To Condense, or Not to Condense? Installation Practices Leave Boiler Savings on the Table

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ABSTRACT

High-efficiency natural gas condensing boilers make up roughly half of the residential heating system replacements in Massachusetts gas efficiency programs and can produce significant energy savings for program participants. But how do these units actually perform when installed to replace very different systems? What does it take for condensing boilers to reach their rated efficiencies in the field? The purpose of this 2014 evaluation conducted for the Massachusetts Program Administrators was to rigorously quantify the natural gas savings associated with high-efficiency boilers and furnaces installed through the Massachusetts High-Efficiency Heating Equipment Rebate Program. This paper focuses specifically on high-efficiency boilers. In this study, the team used a novel approach to meter 70 high-efficiency residential boilers to determine annual heating and hot water loads as well as in-situ efficiency for the average unit installed. The evaluation showed that high-efficiency boilers are not operating to their full energy savings potential. Given that only 12% of metered units operate in condensing mode for significant portions of the heating season, the results suggest that improved contractor education on quality installation practices, system and distribution sizing, and outdoor reset controls would likely improve the operating efficiency of residential condensing boilers. These findings present new challenges for program administrators to evaluate the cost-effectiveness of implementing these improved installation practices.

Introduction

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 a 2014 evaluation of this program 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]

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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. Condensing boilers pass return water through a heat exchanger with the flue gases to recover additional heat. When return water temperatures are low enough, this process condenses the

This paper describes the evaluation methodology, results and implications for high-efficiency boilers.

Methodology

For retrofit space heating and combination heating and hot water boilers, 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 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 boiler performance.
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 such as supply and return water temperatures was particularly important for condensing boilers where efficiency is dependent on return water temperature.

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 low cost-per-participant billing data disaggregation analysis. (see Spencer, Greenberg & Decker 2013)

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

Figure 1. Nested Sampling Approach
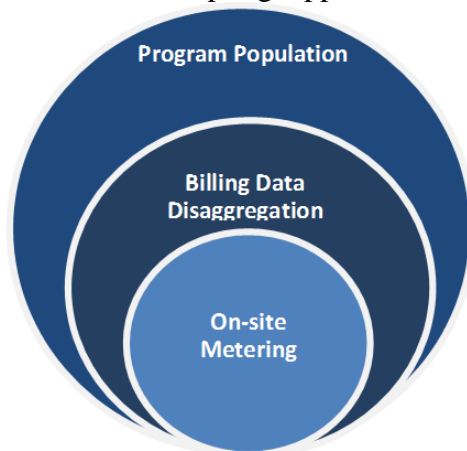
Program population = 5,741; Billing data disaggregation n = 1,688; On-site metering n = 70

water vapor in the flue gas, resulting in latent heat gains into the return water coming back to the boiler and increasing efficiency levels to upwards of 95 percent. However, boilers are not always installed with controls that optimize return water temperatures for maximum efficiency.

We obtained a first 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 team combined measured parameters from each of these analysis components to calculate savings.

Figure 2. Savings Calculation for Heating Equipment

$$Savings = Load \times \left(\frac{1}{AFUE_{base} \times R_{AFUE,base}} - \frac{1}{AFUE_{ee} \times R_{AFUE,ee}} \right)$$
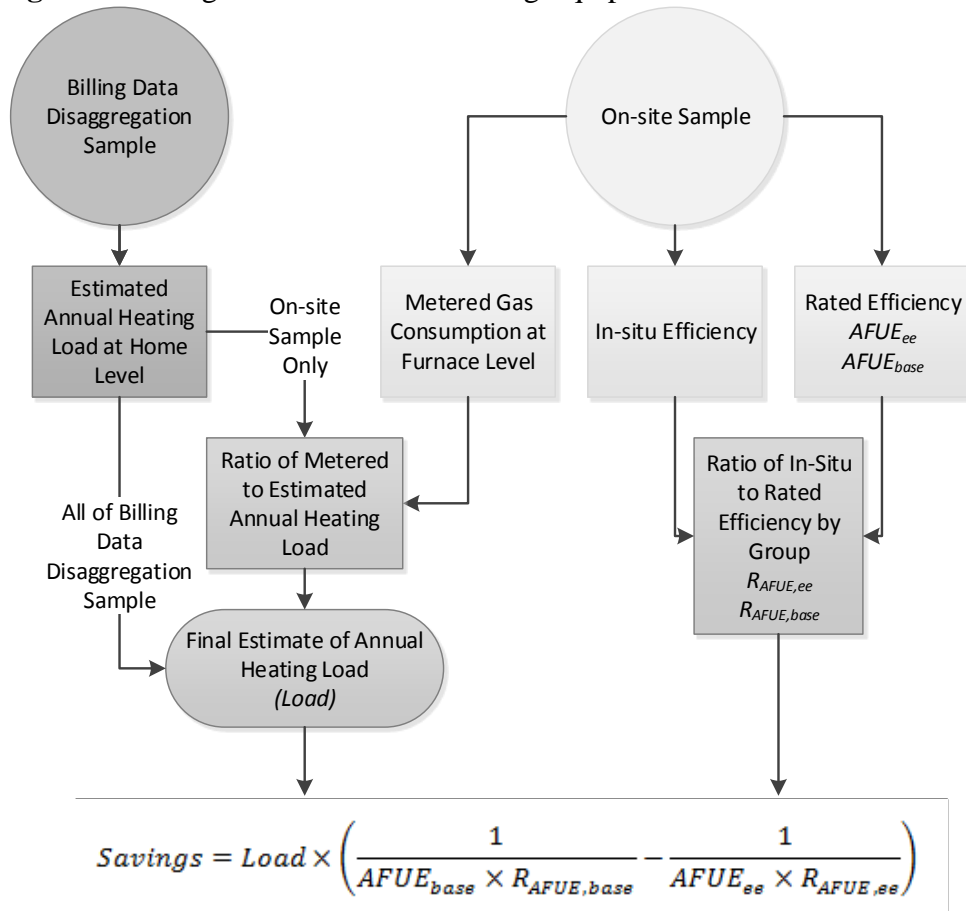
Note: Annual heating load is defined here as the total heat delivered to the home by the furnace or boiler and is calculated as actual consumption divided by actual efficiency.

Long-term Metering Approach

The efficiency of condensing boilers varies with return water temperature and most condensing boilers fully modulate their firing rates 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 (**Table 1**) to determine total gas consumption, assuming a constant flow of water through each boiler's primary loop.[2]

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

Where:

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[2] 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.

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

Table 1. 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

Spot Measurements of Boiler Efficiency

The team performed combustion tests on high-efficiency and 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 standard new and early retirement equipment and a modified protocol for high-efficiency boilers.

High-Efficiency Boilers

As described above, condensing boiler efficiency varies with return water temperature and these boilers are designed to handle a wide range of operating temperatures. 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 the outdoor temperature. 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.

Standard Efficiency Boilers

The team took a series of spot measurements on each 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.

Billing Data Disaggregation

The team 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 of the evaluation report (Tabor et al 2015).

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).[3] The purpose of the modeling was to accurately extrapolate the billing data from the 2013-2014 heating season to a typical weather year. The team 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).[4] 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.
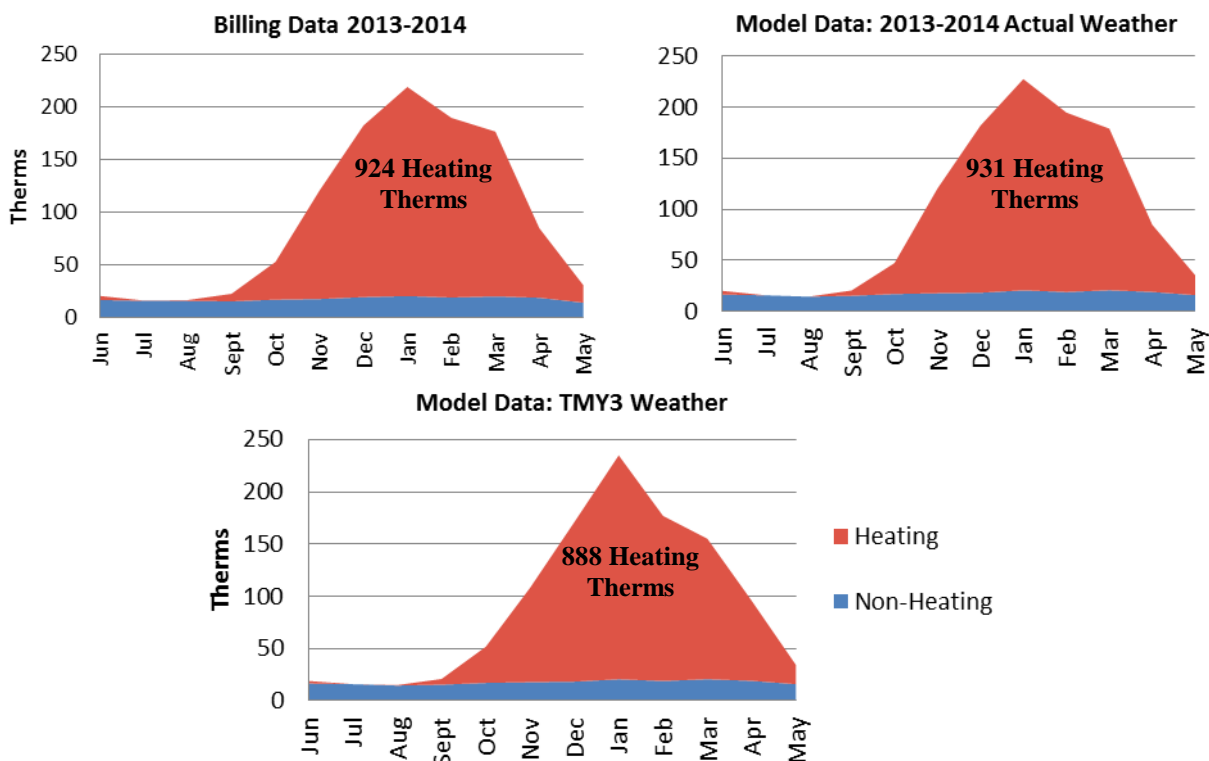

Figure 3. Calibrated Model Outputs for Standard Boilers: Annual Consumption

Results

The team exceeded the sample size target for the billing data disaggregation but fell short of the target for usable metering sites. 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 (unusable for gas consumption estimates) or where the spot measurement data was unusable due to inconsistent operation of the boiler (unusable for efficiency estimates). For more detail on the quality control (QC) processes used to screen metered data, please see Appendix B of the evaluation report (Tabor et al 2015). Unfortunately, there was no overlap between these two groups of excluded sites. Table 2 summarizes the attrition for each group.

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[3] The evaluation team used the EnergyPlus engine with the BEopt software.
[4] 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.

Table 2. 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 3 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, making combined heating and hot water loads more representative of typical boiler loads than heating only. (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.[5]

Table 3. Boiler Heating and Water Heating Consumption Findings

Metric	System Type	Mean	n	Relative Precision at 90% Confidence	Description
2013 – 2014 Heating and DHW Therm 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 Therm 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 Therm *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 Therm *Load*	Standard	954	-	-	Product of typical year heating consumption and average verified efficiency
	Combination	755	-	-	

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[5] Combination heating and hot water units are a single piece of equipment serving heating and hot water loads, with the hot water heat exchanger (and sometimes a small storage tank) enclosed in the unit along with the boiler itself. An indirect water heater is a larger storage tank heated by a hot water loop from the boiler.

Table 4 shows the final adjusted ratios of *in-situ* to rated efficiency for standard new and high-efficiency boilers.

Table 4. 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 of the evaluation report (Tabor et al 2015).

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. The team applied an adjustment factor to account for higher standby losses in gravity-vented equipment. Standby losses for standard efficiency boilers are high 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.[6] The team thus applied an estimated adjustment factor of three percent for standard efficiency and existing boilers measured.[7] 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) 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.

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

[7] 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.
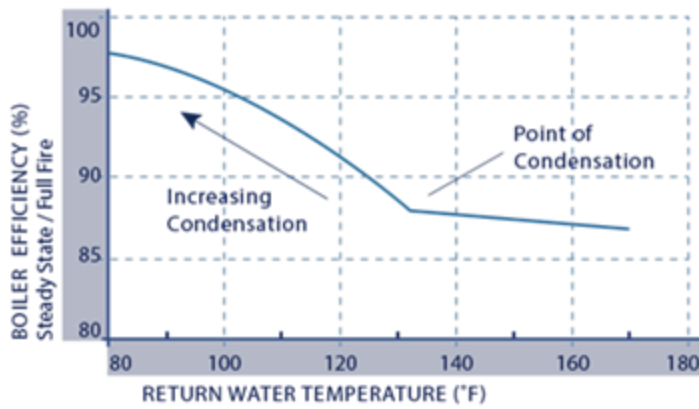
Figure 4. Condensing Boiler Efficiency *(Shen 2013)*

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 the distribution of heating hours by return water temperature (low, varying, and high), along with the proportion of sites falling into each bin. Return water temperature is a function of supply temperature and distribution sizing in the home; higher supply temperatures generally mean that the unit was installed with higher supply set points and no or less aggressive outdoor reset controls.
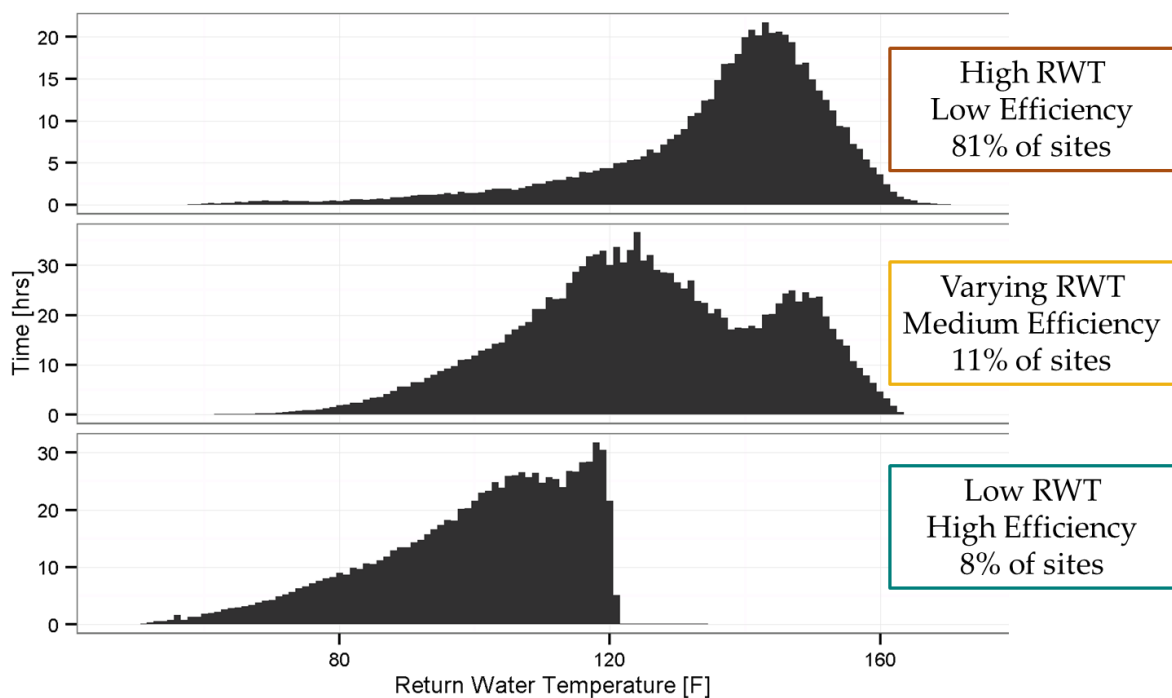

Figure 5. Distribution of heating hours by return water temperature (RWT)

Table 5 shows the final verified savings results for each deemed boiler measure in Massachusetts. Although the high-efficiency boilers performed below their rated AFUE, verified savings ranged from 106 - 113 percent of deemed 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 5. Standard Boiler Verified Savings—Replace on Failure (ROF) Baseline

Measure	AFUE Type	Efficient AFUE	Baseline AFUE	Verified ROF Therm Savings	Deemed ROF Therm Savings	ROF Realization Rate	Relative Precision at 90% Confidence
90% AFUE Boiler	Rated	92.7%	Rated: 82.0% Verified: 79.3%	110	104	106%	10.0%
	Verified	87.2%					
95% AFUE Boiler	Rated	95.0%		137	123	111%	
	Verified	89.4%					
96% AFUE Boiler	Rated	96.0%		148	131	113%	
	Verified	90.3%					

While the realization rates appear high, **Figure 1**Figure 6 illustrates the impact of high-efficiency boilers' low AFUE performance. This finding accounts for a loss of over 60 therms for all measures relative to calculating savings with a rated baseline.
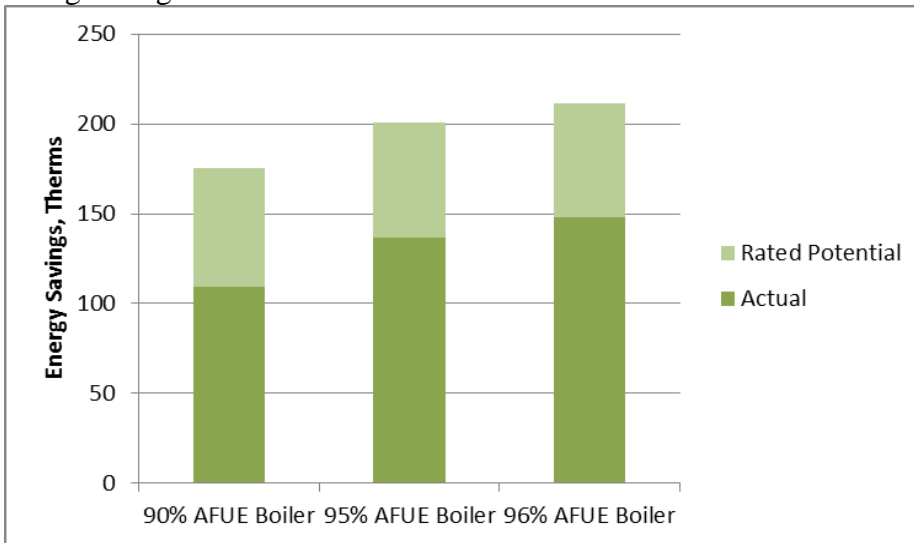

Figure 6. Potential and Actual Boiler Savings

Program Implications and Conclusions

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 a maximum operating efficiency improvement of up to 3 to 4 percentage points from the average efficiency observed in this study (Figure 7).
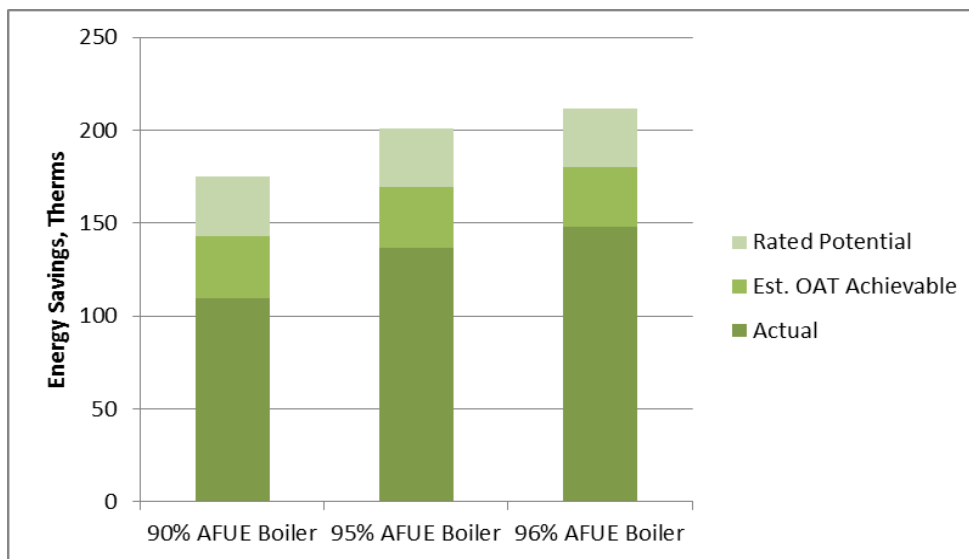

Figure 7. Estimated potential savings from improved outdoor air temperature (OAT) reset controls

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 and terminal equipment 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 that programs 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 supply temperature 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 (i.e. radiators, panels, etc.) 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—or even typical winter 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 8** illustrates two examples of panel radiators, which come in many sizes and styles.

Figure 8. Example Panel Radiators *(DesignerRadiators Direct 2013, JRF)*

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 recommended 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 recommended 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

- If setbacks are desired, customers should anticipate longer warm-up times and program temperature changes accordingly. For example, 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. (Nest, Nest Community).[8] 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 recommended 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 recommended adding some level of quality installation component to the HEHE program for high-efficiency boilers. The program is considering improving contractor education on outdoor reset controls. Because getting boiler controls implemented correctly is not always a prescriptive, "one size fits all" process, the program administrators will continue to research the benefits and costs of the additional components described above:

1) Educating homeowners on how to set thermostats for optimum performance

2) 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

3) Exploring smart thermostat technology options

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[8] Nest "True Radiant" feature claims to adjust for lag in radiant systems and Nest customer feedback indicates lack of compatibility with outdoor reset

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