outdoor reset programs ensure that boilers operate at a steady, relatively low output. The radiators may not feel as hot even when the heat is on, and it will take longer for rooms to come to temperature after a thermostat setback. This can lead to homeowner complaints if residents are accustomed to getting immediate responses from their heating systems. For example, when customers program a night setback the system must warm the house back up in the morning—and homeowners accustomed to a system running 180°F will expect this to happen relatively quickly. A new condensing boiler can provide this kind of response if programmed to allow high supply temperatures, but will not achieve high efficiency levels while doing so. Customers experiencing these patterns for the first time will often call back contractors, who may remove any outdoor reset controls that had been programmed or increase the supply water temperature set point. Unless homeowners understand their new systems and are willing to put in the time to fine-tune them, this pattern will continue and boiler savings will not reach their full potential. Use of improved thermostats with built-in "ramping" of temperatures could also improve the customer experience with these systems and allow more aggressive outdoor resets to be used.

The evaluation team recommends that the program consider including a customer education component to contractor training, so that contractors can educate homeowners on how to manage their new boilers:

- The boiler may run more efficiently without setbacks if a constant, moderate temperature set point is used

[24] Image sources: http://www.designerradiatorsdirect.co.uk/blog/amazing-benefits-of-flat-panel-radiators http://www.jrfheating.com/radiatorsAndTowelHeaters_panel.htm

- If setbacks are desired, customers should anticipate longer warm-up times and program temperature changes accordingly. I.e., if the kitchen should be warmed up to 68 degrees at 7:00 am, the time setting on the thermostat may need to be well before then.

The team also conducted research on thermostat options that could enhance homeowner experiences with proper outdoor reset controls. Unfortunately, it appears that there are not many available options. Some "smart" thermostats such as the Nest can learn warm-up behavior, but do not appear to interact very well with systems that have outdoor reset controls employed.[25] Tekmar makes a thermostat which interacts with outdoor reset controls and can override an outdoor reset curve during morning warm-up ("boost" feature). However, this feature could decrease energy savings since it is focused on comfort and increasing boiler supply temperatures beyond the reset curve.

Given the uncertainty around the effects of programmed setbacks on condensing boiler performance, the team recommends considering additional research in this area to determine whether programmable thermostat savings are appropriate for homes with condensing boilers.

Summary of Boiler Recommendations

The evaluation team recommends adding some level of quality installation component to the HEHE program for high-efficiency boilers. At minimum, the program should consider improving contractor education on outdoor reset controls and investigate incentive options that could increase proper outdoor reset control installation.

Because getting boiler controls implemented correctly is not always a prescriptive, "one size fits all" process, we also recommend continuing to research the benefits and costs of the additional components described above:

1) Training contractors to assess and consider the following options when installing new systems:
    a. Running Manual J calculations for each zone served by the new boiler to determine whether current distribution is adequate to meet home loads at 140°F supply temperature
    b. Adding distribution to meet home loads at 140°F supply temperature
    c. Making envelope improvements such that distribution can meet home loads at 140°F supply temperature
2) Educating homeowners on how to set thermostats for optimum performance

In addition to researching these HEHE initiative options for condensing boilers, the team recommends that the PAs consider additional research in this area to determine whether current programmable thermostat savings estimates are appropriate for homes with condensing boilers.

[25] Nest "True Radiant" feature claims to adjust for lag in radiant systems: https://nest.com/support/article/What-is-True-Radiant
Nest customer feedback indicates lack of compatibility with outdoor reset: https://community.nest.com/ideas/2093

Appendix A. Billing Data Disaggregation

The evaluation team constructed a disaggregation tool to separate the heating and non-heating portion of the post-installation consumption data using the following steps:

1. Estimate non-heating consumption by month using:
   a. Building America inputs (i.e. load shapes and input capacities of non-heating gas appliances)[26]
   b. Installation rates of gas non-heating appliances based on the Massachusetts Residential Appliance Saturation Survey (RASS)[27]
2. Calculate average summer usage based on the mean of participants' July and August gas consumption. July and August usage are most representative of non-heating only consumption.
3. Calibrate the model's non-heating consumption to the summer average calculated in Step 2. This step essentially scales the load shape profile to typical summer usage.
4. Calculate the percentage of heating versus non-heating gas consumption for the post-installation data for each month.
5. Apply the heating percentages by month to each participant's usage to disaggregate the heating portion of the gas consumption data. This calculation is summarized in the following algorithm:

$$HPF_{i,j} = \frac{\frac{\sum_1^k C_{i,j,k}}{k} - C_{i,j,k} * (C_{non-heating})_{i,j}}{\frac{\sum_1^k C_{i,j,k}}{k}}$$

Table 28. Heating Percentage Factor Inputs

Parameter	Description	Units	Source
i	Subscript to specify month (i=1,2,…,12)	–	N/A
j	Subscript to specify year (j=2009,…,2012)	–	N/A
k	Subscript to specify dataset (k=1,2,…,387)	–	Billing data
$HPF_{i,j}$	Heating percentage factor: percentage of gas consumption allocated to heating in month i and year j	%	Calculated
$C_{i,j,k}$	Total heating and non-heating gas consumed in month i, year j, and dataset k	$Therms/month$	Billing data
$(C_{non-heating})_{i,j}$	Average non-heating gas consumption percentage in month i and year j	%	Calculated

Non-heating End Use Calculations

The evaluation team used the following inputs and calculations to determine billing data disaggregation base consumption:

[26] Building America Benchmarking Program Database. U.S. Department of Energy, 2010.

[27] Siems, Antje. "Massachusetts Residential Appliance Saturation Survey (RASS), Volume 1: Summary Results and Analysis." Opinion Dynamics Corporation, 2009. The newer study from 2012 does not provide water heater fuel type by heating fuel type, thus the team used data from RASS 2009. The team also collected home characteristics on site and compared these to the RASS data: as the results were very similar, the team elected to use the RASS values since that study had a much larger sample size.

Water Heater Gas Consumption

$$(C_{Water\ Heater})_i = \left((C_{UA})_i + (C_{Heating})_i\right) * \ n_i * MS_{water\ heater}$$

$$C_{UA} = \frac{(T_{tank} - T_{ambient}) * UA_{tank} * 24\ hrs/day}{\eta_{heating\ element} * 100{,}000\ btu/therm}$$

$$C_{Heating} = \frac{DHW * \frac{Occ_{Nicor}}{Occ_{BA}} * 8.33 * (T_{tank} - T_{mains})}{\eta_{heating\ element} * 100{,}000\ btu/therm}$$

Parameter	Description	Units	Source
i	Subscript to specify month (i=1,2,...,12)	–	N/A
$(C_{Water\ Heater})_i$	Gas consumption of water heater in month i	$therms/month$	Calculated
$(C_{UA})_i$	Gas consumption due to heat loss through tank walls in month i	$therms/day$	Calculated
$(C_{Heating})_i$	Gas consumption due to heating water from the water mains in month i	$therms/day$	Calculated
n_i	Number of days in month i	$days/month$	N/A
$MS_{water\ heater}$	Market share of gas [versus electric] water heaters	%	RASS 2009
T_{tank}	Temperature set-point of water tank (assumed 125 ˚F)	°F	Illinois TRM
$T_{ambient}$	Temperature of ambient air near water tank (assumed 70 ˚F)	°F	Assumed
$(T_{mains})_i$	Location-specific temperature of water mains in month i	°F	Building America Benchmark
UA_{tank}	Thermal transmittance through the tank walls	$\frac{btu}{hr - °F}$	Building America Benchmark
$\eta_{heating\ element}$	Efficiency of the heating element in the water heater (Assumed 76 percent)	%	Building America Benchmark
DHW_i	Daily hot water demand in month i	Gal/day	Building America Benchmark
Occ_{Nicor}	Average household occupancy in the Massachusetts (2.6)	$Persons/household$	RASS 2009
Occ_{BA}	Average household occupancy determined by Building America (2.6)	$Persons/household$	Building America Benchmark

Clothes Dryer and Stove/Oven Consumption

The evaluation team used stove, oven and dryer load shapes from Building America.

Appendix B. Metered Data Analysis

After retrieving the data loggers, the evaluation team processed the data through two main steps for furnaces, and three steps for boilers. For furnaces, the first step was data quality control (QC) and cleaning, and second, transforming the data from a series of on/off events to percent on per hour in order to compute hourly gas consumption for each site. For boilers, an additional round of QC, cleaning, and transformation was required for the more involved spot measurements that accompanied the long term measurements at each site. The long term data for boiler sites also included 15-second data for the supply and return water temperature, which required additional QC checks and enabled a more detailed analysis of system performance.

Calculations: Furnaces

The evaluation team converted the filtered logger data into percent "on" per hour for the logging time period. For dual stage furnaces, because the low stage logger was also "on" when the furnace ran in high stage, the evaluation team subtracted the high stage operation time from the low stage operation time to determine the actual low stage operation time per hour as outlined in the algorithm below:

$$(RunTime_{low})_i = (RunTime_{total})_i - (RunTime_{high})_i$$

Parameter	Description	Units	Source
$(RunTime_{low})_i$	Low stage furnace run time in hour i	$time$	Calculated
$(RunTime_{total})_i$	Total furnace run time in hour i	$time$	"Low" stage logger data
$(RunTime_{high})_i$	High stage furnace run time in hour i	$time$	"High" stage logger data

The evaluation team then converted the run time in each stage to actual gas consumption using the gas consumption spot measurements and the average BTU content of natural gas in Massachusetts.[28] The algorithm below outlines the method for calculating the gas consumption of a dual stage furnace.

$$Gas\ Consumption_i = ((RunTime_{low})_i * InputCap_{low} + (RunTime_{high})_i * InputCap_{high}) * BTU\ Ratio$$

[28] The BTU ratio is a conversion factor for converting cubic feet to BTUs. This ratio varies seasonally and geographically. The final number used is 1034 Btu/ft3, which is the Heat Content of Natural Gas Consumed in Massachusetts in 2013 as provided by the Energy Information Administration (EIA). Online source: http://www.eia.gov/dnav/ng/ng_cons_heat_a_epg0_vgth_btucf_a.htm

Parameter	Description	Units	Source
$Gas\ Consumption_i$	Furnace gas consumption in hour i	$ft^3\ gas$	Calculated
$(RunTime_{low})_i$	Low stage furnace run time in hour i	$time$	Calculated in algorithm above
$(RunTime_{high})_i$	High stage furnace run time in hour i	$time$	"High" stage logger data
$InputCap_{low}$	Gas input rate capacity of the low stage	$\frac{BTU}{hour}$	Nameplate or onsite spot measurement
$InputCap_{high}$	Gas input rate capacity of the high stage	$\frac{BTU}{hour}$	Nameplate or onsite spot measurement
$BTU\ Ratio$	BTU to cubic feet conversion factor	$\frac{ft^3\ gas}{BTU}$	2013 MA Average, EIA

The evaluation team summed the gas consumption in each hour to determine the total gas consumption for the duration of the metering period. The team did not include modulating furnaces in the metering sample because they would require a more complex metering approach. The team does not believe this biases the results because we would expect ratios of billing results to metering results to be similar across modulating and non-modulating units even if actual consumption differs.[29]

Calculations: Boilers

Using the combination of detailed spot measurements and long term data collection at each of the boiler sites, the team estimated both system efficiency and gas consumption of modulating boilers. The steps in the calculations of system efficiency and consumption are outlined here, and explained in more detail below.

1. Calculations with spot measurement data (for each site)
    a. Determine how combustion efficiency varies with return water temperature.
    b. Determine the implied mass flow rate of water through the boiler.
2. Calculations with long term data (for each 15-second interval of data for each site)
    a. Estimate combustion efficiency based on return water temperature
    b. Estimate gas consumption using measured temperature of water leaving and entering the boiler, water mass flow rate, and combustion efficiency estimate.

Estimating boiler combustion efficiency from return water temperature

For condensing boilers, combustion efficiency is known to vary with return water temperature, as in the following:

$$\eta = f(T_R)$$

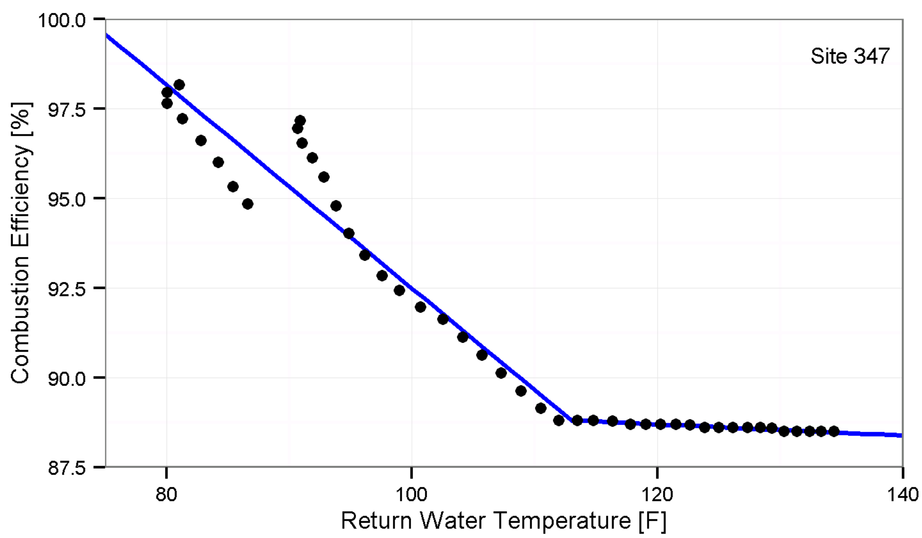
Where:

[29] Modulating furnaces were approximately 17 percent of the rebated furnaces in 2013.

Parameter	Description	Units	Source
η	Combustion Efficiency	%	Measured
T_R	Return Water Temperature	°F	Measured

Specifically, efficiency is high at lower return water temperatures, and efficiency is low at high return water temperatures. Furthermore, there is generally a point at which the relationship between efficiency and return water temperature changes dramatically; this change-point is typically in the range of 115-135°F. As return water temperatures drop below this change-point, the efficiency goes up dramatically, and as return water temperatures increase above this change point, efficiency goes down, but at a less dramatic rate. This relationship is illustrated in Figure 11.

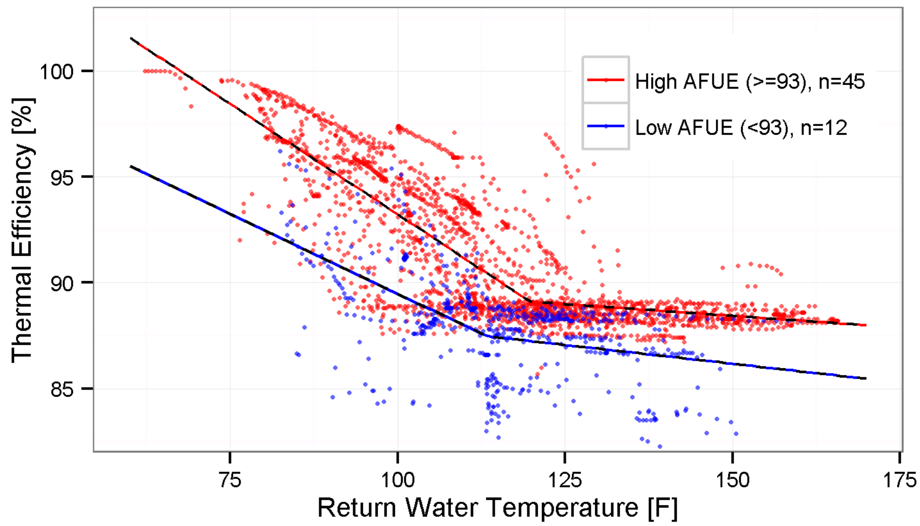
Figure 11. Spot measurement data of return water temperature and combustion efficiency for site 347



The blue line in Figure 11 represents a segmented linear model (SLM). Segmented linear models are essentially the combination of multiple linear models, with change points defining where each sub-model is relevant. For sites like the one in Figure 11, which had ample data across a wide range of temperatures and efficiencies, a unique site-level SLM was created to predict combustion efficiency from return water temperature.

For sites that lacked sufficient data to generate an individual SLM, data was aggregated for multiple sites and two average SLMs were created, one each for sites with high efficiency boilers, and for sites with low efficiency boilers. The split between high and low AFUE was at 93 percent AFUE, this essentially divided the boilers into one group of mostly 95 percent AFUE, and another group of <90 percent AFUE. A graphic of the SLMs for high and low AFUE systems is given in Figure 12.

Figure 12. Segmented linear models (SLMs) and raw data for high and low efficiency systems



Estimating water mass flow rate

During spot measurements, water temperatures (T_S, $T_{R,}$ ΔT), combustion efficiency (η), and gas input rate ($\dot{Q}_{INPUT}$) were all measured simultaneously. With this set of simultaneous measurements, we can estimate the rate of water flow through the boiler ($\dot{m}$). Three basic relationships are combined into the final equation for estimating water mass flow rate. First, the rise in water temperature (ΔT) is the difference between supply and return.

$$\Delta T = T_S - T_R$$

Second, the heat transferred to water by the boiler is given by the following heat transfer equation[30].

$$\dot{Q}_{OUTPUT} = \dot{m} C_p \Delta T$$

Third, the boiler output rate is a function of the fuel input rate and combustion efficiency, as given below.

$$\dot{Q}_{OUTPUT} = \dot{Q}_{INPUT} * \eta$$

Combining the above three relationships, the final formula for estimating water mass flow rate is given below.

$$\dot{m} = \frac{C_p \Delta T}{\dot{Q}_{OUTPUT}} = \frac{C_p \Delta T}{\dot{Q}_{INPUT} * \eta}$$

Where:

[30] In all equations, a dot ($\dot{x}$) above a variable indicates that it is a time-dependent rate, as in water flow rate or energy consumption rate.

Parameter	Description	Units	Source
η	Combustion Efficiency	%	Measured
T_R	Return Water Temperature	°F	Measured
T_S	Return Water Temperature	°F	Measured
ΔT	Temperature Difference ($T_S - T_R$)	°F	Computed
C_p	Heat Capacity of Water	Btu/(gal°F)	Measured
$\dot{m}$	Water Mass Flow Rate	gpm[31]	Computed
$\dot{Q}_{OUTPUT}$	Energy Output Rate	Btu/hr	Computed
$\dot{Q}_{INPUT}$	Energy Input Rate	Btu/hr	Measured

Note that in each of the spot measurements there is some measurement error. All of this error is inherent in the measured parameters in the formulae above, so the final estimate of water mass flow rate includes any measurement error. This error is assumed to be the same during spot measurements and long term data collection, leading to final estimates of boiler performance and fuel consumption that are not biased by measurement error.

Long term data calculations

With the combination of spot measurements and long term metered data, the team estimated two performance metrics for each site: seasonal efficiency and total fuel consumption. Since most boilers serve both space heating and hot water heating loads, the fuel consumption estimate includes a percentage for each end-use. Spot measurement data provided both a means to estimate instantaneous combustion efficiency from return water temperature ($\eta = f(T_R)$), and a method for estimating fuel consumption rate from the combination of combustion efficiency and temperature rise across the boiler, as in the following equation.

$$\dot{Q}_{INPUT} = \frac{\dot{m} C_p \Delta T}{\eta}$$

The final parameter needed to estimate gas consumption is the time that the boiler is on, and an indicator for whether the boiler was serving a DHW load or a space heating load. Since temperature data was collected at 15-second intervals, it was possible to estimate system efficiency and fuel consumption rate every 15 seconds. Multiplying the fuel input rate with the time interval (dt) and the energy density of natural gas (ρ_{NG}) provides an estimate of gas consumption, as in the equation below.

$$Q_{NG} = \sum_{i,GAS=ON} \dot{Q}_{INPUT} * dt_i * \rho_{NG}$$

In this study, seasonal efficiency is defined by the following equation, or the ratio of total system output and total system input.

$$\eta_S = \frac{Q_{OUTPUT}}{Q_{INPUT}}$$

[31] Note that heat output and input are expressed in Btu/hr, while water mass flow rate is in gallons per minute, so a conversion factor of 60 minutes per hour is used in practice, but not shown in formulae for clarity.

Broken down into its constituent parameters, the above equation can be simplified to terms of measured variables only, as in the below equation.

$$\eta_S = \frac{Q_{OUTPUT}}{Q_{INPUT}} = \frac{\sum(\dot{m}C_p\Delta T_i dt_i)}{\sum(\dot{m}C_p\Delta T_i dt_i/\eta_i)} = \frac{\sum(\Delta T_i dt_i)}{\sum(\Delta T_i dt_i/\eta_i)}$$

Note that in the above equation, water mass flow rate is a constant on both sides of the ratio, and cancels out. This means that long term data can still be used to estimate seasonal efficiency for sites that lacked sufficient spot measurement data to provide a site-specific water mass flow rate estimate.

Table 29. Boiler Calculation Nomenclature

Parameter	Description	Units	Source
η_S	Seasonal Efficiency	%	Computed
Q_{OUTPUT}	Energy Output	Btu	Computed
Q_{INPUT}	Energy Input	Btu	Computed
Q_{NG}	Metering Period Natural Gas Consumption	ft^3	Computed
dt	Time interval	sec	Measured
ρ_{NG}	Energy Density of Natural Gas	Btu/ft^3	EIA[32]
i	Time Interval index	-	-

Data QC and Cleaning

The team performed extensive quality control and data cleaning to check data for errors and transform it from its raw form. This section details the key qualities which the team used to identify valid data.

Boiler Spot Measurements

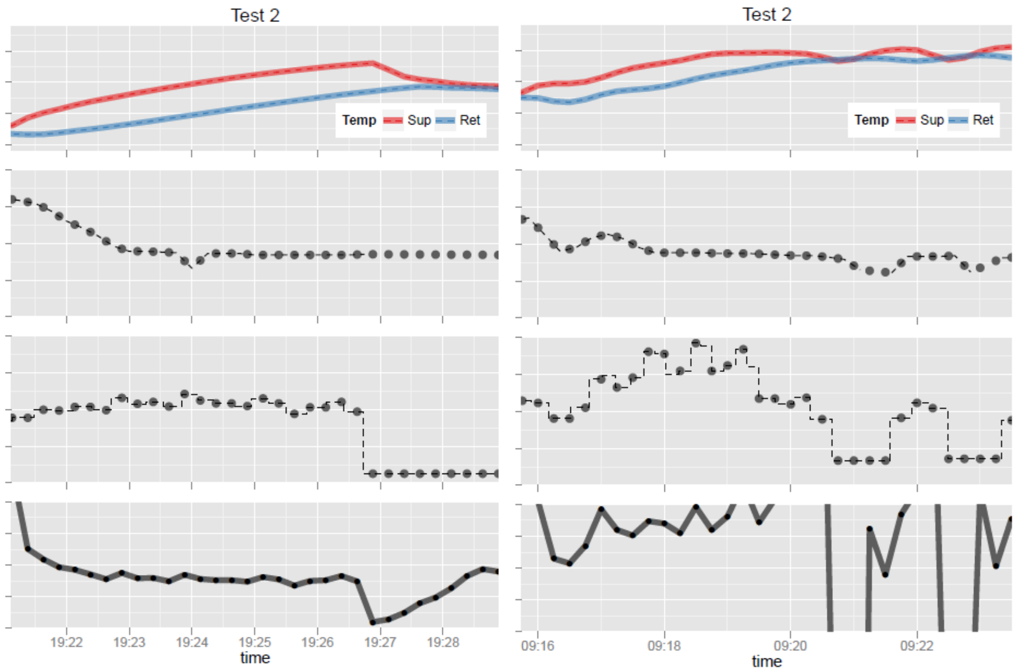
The team checked that the spot measurement data for boilers to ensure that the following conditions were met:

- A consistent, usable estimate of water mass flow rate could be attained
- The boiler was not short-cycling on and off during the tests
- The spot measurements covered a wide range of boiler performance.
    - For boilers that served both space and water heating loads, this range included tests to determine operation in condensing and non-condensing mode, low and high output, and an additional test to characterize performance when serving a hot water load.

Visual QC was the primary method for determining what data was usable, and what was not. Figure 13 shows the three measured variables and one computed variable used to assess each site. From top to bottom they are water temperatures, combustion efficiency, gas input rate, and computed water mass flow rate. The left column of panels corresponds to a successful set of test data, while the right column corresponds to data that could not be used.

[32] EIA database: http://www.eia.gov/dnav/ng/ng_cons_heat_a_epg0_vgth_btucf_a.htm

Figure 13. Spot Measurement QC Examples. Usable data in the left plot, unusable data in the right



For the test data shown on the left, the boiler was performing normally during the test, and operation in high- and low-efficiency ranges was observed. Additionally, with the exception of the beginning and end of the test, the implied water mass flow rate is fairly constant. In the end, the team removed data from the beginning and end of this test and kept the data corresponding to steady-state boiler performance.

For data shown on the right of Figure 13, the boiler was cycling on and off during the test, and both the temperature difference between supply and return and the gas input rate were varying significantly and rapidly, leading to a high and inconsistent estimate of water mass flow rate. This is an example of an entire test that did not yield any usable data.

Long Term Data

For both boilers and furnaces, the primary driver of gas consumption is the gas valve within the heating equipment. When this valve is open, the equipment is consuming fuel, thus a very reliable set of on/off data is required for each site. The next section discusses the visual QC approach taken for on/off loggers, which applies to furnace gas valves, boiler gas valves, and any pump or fan motors, such as domestic hot water pumps.

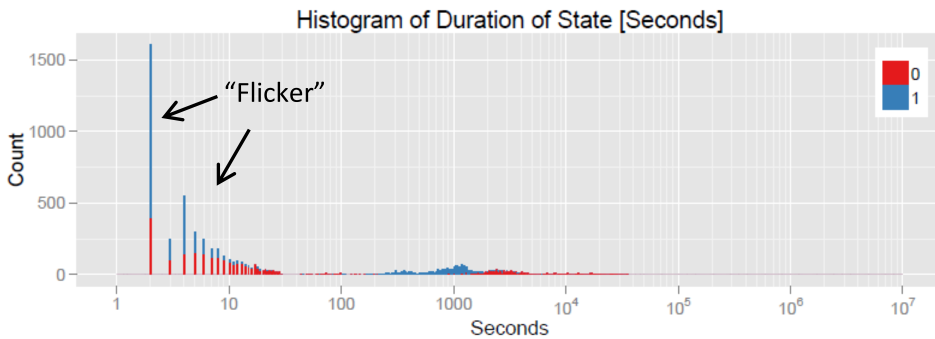
State Logger Visual QC

The evaluation team first analyzed the logger data for quality. We constructed histograms of time between state changes (example in Figure 14) to identify "flicker"[33] in each logger file and applied flicker filters to reflect the actual operation of the furnace. Under the condition where the time between state

[33] "Flicker" occurs when the data logger quickly oscillates between the "on" state and "off" state without characterizing the true operation of the furnace or boiler.

changes is less than the flicker filter limit, the flicker filter corrects the data to the previous state before flicker was observed.

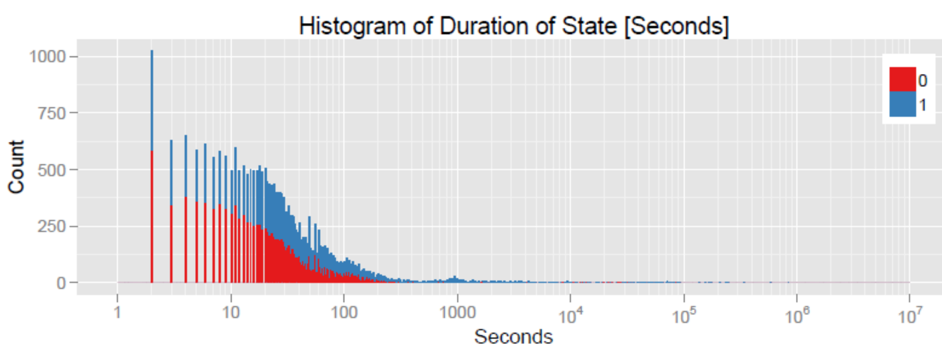
Figure 14. Example of Flicker Identification via Histogram Chart of Event Duration



The x-axis is a logarithmic scale of event duration, and the y-axis shows the frequency of event durations. The two spikes and two and three seconds likely indicate flicker (due to nearby currents or startup pulses) and not actual gas consumption.

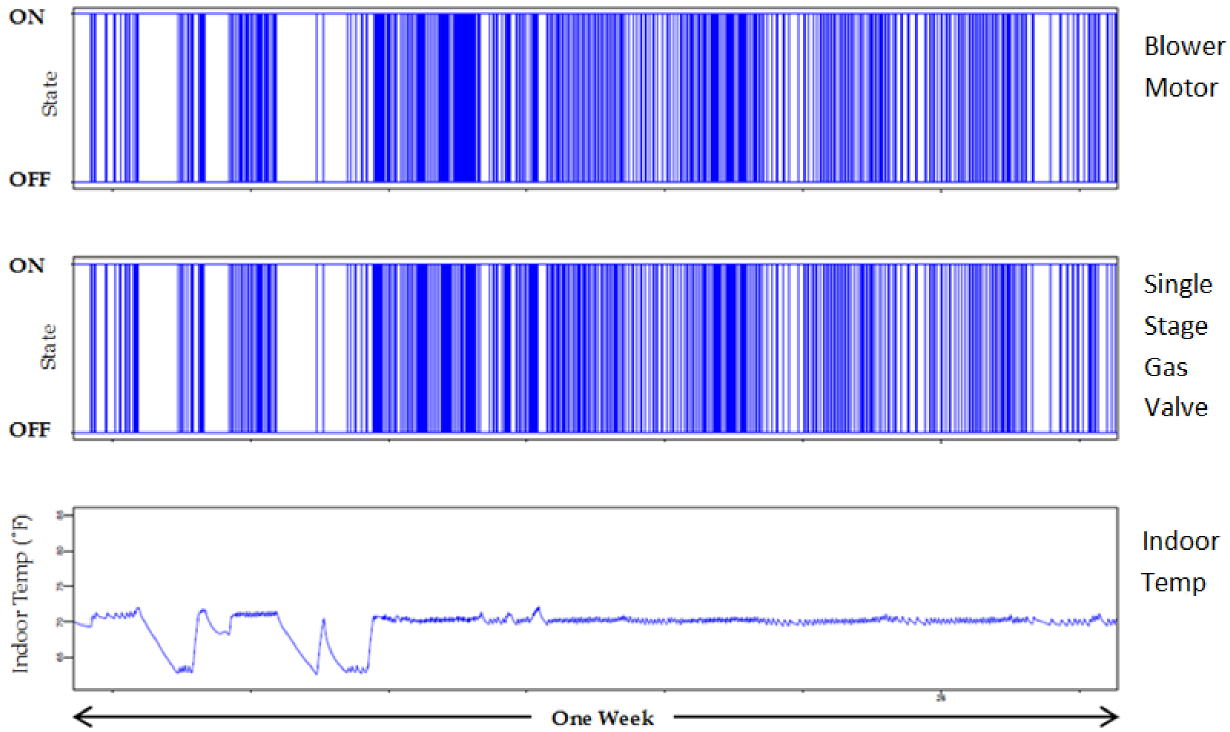
The evaluation team set custom flicker filters for loggers that showed significant flicker slightly above 10 seconds. In the example shown in Figure 15, the team determined that boiler operation is better characterized by setting a flicker filter limit of 20 seconds, which still only reduced the furnace run time estimation by 0.44 percent compared to no flicker filter limit. Generally flicker filters had a trivial effect (between 0 percent and 0.8 percent) on the estimation of furnace run time.

Figure 15: Example of High Flicker Identification via Histogram Chart of Event Duration



For furnaces, Navigant generated weekly, monthly, and seasonal graphs to ensure the blower motor operation, gas valve operation, and indoor temperature data were consistent. Figure 16 shows an example of these weekly graphs, which in this particular case Navigant determined the dataset to be reasonable based on matching blower (top) and single stage gas valve operation (middle) and the temperature setbacks (bottom) associated with lack of furnace operation.

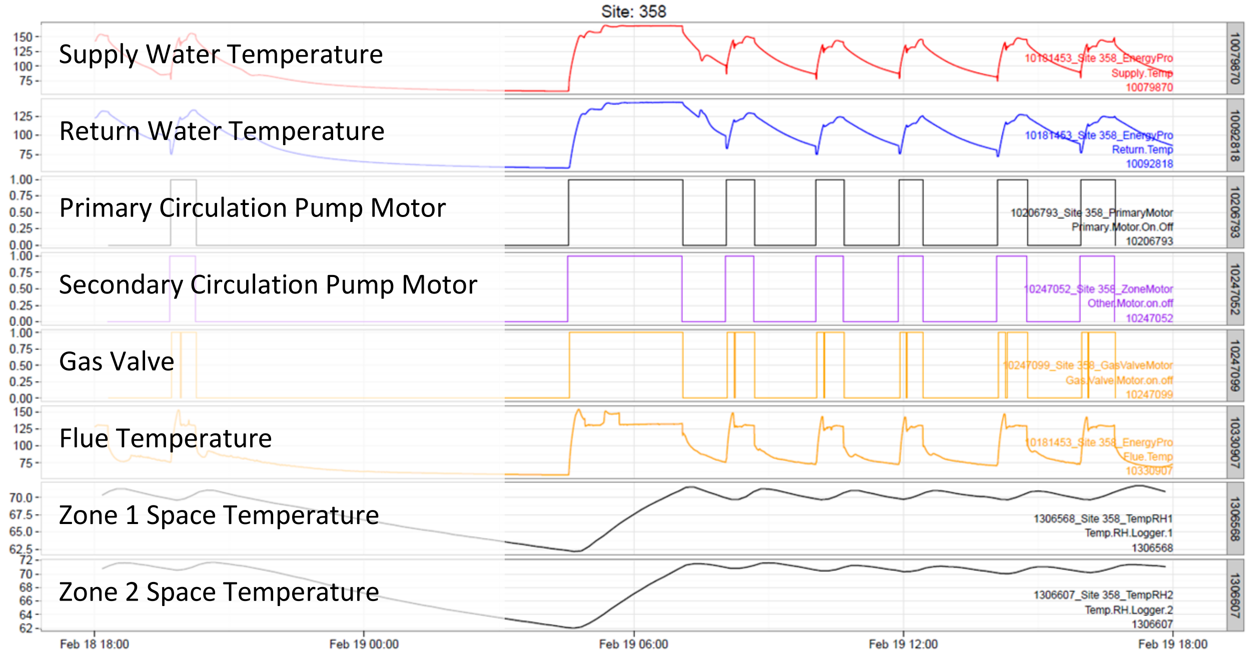
Figure 16: Example Weekly Furnace Operation Graphs



Source: Navigant analysis

For boilers, the evaluation team generated daily and seasonal graphs to ensure circulation pump motor operation, gas valve operation, flue temperature, supply and return water temperature, and indoor temperature data were consistent. Figure 16 shows an example of these daily graphs, which in this particular case the team determined the dataset to be reasonable based on matching primary and secondary circulation pumps, single stage gas valve operation, supply and return water temperatures, flue temperature and the space temperatures associated with heating events.

Figure 17. Example Daily Boiler Operation Graphs



The evaluation team also used meter readings from the installation and retrieval visits as a quality check to ensure that the calculated furnace consumption estimates did not exceed the home's total metered gas use for the same time period. This step improved the team's ability to identify potential "problem" sites and analysis errors.

Boiler Specific Data QC

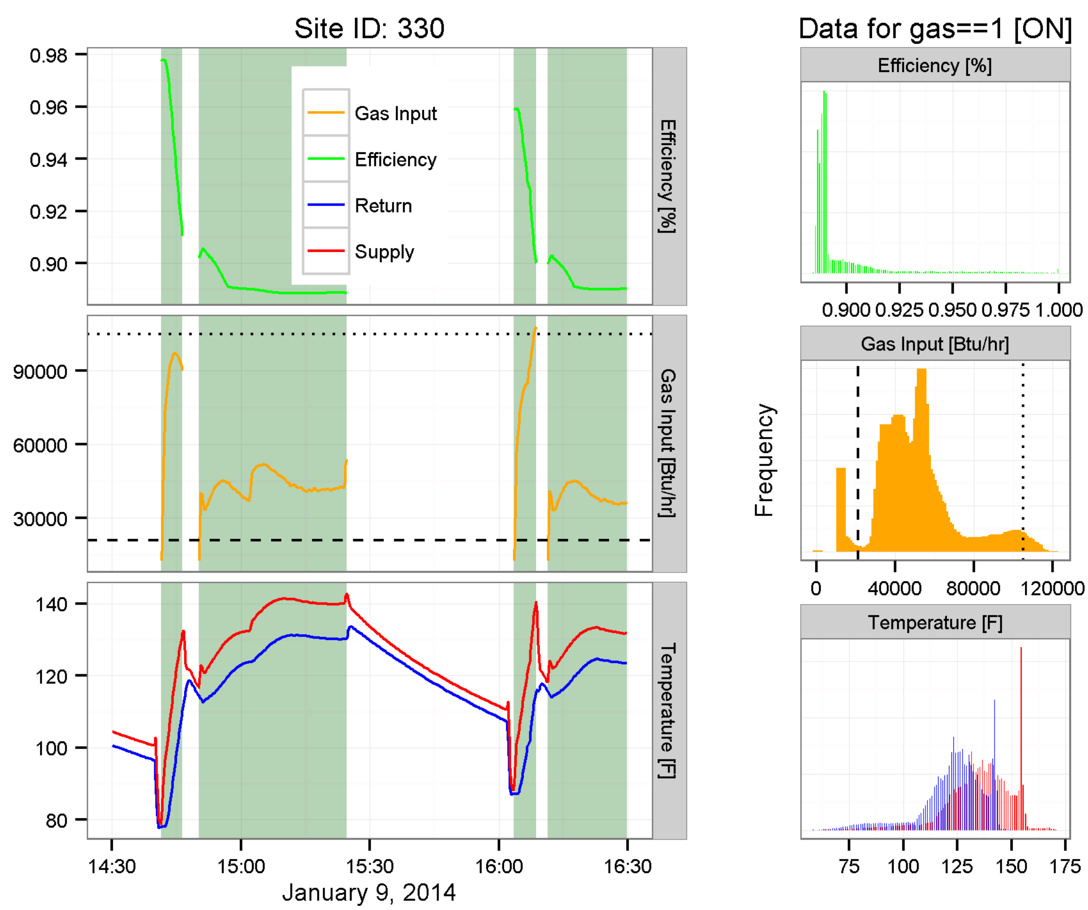
In addition to the primary visual QC step with state logger data, and the initial round of visual QC of spot measurements, the team checked the long term data from boiler sites with an additional level of scrutiny. At a high level, this consisted of spot checking time-series data to ensure that water temperature and gas valve data were synchronized, and representative of a working boiler. The major objectives of visual QC of long term boiler system data were to confirm that:

- When the gas valve is open:
  - Supply and return water temperatures increase or stay high
  - Supply temperature is greater than return temperature
  - Space temperature or domestic hot water temperature increases
  - Flue gas temperature is high
- When gas valve is closed:
  - Supply and Return water temperature decrease, or stay low
  - Flue temperature is low
- Check for false positives and negatives
  - If the gas valve is open and water temperatures stay the same or decrease, this indicates a false positive or evidence that the gas valve and temperature data are out of sync.

- If the gas valve is closed and water temperatures increase, this indicates a false negative and evidence that the gas valve and temperature data are out of sync.
- Domestic hot water checks
    - The above three gas valve checks can also be applied to the domestic hot water pump, and domestic hot water temperature.
    - Ensure that domestic hot water pump and boiler system operate together; there should not be a case where the domestic hot water grows hotter while the boiler is off.

An example of another visual QC tool is given below in Figure 18, which shows a two hour period of raw data on the left and aggregate distributions of data for the entire metering period on the right. The addition of the histograms showing data for the entire metering period help to identify high, low, or unusual areas of fuel input, temperature, and efficiency.

Figure 18. Boiler Data Visualization QC Tool



Left panel shows a two hour period in detail, and right panel shows the aggregate distributions of efficiency, gas input, and water temperatures for the entire metering period.

When all of the boiler quality checks were complete and all unusable data was removed, the final data set used in computations included some sites with a full season of metered data, as well as adequate spot measurements to estimate combustion efficiency and water flow rate. The table below documents what data could be used in each step of the analysis, and an explanation for why some data could not be used.

Figure 19. Detailed Boiler Site Disposition

<table>
<tr><th></th><th>Analysis Phase</th><th>Sites with usable data</th><th>Sites with unusable data</th><th>Explanation</th></tr>
<tr><td rowspan="2">Spot Measurements</td><td>Initial QC</td><td>59</td><td>11</td><td>• ΔT was too small during spot measurements, and implied flow rate was greater than 20 gpm
• Boiler was short cycling during tests
• Only captured low-efficiency, high-output performance, and did not capture the low-output, high-efficiency performance (or vice-versa)</td></tr>
<tr><td>Estimating water mass flow rate</td><td>58</td><td>12</td><td>In one case, the gas meter was not rotating smoothly and consumption estimates were inconsistent</td></tr>
<tr><td rowspan="3">Long-Term Data</td><td>Gas valve state</td><td>56</td><td>14</td><td>Some loggers showed data as 'on' or 'off' for weeks or months at a time, and could not be used. Some showed flicker or other anomalies at the beginning or end of the data, and in such cases we trimmed that end of the data and kept what was usable</td></tr>
<tr><td>Supply and return temperature</td><td>67</td><td>3</td><td>• One site sustained water-damage to the logger.
• One boiler showed severe short-cycling, thus the supply and return are so close together that estimates of consumption are low or negative.
• One site showed return inexplicably hotter than supply towards the end of heating events, rendering consumption estimates unusable.</td></tr>
<tr><td>Sites with full usable long-term data</td><td>54</td><td>16</td><td>See above notes on why individual sets of gas valve or temperature data could not be used.</td></tr>
<tr><td>Summary</td><td>Sufficient for estimating consumption</td><td>42</td><td>28</td><td>This is the final set of sites with usable long term sets of supply and return water temperature and gas valve state data, as well as spot measurements for estimating water mass flow rate. The team eliminated the top and bottom two outliers, leavings 38 sites in the final analysis.</td></tr>
</table>

Appendix C. Uncertainty Calculations

This section describes how the team calculated overall relative precision for both furnaces and boilers. For additional detail on calculating relative precision for each element of the nested sampling design, see Spencer et al.[34]

Furnaces

The team combined sampling error from the following components in order to determine overall relative precision:

- Relative precision on billing data disaggregation estimate of consumption, RP_{disagg}
- Relative precision on ratio of metered estimate to billing data disaggregation, RP_{ratio}
- Relative precision on ratio of in-situ to rated efficiency for baseline units, $RP_{eff,b}$
- Relative precision on ratio of in-situ to rated efficiency for efficient units, $RP_{eff,ee}$

The evaluation team calculated the total relative precision on the final estimate of consumption as follows:

$$RP_{cons} = \sqrt{RP_{disagg}^2 + RP_{ratio}^2}$$

The team then calculated savings based on the adjusted baseline and efficient unit average efficiencies as follows:

$$Savings = Consumption \left(\frac{\eta_{ee}}{\eta_b} - 1\right)$$

Where η_{ee} is the adjusted AFUE of the efficient unit and $\eta_b$is the adjusted AFUE of the baseline unit. The team calculated the relative precision on the delta between the adjusted efficiencies RP_{eff} using the standard error on each adjustment factor:

$$RP_{eff} = \frac{\sqrt{SE_b^2 + SE_{ee}^2}}{\frac{1}{\eta_b} - \frac{1}{\eta_{ee}}} \times t_{eff}$$

The team then combined the terms for the consumption and efficiency delta into the total relative precision on the savings estimate, RP_{tot}:

$$RP_{tot} = \sqrt{RP_{cons}^2 + RP_{eff}^2}$$

[34] Spencer et al., *Revisiting Double Ratio Estimation for Mitigating Risk in High Rigor Evaluation,* 2013 IEPEC.

Boilers

The calculations are different for boilers because the adjusted efficiency of the high-efficiency equipment came from the same set of measurements as the metered estimate of heating and water heating consumption. Since the high-efficiency adjusted AFUE was not an independent measurement, the team conducted the ratio analysis on savings estimates instead of consumption estimates, adjusting for the difference in baseline efficiency in the metered savings calculation. A Monte Carlo simulation method was used to generate a distribution of savings for each boiler, based on the rated baseline efficiency and measured baseline efficiency for each spot measurement site. The team calculated savings as follows:

$$Boiler\ Savings_i = Billing\ Savings_i \times \frac{Metered\ Savings_i}{Billing\ Savings_{met,i}}$$

Where $Billing\ Savings_{met,i}$ is the billing savings estimate for each metered site over the course of the metering period and for a given period (annual or metering period):

$$Billing\ Savings_i = Billing\ Consumption_i \times \left(\frac{\eta_{ee,rated,i}}{\eta_{b,rated}} - 1\right)$$

$$Metered\ Savings_i = Metered\ Consumption_i \times \left(\frac{\eta_{ee,meas,i}}{\eta_{b,rated} \times \theta_i} - 1\right).$$

θ_i is itself a distribution, generated for each billing site i by Monte Carlo sampling from the empirical distribution of the ratio of the average onsite measured efficiency to the verified rated AFUE for all metered sites j:

$$\theta_{i,j} = \left(\frac{E(\eta_{ee,meas,j})}{\eta_{b,rated,j}}\right).$$

Thus the *Metered Savings* is also a distribution, explicitly capturing the uncertainty around the savings at each site.

To calculate the overall relative precision, the team combined the relative precision of the following three terms:

- Relative precision of the mean billing data disaggregation savings estimate, $RP_{disagg,sav}$
- Relative precision of the mean ratio of metered to billing data disaggregation savings estimates, $RP_{ratio,sav}$
- Relative precision of the baseline efficiency adjustment, $RP_{eff,b}$, (θ)

$$RP_{tot} = \sqrt{RP_{disagg,sav}^2 + RP_{ratio,sav}^2 + RP_{eff,b}^2}$$

The total relative precision RP_{tot} is also a distribution. The evaluation team calculated 95 percent confidence intervals around the mean using the MC samples generated for each billing observation. For the purposes of this analysis, the mean is reported and used as the expected value.

The evaluation team also calculated the relative precision on the final estimate of heating and hot water consumption using the same approach as in the furnace analysis, except including hot water as well as heating consumption.

$$RP_{cons} = \sqrt{RP_{disagg,cons}^2 + RP_{ratio,cons}^2}$$

Where:

- $RP_{disagg,cons}$ is the relative precision on billing data disaggregation estimate of consumption
- $RP_{ratio,cons}^2$ is the relative precision on the ratio of metered consumption estimate to the billing data disaggregation consumption estimate

Appendix D. Differences in Housing Stock by Heating System Type

The team analyzed audit data from over 180,000 Home Energy Savings (HES) participants from 2010-2012 to further understand why boiler homes on average have higher annual heating loads than furnace homes. The sample included homes from National Grid, Eversource and Cape Light Compact. Other PAs' data did not include a field for heating system type.

The analysis compared boiler and furnace homes across several home characteristics. Table 30 summarizes the key findings observed for each characteristic. This information is also summarized graphically in Figure 20 through Figure 24.

Table 30. Differences in Housing Characteristics between Boiler and Furnace Homes

Characteristic	Findings
Home age (years)	On average, boiler homes are 7 years older than furnace homes. This is more pronounced for gas homes, where boiler homes are 15 years older than furnace homes.
Home size (square feet)	Average boiler homes are 5 percent larger than average furnace homes. This is more pronounced for oil heated homes: oil boiler homes are 9 percent larger than furnace homes, on average.
Reported equipment size (Btu/hour)	Boiler "auto-sized" capacities from the audit data average 6 percent larger than furnace capacities. This is more pronounced in oil systems, where boilers are an average of 9 percent larger than furnaces.
Home heat loss factors before and after retrofit (Btu/hour/°F)	**Pre-retrofit heat loss factors were 28 percent higher in gas boiler homes than in gas furnace homes.** Overall, boiler homes were 14 percent worse (less insulated) than furnace homes. While this data was available for a smaller subset of participants, it still summarized over 7,600 furnace homes and 19,600 boiler homes. Post-retrofit factors were did not differ as much across system type.
Occupancy	No significant difference observed.
Number of bedrooms	No significant difference observed.
Number of stories	No significant difference observed.

Figure 20. Summary of Key Differing Housing Characteristics

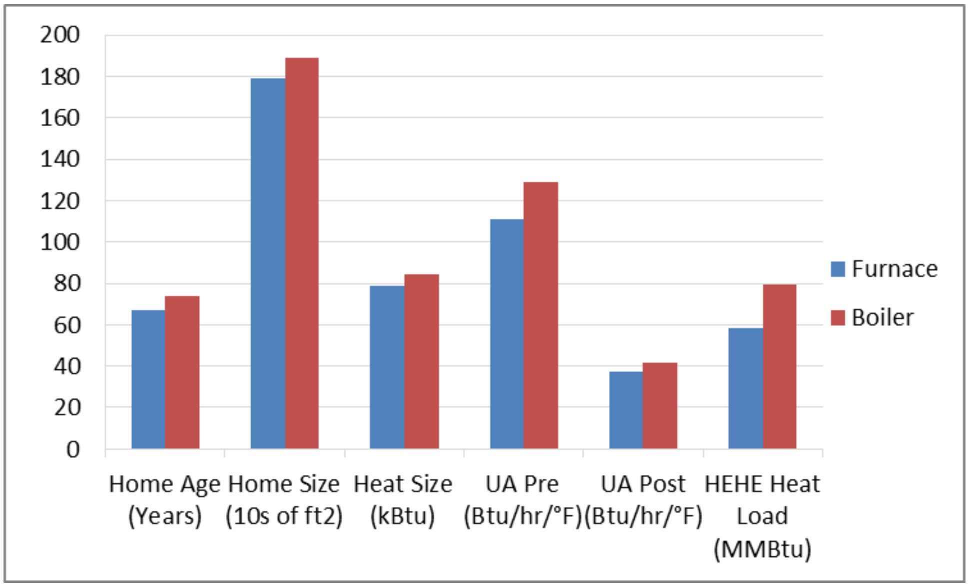


Figure 21. Average Home Age by System and Fuel Type

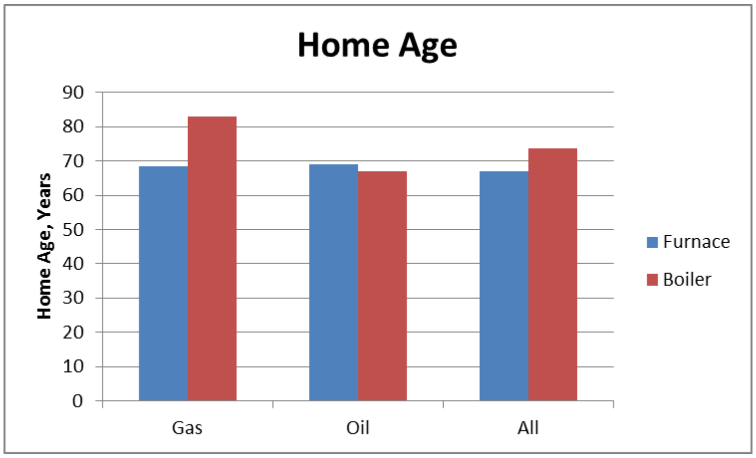


Figure 22. Average Home Size by System and Fuel Type

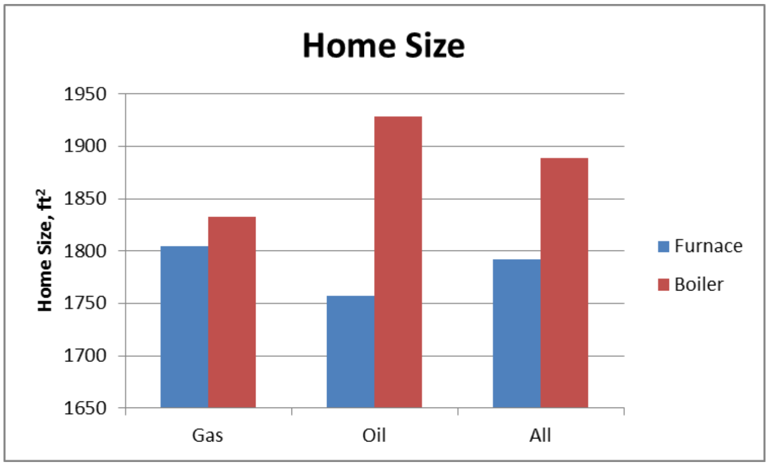


Figure 23. Average Audit Tool Generated Equipment Size by System and Fuel Type

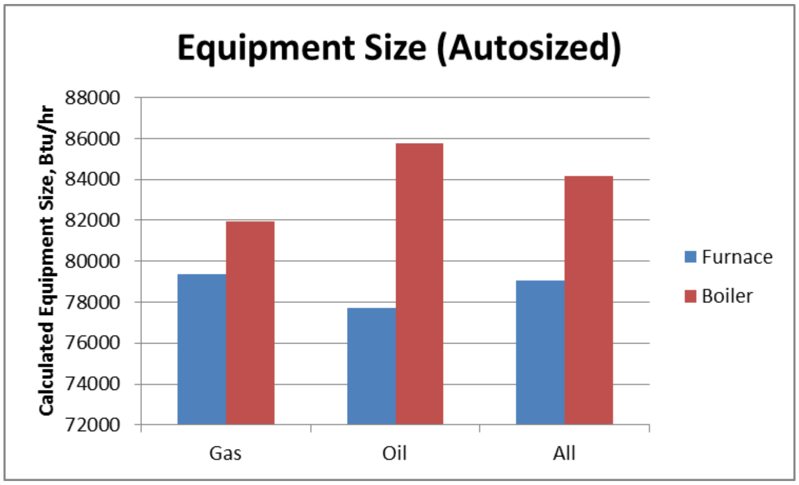
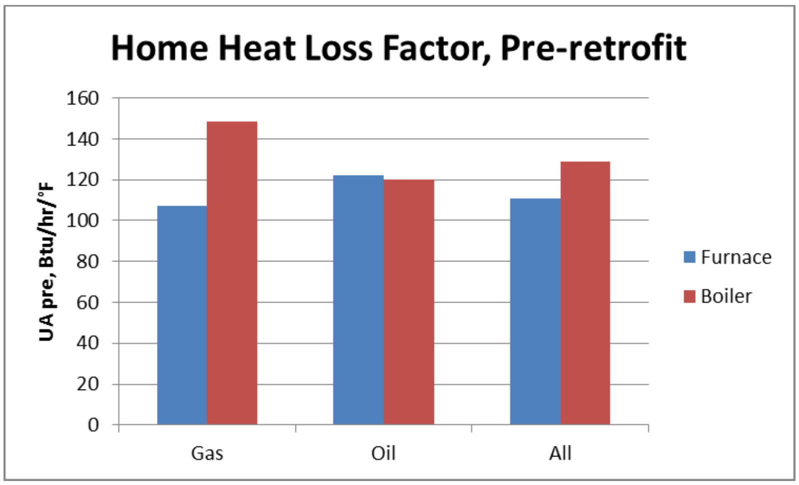


Figure 24. Average Home Heat Loss Factor by System and Fuel Type



Appendix E. Furnace Savings with Deemed Baseline of 80 Percent AFUE

As discussed in the report, the PAs implemented a new baseline of 85 percent during the course of this evaluation. This appendix summarizes savings results based on the previous deemed baseline of 80 percent AFUE, using the evaluation adjustment ratio of measured to rated performance. Table 31 shows results for replace-on-failure units only, and Table 32 shows weighted average results for replace on failure and early retirement units. As in the body of the report, the team used the 11.7 percent early retirement weight from the 2012 net-to-gross evaluation.

Table 31. ROF Furnace Savings Findings: 80 Percent AFUE Baseline

Measure	AFUE Type	Efficient AFUE	Baseline AFUE	Verified Therm Savings	2013 Report TRM Therm Savings	Relative Precision at 90% Confidence
95% AFUE Furnace ROF Baseline	Rated	95.2%	Rated: 80.0% Verified: 81.0%	109	147	8.7%
	Verified	95.4%				
97% AFUE Furnace ROF Baseline	Rated	97.0%		120	162	
	Verified	97.2%				

Table 32. Rolled Up Furnace Results: 80 Percent AFUE Baseline

Measure	Verified ROF Therm Savings	Verified ER Therm Savings	Verified Average Savings	2013 Report TRM Therm Savings
95% AFUE Furnace	109	127	111	159
97% AFUE Furnace	120	139	122	173