Commercial Condensing Boiler Optimization

Conservation Applied Research & Development (CARD)
FINAL REPORT

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Abstract

This report summarizes the findings of a field research study that assessed the impact of real operating conditions on commercial condensing boiler energy efficiency. It also identifies methods for utility programs to improve performance. The study investigated impacts of actual boiler temperature, load fluctuations, tuning, and staging control through long-term field monitoring in 12 buildings in the upper Midwest. While there were significant variations between building types and individual sites, the condensing boilers achieved a little over half of the savings that might be expected from the rated efficiency. The average achieved efficiency of the condensing boilers was 88.6%, which is about 5 percentage points below the average rated efficiency. The study also estimated savings for a number of measures that can cost-effectively improve efficiency both at the time of installation and afterwards. These included low cost control and tuning changes that could have increased savings by as much as 3% and more extensive piping changes that could have achieved another 2% savings in half of the buildings. Finally, local boiler industry professionals were surveyed to gauge the perceived value of possible utility program features that could increase achieved efficiency of condensing boilers. The survey results provided further evidence of the prevalence of opportunities to improve controls, and highlighted the perceived value of commissioning and operator training

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Executive Summary

This report summarizes the findings of a field research study that assessed the impact of real operating conditions on commercial condensing boiler energy efficiency in order to identify methods for utility programs to improve performance. While the sensitivity of condensing boiler efficiency to field operating conditions is widely recognized in the industry, information about actual field operating conditions in Minnesota has generally been limited to only varied anecdotal sources. The investigators conducted both a systematic field study and an industry contact survey to provide more informed guidance for utility program development and refinement.

The field study included long-term monitoring of key operating conditions at 12 buildings that were chosen to be representative of characteristics that are common among commercial condensing boiler installations in Minnesota. Key characteristic variations represented in the chosen sites include building type (e.g. education), boiler system size, boiler system piping, type of controls, and whether it was a condensing boiler system exclusively or a hybrid system (i.e. containing a mix of condensing and non-condensing boilers). The operating conditions were monitored through building automation systems and data loggers with cellular modems to capture data on entering boiler water temperature, load fluctuations, burner tuning (excess air), and staging control. While there were significant variations between building types and individual sites, the condensing boilers achieved a little over half of the savings that might be expected from the rated efficiency alone (compared to a common 80% efficiency baseline for non-condensing boilers). Persistent problems with boiler control and building automation system (BAS) communications prevented the compiling of definitive results for one of the twelve sites. Figure 1 below shows the annual average efficiency of the condensing boilers at each site along with the rated efficiency (and the efficiency of the combination of all boilers at hybrid sites).

The average achieved efficiency of the condensing boilers was 88.4%, 5.6 percentage points below the average rated efficiency of 94%. Multifamily buildings as a group had higher condensing boiler efficiency than other sites because of lower boiler system water temperatures—especially in mild heating season weather. The largest single factor impacting operating efficiency was that the water temperatures entering the condensing boilers were far above the 80°F value used in rating tests. However, suboptimal burner tuning (i.e. extra excess air), burner firing rate control, and cycling control also contributed to performance below rated conditions in a number of buildings. Four of the sites had non-condensing boilers that remained operating in order to provide enough capacity at low outdoor temperatures. The use of the non-condensing boilers in these hybrid systems reduced the overall boiler plant efficiencies by another 1.8 to 5.7 percentage points below the operating efficiencies of the condensing boilers. The high entering water temperatures, sub-optimal tuning, sub-optimal staging control, and the impacts of non-condensing boilers at four sites caused an average boiler plant efficiency of 87.2%, 6.8 percentage points below the average rated efficiency of the condensing boilers.

Figure 1: As Operated Efficiencies of Condensing Boilers and Hybrid Systems

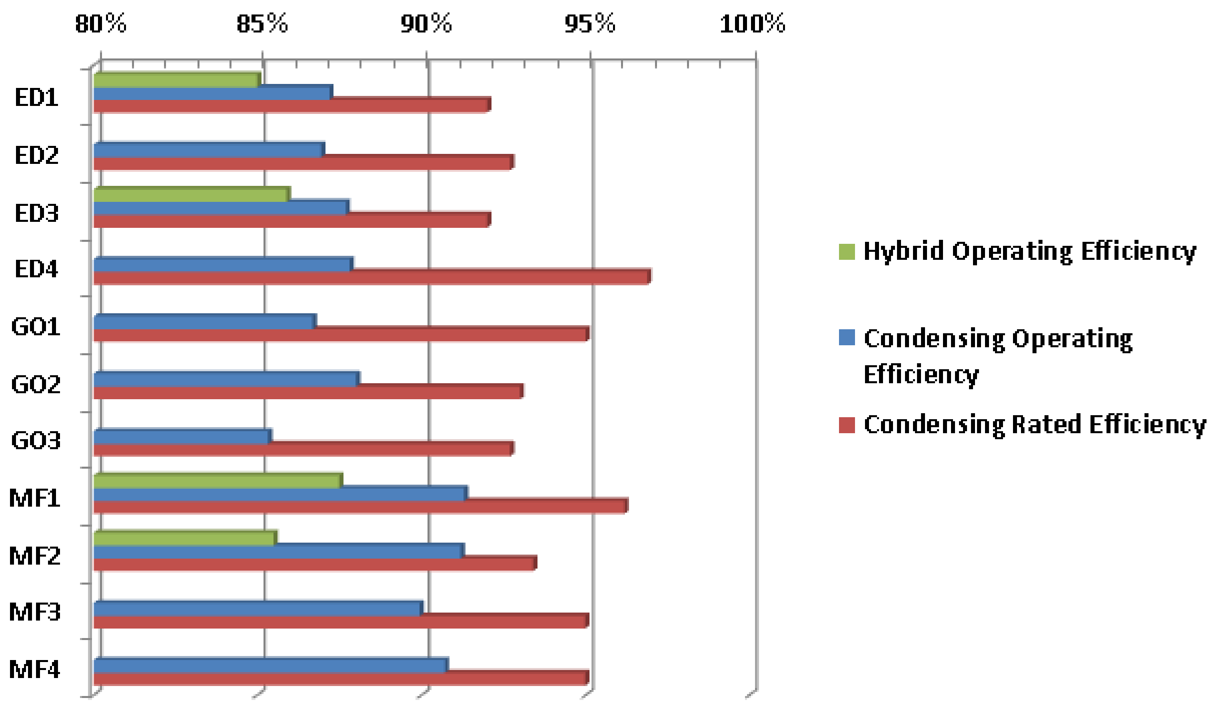


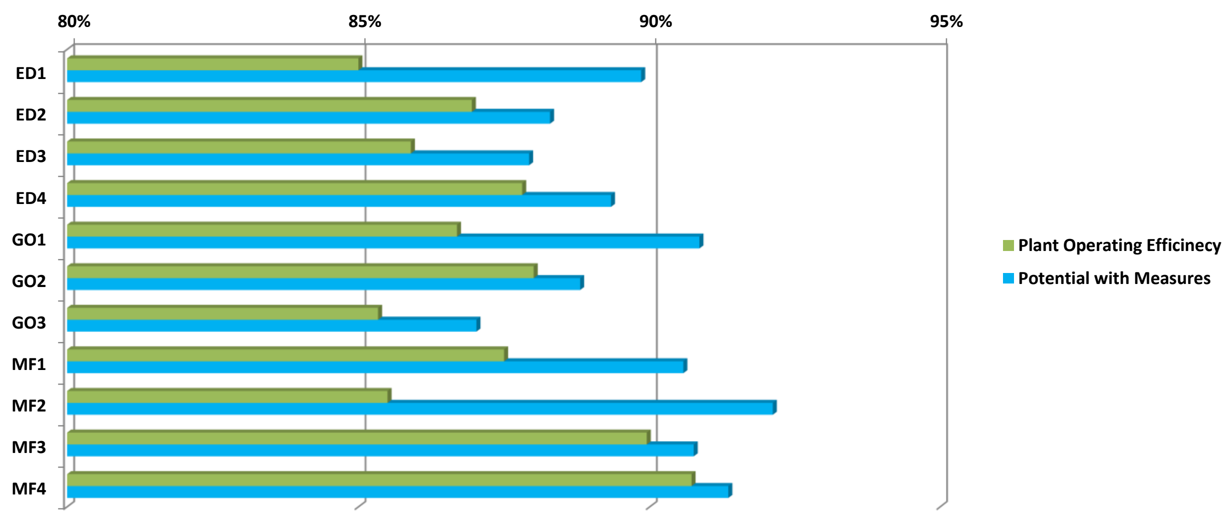
Table 1 Summary of Savings by Measure Type

Measure Type	# of Sites	Average of Sites with Measure	Average Across All Sites	Average [Therm] Savings for Sites with Measure
Reset Control	10	1.54%	1.40%	1,289
Burner Tune Up	10	0.80%	0.72%	574
Staging control	8	1.15%	0.83%	975
Variable Speed Pumping	10	0.48%	0.44%	230
Piping Change	5	2.06%	0.94%	979
Total	11	-	3.97%	2,372

The study also estimated savings for a number of measures with the potential to cost-effectively improve efficiency both at the time of boiler installation and afterwards. Savings estimates were based on assumptions about the degree to which recommended control changes would change the boiler operating conditions (e.g. entering water temperature, cycling, firing rate, and load distribution among boilers). **Table 1** shows the frequency and average savings of potential measures by category. The relatively low cost control and tuning changes could increase average savings by about 3%, and more extensive piping changes could achieve another 2% savings in half of the buildings. About 80 % of the identified savings can be achieved with a simple cost-payback period under 5 years.

Figure 2 shows the annual average boiler system efficiency as found along with the potential efficiency by site if recommended improvements are applied. All of the sites have some low-cost opportunities to improve boiler efficiency, while a few of the sites have opportunities for very large potential efficiency improvements.

Figure 2: Observed and Achievable Efficiency by Site



Hybrid boiler systems had the largest potential for increased savings through better optimization. There was a savings potential of more than 2% through staging control improvement for two of these systems, and opportunities for improvement of sub-optimal piping in three out of four of the hybrid systems. CIP program refinement and development efforts should target hybrid boiler systems.

Local boiler industry professionals were also surveyed to gauge the perceived value of utility program features to increase condensing boiler efficiency. The survey results provided further evidence of the prevalence of opportunities to improve controls, and highlighted the perceived value of commissioning and operator training.

The survey responses highlighting the importance of commissioning and operator training are indicative of the general study findings that numerous technical details can impact the achievable efficiency and savings of condensing boilers in commercial buildings in Minnesota. The vast majority of monitored sites could improve performance with more optimal adjustment of a number of different items—most notably boiler temperature control. Improvements in technical details of piping layout (typically combined with control adjustments) also provide an opportunity for additional savings at about half the sites, with relatively high first cost and savings per site.

Introduction

This project was undertaken to evaluate the operating efficiency of existing condensing boiler installations in commercial buildings and the potential for increased cost-effective savings at these sites, as well as to provide direction for the development of CIP program strategies for condensing boilers in commercial buildings. It had previously been observed that sub-optimal system and/or control issues in individual buildings reduce the savings achieved by condensing boilers to about half of the savings estimated by simply using published efficiency ratings. To date, the limited research into how efficiency programs can impact savings has not led to effective utility program changes. This project aims to systematically study the impact of field conditions on the efficiency of condensing boilers and the potential benefits of specific CIP program strategies.

Towards these ends, the project conducted field monitoring of condensing boiler systems at 12 representative buildings over several months to evaluate the operating efficiencies and potential for additional savings through low to moderate cost system changes. Detailed information about building type, systems, boilers, and design process was reviewed for correlations with achieved operating efficiency and/or additional savings potential. Interviews with local boiler industry representatives also evaluated the potential value of numerous CIP program strategy options.

Background

Condensing Boiler Efficiency Considerations

Unlike most natural gas-fired equipment, the operating efficiency of condensing boilers can change significantly with operating conditions. Unfortunately, the optimal conditions for maximizing condensing boiler efficiency are the exact conditions that designers and operators have rightly tried to avoid with conventional boilers. This means that optimizing boiler efficiency is often most challenging when replacing conventional boilers in existing buildings and/or when boilers are operated by seasoned facilities staff. The subsections below outline how condensing boilers achieve efficiency beyond what is possible with conventional boilers and the implications that this has in terms of their unique sensitivity to operating conditions.

How Condensing Boilers are More Efficient

The *steam* that can typically be seen forming at the chimneys of boiler systems during cold weather is the key to the efficiency advantages of condensing boilers. When natural gas and air burn together (as is the case for the majority of commercial boilers in Minnesota) water vapor is one of the natural products that occur, representing about 12% of the gases that exit a boiler system chimney. This water vapor is really diluted *steam* that packs a big punch when it comes to heating energy potential, as each pound can theoretically heat about 6 gallons of water. While the design of conventional boilers intentionally allows all of the *steam* in the combustion gases to escape out the chimney,[1] condensing boilers are able to capture a portion of the valuable heat in the *steam* by condensing it to water before it leaves the boiler.

Boiler efficiencies of 90% or above are only achieved when a boiler is condensing part of the *steam* in the flue gases. However, a boiler's ability to condense this *steam* varies greatly with the actual operating conditions that are imposed upon a boiler in a building. Regardless, condensing boilers are generally at least a few percentage points more efficient than conventional boilers under all conditions. This is primarily because the safety factors built into conventional boilers to avoid the potential for condensation of water vapor within a boiler are not needed in the design of the heat exchangers for condensing boilers. Higher insulation levels and much smaller water tanks are also typical in condensing boilers, and provide secondary efficiency benefits. These two design aspects that allow condensing boilers to achieve efficiencies 5 to 15% greater than conventional boilers are highlighted below. Figure 3 below shows their impact in typical boiler situations.

- Actual condensation (allows 90%+ efficiency)
- No safety factors to prevent condensation (gives a few percentage point gain—typically to the high 80's)

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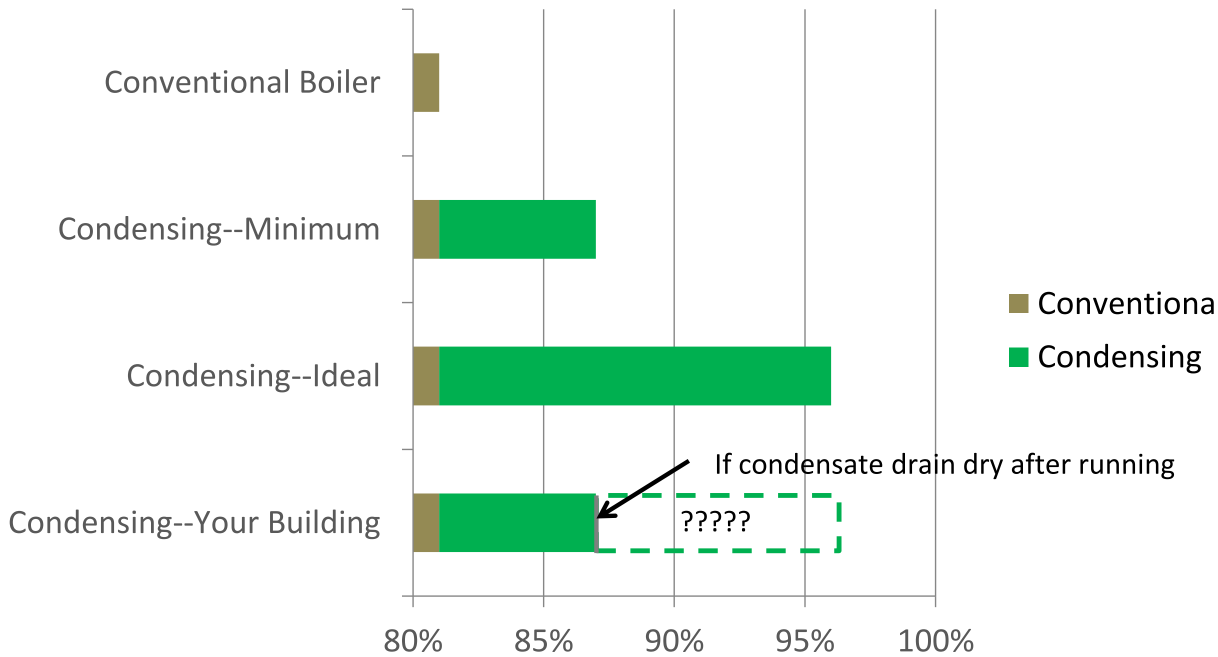
[1] Conventional boilers avoid condensation of water vapor in the flue gases because this condensed water can rapidly corrode the materials that have traditionally been used in boiler heater exchangers. The presence of certain contaminants in natural gas tends to make the condensed water even more corrosive than ordinary water.

Figure 3. Range of Efficiency Gain with Condensing Boilers



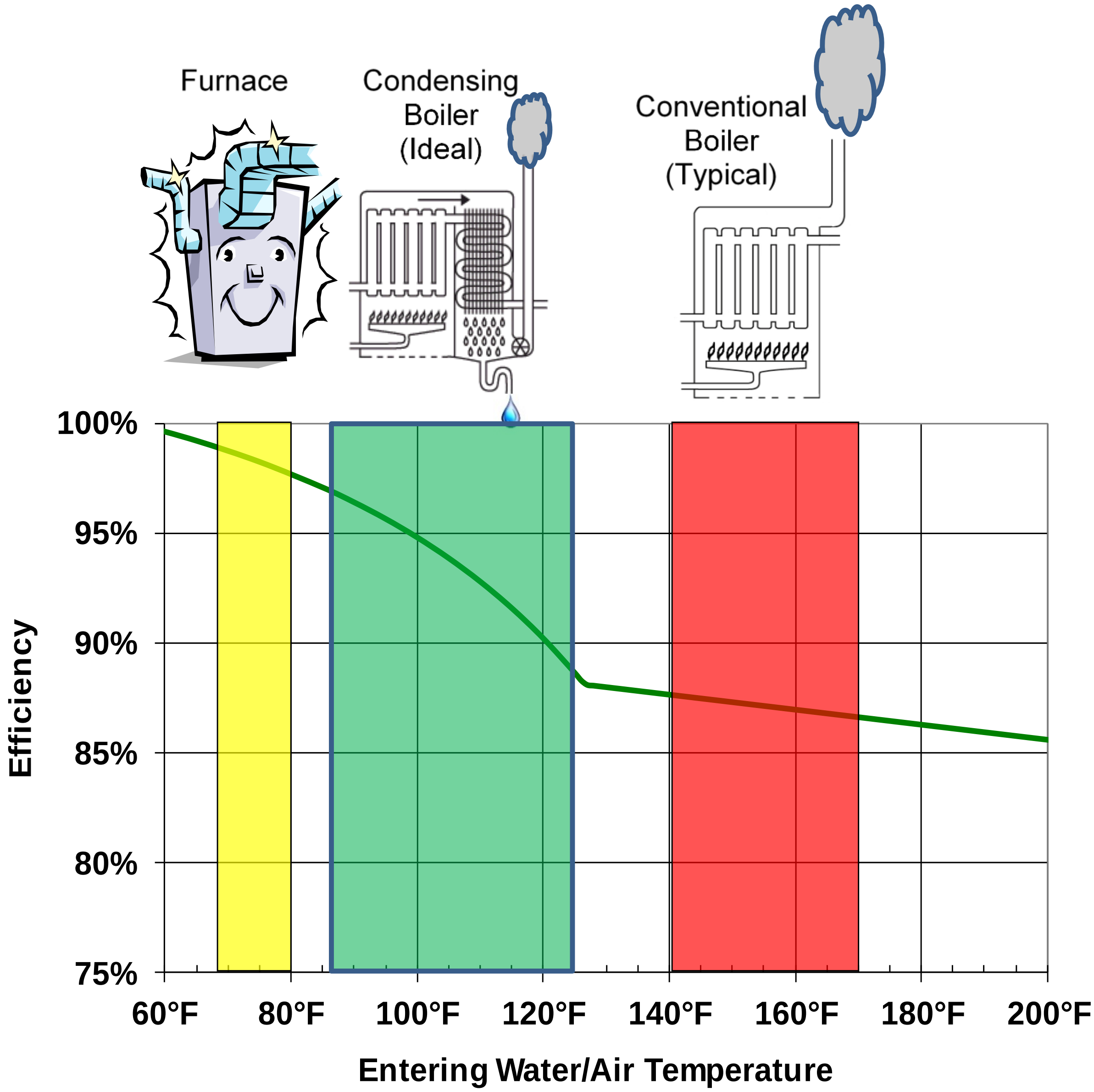
Factors Uniquely Impacting Condensing Boiler Efficiency

Unlike most natural gas-fired equipment, the operating efficiency of condensing boilers can change significantly with operating conditions. As noted in the previous section, much of the potential efficiency benefit of condensing boilers is associated with the extra heat captured when a portion of the water vapor generated by combustion is condensed instead of lost out the vent. The following operating variables can each have a significant impact both on whether a boiler condenses and on how much it condenses.

Entering Water Temperature

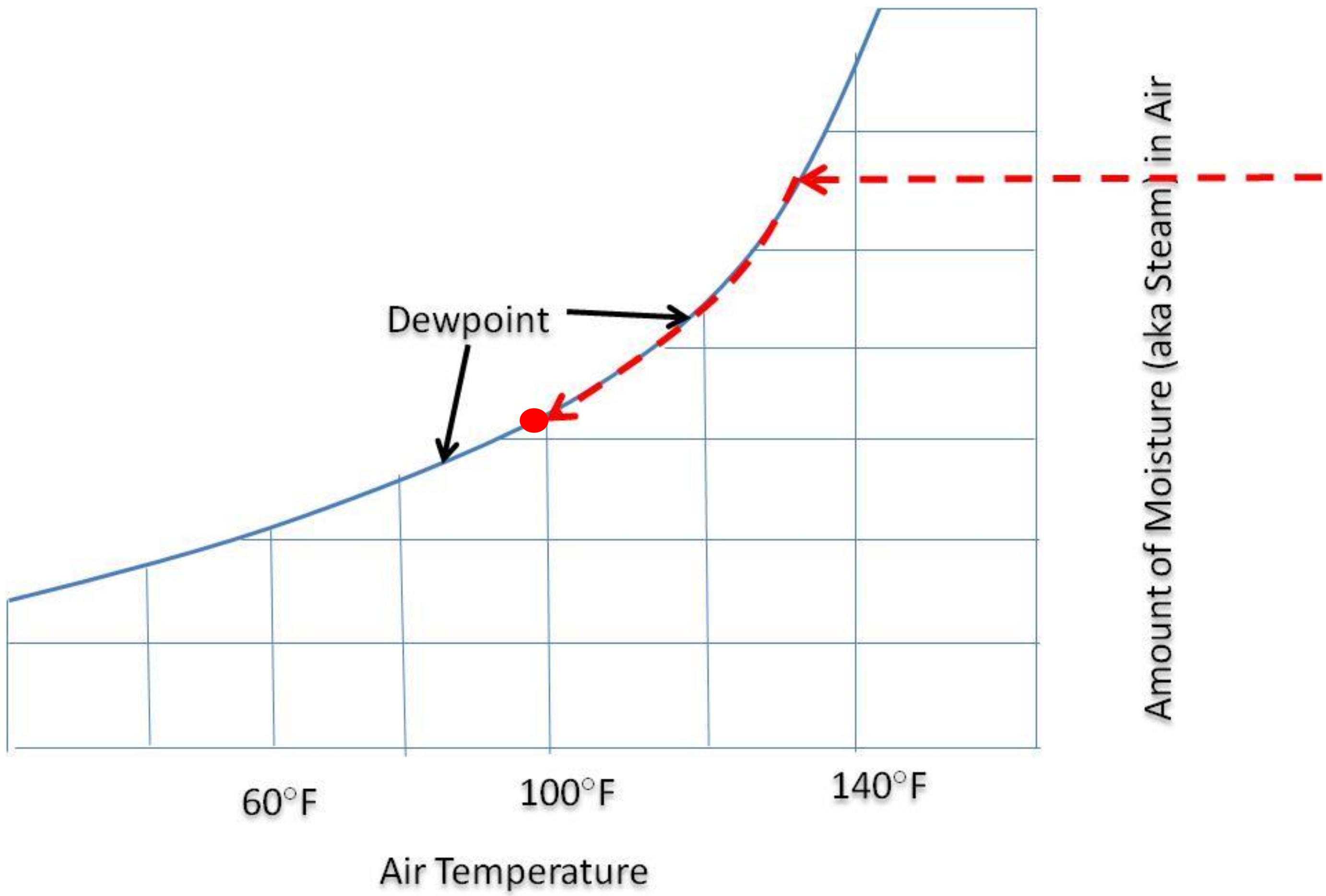
Far and away the most important operating factor affecting condensing boiler efficiency is the temperature of the water entering the boiler (before it is heated). The line in Figure 4 shows how the efficiency of a condensing boiler changes with the temperature of the entering water. The efficiency begins to increase sharply as the entering water temperature drops below the temperature at which condensation starts, and it continues to increase as the entering water temperature drops. Note that the red bar shows the typical entering water temperature range for conventional boiler systems (140°F to 170°F) and the green bar shows the ideal entering water temperature range for condensing boilers (80°F to 125°F). On the other hand, the yellow bar shows that condensing furnaces don't have much of a temperature sensitivity issue because the temperature of the air they heat (70°F to 80°F) is always well below the typical point of condensation.

Figure 4. Boiler and Furnace Efficiency Dependence on Entering Water or Air Temperature



The sharp gains in efficiency that come with dropping entering water temperature occur as the water entering the boiler gets far enough below the dewpoint of the flue gas mixture (downstream of the burner) to condense water vapor from the flue gas mixture. Just like how the moisture in the air condenses on a cold can of soda when the water vapor in the air is cooled down to the air's dewpoint temperature, the moisture within a boiler's flue gasses condenses when it is cooled down to the flue gas dewpoint. Figure 5 shows how flue-gas condensation starts and increases as the temperature drops below the dewpoint. The dewpoint is the curve at the top of the psychrometric chart where the air is saturated and holds as much water as it can for a given (dry bulb) temperature. Cooler air simply has a lower capacity to hold water vapor so the moisture condenses (gives off a large amount of heat) as the flue gases are cooled below the dewpoint temperature. While a cold can of soda is usually well below the dewpoint of indoor air, the temperature of the water that enters a boiler is often above the dewpoint of the flue gases—especially in systems designed for conventional boilers where condensation is to be avoided.

Figure 5. Flue Gas Condensation Below Dewpoint



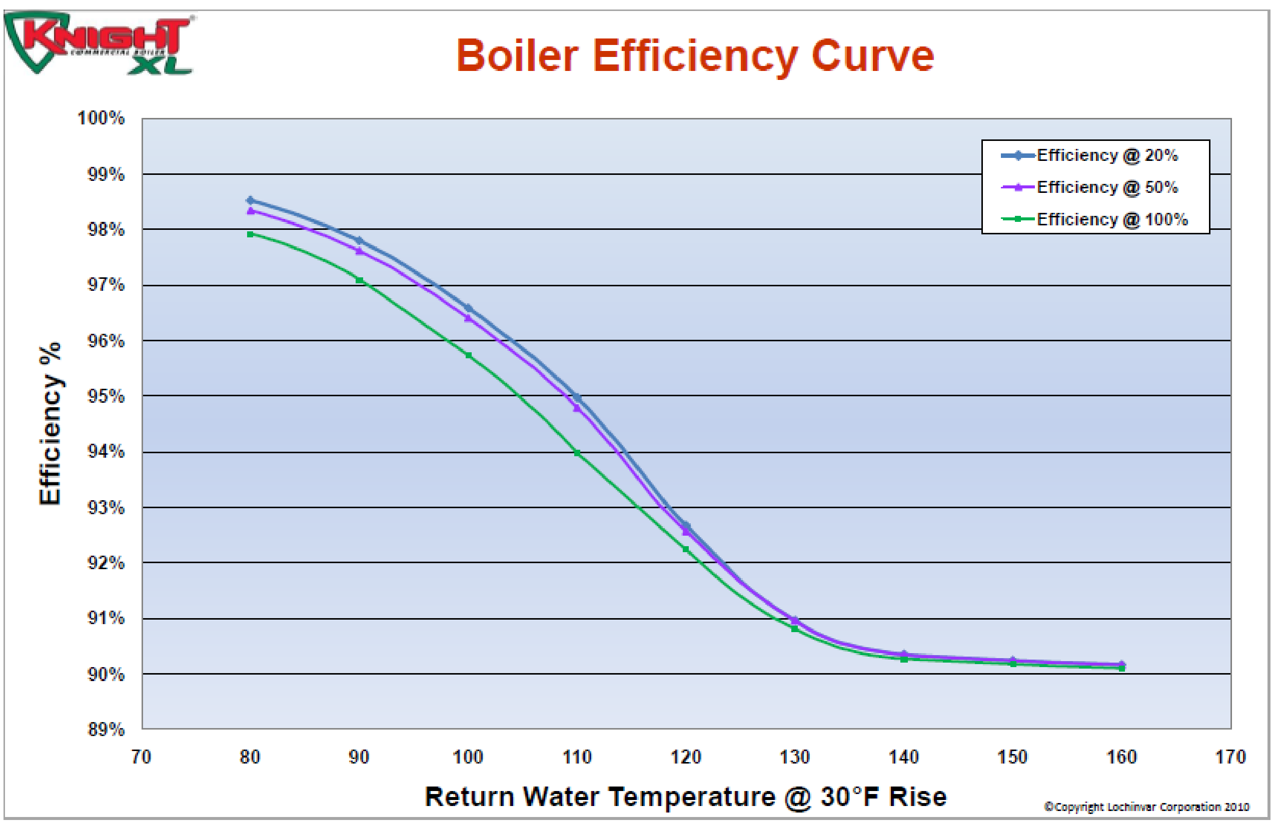
When condensing boilers are installed in buildings that are designed for conventional boilers, numerous factors can limit the ability to bring the entering water temperature down into the ideal operating temperature range. Boiler plant considerations such as boiler controls, boiler piping, and pump controls are some of the factors. In addition, the various devices used to heat the building (e.g. radiators, hot water heating coils in air handling units, and VAV reheat coils) can also be factors. These have typically been sized to provide adequate heat (in very cold weather) for boiler water temperatures maintained at 160°F when entering the boiler and 180°F when leaving the boiler. While hydronic (hot water) boiler systems typically do use outdoor reset controls to automatically reduce boiler temperature as the outside temperature rises, the sizing of these heating devices still places a lower limit on the degree to which the entering boiler water temperature can be reduced in mild weather.

Strategies to reduce the flow of boiler system water through the building can often improve efficiency by reducing the temperature of the water temperature entering the boiler. Variable speed pumping is the most common strategy to reduce entering boiler water temperature and still maintain a temperature drop though the building heating loop as the load drops in mild conditions.

Part-Load Operation

Unlike many types of heating equipment, condensing boilers tend to have a moderate increase in efficiency, instead of an energy penalty, as the load drops down into low part-load conditions. This is because at low part-loads, the flue gases travel through the heat exchanger slower and, therefore, get cooled down to a lower temperature (which means that more water vapor is condensed out of the flue gases). Since most condensing boiler systems in multifamily or commercial applications have multiple boilers, the way in which the boiler system controller manages the staging and balancing of heating load between multiple boilers is another variable that can impact operating efficiency. Figure 6 shows how part-load conditions (% firing rate) have an impact on efficiency that is secondary to (and varies with) the entering return water temperature. Note that this secondary impact is negligible when the entering water temperature is too high for condensation and tends to be largest once the entering water temperature is significantly below the temperature where condensation begins.

Figure 6. Secondary Impact of Part-Load on Efficiency (Lochinvar, LLC, 2013)

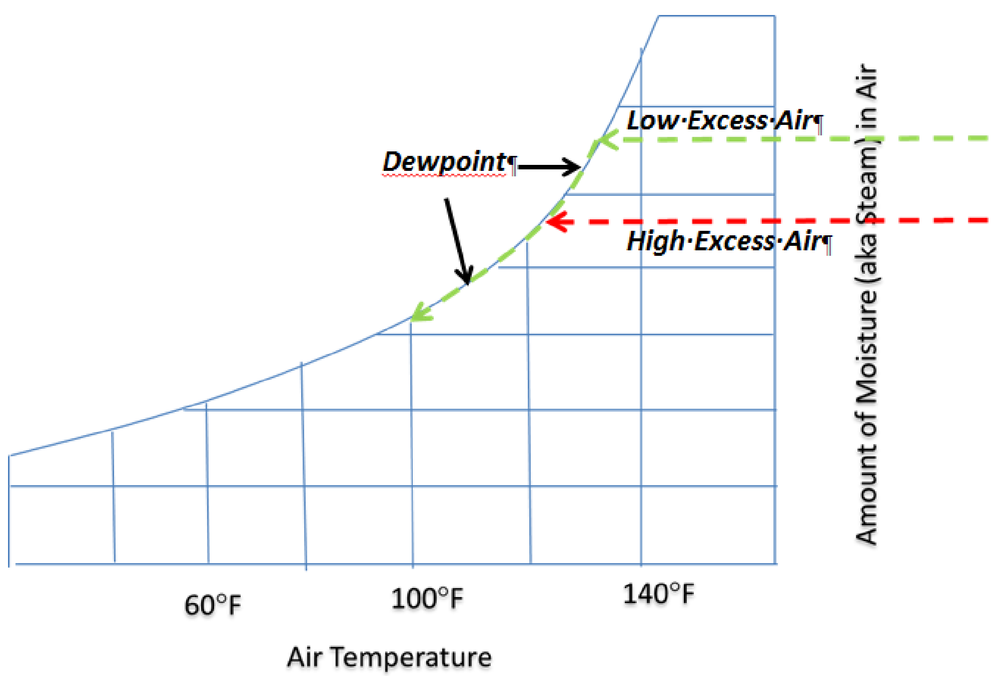


While we began this project with full awareness of the above noted beneficial impact of part-load operation on the efficiency of virtually all condensing boilers, we later became aware of a second, model specific factor with the potential to have a large detrimental impact on the efficiency of specific condensing boilers. This factor has the potential for a dramatic increase in the percentage of excess air (and air/fuel ratio) at low part-loads [see section Classic Burner Tune-Up/Excess Air Issues for further explanation of the efficiency impact of excess air]. Besides some models with designs that allow for variations in air/fuel ratio at different firing rates, some specific models recommend adjustments at low firing rates that would reduce the efficiency much more than can be achieved by having the flue gases flow through the boiler heat exchanger more slowly.

Classic Burner Tune-Up/Excess Air Issues

While burner air/fuel ratio adjustments made during boiler tune-ups help optimize the efficiency of any boiler, the efficiency impact on condensing boilers is amplified. Tune-up savings of conventional boilers is achieved by reducing the amount of excess air that flows through the boiler and carries heat out the vent (chimney).[2] In condensing boilers, this excess air also dilutes the water vapor thereby reducing the temperature at which condensation starts (~ the dewpoint) and the amount of water that can be condensed at any given entering water temperature below the dewpoint. The impact of the dilution of the water vapor by excess air on dewpoint and condensation is depicted in Figure 7.

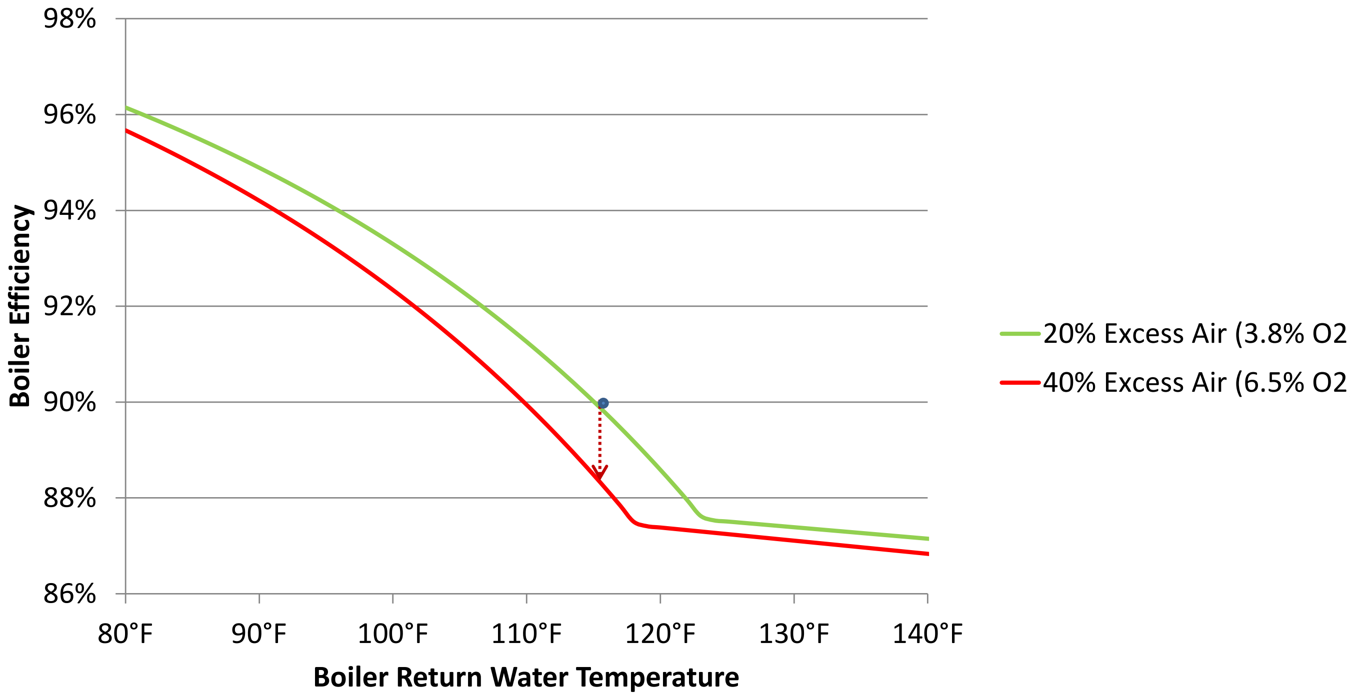
Figure 7. Excess Air Impact on Dewpoint & Condensation



[2] Excess air is typically defined as a percentage that is calculated as the ratio of actual air flow to the amount of air that is theoretically needed to provide the exact amount of oxygen for burning the fuel (natural gas) minus 100%. For example, if the ratio of actual air flow to theoretical air flow is 1.3, the boiler is said to have 30% excess air. For natural gas boilers, some excess air is needed (and required by code) to make sure that the natural gas is completely burned and that there is not significant generation of carbon monoxide.

An example of the resulting efficiency impact is shown in Figure 8.

Figure 8. Excess Air/Burner Tuning Impact on Efficiency



On the figure above, a 20% increase in excess air shift the curve to the left

Note that having excess air beyond the minimum required effectively shifts the efficiency curve to the left, which reduces the efficiency at any given entering water temperature. When the entering water temperature is in the range of possible condensation (80°F to 125°F), this has a much bigger impact because of the reduction in the ability to condense.

Manufacturers' literature provides varying guidelines for the amount of excess air. For most products there is a limited range of values as would be expected given the impact on efficiency. Some have guidelines that suggest more than a 2:1 variation in the amount of excess air is okay, and most larger boilers have guidelines for the measuring and fine-tuning of the amount of excess air at different part-load ranges, besides at 100% firing rate. As noted in the above section, some specific condensing boiler models have recommend increases in excess air at low firing rates that are high enough to dramatically reduce the operating efficiency below what it would be at full firing rate (with the lower excess air percentage).

Commercial Boiler Efficiency Test Procedures and Standards

Industry Standards for Testing and Rating Efficiency

Commercial boiler test procedures that provide a single efficiency rating value have been designed to be practical for accurate laboratory testing in a way that will give an "apples to apples" comparison based on long-term steady state operation at full-load conditions.

However, the test procedure conditions do not reflect any common boiler system design conditions, and do not provide an accurate representation of operation during varying off-design conditions.

The long-standing industry standard uses water temperatures of 80°F entering the boiler and 180°F leaving the boiler. Because of the sensitivity of condensing boiler efficiency to entering water temperature (see sub-section Entering Water Temperature within the Factors Uniquely Impacting Condensing Boiler Efficiency section) and the fact that most condensing boiler installations do not involve entering water temperatures this low, the rated efficiency value is usually well above the annual average actual efficiency achieved in the field. The version of this standard currently referred to by the Code of Federal regulations is BTS-2000 Rev 06.07 (10 CFR Part 431.86). While the organization that developed this standard has since replaced it with ANSI/AHRI Standard 1500: 2015 Standard for Performance Rating of Commercial Space Heating Boilers (Air-Conditioning, Heating, and Refrigeration Instittue), the code reference to this standard has yet to be updated. In any case, rated efficiency values for condensing boilers tend to overestimate savings when savings estimates are based on a simple comparison between new and existing boiler rated efficiencies.

Industry testing and rating standards that are applied at appropriate operating conditions are not yet in effect and have not been widely implemented. While ASHRAE has had a project committee working for 20 years on developing a Method of Testing for Rating Commercial Space Heating Boiler Systems that uses more realistic temperatures and takes part load operation into account to some degree (Beliso, Huestis, D'Albora, & Stein, 2012), this standard 155P has not yet received final approval by the developing organization. Underwriters Laboratories also has a test standard that can be applied at more appropriate temperatures and at different part-load conditions (Underwriters Laboratories, 2013), but this has not been widely used by multiple manufacturers in a consistent manor.

Efficiency Curves Available from Manufacturers

While all boiler manufacturers report the single-point rated boiler efficiency based on BTS-2000, the reporting and basis of efficiency curves for varying entering water temperatures and firing rates is inconsistent. While a few manufacturers have not had efficiency variation information available on a website and have not been able to provide any upon inquiry, many do readily provide a graph for each boiler product line that has a set of curves showing how the efficiency varies with both entering water temperature and percent firing rate (part load). Even so, most manufacturers are not able to provide a clear indication of the testing and rating, or calculation procedure used to generate the curves. Moreover, where information is provided (e.g. water temperature rise through the boiler), these conditions tend to vary from manufacturer to manufacturer. Likewise, despite the large impact of varying amounts of excess air on efficiency and the sometimes wide tolerances in guidelines for excess air, the efficiency curves readily available from manufacturers have had no information about the excess air conditions upon which the curves are based. Figure 9 and Figure 10 show samples of efficiency curves readily available from two manufacturers. The key differences in temperature rise and whether or not part load operation is included are apparent.

Figure 9. Sample 1 of Efficiency Curves from Manufacturer (Aerco)

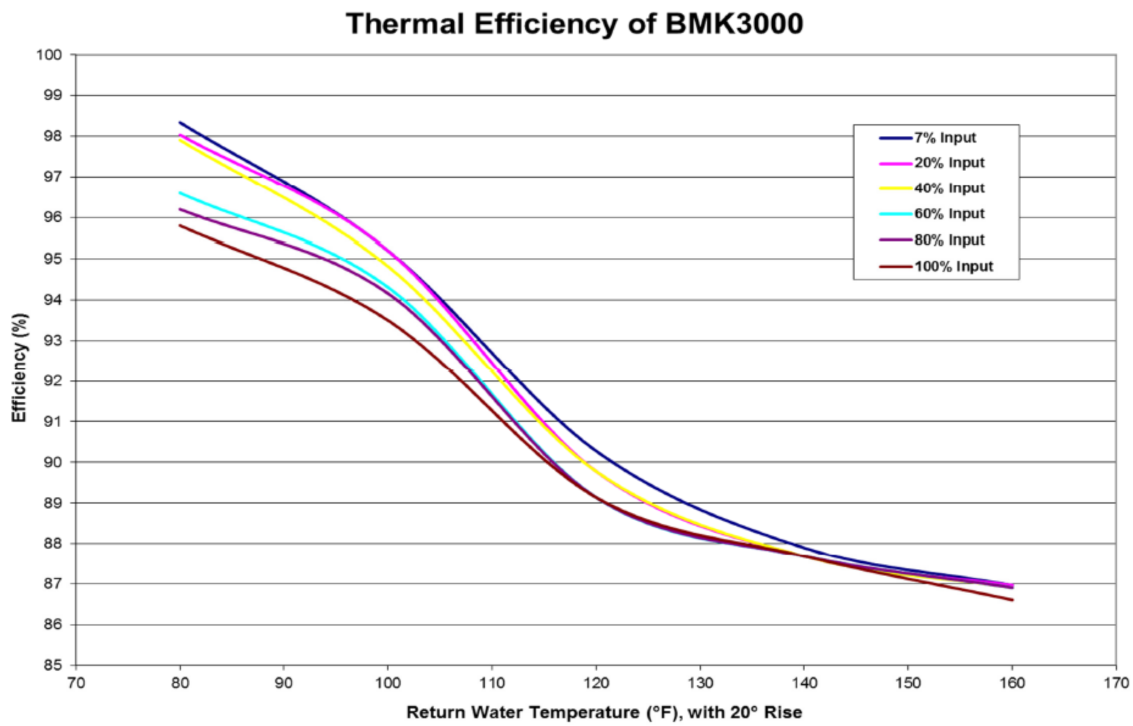
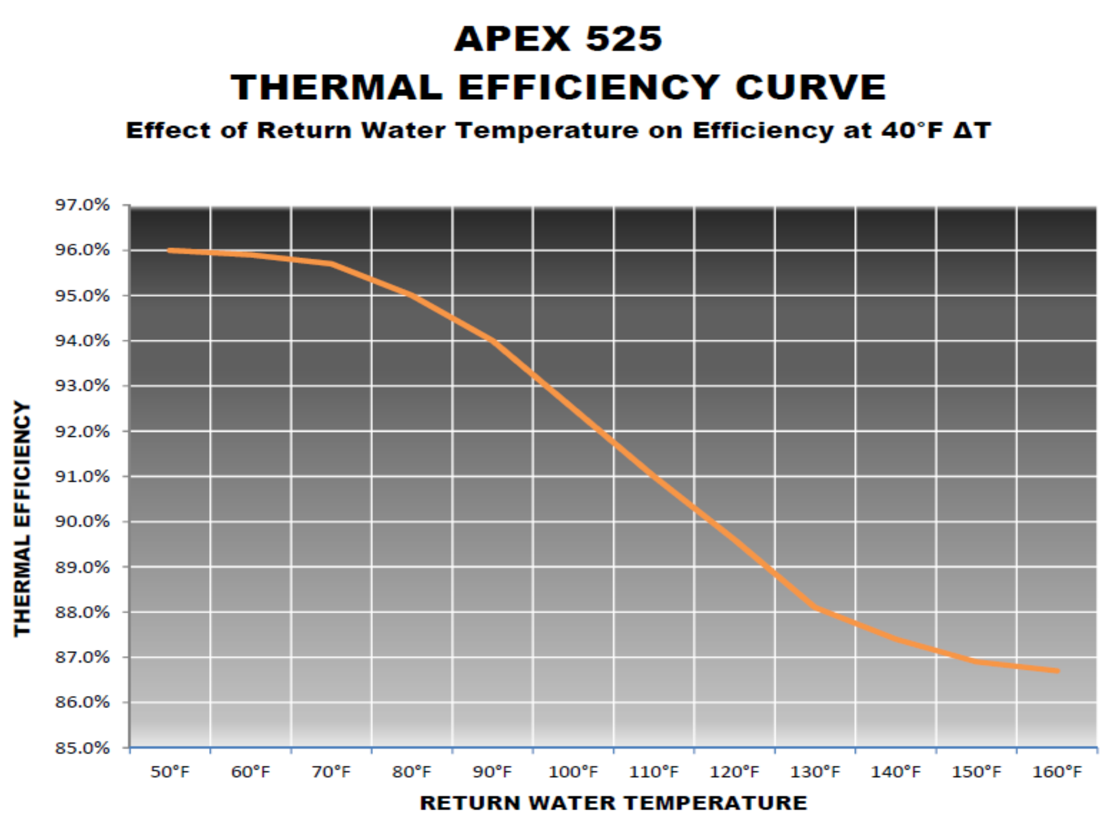


Figure 10. Sample 2 of Efficiency Curve from Manufacturer (Thermal Solutions, Inc)



Research Background and Initiatives Outside of Minnesota

The Consortium for Energy Efficiency completed a comprehensive assessment of market and technical issues related to achieving optimal savings from commercial condensing boilers in 2001 (Consortium for Energy Efficiency, 2001) and began an initiative in 2011 that has promoted more complex technical requirements for commercial condensing boiler incentive programs than those required for most utility equipment rebate programs (Consortium for Energy Efficiency, 2011). In keeping with many other quality installation programs, accurate sizing is a major theme of this initiative, along with minimum equipment efficiency. However, the assessment and initiative also go well beyond other typical utility program features to stress the importance of modulating burners (which can run at firing rates of 25% or less), outdoor reset controls, and the ability of the condensing boiler system to operate with entering water temperature below 130°F. Another key aspect of the initiative is the recommendation that all of these requirements—which include factors beyond just equipment efficiency, such as sizing, control, and the system's ability to operate at low temperatures— be met for a project to be eligible for condensing boiler rebates.

While the above research and initiative have been important steps in the right direction towards optimizing the installation of condensing boilers in commercial buildings, there have been significant changes in the industry since the 2001 comprehensive market assessment. In addition, the consortium's member utilities have done little to incorporate the complete set of technical requirements into their programs. The following are key changes to the market since 2001:

- The number of manufacturers producing condensing boilers and the variety of product lines offered has increased greatly.
- Most of the condensing boilers have much greater control capabilities built in, or offered as, a standard option within the boiler package.
- Virtually all condensing boiler products offered have modulating burners with at least 5:1 turndown (minimum firing rate is ≤20% of full capacity).
- Condensing boilers have come to dominate the commercial boiler market instead of being a small fraction of the market.

To achieve the most success in achieving optimal savings and market acceptance in large-scale utility programs, these market changes have to be considered in efforts to optimize utility program savings that can be achieved in commercial condensing boiler installations.

Minnesota CIP Program Context

Overview of Utility Energy Efficiency Programs in Minnesota

The Next Generation Energy Act of 2007 (NGEA) established energy-saving goals of 1.5 percent of average retail sales for each electric and gas utility that operates in Minnesota through the Conservation Improvement Program (CIP) (Minnesota Department of Commerce, Division of Energy Resources, 2014). The Minnesota Department of Commerce, Division of Energy

Resources (DER) oversees CIP to ensure that ratepayer dollars are used effectively and that energy savings are reported as accurately as possible.

Each utility develops its own conservation plan, which is reviewed and approved by DER along with associated energy savings calculations. DER has also facilitated the development and maintenance of a Technical Reference Manual that provides Minnesota utilities with guidance regarding energy savings calculations. Traditionally, utility programs have focused on providing incentives to customers for purchasing energy efficient products instead of standard efficiency products. As utilities strive to meet higher energy savings goals, DER and Minnesota utilities are piloting new approaches to save energy. For example, offering packaged services and measuring savings that result from operation and maintenance or behavioral measures, such as fine-tuning building control systems or simply turning off lights when not in use.

Typical programs for commercial or industrial customers have included:

- Rebates for high efficiency boilers, chillers, and rooftop units,
- Rebates for high efficiency lighting and lighting control systems,
- Rebates for high efficiency motors and drives,
- Building recommissioning studies, and
- Manufacturing process improvements that reduce energy intensity and improve productivity.

Ongoing CIP Commercial Boiler Programs in Minnesota

Utility financial incentives are available for commercial condensing boilers. This technology scored the highest among commercial measures in Navigant Consulting, Inc.'s 2009 Minnesota Gas Energy Efficiency Potential study (Navigant Consulting, 2009). Condensing boiler efficiency rebates are popular among customers as the market share of condensing boilers in commercial buildings has increased dramatically over the last several years. In 2011 the number of incentives for Xcel's program was double the initial projection. In 2014, Minnesota's two largest utilities combined provided rebates for 368 condensing boiler installations with estimated totals of over $1.3 million in rebates and 84,000 decatherms of attributed savings (CenterPoint Energy, 2012) (CenterPoint Energy, 2015) (Xcel Energy, 2015). However, the great sensitivity of condensing boiler efficiency to in-place operating conditions means that a number of these installations are achieving as little as half of the theoretical savings associated with the difference in rated boiler efficiency. Achieving maximum savings in retrofits often requires some control and/or piping modification because the optimal operating conditions for condensing boilers are exactly the conditions that lead to premature failures of "standard" boilers. This project aims to better quantify the degree to which building and system factors impact the operating efficiency of various condensing boiler installations in Minnesota, as well as the potential to increase savings through low to moderate cost upgrades. The results should be very useful for increasing the savings per installation for a technology that is already promoted through CIP rebates.

It is also noteworthy that the two largest natural gas utilities in Minnesota have taken notice of the *less than rated* savings issue for commercial condensing boilers, and at the time this research project began each was taking a different, simplified approach to address this issue so that their

CIP reported savings projections were more representative of the actual savings realized. One of the utilities asked each project's designer to calculate and document boiler operating efficiency at design conditions. While this takes into account site-specific issues, it only does so in the context of very cold weather and the efficiency tends to be much higher for most of the heating season. The other utility subtracted a small, fixed number of percentage points from the rated efficiency of the condensing boilers.

Research and Development Funding Need

The program elements evaluated in this project involve a high level of technical services and/or requirements that CIP programs have had difficulty justifying without reliable data on energy impact and expected cost-effectiveness of the approaches. In addition to evaluating the as-operated efficiency of a variety of sites and site-specific savings opportunities, this project set out to evaluate the potential energy savings impact and the appropriateness of the following strategies that could be recommended for condensing boiler optimization:

- *Focused Evaluations of Condensing Boiler Systems* to evaluate individual existing condensing boiler systems to identify low to moderate cost actions that achieve additional savings.
- *Prescriptive Rebates for Common Condensing Boiler Optimization Measures(s)* to both increase awareness of and simplify rebates for actions that are found to commonly provide cost-effective savings.
- *Training of Building Operators* to provide the knowledge needed for an operator to effectively work to achieve long-term optimal operation of condensing boiler system controls.
- *Robust Technical Requirements for New Condensing Boiler Rebates* to ensure that key factors affecting achieved savings are addressed most cost-effectively at the time of initial installation.
- *Education of Condensing Boiler System Retrofit Designers* to contribute both to higher savings for rebated installations and market transformation.

The lessons learned will be valuable for guiding the refinement of existing programs and the possible addition of new services that would make it possible to increase the amount of savings achieved.

Methodology

Preliminary Market Study & Site Selection

CEE worked with utilities and local boiler industry representatives to determine the most important building types and characteristics for the condensing boiler market. Previous national market data indicated that schools, federal government buildings, apartment buildings, and office buildings were the most important building types, and in our previous work in buildings we had anecdotally noted a number of condensing boiler installations within Minnesota in schools, government buildings and apartment buildings. This initial impression of key building types for the condensing boiler market was updated through discussions and follow-up correspondence with 10 local market players. A summary of how those interviewed represent the local boiler industry is in Table 2.

Table 2. Summary of Preliminary Market Study Contacts

Category	Number
Manufacturers' Representatives	4
Equipment Distributors	1
Contractors	2
Natural Gas Utilities	3
Total of Local Contacts	10
Boiler Manufacturers Represented	15

Project engineering staff conducted these interviews so that besides basic market information, we could have in-depth discussions about a variety of technical aspects of local installations and efficiency issues. In addition to information about the relative number of condensing boiler installations for different types and sizes of buildings, we asked appropriate industry representatives about the prevalence of other installation characteristics that may have an impact on the efficiency achieved and/or potential for further improvement. This included:

- Project process (design/build vs. spec/bid/build);
- Type of air-handling and heating distribution system (e.g. baseboard radiation vs. single zone air handlers);
- Boiler capacity control (# of boilers per system and on/off vs. high/low or modulating burners);
- Tie in with domestic hot water heating system;
- Use of variable speed pumping; and
- Whether outdoor reset control is prepackaged with boiler or separate.

We had also hoped to supplement the local market study interview results with national or regional boiler market share data, but found that boiler market share data is not readily available as it is for most HVAC equipment (E Source, 2013). Therefore, the local industry contact interviews provided the majority of the information that guided the determination of a set of selection criteria.

After the site selection criteria were prepared, project staff's efforts to recruit potential research participant sites included outreach to facility owners that CEE had previously worked with, and follow up on leads generated through requests for assistance from the following industry contacts: the two largest local gas utilities, other local industry contacts included in the preliminary market assessment. DER also provided leads from a database of boiler replacements paid for with ARRA funding that was channeled through DER. In most cases where another organization was providing CEE with the lead, the other organization made an initial contact with each site's representative to ask for permission to share their contact information with research program staff. Initial project staff discussions with potential site candidates determined whether or not the site was likely to be appropriate and the building owner was interested in participating in the research project. When both of these were the case, on-site visits were conducted with consistent data collection being guided by a site-screening information form. Where site screening results verified the appropriateness of a site for inclusion in the study, a formal participation agreement was executed and on-site monitoring established.

Field Monitoring

Long-Term Boiler Operating Conditions

Long-term monitoring of boiler operating conditions was conducted to observe the actual in-field operating conditions over the range of outdoor temperature and load conditions experienced by the boiler plant in each building. While the most critical variable monitored was each boiler's entering water temperature and boiler firing rate (because of efficiency dependency on these variables, per Figure 9 and Figure 10) monitoring also included a number of other items as noted in Table 3. The monitoring periods for individual sites varied and ranged from November of 2013 through November of 2014. The data collection interval at each site was either every 5 minutes or every 15 minutes.

Long-term field data collection of operating conditions was primarily carried out through pre-existing Building Automation Systems (BAS) for 8 of sites, and the other 4 sites (all multifamily buildings) had field data collected through Campbell Scientific CR3000 dataloggers supplied by CEE. The BAS trend data measured a snapshot at the exact time of the data collection interval, while the dataloggers generally averaged data over the interval time period. The 4 primary datalogger sites used cell modems and monitored via a combination of Mod-bus communication with a boiler on-board controller and separate sensors installed by project staff. Two of the primarily BAS monitored sites required the supplemental use of Campbell Scientific dataloggers where key items were either not available through the BAS or were found to be unreliable after repeated attempts to have a controls contractor resolve the issue. Project funding was needed to upgrade BAS system capabilities at two sites to allow for monitoring of all the key boiler operating variables.

Table 3. List of Variables Monitored at a Typical Site

VARIABLE	PURPOSE(S)
Critical Variables	
a) Entering Water Temperature for Each Boiler	The single most important condition that determines the steady-state operating efficiency of a condensing boiler.
b) Burner Firing Rate for Each Boiler	The second most important condition that determines the steady-state operating efficiency of a condensing boiler; Indicates the energy use rate at that time
c) Burner On Time for Each Boiler	Used with Firing Rate to indicates the energy use rate for that time period; Indicates the cycling behavior of the boiler.
Secondary Variables	
a) Supply Water Temperature for Each Boiler	Provides a reality check on the accuracy of Entering Water Temperature and Firing Rate measurements; When compared to Entering Water Temperature, gives an indication of the potential to reduce flow rates; Provides insight into control behavior
b) Speed of Variable Speed Pumps	Gives an indication of the current flow control behavior
c) Outdoor Temperature	Available as a proxy for NOAA outdoor temperature data when doing frequent checks of data integrity*
d) System Supply Water Temperature	Provides a reality check on the accuracy of Entering Water Temperature and Firing Rate measurements; When compared to Entering Water Temperature, gives an indication of the potential to reduce flow rates; Provides insight into control behavior
e) Averages of Variables Over Boiler On-Time	In some cases, gives a more representative indication of Entering Water Temperature when a boiler was operating under cycling conditions.

*NOAA data was only updated periodically and typically wouldn't be available to verify expected boiler operation dependency on weather)

The project team experienced severe problems with communication between the boiler on-board controls and the BAS or datalogger at two sites (GO4 and MF1). Inconsistencies in the transfer of data variables at site GO4 were never resolved after multiple attempts by a controls contactor, and these inconsistencies made the data from this site useful for only anecdotal observations. At site MF1, the manufacturer and contractor went through repeated rounds of ordering and installing control interface upgrades before communication was finally reliably established.

Remote communication was used for frequent data collection and verification at 10 of the sites, while limits on remote access required on-site visits for BAS trend data collection at two sites within 3 miles of CEE's office. The remote data collection was performed automatically on a nightly basis for the datalogger sites. Three of the BAS sites with remote data collection had recurring difficulties or delays in obtaining trend data because of factors such as a new BAS installation and an older system not being able to interface with computers using newer operating systems. The modems connected to the dataloggers also failed and needed to be replaced at three of the four multifamily sites.

At MF2, MF3, and MF4, HOBO temperature loggers were also installed to measure temperatures in common spaces over the course of the season. This data was collected very infrequently.

Data from the nearest NOAA weather station was used as the source for outside temperature. While many sites had local outdoor temperature sensors, they did not all correlate well with the NOAA data due to issues such as sunlight hitting a sensor for a portion of the day or apparent bias. Because outdoor temperature was primarily to be used to project the results over the course of typical weather year, this also provided the most direct and reliable relationship.

Data from the various sources was combined using TRAVIS software that CEE specifically developed to convert data from a wide variety of BAS file formats, time intervals, and weather data sources into a consistent format for use in analysis. Procedures for downloading and pre-processing of trend data were standardized for the majority of sites to allow ongoing performance of this task to be carried out by a research analyst or technician. New data was regularly compared to previous data using Tableau software to identify any potential problems with data reliability.

Short-Term Flue Gas Oxygen Measurements

The project scope was expanded to include short-term monitoring of flue-gas oxygen for a sampling of the boilers in response to preliminary market study findings that indicated large increases in burner excess air at low firing rates could have a dramatic impact on condensing boiler part-load efficiency. Project staff prepared a roving setup consisting of a Campbell Scientific datalogger and two high precision sensors capable of measuring oxygen concentration directly in a boiler's flue. The Honeywell MF010-0-LC3 series low temperature oxygen sensors used had a listed accuracy of 0.5 percentage points, and lab tests consistently showed better than 0.25 percentage points accuracy in measuring percent oxygen by volume. This roving setup was installed temporarily at 11 of the 12 sites for a period of several days to several weeks in order to capture data over a range of firing rates for 1 or 2 boilers at each site.[3] As they were installed at each site, the sensors were self-calibrated in air. Data was averaged and stored for intervals as short as one minute. Figure 11 shows the oxygen sensor installed in a boiler flue at one site, with the datalogger enclosure on the top of the boiler. Data from the short-term monitoring of flue-gas oxygen concentration was time-synched and combined with the long-term monitoring of boiler firing rate using CEE's TRAVIS software before being analyzed in detail. The "wet" in-flue measurements were converted to the traditionally used "dry" gas measurement values typically referred to in manufacturer's literature and elsewhere. This was necessary because the concentration measured directly in the flue is lower than the concentration measured by most combustion analysis equipment that draws a gas sample and condenses the water out before measuring the percent oxygen.

[3] The boiler make, model, installing firm, and installation timeline were the same for sites MF3 and MF4, so flue-gas measurements from MF4 were deemed to be representative of the boilers at site MF3.

Figure 11. Flue Gas Oxygen Sensor Installation at MF1

Analysis of Monitored Data

Manufacturers' curves of condensing boiler efficiency as a function of entering water temperature are used as the foundation for boiler operating efficiency calculations and potential savings associated with changing those operating conditions. While the lack of certification and information about burner tuning may make comparisons between sites imperfect, these curves adequately represent the trends of efficiency changes with operating conditions that is this study's focus. The use of these curves as models for calculating boiler efficiency as a function of operating conditions was critical (along with the use of in-place BAS systems) to allow this field study to be conducted more cost-effectively than would have been possible with direct boiler efficiency measurements. This is because the models generally depend on, but are not supersensitive to, data that is commonly measured with BAS systems. The level of inaccuracy found in BAS measurements of these parameters is acceptable because the efficiency is not supersensitive to variations of less than 1 degree in temperature. On the other hand, direct measurements of boiler efficiency are very sensitive to a number of items that are difficult and/or expensive to measure accurately, especially over varying conditions.

As Found Operating Efficiency per Manufacturers' Curves

While CEE has extensive experience with whole building energy simulation, we were able to more accurately and cost-effectively represent the boiler operating efficiency over the course of a typical year through the use of spreadsheet based calculations using BIN analysis of measured data and Typical Meteorological Year (TMY) data. We used this approach for two key reasons:

1) The spreadsheet approach allows direct incorporation of measured boiler system load and operating conditions over a variety of real conditions instead of loads and conditions that are calculated from numerous, cascading assumptions about the building, the schedule, and the systems; and
2) The spreadsheet approach provides more flexibility to control the model calculation of boiler efficiency as a function of multiple operating variables (based upon calculated or empirical performance data).

Because all but one test site had multiple boilers, and the non-multifamily sites had markedly different operating modes, BIN analysis of monitored data was conducted separately for each stage of operation and operating mode using Tableau software. The operating modes were broken down into occupied and unoccupied for most sites, with a summer mode and morning warm-up mode being added where data review showed different trends during these time periods. Most sites had automatic rotation of the lead-lag sequencing, so data pre-processing using Excel was carried out to determine the sequencing order and to properly assign the key boiler operating characteristics to the appropriate stage (e.g. lead, second, etc.) Then for each 5°F outdoor air temperature BIN, the variables noted in Table 4 were calculated. This included a breakdown of the amount of time and average firing rate for firing rate BINS of 20% (i.e. 20-40%, 40-60%, 60-80%, and 80-100%). This data was used to characterize each of the stage's and mode's boiler operating conditions at a given outdoor temperature (within 5°F).

Table 4. Data Averaged For Each Boiler Stage and Outdoor Temperature BIN

Simple Variables	Complex Variables
Average Entering Water Temperature	**Time Within Each 20% Firing Rate BIN**
Average Firing Rate	**Average Firing Rate Within Each 20% Firing Rate BIN**
Burner Fraction On-Time	**On Cycles Per Hour**

For each outdoor temperature BIN and 20% firing rate range, the boiler steady-state efficiency was calculated using the entering water temperature, average firing rate within the BIN, and regression curve fit to the manufacturer's performance chart. Weighted averages of the firing rate and efficiency in each firing rate BIN was then used with the burner fraction on-time to calculate the average steady-state input and output for the outdoor temperature BIN. For BINS where a boiler stage did not operate continuously, off-cycle and cycling energy losses were subtracted from the steady-state efficiency based output rate to obtain an average output rate for the BIN. Finally, the input and output rates for each BIN were multiplied by the hours in that outdoor temperature BIN (based on TMY2 data) and stage condition to get the contribution to the boiler plant's annual energy input and output. These contributions for each stage, mode, and outdoor temperature BIN were summed for each site to obtain an annual operating efficiency. A sample of the BIN spreadsheets for one site is shown in Appendix B.

Burner Tuning Efficiency Impact

Burner tuning impact was evaluated by assuming that the performance curves provided by manufacturers represent operation at the lowest excess air recommended, and by calculating the change in efficiency that would be expected when excess air (as indicated by flue gas oxygen concentration measurements) is varied. This was done by direct calculations from the chemistry of natural gas combustion in air and matching assumptions of water condensed and flue gas temperature to the manufacturer's reported efficiency data and making adjustments to the excess air.

Optimization Opportunities at Monitored Sites

In addition to determining current operating efficiency over the course of a typical year based on observed operating conditions, detailed review and analysis of the trend data on the various system loads was used to project the degree to which the boiler operating conditions could be changed to further optimize the boiler efficiency while still meeting the needs of the building heating systems. The evaluation of potential changes to operating conditions and subsequent additional energy savings for each site was based on both trend data analysis and potential system and control changes that might be made cost-effectively given the facility's boiler system and building equipment configurations. Field data collection beyond the central boiler plant was also used where available to evaluate the degree to which specific heating devices might be limiting the potential to reduce the boiler system water temperature. These additional measurements included monitoring of hallway and other commons space temperatures at multifamily buildings and monitoring of air handling heating valve positions at a limited number of the BAS sites.

Savings projections for identified measures were evaluated by making incremental changes to each site's BIN model of annual performance outlined in detail in the *As Found Operating Efficiency per Manufacturers' Curves* section. The degree to which various operating conditions were predicted to change was based on a combination of engineering judgment, each site's data, and observations at similar test sites. The specific measures and key assumptions made for each measure are documented in Appendix C. While most measure savings estimates were based on projected operating conditions, two sites (ED3 and ED4) that made control changes during the course of the study showed savings and were treated as an improvement from the original condition (i.e. the savings were counted in the totals for this project). Savings for these items were evaluated by comparing BIN analysis from the pre and post-changed conditions.

While the majority of measures could be accurately evaluated with simple adjustments to the parameters in Table 4, more detailed analysis of energy losses associated with a boiler (or multiple boiler stages) cooling down while idle and then heating back up for a very short period of use (e.g. during a morning warm-up period) was required to accurately represent the change between as-found conditions and improved staging control.

The first cost of the potential changes was estimated with a combination of data from RS Means and contractor budget estimates. Where possible, the site-specific cost estimates from each site owner's preferred contractor were the primary source of cost data. For four of the sites, these site-specific cost estimates were not available due to unresponsiveness from a contractor and/or site contact after multiple inquiries. With the similarity of improvement measures across sites, measure costs for these four sites were estimated based on professional experience and estimates from the other sites.

Industry Contacts Survey

The project included a formal survey to obtain feedback from local industry professionals about current practices related to key factors that impact condensing boiler operating efficiency, their impressions of the importance of these key factors, and their perceptions of the potential value of possible CIP program strategies that might increase the savings of condensing boiler installations. Both objective and open-ended questions were included to allow for a quantitative evaluation of various items, and to capture as much potentially useful insights as possible.

The content of the survey was informed by the preliminary market assessment and preliminary field monitoring results. The survey was developed to be administered on-line via a link that was emailed to the pool of potential survey participants. The complete survey form can be found in Appendix D. The primary sections of the survey were:

- Respondent's role in the industry
- Market conditions for key operational efficiency issues
- Reported importance of key efficiency factors
- Individual and ranked evaluation of possible CIP program strategies

The possible CIP program strategies evaluated in the survey are listed in Table 5.

The goal was to survey 35 individuals that represent a variety of facets of the local boiler industry including:

- Contractors,
- Designers,
- Boiler manufacturers' representatives
- Distributors,
- Facility Owners & Operators, and
- Utility Program Staff

Table 5. CIP Program Approaches Addressed by Survey

APPROACH NAME	DESCRIPTION
New Installations	
a) Piping Design Review	The piping design is reviewed by a third-party expert to identify common problems
b) Control Sequence Review	The control sequences are reviewed by a third-party expert to identify common problems
c) Site-Specific Savings Estimate	A more accurate savings estimate (compared to boiler efficiency ratings) based on the unique system and operating plan
d) Bonus Rebate for Quality Design	A bonus rebate (above and beyond a high-efficiency boiler rebate) for installations that meet a set of stricter system design requirements
e) Bonus Rebates for Individual Design Features	Bonus rebates for incorporating individual design features that can increase the boiler's efficiency (e.g. specific boiler control capabilities)
f) Commissioning of Installation and Controls	A commissioning agent verifies proper installation and control during and after installation
g) New Training Options for Designers & Installers	New training options for engineers and contractors on how to maximize the efficiency of condensing boilers
Existing Installations	
a) Specialized Engineering Review	A specialized on-site engineering review and consultation of system optimization opportunities
b) Gas Rebate for Variable Speed Drive	A gas utility rebate for variable speed drive control that increases boiler efficiency
c) Rebates for Control Upgrades	Rebates for control equipment upgrades
d) Rebates for Optimizing Control Settings	Rebates for changing settings of existing controls to optimize efficiency
e) Resources on Optimal Control & Operation	Technical resources that provide guidance on optimal condensing boiler control and operation (e.g. graphs, online tools)
f) Site-Specific Guide for Controls	An expert prepares a site-specific guide for control settings and adjustment
g) New Training Options for Operators	New training options for operators on how to maximize the efficiency of condensing boilers

A list of 105 potential survey participants was compiled by combining information from the preliminary market assessment, previous organization contacts, and special efforts to identify key contacts within the categories above that were underrepresented in preliminary lists. A summary of the number of contacts by industry role is shown in Table 6.

Table 6. Local Industry Contact Survey Pool

Industry Role	# in Pool
Mechanical Contractor	18
Controls Contractor	7
Design Firm	10
Boiler Manufacturer's Representative	18
Equipment Distributor	14
Facility Owner or Operator	32
Utility Program Staff	6
Total	105

An initial group of 72 contacts was targeted with emails that contained a link to the survey, and with phone calls (up to 3 until reached for a conversation) to ask for participation in the on-line survey. Another 33 contacts received only email solicitations to complete the survey. Two email reminders were sent to those that had not completed the survey in a timely manner. The second reminder included the announcement of the incentive of a drawing for a Target gift card and a deadline for completing the survey.

Results

Preliminary Market Study & Site Selection

Besides providing information to guide the selection of sites that were representative of the typical variations in local installations, the preliminary market study also showed a number of clear trends that have significant implications for CIP programs. The most notable finding was that over the several years preceding this research project, the condensing boilers have come to dominate the commercial boiler market. In addition to indicating that condensing boilers had become the default choice, the preliminary market study also noted that virtually all condensing boiler installations use modulating burners, multiple boilers, and variable speed pumping on the main building heat loop. Other preliminary market study findings are reflected in the site selection guidelines that are summarized here in Table 7 (in descending order of priority) and fully detailed in Appendix A.

Table 7. Summary of Site Selection Guidelines & Selections

Criteria	Goal	Actual Sites
Building Type	3-5 multifamily; 3-4+ education; 3-4+ office/government	4 multifamily; 4 education; 4 office/government
Boiler(s) Used in Summer	1 to 4	6
Service Water Heating Tie-In	1 to 4	2
Hybrid System (Includes Non-Condensing Boiler[s])	3 to 4	4
# of Boilers	≤ 3 single boiler	1 single boiler
Boiler Piping	≥ 6primary/secondary; ≥4 variable primary	9 primary/secondary; 3 variable primary
Located Outside of Minneapolis-St. Paul Metropolitan Area	≥ 2	3
Project Type	≥ 4 design/build; ≥ 4 plan and specification	6 design/build; 6 plan and specification
Design & Contracting Firms	≤ 50% of any project type by same firm	≤ 50% of any project type by same firm
Main Pump Variable Frequency Drive	≥ 8 with VFD	6 with VFD
Boiler Manufacturer	2+ each: Aerco, Fulton, Lochinvar; 1+ each: Hydrotherm, Bryan; Various others	3 Aerco, 1 Fulton, 4 Lochinvar; 2 Hydrotherm, 0 Bryan; 1 Burnham/Alpine, 1 Camus
Burner Staging	≥ 10 fully modulating	12 (all) fully modulating
O_2 Trim Control	≥ 1	0
Control Type	3+ on board; 3+ BAS ; 2+ separate dedicated	5 on board; 4 BAS; 3 separate dedicated
System Size	6+ > 1 MMBtu; 3+ < 1 MMBtu	9 > 1.25 MMBtu; 3 < 1.25 MMBtu
Installation Age	On board w/BAS tie-in	Separate Dedicated tied to BAS

Table 7 also shows a summary of the sites selected. The most important things to note about the site selection guidelines is the priority of getting about 4 sites each from the following building categories: education, multifamily, and office/government and a representative variety of key boiler plant characteristics such as: summer-time operation, domestic water heating, piping arrangement, control type, variable speed pumping, and make/model of boiler. Two closely linked site selection guidelines that had notable adjustments from the original goals noted above were reductions in the number of installations with variable primary flow and with variable speed pumping of the building heating loop. These adjustments were made because the findings from site-screening were showing these two features to be less prevalent than the preliminary market study findings suggested. Although the capacity that was used as a breakpoint between small and large systems was adjusted to a higher value, this was not considered to have a significant impact because the piping and variable speed pumping characteristics that were expected to be observed only in small systems were more prevalent than expected among larger study test sites. Site by site characteristics can be found in Table 8.

The vast majority of potential sites were found through CEE's previous relationships with building owners. Ultimately, 8 of the 12 final sites were identified exclusively through CEE's pre-existing contacts, 2 through local industry (non-utility) contacts involved in the preliminary market study, and 2 through DER's ARRA funded installation contacts. A total of 19 sites were visited, with 7 screened out of the study because of a lack of BAS connection (for remote data collection) or boiler system characteristics that did not fit the study priorities well.

Table 8. Individual Test Site Characteristics

Site ID→	ED1	ED2	ED3	ED4	GO1	GO2	GO3	GO4	MF1	MF2	MF3	MF4
Building Type	Secondary School	K-12 School 78%; office 22%	Post-Secondary School	Post-Secondary School	Office/ Lobby/ Skyway	Office	Government (Licenses &.Library)	Government (Community Center)	Apartment	Apartment	Apartment	Apartment
Boiler(s) Used in Summer	No	Yes	Yes	Yes	No	Yes	Yes	No	No	No	Yes (SHW Only)	No
SHW Tie-In	Yes	No	No	No	No	No	No	No	No	No	Yes	No
Hybrid	Yes	No	Yes	No	No	No	No	No	Yes	Yes	No	No
# Boilers	3	2	3	7	1	6	2	5	3	3	3	3
BAS	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No
Project Type	Plan/ spec	Design/ build	Plan/ spec	Plan/ spec	Plan/ spec	Plan/ spec	Plan/ spec	Design/ build	Design/ build	Design/ build	Design/ build	Design/ build
Main/Bldg Pump VFD	Yes	Yes	Yes	Yes	No	Yes	Yes	No	No	No	No	No
Boiler Manufacturers	Aerco	Hydro-therm	Aerco	Fulton Vantage	Camus	Aerco	Hydro-therm	Burnham (Apex)/ Alpine	Lochinvar (Sync)	Lochinvar (Knight Floor Mount)	Lochinvar (Knight Wall Mount)	Lochinvar (Knight Wall Mount)
Condensing Boiler Model(s)	Benchmark 2.0	KN-30 & KN-20	Benchmark 2.0	VTG-4000DF	Dynaflame	Benchmark 3.0	KN-10	APX500 / ALP500F(or N)	SBN1500	KBN501	WHN399	WHN399
# of Condensing Boilers	2	2	1	7	1	6	2	5	1	1	3	3
# of Non-Condensing Boilers	1	0	2	0	0	0	0	0	2	1	0	0

Site ID→	ED1	ED2	ED3	ED4	GO1	GO2	GO3	GO4	MF1	MF2	MF3	MF4
Burner Staging	Fully modulating	Fully modulating 5:1	Fully	Fully	Fully	Fully modulating	Fully Modulating	Fully modulating	Fully modulating	Fully modulating	Fully modulating	Fully modulating
O2 Trim	No	No	No	No	No	No	No	No	No	No	No	No
Control Type	Separate Dedicated tied to BAS	On board w/BAS tie-in	On board w/BAS tie-in	Separate Dedicated tied to BAS	BAS Reset w/On Board Modulation to Fixed Setpoint	Separate dedicated from mfgr	BAS	BAS Reset w/On Board Modulation to Fixed Setpoint	On-board only	On-board only	On-board only	On-board only
System Size	29.1 MMBtu	5 MMBtu	6.4 MMBtu	28 MMBtu	5 MMBtu	18 MMBtu	2 MMBtu	2.5 MMBtu	5.5 MMBtu	~1.1MM Btu	1.2 MMBtu	1.2 MMBtu
Installation Date	2006	2011	2005	2010	2008	~2011	~2009	~2011	~2010	Summer 2011	Summer 2012	Summer 2012

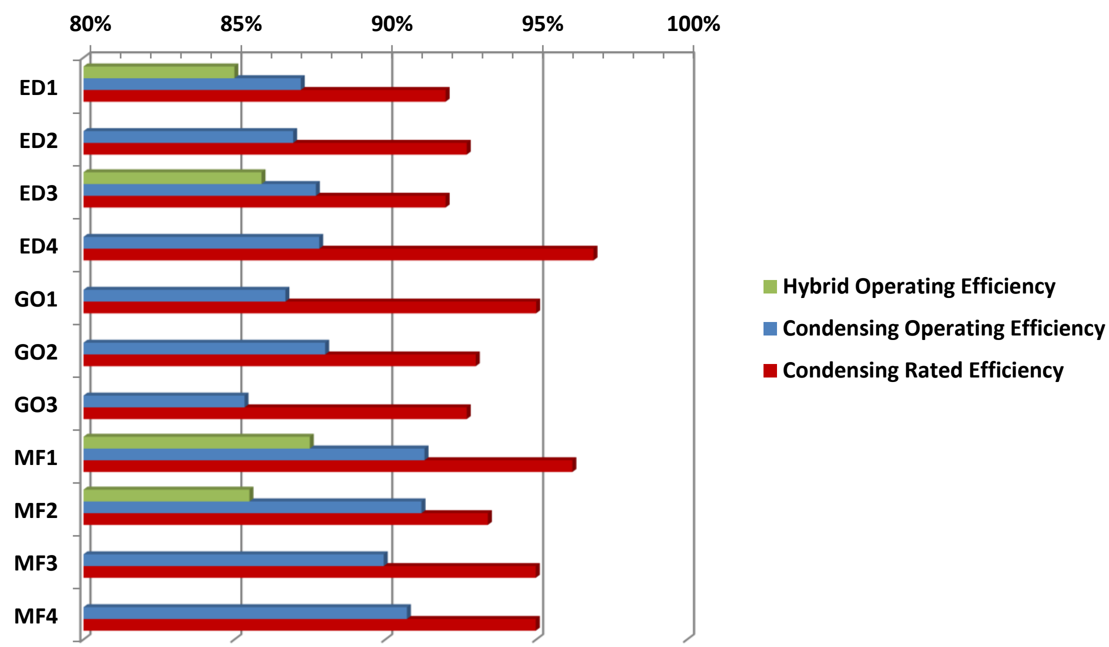
As Found Operating Efficiencies

The operational efficiency results are presented in two sections. Because available manufacturers' curves did not include burner tuning/excess air conditions, efficiency evaluation results are first presented without consideration of excess air. Then the magnitude of the impact of observed and manufacturers' recommended variations in excess air are noted separately.

Efficiency per Manufacturers' Curves

The as found boiler operating efficiencies based on monitored entering water, part-load and cycling conditions appear in Figure 12, and these values are also reported in Table 9.[4] The average condensing boiler operating efficiency across the sites was 88.7 percent compared to the average rated efficiency of 94 percent. The closest any site came to achieving rated efficiency was 2.2 percentage points below at site MF2. When the impacts of conventional boilers in hybrid systems (both condensing and conventional boilers) is considered for the four hybrid sites, the average boiler plant operating efficiency across all sites was 87.2 percent , and 4.3 percentage points below rated efficiency was the best result achieved (at site MF4). The impact of various factors on boiler performance is noted in the following paragraphs.

Figure 12. As Operated and Rated Boiler Efficiencies



[44] For site GO4 long-term inconsistent reliability problems with communication between the BAS system and the boilers (as well as the controller with new temperature sensors) prevented the collection and processing of data that was adequate for reliable conclusions regarding annual efficiency and quantification of the potential for additional savings.

Table 9. As Operated and Rated Boiler Efficiencies

Site ID	Condensing Operating Efficiency*	Hybrid Operating Efficiency*	Plant Operating Efficiency	Condensing Rated Efficiency	Conventional Rated Efficiency
ED1	**87.2%**	**85.0%**	**85.0%**	**92.0%**	**79.7%**
ED2	**86.9%**		**86.9%**	**92.7%**	
ED3	**87.7%**	**85.9%**	**85.9%**	**92.0%**	**80.0%**
ED4	**87.8%**		**87.8%**	**96.9%**	
GO1	**86.7%**		**86.7%**	**95.0%**	
GO2	**88.0%**		**88.0%**	**93.0%**	
GO3	**85.3%**		**85.3%**	**92.7%**	
MF1	**91.3%**	**87.5%**	**87.5%**	**96.2%**	**83.0%**
MF2	**91.2%**	**85.5%**	**85.5%**	**93.4%**	**80.0%**
MF3	**89.9%**		**89.9%**	**95.0%**	
MF4	**90.7%**		**90.7%**	**95.0%**	
Average	**88.4%**	**86.0%**	**87.2%**	**94.0%**	**80.7%**

*Assuming that each boiler is tuned the same as in the published manufacturers' performance curves.

As expected, higher than optimal boiler entering water temperature was the largest factor preventing the achievement of rated boiler efficiency. Figure 13 shows how the entering water temperature for the lead boiler at each site varied over the local range of outdoor temperatures. Condensation (and the associated start of the efficiency boost) generally only occurs when the entering water temperature is below the dashed line, and operating efficiency continues to increase as the temperature drops towards the rating condition of 80°F entering water temperature.

Figure 13. Entering Water Temperature Variations

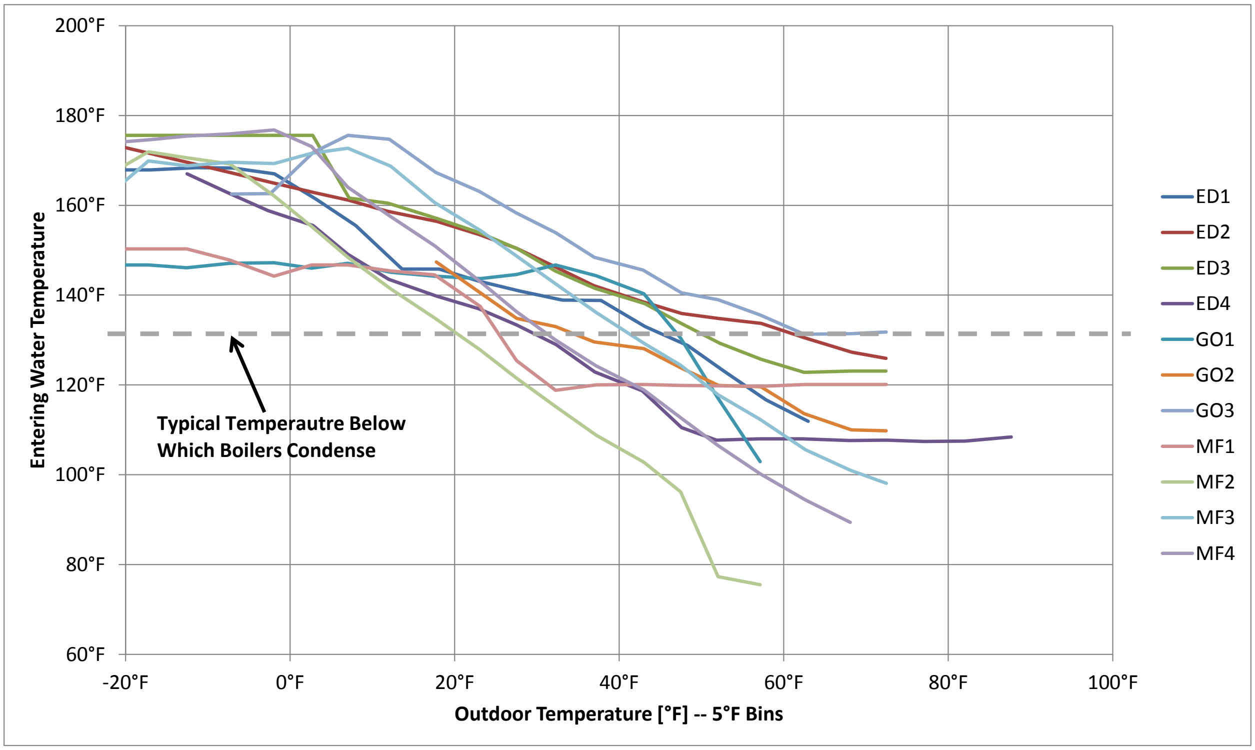


Figure 14. Sample Annual Load Variations with Outdoor Temperature

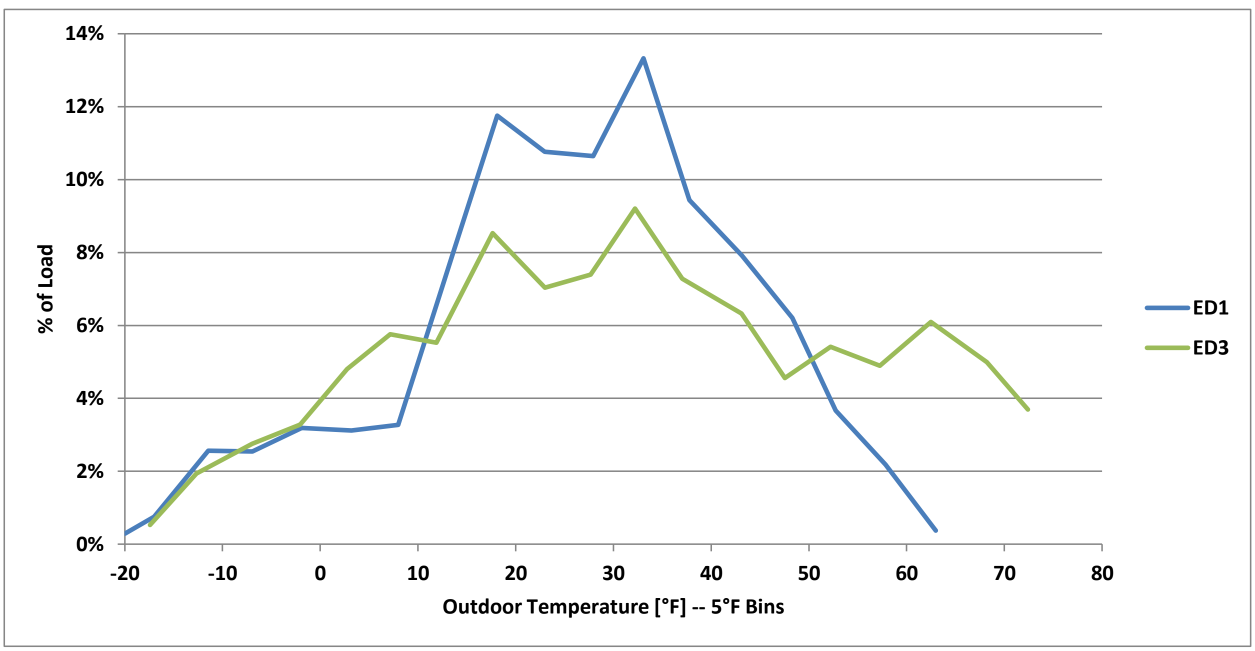
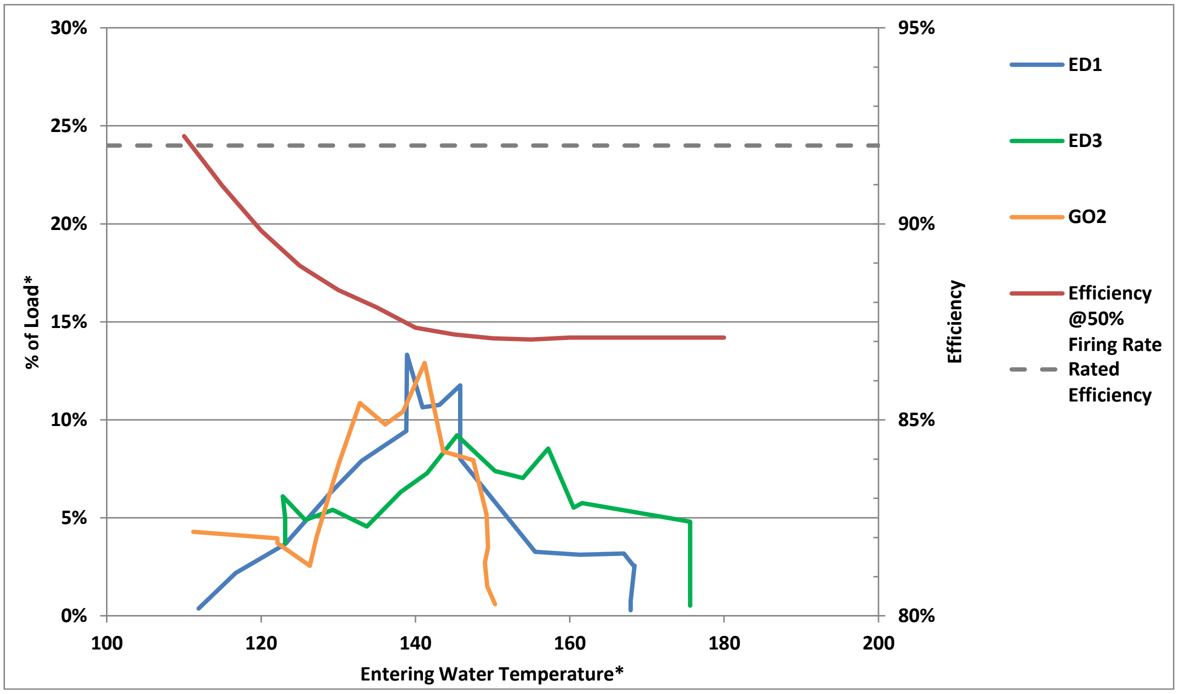


Figure 14 shows examples of how the percentage of annual boiler load varies with outdoor temperature in order to show that most sites have a majority of their load occurring when the boilers are not condensing at all.

Samples of how combining entering water temperature variations with annual load variations impact efficiency over the course of a season are shown in Figure 15. This shows data from multiple sites that have the same make of boiler. The rated efficiency could only have been achieved with operating temperatures that were dramatically lower than observed.

Figure 15. Sample Impacts of Entering Water Temperature on Efficiency



*Based on averages of 5°F outdoor temperature BINs.

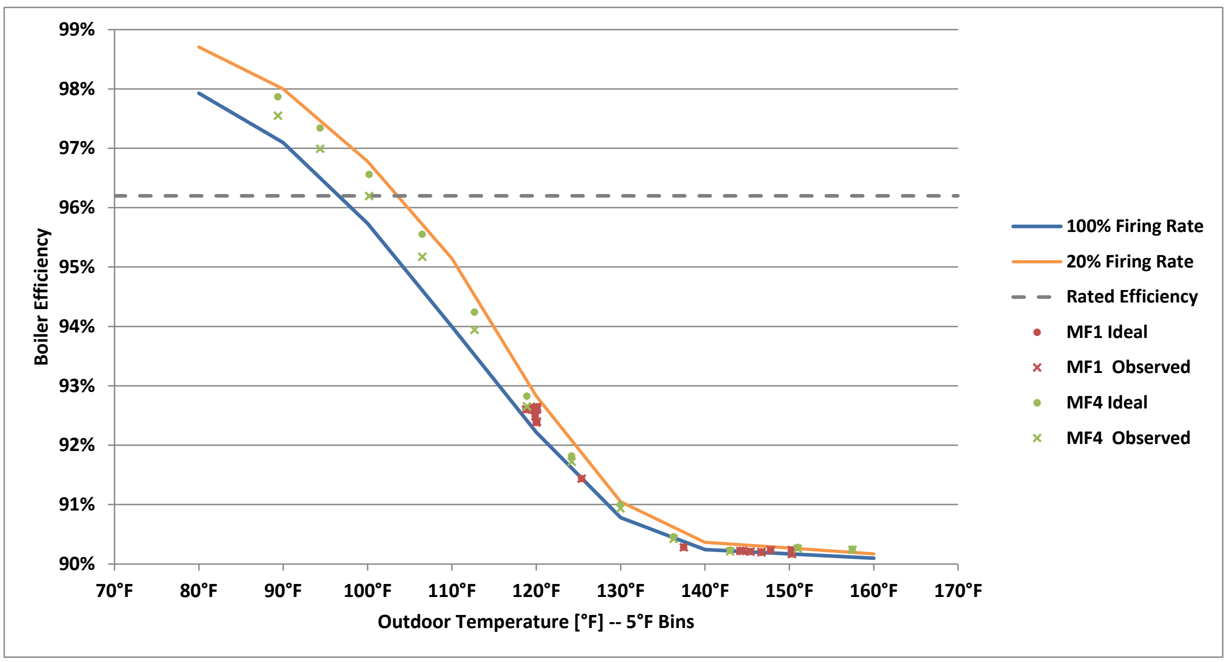
Secondary impacts on operating condensing boiler efficiency included part-load staging and cycling issues. A summary of the issues by site is presented in Table 10. While boiler purge losses at start-up tended to be minimal, significant efficiency variations at a number of sites were found to be associated with suboptimal part-load control and/or frequent operation of boiler(s) that could be idle. The most extreme example of poor cycling control was at site GO1, which had a single boiler cycling on at near full fire for less than one minute at a time due to poor coordination between the building automation system and the boiler's built-in modulation controls. Even when using on-board controls, sites MF3 and MF4 also had severe short-cycling with all of the three boilers typically cycling from off to near full fire within 2 minutes, and then cycling off again within 5 minutes. In addition to running at higher percentage firing rates while on, this short-cycling puts extra wear on equipment and causes excess heat loss from the boiler plant by keeping all of the boilers hot.

Figure 16 shows some examples of how part-load control impacts efficiency, but in a way that is secondary to the impact of boiler entering water temperature. Suboptimal staging control caused the boilers at site MF4 to cycle on and off frequently at high firing rates instead of operating for longer periods of time at lower firing rates. On the other hand, site MF1 has a closer to ideal control of the boiler cycling and firing rates.

Table 10. Summary of Short-Cycling and Staging Issues

Site	Staging Control Notes (Aside from Temperature Control)
ED1	Condensing boilers dropped to low load when conventional boiler came on
ED2	Okay
ED3	Conventional boilers were often briefly brought on-line during morning warm-up
ED4	Moderate short-cycling with extra stages being brought on for short periods of time
GO1	Severe short-cycling of the single boiler at a high firing rate
GO2	Okay
GO3	Low to moderate short-cycling
GO4	Moderate short-cycling
MF1	Condensing boilers dropped to low load when conventional boiler came on
MF2	Moderate short-cycling at around 75% firing rate when a lower firing rate would meet load
MF2	Severe short-cycling of all 3 stages at high firing rates during low load periods
MF4	Severe short-cycling of all 3 stages at high firing rates during low load periods

Figure 16. Sample Impacts of Part-Load Control on Efficiency



Lastly, for two of the hybrid systems (MF1 and MF2), constant heat loss via hot water pumping through an idle conventional boiler brought down the achieved plant efficiency considerably — even during time when the idle boiler was not needed. More specific quantification of the impact of addressing this and each of the above factors is presented in the *Optimization Opportunities at Monitored Sites* section.

Burner Tuning Efficiency Impact

A number of the manufacturers of the boilers that were installed at the test sites recommend a wide enough range of excess air such that the efficiency variation could be as much as 2.1%

within this range, plus 3 boilers were found to be outside the manufacturers' recommended range. While most of the out of range boilers had higher excess air (and lower efficiency), it was also noted that the higher excess at low firing rates recommended by some manufacturers seemed to be ignored so that the percentage of excess air varied little with firing rate. While this could have potential safety and environmental implications, it does avoid the expected potential for reduction in efficiency with firing rate.

Figure 17. Recommended and Observed Flue Gas Concentration Variations at 50% Fire

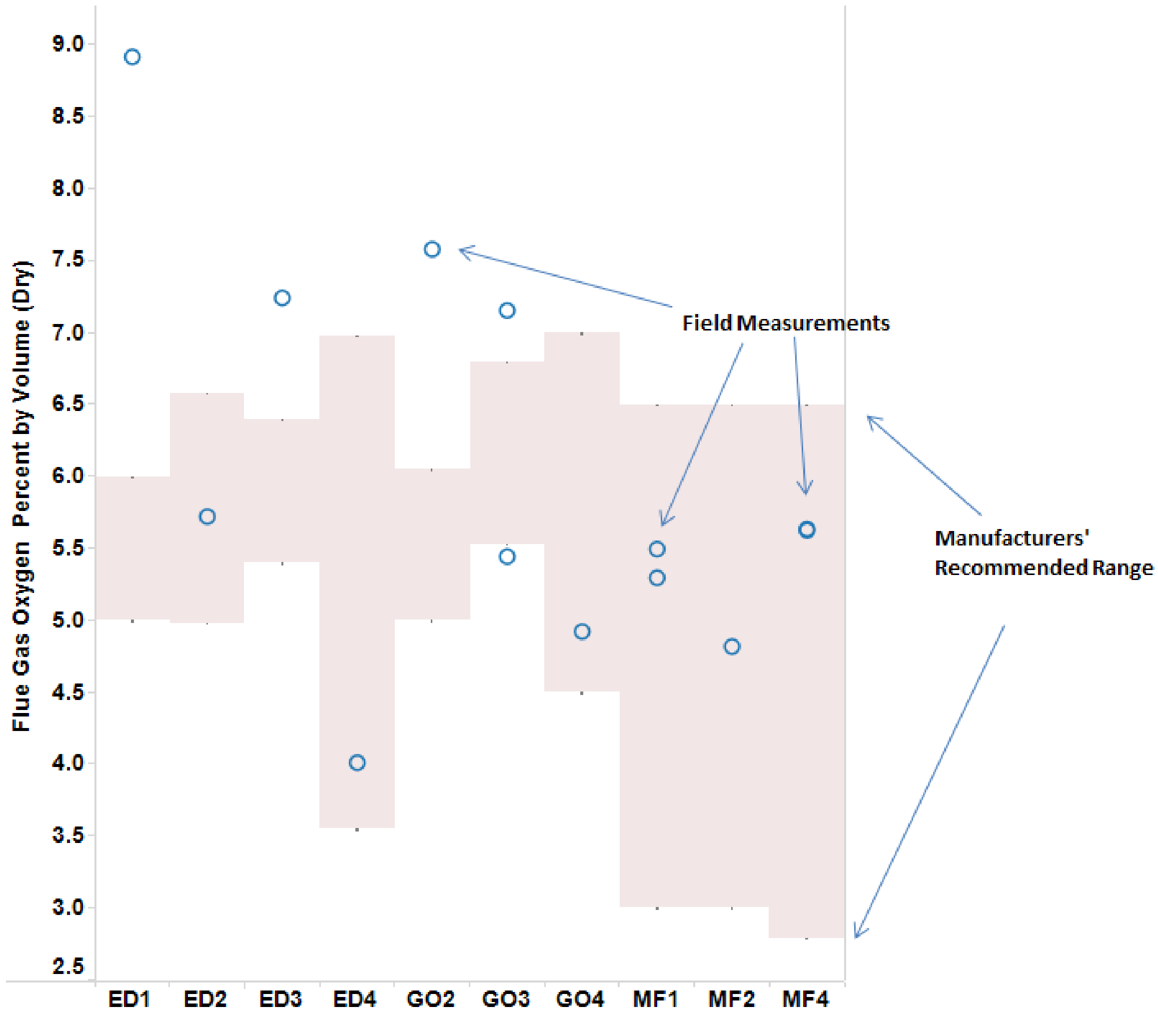
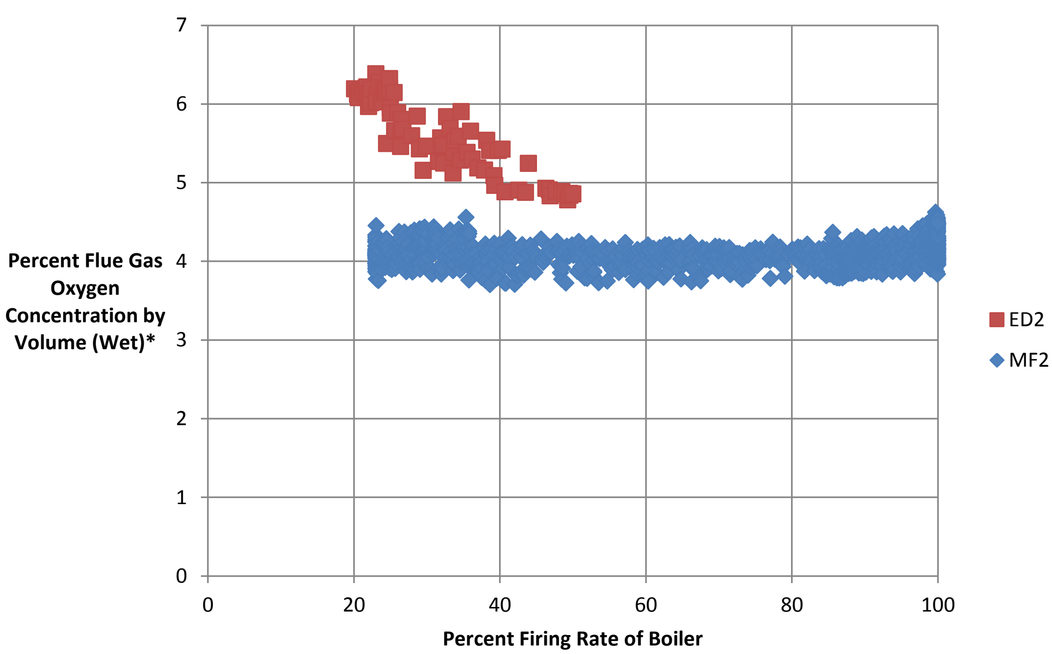


Figure 17 shows the manufacturers' recommended range of flue gas oxygen concentrations for each of the sites along with the observed field values. Two-thirds of the sites were within the recommended range, and one boiler at site GO3 was above the range due to partially disconnected combustion air ducting that caused air to be drawn from the boiler room. This is shown in Figure 18.

Figure 18. Partially Disconnected Combustion Air Inlet at Site GO3

Although information during the preliminary market assessment suggested that significant increases in excess air occur at low firing rates, our measurements generally did not find as dramatic a trend in this direction as expected. Figure 19 shows examples of the observed variation in oxygen concentration with firing rate compared to the manufacturer's guidelines. While the guidelines suggest dramatically higher excess air at low firing rates, the observed variations did not follow this trend to the degree that was feared.

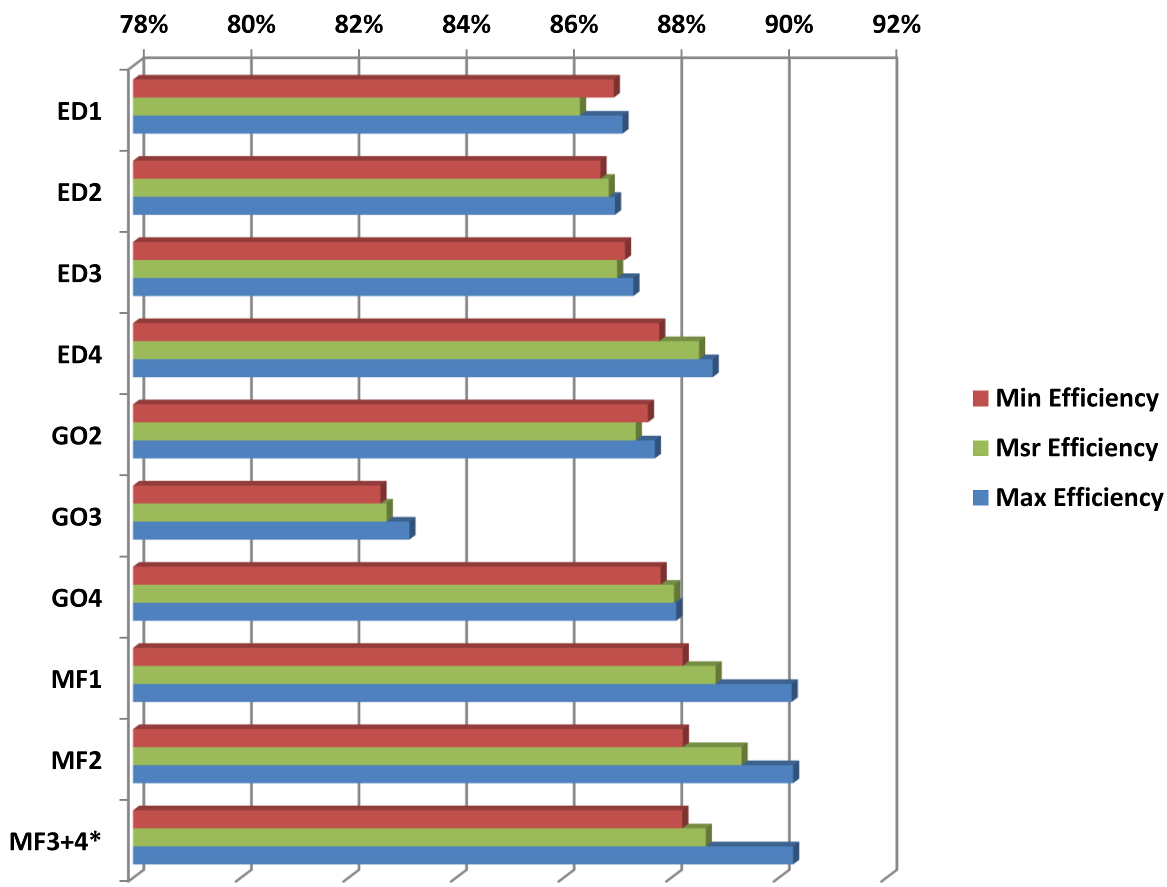
Figure 19. Sample Variations of Flue Gas Oxygen with Firing Rate



*The field measurement of *wet* flue gas oxygen were 0.3 to 0.7 percentage points lower than typically measured *dry* values.

The potential efficiency gains that would result from bringing the observed excess air for each boiler down to the minimum manufacturer recommended values are shown in Figure 20. The red and blue bars show the bounds of efficiency based on manufacturers' recommended ranges of flue-gas oxygen, and the green bar shows the field measured condition. It is presumed that most boilers can be tuned to match the maximum efficiency based on this range. The average efficiency change for doing so would be 0.6 percentage points (providing 0.7% savings) with one-third of the boilers outside of the recommended range of excess air. Another indication of potential tune-up savings is the difference in efficiency between the maximum and minimum excess air recommended, and this range itself allows for an average variation of 0.9 percentage points (with savings of 1.0% from going to the maximum to the minimum).

Figure 20. Potential Efficiency Gains from Tune-Ups at 140°F Entering Water Temperature



*Sites MF3 and MF4 have the same make and model of boiler, as well as the same installing contractor, so the results from site MF4 were assumed to be representative of site MF3.

The tune-up efficiency change potential and the growing share of existing buildings with condensing boilers should be considered in the planning of boiler tune-up programs. It was expected that reducing excess air would have a bigger impact on the efficiency of condensing boilers compared to conventional boilers, but the study's findings regarding potential savings were well below the values typically assumed for boiler tune-up programs based on Minnesota's Technical Reference Manual. It is unclear if this discrepancy is related to potential differences between condensing boilers and conventional boilers in terms of tendency to be set up at low excess air, or if it is related to limits on the recommended range of excess air. While this study's findings raise questions about appropriate planning for tune-up programs, a more detailed analysis of the possible implications is needed and was beyond the scope of this project.

Optimization Opportunities at Monitored Sites

Possible boiler performance improvement opportunities were identified at all sites, with an average potential savings of 3.7% across the sites. The individual measure and total savings by site are shown in Figure 21. A discussion of the results follows the summary plot and table below, and more detailed descriptions of the improvement measures at each site can be found in Appendix C.

Figure 21. Potential Additional Savings Summary

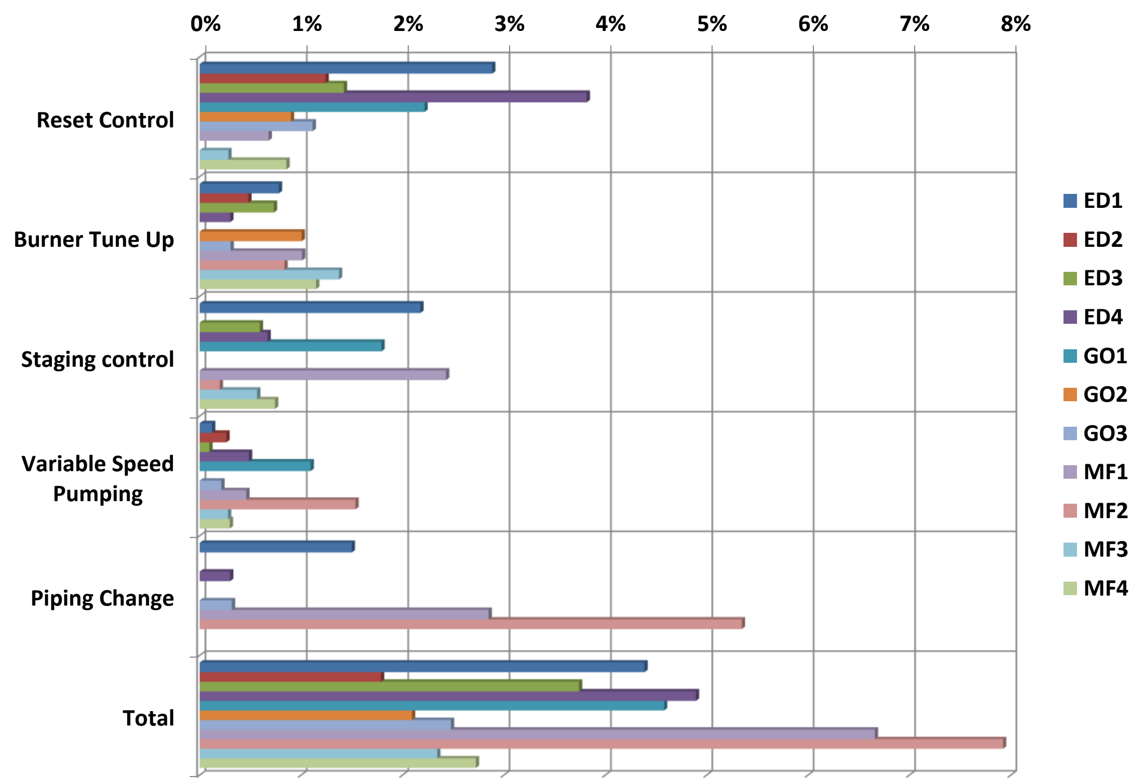


Table 11. Additional Annual Energy Savings Potential by Site & Measure Type (Therms)

Site	Outdoor Reset	Burner Tune-Up	Staging Control	Variable Speed Pumping	Piping	Combined
ED1	4,037	898	3,045	171	2,103	4,608
ED2	642	248		136		926
ED3	1,167	519	680	78		2,901
ED4	1,758	139	308	224	138	906
GO1	2,120		1,714	1,046		4,379
GO2	2,252	2,525				5,248
GO3	229	63		44	65	484
MF1	489	728	1,749	334	2,049	4,787
MF2		85	52	156	542	803
MF3	70	327	141	66		582
MF4	127	171	111	44		259
Total	12,892	5,703	7,799	2,300	4,897	25,883

*Site GO4 could also have achieved savings from outdoor reset control, variable speed pumping, and piping changes, but these savings were not quantified due to persistent data quality issues.

Measure cost and resulting payback for each site and measure are shown in the Table 12 and Table 13. Payback calculations are based on an assumed natural gas cost of $0.70 per therm and electric cost impacts are ignored.

Table 12. Cost for Optimization Measures by Site and Type

Site	Outdoor Reset	Burner Tune-Up	Staging Control	Variable Speed Pumping	Piping
ED1	$3,000	$800	$3,000	$7,500	$2,000
ED2	$1,000	$600		$30,000	
ED3	$1,200	$400	$1,500	$1,200	
ED4	$800		$1,000	$800	$2,000
GO1	$1,500		$2,000	$10,000	
GO2	$1,150	$1,600			
GO3	$200	$1,000		$1,500	$10,000
MF1	$2,200	$1,200		$40,000	$30,000
MF2		$1,200	$1,200	$3,500	$15,000
MF3	$120	$500	$2,300	$3,500	
MF4	$120	$500	$300	$3,500	
Average	$1,130	$870	$1,600	$10,200	$12,000

Table 13. Payback (Years) for Optimization Measures by Site and Type

Site	Outdoor Reset	Burner Tune-Up	Staging Control	Variable Speed Pumping	Piping
ED1	1.1	1.3	1.4	62.6	1.4
ED2	2.2	3.5		314.1	
ED3	1.5	1.1	3.2	21.9	
ED4	0.7		4.6	5.1	20.7
GO1	1.0		1.7	13.7	
GO2	0.7	0.9			
GO3	1.2	22.8		23.9	107.0
MF1	6.4	2.4		171.3	20.9
MF2		20.2	33.1	32.1	39.5
MF3	2.4	2.2	20.3	75.2	
MF4	1.3	3.5	3.9	113.1	
Median	1.3	2.4	3.9	47.3	20.9

Table 14 shows a summary by site of the most comprehensive combination of optimization measures that together have a payback of 5 years or less. While one site did not have any cost-effective optimization opportunities, all of the others had multiple measures in their cost-effective package of optimization measures. These cost-effective payback packages include 80% of the study's identified savings and have an overall simple payback of 2.6 years.

Table 14. Economic Improvement Package Summary by Site

(X = Included; O = Excluded; Blank = No Opportunity)

Site	Outdoor Reset	Burner Tune-Up	Staging Control	Variable Speed Pumping	Piping	Package Cost	Package Savings (Therms)	Payback (Years)
ED1	X	X	X	O	X	$8,800	4,437	2.8
ED2	X	X		O		$1,600	789	2.9
ED3	X	X	X	O		$3,100	2,822	1.6
ED4	X		X	X	O	$2,600	768	4.8
GO1	X		X	X		$13,500	4,379	4.4
GO2	X	X				$2,750	5,248	0.7
GO3	X	X		O	O	$1,200	375	4.6
MF1	X	X		O	O	$3,400	1,217	4.0
MF2		O	O	O	O	NA		NA
MF3	X	X	O	O		$620	376	2.4
MF4	X	X	X	O		$800	420	2.7
Sum	10	8	5	2	1	$38,370	20,831	2.6

Results by Measure Type

Outdoor Reset Control. Adjusting or replacing the outdoor reset control strategy was the most consistently significant opportunity across the sites. For the sites where this was relevant, the average savings associated with this measure was 1.5%, and across all sites (including the one site where no change was recommended) the average savings was 1.4% (Table 15). Optimizing outdoor reset control was expected to have the largest potential impact compared to other measure types because of large variation in boiler efficiency with entering return water temperature. While the additional savings potential for this measure didn't make up as much of the difference between rated and observed operating efficiency as hoped, it still appears to be both the most universally applicable measure and the measure with the highest programmatic savings potential. Much of the reset optimization savings could be achieved without any equipment or controls replacement, although a small number of the sites could not fully optimize the reset control without more extensive changes (e.g. replacement of air handler three-way valves with two-way valves).

Table 15. Estimated Savings by Measure Type

Measure Type	# of Sites	Average Savings for Sites where Measure Applicable	Average Savings Across All Sites
Reset Control	10	1.5%	1.4%
Burner Tune Up	10	0.8%	0.7%
Staging control	8	1.2%	0.8%
Variable Speed Pumping	10	0.5%	0.4%
Piping Change	5	2.1%	0.9%
Total	11		3.0%

*The differences in average savings between the measure types are not statistically significant.

Burner Tune-Ups. Traditional burner tune-ups showed the fourth highest average savings potential across all sites at 0.7%, with an average savings potential of 0.8% for the 11 sites where they were necessary (Table 15). More discussion of burner tune-up issues can be found in the *Burner Tuning Efficiency Impact* section on page 35.

Staging Control. As outdoor reset control adjustment was expected to be the dominant optimization factor, we did not expect to find that three-fourths of the sites would have staging control optimization opportunities. The pre-existing staging control issues that were addressed by the recommended measures are reported in Table 10. Specific proposed measures to address these issues are expected to provide an average savings of 1.2% for the sites with control optimization opportunities and 0.8% across all sites (Table 15). Projected energy savings from better staging control could be achieved at these sites primarily through one or both of two strategies. The first is operation at lower, more efficient firing rates. The second is reduction of inefficient short-cycling that heats up a boiler for only a short run time. As with the outdoor reset issue, improving staging control is easily addressed in a practical way at relatively low cost in existing installations. In new installations the issue could be addressed even more cost-effectively.

Variable Speed Pumping. Almost all sites had an opportunity to either better optimize the control of existing variable speed pumping capabilities on the building heating loop or to add such capabilities. However, the average potential savings was estimated at only 0.5% per relevant site and 0.4% across all sites (Table 15). Half of the sites already had a building loop pump variable speed drive in place at the commencement of the study. Even taking this into consideration, it was expected that this measure would have more significant savings potential because lowering the building heating loop supply flow rate brings down the building return water temperature. However, the ability to reduce the entering water temperature through variable speed pumping is secondary to an outdoor reset control. Besides having low savings, the cost and logistics to address variable speed pumping (and piping) issues is greater than other measures considered because a separate BAS contractor must be used in many cases. The relatively small changes in temperature from variable speed pumping only significantly impacts boiler efficiency when a boiler is already operating within, or at least very near, condensing conditions—a situation that was found not to be happening at a majority of the time at most sites.

Piping Changes. When applicable, piping changes were shown to have the highest average saving potential (2.1%) of all measures. However, across all sites it averaged the second highest potential (0.9%) (Table 15). We saw piping change opportunities at half of the test sites and were surprised to see that many sites. Re-piping within the boiler plant was recommended at four of the sites, and the recommendations for the other two involved piping work within the distribution system (e.g. conversion from three-way to two-valves for specific pieces of equipment). Both of the two biggest individual building opportunities for optimization through piping changes involved better isolation of pre-existing conventional boilers when they are not needed (in order to reduce heat losses from hot water that is continuously circulating through a large boiler). While most of the piping changes had significant cost associated with the changes necessary to optimize these existing installations, the boiler plant piping changes needed to realize additional savings are generally expected to be much less expensive if put in place at the time of initial installation.

Savings Correlations to Site Characteristics

The most important factor in the potential for additional savings appears to be whether or not a building has a hybrid system (i.e. a boiler system that uses a combination of condensing and conventional boilers). The 4 buildings with hybrid systems (ED1, ED3, MF1 and MF2) were 4 of the 5 sites with the highest additional savings potential, and these sites all had average savings of 5.7% compared to 2.5% for the other sites. While achieving the potential savings at site MF1 would require relatively expensive piping changes, the cost of this difference in piping could be minimized if addressed at the time of installation. Moreover, the other 3 hybrid sites could achieve savings without such extensive changes.

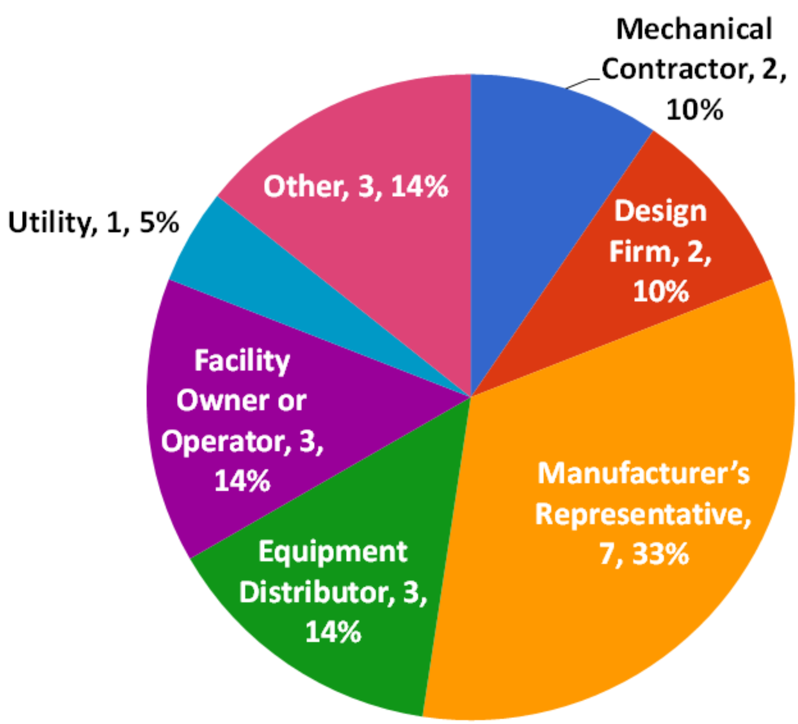
While not statistically significant, multifamily and education buildings tended to show a much higher percentage savings than the government/office buildings, with an average of 4.9% and

3.7% compared to 1.9%. However, a large fraction of the savings in the multifamily test sites was related to opportunities unique to the hybrid systems in two of the buildings. While there were also two hybrid sites among the education buildings, a greater amount of their projected savings were associated specifically with outdoor reset control optimization.

Industry Contacts Survey Results

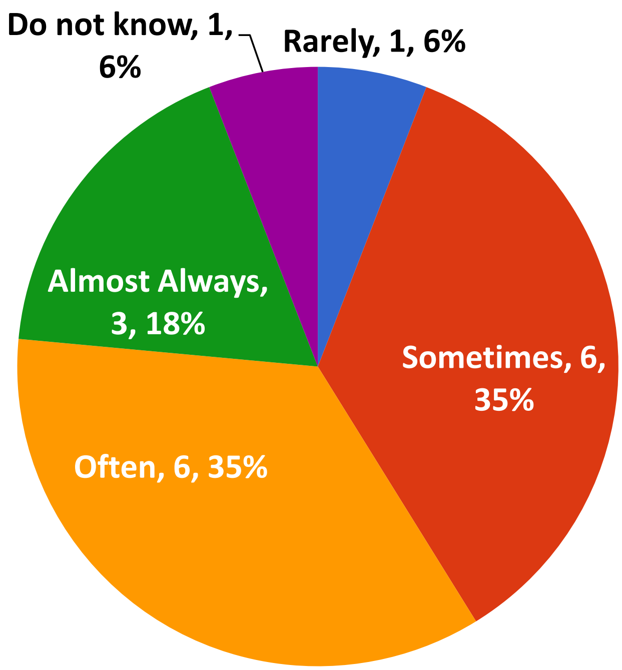
The survey helped corroborate key observations in the test sites, and provided valuable insights into the perceived value of possible CIP program approaches to increase operational efficiency of condensing boilers. The survey was partially completed by 21 of the 105 contacts identified, and fully completed by 17. The respondents were heavily weighted towards those that sell boilers in Minnesota, whether manufacturers' representatives or wholesalers, as shown in Figure 22. While the most important survey findings are discussed below, the full survey results are presented in Appendix E.

Figure 22. Survey Participant's Primary Role Related to Condensing Boilers



From the responses shown in Figure 23 it is clear that the majority of survey participants are well aware that there are issues with condensing boilers having in-field performance well below the industry standard rating. Still, the general perception seems to be that they achieve higher efficiencies more frequently than was observed in the field test sites.

Figure 23. Survey Participant Report of How Often Condensing Boilers Achieve Rated Efficiency



Current Practices and Issues

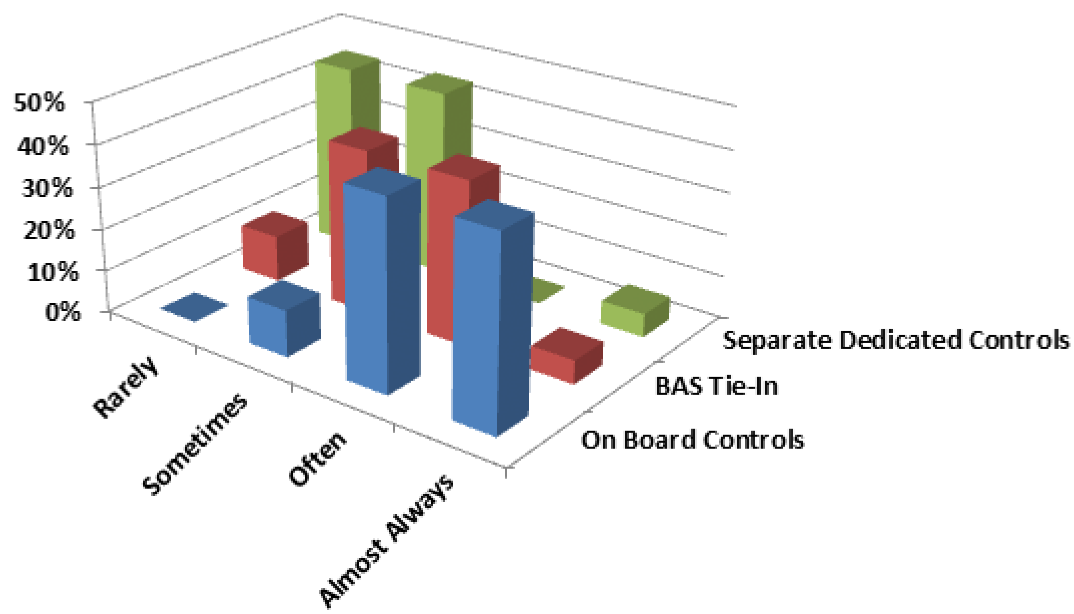
The industry contact survey results provided validation that key observations at the 12 test sites are fairly representative of the larger population of condensing boiler installations in Minnesota.

The most notable finding is that the large number of control issues found in the test sites appears to be reflected in the larger population of condensing boiler installations in Minnesota. Table 16 shows the ranking of the most commonly reported issues with the top 2 being exclusively control issues, and 4 of the top 5 being at least partially related to controls. The market penetration of various boiler control system types is shown in Figure 24. Survey Report of Control System Types, with on-board boiler controls being the most prevalent primary approach and Building Automation System (BAS) tie-in also being common. Difficulties with control coordination between a BAS and boilers was specifically found to be the second most commonly reported issue, but the high frequency of short-cycling and other control issues found in the field sites makes it clear that control issues go far beyond the challenges associated with BAS systems.

Table 16. Survey Reports of Most Common Issues Impacting Efficiency (n = 18)

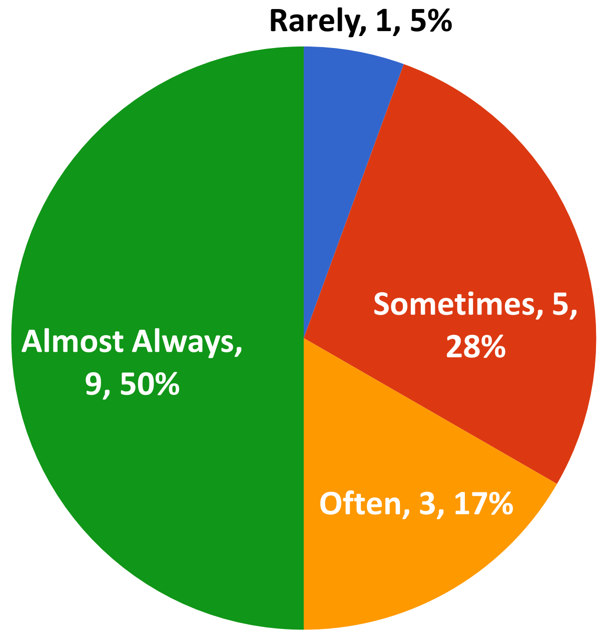
Issue	Percent
Turning off and on frequently (short cycling)	67%
Difficulties coordinating control between a BAS and the boiler(s)	61%
Piping arrangements circulate water through an idle, non-condensing boiler	44%
Boiler minimum temperature limited by the need to heat service hot water	44%
Outdoor reset control does not lower temperature as much as it could in mild weather	39%

Figure 24. Survey Report of Control System Types



The survey results also suggests that while variable speed drives are very common in commercial condensing boiler installations, they are far from universal (as was suggested by the preliminary market assessment findings). This is shown in Figure 25. These survey findings are consistent with the test sites that showed variable speed pumping dominance in larger facilities, but not in smaller facilities or in those with more basic HVAC equipment.

Figure 25. Survey Reported Use of Variable Speed Drives on Building Loop



The general trends noted in responses to open-ended questions asking for additional comments or suggestions were generally consistent with the other results, with a couple of other issues identified. The vast majority of comments related to control issues with temperature control being the most common control concern, but the control issues identified also included pump and pump control. Two issues brought up that were not specifically asked about in the survey were water treatment and variable speed pumps on individual boilers in systems that are piped primary-secondary. Poor water treatment was mentioned by one respondent as a factor that dramatically reduces efficiency (and performance) in some buildings. Two respondents noted the importance of variable speed control of individual boilers in primary-secondary piped systems. They both mentioned that during conditions of low flow on the main building loop, this variable speed control of boiler pumps is important to prevent recirculation of water from the boiler supply to the return (which increases boiler entering water temperature).

CIP Program Approaches

Although individual rating of program approaches didn't show many standouts of specific approaches that were valued well above others, the responses did show clear favorites when participants were asked to rank the possible program approaches relative to each other. It should be noted that the results of this type of survey is likely to be skewed against some of the more novel CIP program strategies that are more difficult to get survey participants to fully understand within the constraints of the on-line survey. Participants rated most suggested program approaches favorably, with the one exception of p*roviding a more accurate savings estimate*. The individual ratings did suggest that the most valued possible program options for new installations and existing installations were *new training options for engineers and contractors* and *rebates for changing settings of existing controls to optimize efficiency,* respectively. However, the relative rankings shown in Table 17 and Table 18 more dramatically showed one approach within each category as a clear favorite. For new installations *Commissioning of Installation and Controls* was the favorite of 44% of participants while *New Training Opportunities for Operators* had the same high 44% favorite ranking for existing installations.

Table 17. Selection of Most Valuable Possible CIP Item for New Installation (n = 18)

Potential Program Element	Percent
a) Piping Design Review	11%
b) Control Sequence Review	11%
c) Site-Specific Savings Estimate	6%
d) Bonus Rebate for Quality Design	11%
e) Bonus Rebates for Individual Design Features	6%
f) Commissioning of Installation and Controls	***44%***
g) New Training Options for Designers & Installers	11%

Table 18. Selection of Most Valuable Possible CIP Item for Existing Installation n = 18)

Potential Program Element	Percent
a) Specialized Engineering Review	11%
b) Gas Rebate for Variable Speed Drive	6%
c) Rebates for Control Upgrades	6%
d) Rebates for Optimizing Control Settings	*17%*
e) Resources on Optimal Control & Operation	11%
f) Site-Specific Guide for Controls	6%
g) New Training Options for Operators	***44%***

Respondents' comments to open-ended solicitation for additional comments included more — specific direction/training to designers and operators. A common theme in these CIP program approach survey findings is a perceived value in more training—for designer, contractors and especially operators—and for services like commissioning and control adjustment to ensure that details of installation and operation are optimal.

Conclusion and Recommendations

The most important study findings related to CIP programs are summarized in Table 19. Findings 1 through 3 suggest that previously used CIP program assumptions for boiler replacement and tune-up programs overestimate program impact in the current market. On the other hand, findings 4 and 5 indicate that greater savings for boiler replacements can be realized with new program features.

Table 19. Key Study Findings for CIP Programs

	Finding	CIP Implications
#1	Market Penetration--Condensing boilers dominate the commercial boiler market across all building types and sizes.	Program impact and cost-effectiveness calculations should consider that a high percentage of participants would have installed condensing boilers in the absence of the program.
#2	In Field Efficiency--While still significantly better than conventional boilers, the operating efficiencies of commercial condensing boilers tends to be far below their rated efficiencies.	Program impact and cost-effectiveness calculations for condensing boiler installations should be based on conservative savings estimates.
#3	Tune-Up Savings Magnitude--While condensing boilers tend to have tune-up savings amplified, the potential savings was still far below current CIP program assumed savings for tune-ups.	Consider a fresh evaluation of the savings achieved through boiler tune-ups of conventional commercial boilers based on current market conditions.
#4	Additional Savings Potential--Greater savings can be achieved through various control, piping, pumping and burner tuning optimization--especially for hybrid systems.	Additional program requirements and/or services can potentially achieve greater savings among current and past condensing boiler rebate program participants.
#5	Cost Effectiveness of Changes—About three-fourths of the identified savings potential can be achieved with a payback of five years or less. Burner tuning, outdoor reset control, and staging control are most common and cost-effective.	The vast majority of identified savings potential could be achieved through program initiatives focused entirely on burner tuning and boiler system controls.
#6	Perceived Value of Possible CIP Program Features--Local industry contacts expressed that a number of possible new CIP program service or requirement changes would be worthwhile, but commissioning, training, and support for changing of existing installation control settings are the most valuable among those proposed.	Boiler program enhancements and/or additional services should be implemented--especially in the areas of commissioning, training, optimized control adjustment, and other approaches to improve the execution of key technical details that impact efficiency.

Beyond CIP program implications, the biggest surprise to the project team was the widespread prevalence of sub-optimal control set-up and settings leading to short-cycling and other suboptimal staging control of boilers. While we had expected issues with suboptimal temperature settings to be very common, the frequency of other control issues further highlighted the potential benefits of achieving better control optimization through training, commissioning, technical program requirements, or other means.

While opportunities to achieve savings through piping changes were less common across the sites, the limited number of sites with these opportunities had relatively large potential for savings. While the piping and variable speed drive changes tended to be cost-prohibitive to correct in existing installations, these might be much more cost-effectively dealt with at the time of design and installation.

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Appendix A: Site Selection Guidelines

The following guidelines will be given priority consideration in selecting the 12 boiler systems that will be monitored. The highest priority items are listed first, with the priority decreasing throughout the list. The priority also decreases for most sub-items after the first sub-item within an item. This list provides an idealized set of site selection characteristics that will need to be balanced against the reality of what characteristics are found within specific buildings as we work with CEE clients and with multiple utilities (and other industry contacts) to identify specific potential sites

1. **Building Type / Heat Distribution System Type**. Condensing boilers have become the default choice for boiler replacement and new construction for commercial buildings that have a boiler system. Schools and apartment buildings appear to be the two most important types of buildings, with office buildings next highest in importance. Apartment buildings have two unique tendencies: 1) No forced-air heating served by the boiler, and 2) Service hot water is sometimes heated by the boiler system with an indirect water heater (aka “sidearm”). Therefore, the selection of a representative number of apartment buildings (or other buildings with these characteristics) has a higher priority than the distribution between the other building types.
    a. 3-5+ apartment buildings (or other buildings with only radiators)
    b. 3-4+ schools (with forced air equipment)
    c. 3-4+ office and/or government buildings (forced air equipment with year-round occupancy)
2. **Service Hot Water Tie-In**. This appears to be more prevalent in apartment buildings. Other buildings tend to have a small enough SHW load that one boiler would be oversized for a SHW heat exchanger and would have to cycle on and off too much.
    a. 1-4 systems with indirect SHW heating by boiler system
3. **Number & Type of Boilers in System**. It is clear that a majority of boiler systems have multiple boilers. In addition, market interviews suggest that about a third of boiler replacement projects have at least one original non-condensing boiler left in place as part of the boiler system. This combination of non-condensing and condensing systems is referred to as a hybrid system.
    a. 3-4 hybrid systems (at least one each condensing boiler and non-condensing boiler)
    b. ≤ 3 single boiler buildings
4. **Size/Type of Boiler & Piping**. Boiler flow rate and piping configurations are primarily dictated by the type of heat exchanger design. These flow rate and piping configurations can have a big impact on the return water temperatures—and therefore efficiency—so it is important to capture some representation of each of the two combinations of heat exchanger type and piping configuration.
    a. ≥ 6 water tube boilers—primary/secondary piping of plant
    b. ≥ 4 fire tube boilers (including cast iron and plate/frame heat exchangers)—variable primary piping of plant (most with automatic valve control of flow through boilers)

5. **Location or BAS**. Ongoing field data collection will be much more expensive in cases where existing BAS systems cannot be used for ongoing data collection—especially for sites that are not in the Minneapolis-St. Paul metropolitan area.
    a. 0 sites without remote data collection capability outside of the Minneapolis-St. Paul metropolitan area
    b. ≥ 2 sites outside of the Minneapolis-St. Paul metropolitan area
6. **System Designers**. Both design/building and plan/spec projects are common according to initial industry interviews. Because of the importance of piping and control details, the sites should represent a variety of different system designers and contractors.
    a. ≥ 4 design/build projects
    b. ≤ 50% of these by any one contractor
    c. ≥ 4 plan/spec projects
    d. ≤ 50% of these by any one engineer
7. **Building Owners/Managers**. The building owner/management that had the condensing boiler(s) installed and maintain ongoing operations can have a very big impact on both the installation characteristics and optimal operation.
    a. ≤ 2 sites with the same owner or management company except where a large degree of local control exists (e.g. state ownership of separate MnSCU campuses).
8. **Pump Speed Control**. Variable speed drives control the main system pumps in most engineered retrofits and new construction projects. However, only a growing minority of contractor driven (design/build) retrofit projects have variable speed pumping.
    a. ≥ 8 variable speed drives on main pump
9. **Boiler Manufacturers**. Different boiler manufacturers (and even different product lines within the same manufacturer) are generally expected to have some variation in both the rated efficiency and the variation of efficiency with return water temperature and/or load fraction. There is also expected to be variation in application limitations. The list below is expected to change as we characterize the similarities and differences between the commercial condensing boiler product lines that are most commonly installed in Minnesota. Breakdowns of specific product lines within manufacturers may be added, and multiple manufacturers of similar products may be combined. Future project documents will use more generic technical definitions of boiler characteristics in lieu of specific brand names, but that is not practical at this stage of the project (before key technical differences and similarities are better understood).
    a. ≥ 2 Aerco
    b. ≥ 2 Fulton
    c. ≥ 2 Lochinvar
    d. ≥ 1 Hydrotherm
    e. ≥ 1 Bryan
10. **Burner Staging Type**. Virtually all current models of condensing boilers are installed with fully modulating burners with at least a 5:1 turndown.
    a. ≥ 10 fully modulating burner
11. **Burner Fuel/Air Ratio Control**. Built in O_2 trim control has recently been becoming more common—especially in the larger boilers.
    a. ≥ 1 boilers with O_2 trim control of linkageless burner.

12. **Control Type**. Most condensing boiler product lines at least have an option for on-board controls with outdoor reset capability, and often multiple-boiler staging coordination capability. The Consortium for Energy Efficiency had previously recommended the use of such on-board controls over the use of separate controls. On the other hand, many local installations—especially engineered projects—have recently standardized on the use of a separate boiler staging control that has the capability to directly control the modulation of multiple boilers across multiple boiler manufacturers, as well as the ability to interface with a BAS. Initially it appears that this control is equivalent in capability to on-board controls. There are also anecdotal reports of very poor boiler control when a BAS system is used to directly provide staging control of boilers (rather than only passing along a boiler system level supply temperature setpoint and/or a simple active/inactive signal).
    a. ≥ 3 systems with on-board controls only
    b. ≥ 2 systems with separate multiple boiler controller that has modulating capability
    c. ≥ 3 system(s) with direct control by BAS (or separate controller) that are not capable of direct control of the modulation of each boiler
13. **Boiler System Size**. Most system design issues reportedly do not change very significantly with system size. The most notable exception is that the water tube boilers tend to be more much more common for smaller sizes (<~750,000 Btu/hr input per boiler) while fire-tube boilers tend to dominate at very large sizes (>~1.5 million Btu/hr input per boiler). Therefore, the system size variation is considered secondary to the item 4) Size/Type of Boiler & Piping, and the selection of various types of boilers is expected to provide an adequate variation in system size.
    a. ≥ 6 systems > 1,000,000 Btu/hr input rate
    b. ≥ 3 systems ≤ 1,000,000 Btu/hr input rate
14. **Installation Date**. Installation that have been in place for at least one full heating season are preferred due to the greater likelihood that automatic boiler control settings and other operational adjustments will be stable over the monitoring time period. Installations greater than 4 years old will tend to be avoided so that more current boiler products, piping practices and control set-ups are as fully represented as possible.
    a. ≤ 2 sites with all boilers in place more than 4 years
    b. ≤ 3 sites with any boilers in place for less than 1 year

Appendix B: Sample of BIN Analysis Spreadsheet

Table 20. Tab 1: Site Summary

Site Annual Use and Efficiency Calculations. Site MF4. 3 Equal Size Boilers that Rotate Lead

Bin Min	Bin Max	Hours	On Time Stage 1	On Time Stage 2	On Time Stage 3	On Time System	Capacity Stage 1	Capacity Stage 2	Capacity Stage 3	Capacity Total	Therms Stage 1	Therms Stage 2	Therms Stage 3	Therms Total	Output Stage 1	Output Stage 2	Output Stage 3	Output Total	Efficiency Stage 1	Efficiency Stage 2	Efficiency Stage 3	Efficiency Total
	-20°F	19	100.0%	100.0%	100.0%	100.0%	50.7%	50.7%	48.2%	149.6%	38	38	37	113	33	33	32	98	86.6%	86.6%	86.6%	86.6%
-20°F	-15°F	17	100.0%	100.0%	100.0%	100.0%	49.1%	48.2%	47.2%	144.5%	33	33	32	98	29	28	28	84	86.2%	86.2%	86.3%	86.3%
-15°F	-10°F	43	100.0%	100.0%	100.0%	100.0%	46.4%	45.9%	45.8%	138.1%	80	79	79	237	68	68	67	203	85.8%	85.8%	85.8%	85.8%
-10°F	-5°F	81	100.0%	100.0%	100.0%	100.0%	45.0%	44.7%	44.7%	134.4%	145	144	144	434	124	123	123	371	85.4%	85.4%	85.4%	85.4%
-5°F	0°F	114	100.0%	99.9%	99.9%	100.0%	42.3%	42.3%	42.3%	126.8%	192	192	192	577	163	163	163	489	84.8%	84.8%	84.8%	84.8%
0°F	5°F	166	87.0%	84.4%	78.6%	87.0%	43.2%	41.5%	37.8%	122.6%	282	270	246	798	245	234	213	692	86.9%	86.8%	86.6%	86.8%
5°F	10°F	278	69.0%	63.1%	35.4%	69.0%	46.6%	42.8%	25.7%	115.1%	510	468	280	1,258	456	418	249	1,124	89.4%	89.3%	89.0%	89.3%
10°F	15°F	335	62.0%	54.9%	28.8%	62.0%	43.9%	38.8%	22.4%	105.1%	587	517	296	1,401	528	464	264	1,257	89.9%	89.8%	89.2%	89.7%
15°F	20°F	522	58.0%	51.0%	20.2%	58.0%	40.7%	35.6%	15.9%	92.2%	857	735	349	1,942	770	660	310	1,741	89.9%	89.8%	88.9%	89.7%
20°F	25°F	470	47.0%	38.4%	23.0%	47.0%	34.5%	28.2%	17.6%	80.3%	674	540	346	1,560	605	484	308	1,397	89.7%	89.6%	89.1%	89.5%
25°F	30°F	500	39.0%	30.5%	22.4%	39.0%	29.3%	22.7%	17.0%	69.0%	607	468	354	1,429	545	420	316	1,281	89.9%	89.7%	89.4%	89.7%
30°F	35°F	644	32.0%	24.5%	19.2%	32.0%	24.8%	19.0%	14.9%	58.6%	664	507	397	1,568	600	457	356	1,413	90.3%	90.1%	89.8%	90.1%
35°F	40°F	546	26.0%	19.8%	15.6%	26.0%	19.7%	15.0%	11.8%	46.6%	449	341	267	1,058	409	309	242	960	91.0%	90.7%	90.3%	90.7%
40°F	45°F	511	20.0%	16.0%	14.2%	20.0%	14.7%	11.7%	10.3%	36.7%	310	246	217	772	284	225	198	707	91.8%	91.5%	91.2%	91.5%
45°F	50°F	426	17.0%	12.1%	10.7%	17.0%	12.1%	8.4%	7.4%	27.9%	210	147	129	486	195	136	119	450	93.0%	92.5%	92.2%	92.6%
50°F	55°F	583	13.0%	9.4%	7.9%	13.0%	9.0%	6.4%	5.2%	20.6%	215	152	125	492	202	142	116	461	94.1%	93.5%	93.1%	93.7%
55°F	60°F	624	10.0%	6.9%	5.8%	10.0%	6.9%	4.5%	3.9%	15.3%	177	117	99	393	168	111	93	371	95.0%	94.3%	94.0%	94.6%
60°F	65°F	803	6.0%	3.9%	2.9%	6.0%	4.1%	2.5%	1.9%	8.5%	135	84	61	279	129	79	57	265	95.5%	94.7%	93.8%	94.9%
65°F	70°F	640	3.0%	1.4%	1.6%	3.0%	2.0%	0.9%	1.0%	3.8%	52	23	26	101	50	22	25	96	95.6%	94.2%	94.2%	94.9%
70°F	75°F	470	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0	0	0	0	0	0	0	0				
75°F	80°F	438		0.0%	0.0%	0.0%					0	0	0	0	0	0	0	0				
80°F	85°F	324		0.0%	0.0%	0.0%					0	0	0	0	0	0	0	0				
85°F	90°F	152		0.0%	0.0%	0.0%					0	0	0	0	0	0	0	0				
90°F	95°F	54		0.0%	0.0%	0.0%					0	0	0	0	0	0	0	0				
95°F	100°F	-		0.0%	0.0%	0.0%					0	0	0	0	0	0	0	0				
100°F		-		0.0%	0.0%	0.0%					0	0	0	0	0	0	0	0				
			49.5%	35.2%	30.2%	38.0%	28.2%	25.5%	21.0%	74.8%	6,218	5,103	3,676	14,997	5,604	4,577	3,280	13,462	90.1%	89.7%	89.2%	89.8%

Table 21. Tab 2: Boiler Stage 1

Site Annual Use and Efficiency Calculations. Site MF4. Condensing Boiler Stage 1 of 3

Bin Min	Bin Max	Hours in Season	Avg Tout	% Runtime	% input rate while on	% of Stage's Capacity	<20% Firing Rate: % Runtime in T Bin	<20% Firing Rate: % Input Rate While On	<20% Firing Rate: Efficiency	20-40% Firing Rate: % Runtime in T Bin	20-40% Firing Rate: % Input Rate While On	20-40% Firing Rate: Efficiency	40-60% Firing Rate: % Runtime in T Bin	40-60% Firing Rate: % Input Rate While On	40-60% Firing Rate: Efficiency	60-80% Firing Rate: % Runtime in T Bin	60-80% Firing Rate: % Input Rate While On	60-80% Firing Rate: Efficiency	80-100% Firing Rate: % Runtime in T Bin	80-100% Firing Rate: % Input Rate While On	80-100% Firing Rate: Efficiency	Avg Use Rate (Btu/hr)	Annual Use (therms)	Return Water Temp	SS Eff	Avg Output Based on Steady State	Cycles Per Hour	Avg Cycling Loss (Btu/hr)	Off-Cycle Loss Rate	Avg Output (Btu/hr)	Annual Output (therms)	Effective Efficiency
	-20°	19	-21.8	100%	50.7	51%	0%	0%	86.6%	0%	0%	86.6%	100%	51%	86.6%	0%	0%	86.6%	0%	0%	86.6%	202,253	38	173.9	86.6	175,207	0.0	-		175,207	33.3	86.6%
-20°	-15°	17	-17.2	100%	49.1	49%	0%	0%	86.2%	0%	0%	86.2%	100%	49%	86.2%	0%	0%	86.2%	0%	0%	86.2%	195,949	33	174.6	86.2	168,985	0.0	-		168,985	28.7	86.2%
-15	-10°	43	-12.6	100%	46.4	46%	0%	0%	85.8%	2%	39%	85.8%	98%	47%	85.8%	0%	0%	85.8%	0%	0%	85.8%	185,056	80	175.4	85.8	158,704	0.0	-		158,704	68.2	85.8%
-10°	-5°F	81	-7.3°	100%	45	45%	0%	0%	85.4%	10%	38%	85.4%	90%	46%	85.4%	0%	0%	85.4%	0%	0%	85.4%	179,620	145	175.9	85.4	153,469	0.0	-		153,469	124.3	85.4%
-5°F	0°F	114	-2.0°	100%	42.3	42%	0%	0%	84.8%	24%	38%	84.8%	76%	44%	84.8%	0%	63%	84.9%	0%	0%	84.8%	168,833	192	176.8	84.8	143,214	0.0	-		143,214	163.3	84.8%
0°F	5°F	166	2.6°F	87%	49.7	43%	0%	13%	87.0%	27%	37%	87.0%	54%	46%	87.0%	12%	71%	87.1%	6%	85%	87.2%	169,651	282	173.1	87.1	147,702	1.2	113	171	147,418	244.7	86.9%
5°F	10°	278	7.0°F	69%	67.5	47%	0%	14%	89.7%	9%	36%	89.7%	38%	49%	89.7%	16%	71%	89.7%	37%	91%	89.7%	183,622	510	164	89.7	164,781	2.6	219	370	164,192	456.5	89.4%
10°	15°	335	12.2°	62%	70.8	44%	0%	16%	90.3%	9%	36%	90.3%	29%	50%	90.3%	16%	70%	90.2%	46%	92%	90.2%	175,358	587	157.5	90.2	158,209	2.6	207	421	157,581	527.9	89.9%
15°	20°	522	17.6°	58%	70.1	41%	0%	11%	90.3%	1%	33%	90.3%	35%	50%	90.3%	20%	73%	90.3%	44%	88%	90.2%	164,171	857	151	90.2	148,149	2.6	190	431	147,528	770.1	89.9%
20°	25°	470	23.1°	47%	73.4	34%	0%	15%	90.2%	1%	33%	90.2%	13%	50%	90.2%	32%	73%	90.2%	54%	86%	90.2%	143,370	674	143	90.2	129,313	2.6	172	488	128,653	604.7	89.7%
25°	30°	500	27.5°	39%	75	29%	0%	15%	90.5%	2%	33%	90.5%	5%	52%	90.5%	38%	74%	90.4%	56%	85%	90.4%	121,388	607	136.3	90.4	109,744	2.4	144	507	109,094	545.5	89.9%
30°	35°	644	32.3°	32%	77.5	25%	0%	15%	91.0%	0%	31%	91.0%	1%	52%	91.0%	36%	74%	90.9%	63%	85%	90.9%	103,169	664	130	90.9	93,803	2.1	111	508	93,184	600.1	90.3%
35°	40°	546	37.2°	26%	75.8	20%	0%	14%	91.9%	0%	28%	91.8%	1%	53%	91.8%	44%	74%	91.7%	55%	84%	91.7%	82,265	449	124.2	91.7	75,442	1.7	80	494	74,868	408.8	91.0%
40°	45°	511	43.0°	20%	73.3	15%	0%	10%	92.9%	0%	31%	92.8%	1%	52%	92.7%	75%	74%	92.6%	24%	82%	92.6%	60,618	310	118.9	92.6	56,153	1.3	54	473	55,626	284.2	91.8%
45°	50°	426	47.5°	17%	71.1	12%	0%	17%	94.3%	0%	31%	94.2%	1%	53%	94.1%	95%	73%	93.9%	3%	83%	93.8%	49,334	210	112.7	93.9	46,336	1.1	41	424	45,871	195.4	93.0%
50°	55°	583	52.0°	13%	69	9%	0%	4%	95.7%	0%	31%	95.5%	0%	52%	95.3%	98%	71%	95.2%	1%	90%	94.9%	36,831	215	106.5	95.2	35,045	0.9	26	370	34,649	202.0	94.1%
55°	60°	624	57.1°	10%	68.8	7%	0%	13%	96.6%	0%	31%	96.5%	1%	55%	96.3%	93%	70%	96.2%	6%	88%	96.0%	28,308	177	100.2	96.2	27,224	0.7	17	308	26,899	167.8	95.0%
60°	65°	803	62.6°	6%	68.8	4%	0%	0%	97.4%	0%	27%	97.3%	1%	56%	97.1%	97%	70%	97.0%	3%	89%	96.8%	16,774	135	94.4	97.0	16,267	0.4	7	238	16,022	128.7	95.5%
65°	70°	640	68.1°	3%	66.8	2%	0%	0%	97.9%	0%	28%	97.8%	5%	53%	97.6%	95%	69%	97.5%	0%	0%	97.9%	8,174	52	89.4	97.5	7,973	0.2	2	157	7,813	50.0	95.6%
70°	75°	470	72.5°																												-	
75°	80°	438	76.9°																												-	
80°	85°	324	82.1°F																												-	
85°	90°	152	87.8°																												-	
90°	95°	54	91.9°																												-	
95°																															-	
		8760	45.0°	52.1%																		2,274,744	6,218	127.9		2,015,720					5,604	90.1%

Table 22. Tab 3: Boiler Stage 2

Site Annual Use and Efficiency Calculations. Site MF4. Condensing Boiler Stage 2 of 3

Bin Min	Bin Max	Hours in Season	Avg Tout	% Run tme	% input rate while on	% of Stage's Capacity	<20% Firing Rate: % Runtime in T Bin	<20% Firing Rate: % Input Rate While On	<20% Firing Rate: Efficiency	20-40% Firing Rate: % Runtime in T Bin	20-40% Firing Rate: % Input Rate While On	20-40% Firing Rate: Efficiency	40-60% Firing Rate: % Runtime in T Bin	40-60% Firing Rate: % Input Rate While On	40-60% Firing Rate: Efficiency	60-80% Firing Rate: % Runtime in T Bin	60-80% Firing Rate: % Input Rate While On	60-80% Firing Rate: Efficiency	80-100% Firing Rate: % Runtime in T Bin	80-100% Firing Rate: % Input Rate While On	80-100% Firing Rate: Efficiency	Avg Use Rate (Btu/hr)	Annual Use (therms)	Return Water Temp	SS Eff	Avg Output Based on Steady State	Cycles Per Hour	Avg Cycling Loss (Btu/hr)	Off-Cycle Loss Rate	Avg Output (Btu/hr)	Annual Output (therms)	Effective Efficiency
	-20°F	19	-21.8°	100%	50.7	51%	0%	0%	86.6%	0%	0%	86.6%	100%	51%	86.6%	0%	0%	86.6%	0%	0%	86.6%	202452.6	38	173.9	86.6%	175,380	0.0	-		175,380	33.3	86.6%
-20°F	-15°F	17	-17.2°	100%	48.2	48%	0%	0%	86.2%	0%	0%	86.2%	100%	48%	86.2%	0%	0%	86.2%	0%	0%	86.2%	191,812	33	174.6	86.2%	165,417	0.0	-		165,417	28.1	86.2%
-15°F	-10°F	43	-12.6°	100%	45.9	46%	0%	0%	85.8%	4%	39%	85.8%	96%	46%	85.8%	0%	0%	85.8%	0%	0%	85.8%	183,119	79	175.4	85.8%	157,044	0.0	-		157,044	67.5	85.8%
-10°F	-5°F	81	-7.3°F	100%	44.7	45%	0%	0%	85.4%	11%	38%	85.4%	89%	46%	85.4%	0%	0%	85.4%	0%	0%	85.4%	178,309	144	175.9	85.4%	152,349	0.0	-		152,349	123.4	85.4%
-5°F	0°F	114	-2.0°F	100%	42.3	42%	0%	0%	84.8%	25%	38%	84.8%	75%	44%	84.8%	0%	62%	84.8%	0%	0%	84.8%	168,701	192	176.8	84.8%	143,103	0.0	-		143,103	163.1	84.8%
0°F	5°F	166	2.6°F	84%	49.2	42%	0%	14%	87.0%	29%	37%	87.0%	54%	46%	87.0%	11%	71%	87.0%	6%	84%	87.1%	162,669	270	173.2	87.0%	141,540	1.2	110	204	141,226	234.4	86.8%
5°F	10°F	278	7.0°F	63%	67.8	43%	0%	14%	89.7%	9%	36%	89.7%	39%	49%	89.7%	12%	71%	89.7%	40%	90%	89.7%	168,398	468	164.1	89.7%	151,096	2.5	211	440	150,445	418.2	89.3%
10°F	15°F	335	12.2°F	55%	70.6	39%	0%	15%	90.3%	10%	36%	90.3%	31%	50%	90.3%	10%	70%	90.2%	49%	91%	90.2%	154,356	517	157.6	90.2%	139,255	2.5	196	499	138,560	464.2	89.8%
15°F	20°F	522	17.6°F	51%	69.8	36%	0%	15%	90.3%	2%	34%	90.3%	40%	50%	90.3%	16%	73%	90.3%	42%	87%	90.2%	140,881	735	151.1	90.2%	127,137	2.4	179	501	126,457	660.1	89.8%
20°F	25°F	470	23.1°F	38%	73.5	28%	0%	15%	90.2%	2%	33%	90.2%	16%	49%	90.2%	31%	74%	90.2%	51%	85%	90.2%	114,934	540	143	90.2%	103,666	2.4	156	563	102,947	483.9	89.6%
25°F	30°F	500	27.5°F	31%	74.5	23%	0%	14%	90.5%	3%	32%	90.5%	5%	49%	90.5%	42%	74%	90.4%	50%	85%	90.4%	93,578	468	136.3	90.4%	84,603	2.1	127	574	83,903	419.5	89.7%
30°F	35°F	644	32.3°F	25%	77.4	19%	0%	14%	91.0%	0%	31%	91.0%	1%	52%	91.0%	37%	74%	90.9%	62%	85%	90.9%	78,779	507	130	90.9%	71,628	1.8	95	558	70,974	457.1	90.1%
35°F	40°F	546	37.2°F	20%	76	15%	0%	15%	91.8%	0%	31%	91.8%	1%	52%	91.8%	48%	74%	91.7%	51%	84%	91.7%	62,488	341	124.4	91.7%	57,286	1.5	70	531	56,685	309.5	90.7%
40°F	45°F	511	43.0°F	16%	73.1	12%	0%	10%	92.8%	0%	31%	92.8%	1%	54%	92.7%	77%	74%	92.6%	22%	82%	92.5%	48,096	246	119.2	92.6%	44,528	1.2	48	494	43,986	224.8	91.5%
45°F	50°F	426	47.5°F	12%	69.6	8%	0%	11%	94.2%	0%	33%	94.1%	2%	53%	94.0%	94%	72%	93.8%	4%	83%	93.7%	34,514	147	113.2	93.8%	32,383	0.9	32	442	31,909	135.9	92.5%
50°F	55°F	583	52.0°F	9%	67.8	6%	0%	13%	95.5%	0%	32%	95.4%	2%	56%	95.2%	97%	70%	95.1%	2%	88%	94.9%	26,107	152	107	95.1%	24,822	0.7	21	379	24,421	142.4	93.5%
55°F	60°F	624	57.1°F	7%	65.6	5%	0%	6%	96.5%	0%	33%	96.4%	6%	55%	96.2%	88%	68%	96.1%	5%	89%	95.9%	18,789	117	100.9	96.1%	18,053	0.6	14	314	17,725	110.6	94.3%
60°F	65°F	803	62.6°F	4%	64.2	3%	0%	16%	97.3%	0%	35%	97.2%	5%	56%	97.0%	93%	67%	96.9%	2%	98%	96.6%	10,418	84	94.9	96.9%	10,099	0.3	5	229	9,864	79.2	94.7%
65°F	70°F	640	68.1°F	1%	60.9	1%	0%	16%	97.7%	1%	32%	97.6%	19%	55%	97.5%	79%	67%	97.4%	0%	90%	97.2%	3,607	23	90.7	97.4%	3,514	0.1	1	116	3,396	21.7	94.2%
70°F	75°F	470	72.5°F																									-		-	-	
75°F	80°F	438	76.9°F																									-		-	-	
80°F	85°F	324	82.1°F																									-		-	-	
85°F	90°F	152	87.8°F																									-		-	-	
90°F	95°F	54	91.9°F																									-		-	-	
95°F	100°F																											-		-	-	
100°F																												-		-	-	
		8760	45.0°F	48.2%																			5,103	117.0							4,577	89.7%

Table 23. Tab 4: Boiler Stage 3

Site Annual Use and Efficiency Calculations. Site MF4. Condensing Boiler Stage 3 of 3

Bin Min	Bin Max	Hours in Season	% Runtime	% input rate while on	O2 % input	% of Stage Capacity	<20% Firing Rate: % Runtime in T Bin	<20% Firing Rate: % Input Rate While On	<20% Firing Rate: Efficiency	20-40% Firing Rate: % Runtime in T Bin	20-40% Firing Rate: % Input Rate While On	20-40% Firing Rate: Efficiency	40-60% Firing Rate: % Runtime in T Bin	40-60% Firing Rate: % Input Rate While On	40-60% Firing Rate: Efficiency	60-80% Firing Rate: % Runtime in T Bin	60-80% Firing Rate: % Input Rate While On	60-80% Firing Rate: Efficiency	80-100% Firing Rate: % Runtime in T Bin	80-100% Firing Rate: % Input Rate While On	80-100 % Firing Rate: Efficiency	Avg Use Rate (Btu/hr)	Annual Use (therms)	Return Water Temp	SS Eff	Avg Output Based on Steady State	Cycles Per Hour	Avg Cycling Loss (Btu/hr)	Off-Cycle Loss Rate	Avg Output (Btu/hr)	Annual Output (therms)	Effective Efficiency
	-20°	19	100%	48.2	N/A	48%	0%	0%	86.6%	0%	0%	86.6%	100%	48%	86.6%	0%	0%	86.6%	0%	0%	86.6	192,278	37	173.9	86.6%	166,566	0.0	-		166,566	31.6	86.6%
-20°	-15°	17	100%	47.2	N/A	47%	0%	0%	86.3%	1%	0%	86.3%	99%	47%	86.3%	0%	0%	86.3%	0%	0%	86.3	187,649	32	174.5	86.3%	161,935	0.0	-		161,935	27.5	86.3%
-15	-10°	43	100%	45.8	N/A	46%	0%	0%	85.8%	5%	39%	85.8%	95%	46%	85.8%	0%	0%	85.8%	0%	0%	85.8	182,663	79	175.4	85.8%	156,652	0.0	-		156,652	67.4	85.8%
-10°	-5°F	81	100%	44.7	N/A	45%	0%	0%	85.4%	11%	38%	85.4%	89%	46%	85.4%	0%	0%	85.4%	0%	0%	85.4	178,211	144	175.9	85.4%	152,266	0.0	-		152,266	123.3	85.4%
-5°F	0°F	114	100%	42.3	N/A	42%	0%	0%	84.8%	27%	38%	84.8%	72%	44%	84.8%	0%	63%	84.8%	0%	0%	84.8	168,517	192	176.8	84.8%	142,947	0.0	-		142,947	163.0	84.8%
0°F	5°F	166	79%	48.1	N/A	38%	0%	14%	86.8%	30%	36%	86.8%	54%	46%	86.8%	12%	71%	86.9%	4%	83%	87.0	148,329	246	173.5	86.9%	128,833	1.3	125	280	128,428	213.2	86.6%
5°F	10°	278	35%	72.6	N/A	26%	0%	14%	90.0%	14%	35%	90.0%	21%	46%	90.0%	10%	73%	89.9%	56%	90%	89.9	100,663	280	162.3	89.9%	90,534	2.0	168	742	89,624	249.2	89.0%
10°	15°	335	29%	77.8	N/A	22%	0%	16%	90.3%	14%	35%	90.3%	10%	46%	90.3%	6%	73%	90.3%	70%	90%	90.2	88,475	296	155.5	90.2%	79,842	1.9	146	754	78,942	264.5	89.2%
15°	20°	522	20%	78.8	N/A	16%	0%	15%	90.2%	1%	31%	90.2%	1%	54%	90.2%	24%	75%	90.2%	74%	87%	90.2	66,892	349	147.9	90.2%	60,331	1.5	109	759	59,463	310.4	88.9%
20°	25°	470	23%	76.6	N/A	18%	0%	17%	90.2%	0%	30%	90.2%	1%	51%	90.2%	42%	75%	90.2%	57%	85%	90.2	73,612	346	142.2	90.2%	66,400	1.8	117	685	65,598	308.3	89.1%
25°	30°	500	22%	75.8	N/A	17%	0%	14%	90.5%	0%	33%	90.5%	1%	53%	90.5%	46%	75%	90.4%	52%	85%	90.4	70,816	354	136.1	90.4%	64,031	1.7	104	631	63,296	316.5	89.4%
30°	35°	644	19%	77.4	N/A	15%	0%	13%	90.9%	0%	29%	90.9%	1%	51%	90.9%	42%	75%	90.9%	57%	85%	90.9	61,582	397	130.4	90.9%	55,966	1.5	81	595	55,290	356.1	89.8%
35°	40°	546	16%	75.7	N/A	12%	0%	15%	91.8%	0%	31%	91.7%	1%	50%	91.7%	54%	75%	91.6%	45%	84%	91.6	48,984	267	124.9	91.6%	44,870	1.3	61	558	44,251	241.6	90.3%
40°	45°	511	14%	72.6	N/A	10%	0%	14%	92.7%	0%	31%	92.7%	1%	52%	92.6%	80%	74%	92.5%	18%	82%	92.5	42,432	217	119.6	92.5%	39,253	1.1	45	505	38,702	197.8	91.2%
45°	50°	426	11%	68.9	N/A	7%	0%	17%	94.1%	0%	28%	94.0%	2%	54%	93.9%	95%	71%	93.7%	2%	84%	93.6	30,321	129	113.6	93.7%	28,424	0.8	29	449	27,946	119.0	92.2%
50°	55°	583	8%	66.4	N/A	5%	0%	18%	95.4%	0%	31%	95.3%	6%	55%	95.1%	93%	69%	95.0%	1%	95%	94.6	21,436	125	107.5	95.0%	20,366	0.7	20	386	19,959	116.4	93.1%
55°	60°	624	6%	66.5	N/A	4%	0%	0%	96.5%	0%	26%	96.4%	8%	55%	96.2%	86%	68%	96.1%	6%	91%	95.8	15,835	99	101	96.1%	15,212	0.5	12	311	14,889	92.9	94.0%
60°	65°	803	3%	64.4	N/A	2%	0%	0%	97.2%	0%	0%	97.2%	15%	54%	96.9%	81%	66%	96.8%	3%	98%	96.5	7,589	61	95.7	96.8%	7,349	0.3	5	224	7,120	57.2	93.8%
65°	70°	640	2%	61.9	N/A	1%	0%	0%	97.8%	1%	36%	97.6%	9%	54%	97.5%	90%	65%	97.4%	0%	90%	97.2	4,075	26	90.7	97.4%	3,970	0.1	2	131	3,838	24.6	94.2%
70°	75°	470																										-		-	-	
75°	80°	438																										-		-	-	
80°	85°	324																										-		-	-	
85°	90°	152																										-		-	-	
90°	95°	54																										-		-	-	
95°																												-		-	-	
		8760	41.4%																				3,676	129.8							3,280	89.2%

Appendix C: Improvement Recommendation Details by Site

Table 24. Improvement Recommendation Details for Education Sites

Site	Outdoor Reset	Tune Up	Staging Control Change	Variable Speed Pumping	Piping Recommendation
ED1	Description: Switch from Control that Directly Varies Input Rate with Outdoor Temeprature to Outdoor Resent Control with Somewhat Aggressive Settings Assumptions: 1) Occupied EWT will be 10F lower; 2) Unoccupied EWT will be 25F lower	Description: Adjust Air Fuel Ratio to Improve Efficiency Assumptions: Will have minimum manufacturer's recommended oxygen concentration	Description: Change Staging so That the Two Condensing Boilers Continue to be Lead When the Conventional Boiler is Needed Assumptions: The two condensing boilers will operate at or near full-load when the large, conventional boiler is brought online to provide enough capacity, and the conventional boiler will carry less load.	Description: Convert Several 3-way Valves to 2-way Valves to Increase Building System Temperature Drop Key Assumptions: 1) EWT (entering water temperature) will be reduced by 15°F at 0°F outdoor temperature; 2) EWT will be reduced by 5°F at 75°F outdoor temperature; 3) EWT will be reduced by a linear sliding scale between (and beyond) these two outdoor temperatures	Description: Address Issues with Equipment Served by Hot Water Valve 10 to Allow Lower Boiler Temperatures Assumption: EWT settings will be reduced by 10°F (must be done in conjunction with outdoor reset control change)
ED2	Description: Reduce Setpoints in Mild Weather with Scheduled Overnight Setback of Boiler Temperature Assumptions: 1) Occupied EWT will be 20°F lower @75°F outdoor temperature decreasing to no change at 0°F ; 2) Unoccupied EWT will be 15°F lower than the occupied EWT	Description: Adjust Air Fuel Ratio to Improve Efficiency Assumptions: Will have minimum manufacturer's recommended oxygen concentration	NA	Description: Adjust Pump Speed Control Key Assumptions: 1) EWT (entering water temperature) will be reduced by 30% of the current system temperature drop at 50°F outdoor temperature and above; 2) EWT will be reduced by 10% of the current system temperature drop at 0°F outdoor temperature and below; 3) Between 0°F and 50°F outdoor temperatures, the EWT will be reduced from 10% to 30% of the current system temperature drop on a sliding scale	NA
ED3	Description: Quantify Savings from Setpoint Reductions Done Part-Way Through Monitoring Period & For Additional Recommended Setpoint Reductions in All Weather with Scheduled Overnight Setback of Boiler Temperature Assumptions: 1) Occupied EWT will be 10°F lower; 2) Unoccupied EWT will be another 20°F lower.	Description: Adjust Air Fuel Ratio to Improve Efficiency Assumptions: Will have minimum manufacturer's recommended oxygen concentration	Description: Disable 2nd and 3rd Stage Boilers Above 5°F Outdoor Temeprature to Prevent Their Very Short-Tem Infrequent Use During Morning Warm-Up Periods (with substantial heat loss between cycles) Assumptions: The lead boiler will need to operate longer to meet the warm-up load.	Description: Adjust Pump Control to Achieve Much Lower Speed Key Assumption: The EWT will be reduced by 50% of the current system temperature drop through the building	NA
ED4	Description: Quantify Savings from Setpoint Reductions Done Part-Way Through Monitoring Period & For Additional Recommended Setpoint Reductions in All Weather Assumption: EWT will be 5°F lower at all outdoor temperatures.	No	Description: Ensure Timely Switch to Summer Mode and Adjust Controls to Reduce Short-Cycling and Rotate Boilers Less Frequently Key Assumption: The daily heating up and cooling down of one boiler stage for short-term setback recovery at outdoor temepratures below 30°F will be prevented	Description: Adjust Pump Control to Achieve Much Lower Speed Key Assumption: The EWT will be reduced by 100% of the current system temperature drop through the building.	Description: Adjust BAS Control to Modulatee Valves to <<100% When AHUs Off or At Part Load Assumption: Will reduce EWT by 60% of the current building loop temperature drop

Table 25. Improvement Recommendation Details for Multifamily Sites

Site	Outdoor Reset	Tune Up	Staging Control Change	Variable Speed Pumping	Piping Recommendation
MF1	Description: Modify Controls to Continue Reducing EWT When Outdoor Temperature is Above 30°F Assumptions: Above 30°F outdoor temperature the EWT will be reduced by 0.5°F for every 1°F increase in outdoor air temperature (currently constant ~120°F in this range)	Description: Adjust Air Fuel Ratio to Improve Efficiency Assumptions: Will have minimum manufacturer's recommended oxygen concentration	Description: Boiler Control Temperature and Staging Settings Were Modified During the Course of Monitoring. Additional Changes Will Maintain Load on Condensing Boiler When Conventional Comes On Assumptions: Monitored data was used to characterize the change of multiple variables. Condensing boilers will operate near full load when conventional boiler is needed in cold weather	Description: Add a Variable Speed Pump Control to Reduce Flow Above 20°F Outdoor Air Temperature Key Assumption: When the outdoor temperature is above 20°F, the EWT will be 5°F lower	Description: Repipe so Water Returning from Building Goes Through Condensing Boilers First and Pipe Conventional Boilers Primary Secondary to Avoid Constant Hot-Water Flow Through Assumptions: 1) Conventional boilers will be cold during mild weather; 2) Aggressive pump speed control will allow EWT to be reduced by 8°F when conventional boiler is on (water will be preheated to condensing boilers)
MF2	NA	Description: Adjust Air Fuel Ratio to Improve Efficiency Assumptions: Will have minimum manufacturer's recommended oxygen concentration	Description: Adjust Controls to Greatly Reduce Cycling & Firing Rate & Modify Controls to Better Coordinate with Conventional Boiler Key Assumptions: 1) Firing rate will be well below 50% until the boiler runs continuously; 2) Cycling rates will be no more than one-fourth of the previous cycling rate; 3) Condensing boiler will still operate near full capacity when the conventional boiler cycles at very cold outdoor temperatures	Description: Add a Variable Speed Pump Control Key Assumptions: The EWT will decrease by two-thirds of the current temperature drop through the building	Description: Install Motorized Damper on Combustion Air and Eliminate Constant Flow Through Conventional Boiler Assumption: Off-Cycle loss of conventional boiler will be eliminated except during below zero weather.
MF3	Description: Increase Temp in Coldest Weather & Moderately Reduce Setpoints at Other Times--Especially Mild Weather Assumptions: For space heating, EWT will be 175°F below 5°F outdoor temperature, 10°F lower EWT at 70°F outdoor temperature, 5°F lower EWT at 5°F outdoor temperature, and linearly 5-10°F lower between 5°F and 70°F outdoor temperatures	Description: Adjust Air Fuel Ratio to Improve Efficiency Assumptions: Will have minimum manufacturer's recommended oxygen concentration	Description: Adjust Controls to Greatly Reduce Cycling & Firing Rates, Plus Add Swithover so ThatOnly Boiler 1 Runs in Mild Weather and That in Colder Weather Boiler 1 is Dedicated to Domestic Water Heating While Boilers 2 and 3 Handle the Space Heating Load Key Assumptions: 1) Firing rate for space heating will be well below 50% until all available stages are running continuously; 2) Boilers 2 and 3 will spend very little time cycling so that they will seldom be off while they are hot.	Description: Add a Variable Speed Pump Control Key Assumptions: 1) When the space heating load is equivalent to 1 boiler or more (3 are present), the EWT will be 5°F lower; 2) When the space heating load is less than 10% of one boiler's capacity, the EWT will be 2°F lower; 3) When the space heating load is between 10% and 100% of one boiler, the reduction in EWT will vary linearly between 2°F and 5°F.	NA
MF4	Description: Adjust Outdoor Reset Settings to Achieve Lower Temperatures in Mild Weather Assumptions: 1) EWT will be 173°F at outdoor temperatures of 5°F and below; 2) EWT will be 90°F at outdoor temperatures of60°F and above; 3) Between 5°F and 60°F outdoor temperatures, the EWT will be vary on a linear sliding scale betweeen these two points	Description: Adjust Air Fuel Ratio to Improve Efficiency Assumptions: Will have minimum manufacturer's recommended oxygen concentration	Description: Adjust Controls to Greatly Reduce Cycling & Firing Rate (observed to have all three boilers cycle on and then off within 2-3 minutes at low and moderate loads) Key Assumptions: 1) Firing rate for space heating will be well below 50% until all available stages are running continuously; 2) Cycling rates will be no more than one-third of the previous cycling rate.	Description: Add a Variable Speed Pump Control Key Assumptions: 1) At outdoor temperatures above 25°F, the EWT will be reduced by one-third of the current system temperature drop through the building ; 2) At outdoor temperatures between 0°F and 25°F, the EWT will be reduced by one-fifth of the current system temperature drop through the building	NA

Appendix D: Industry Contact Survey Tool

Are Your Commercial Condensing Boiler Installations Living up to Expectations?

Introduction

1. Please enter your name and email address.

*(*Note that we will not publicly identify responses for any specific survey participant, but are maintaining a list of participants to document the number of individuals surveyed for state billing purposes, and to allow follow up clarification on any comments submitted.)* *

First Name

Last Name

Email

2. What is your primary **role of your company** related to condensing boilers? (Please select one of the following.)

- Mechanical Contractor
- Controls Contractor
- Design Firm
- Manufacturer's Representative
- Equipment Distributor
- Facility Owner or Operator
- Utility
- Other

3. What is your primary **responsibility** related to condensing boilers? (Please select one of the following.)

- System Design
- Boiler Installation
- Boiler Service
- Operation of Boilers
- Facility Owner or Administrator
- Boiler Sales
- Technical Support
- 3rd Party Efficiency Program or Funding (e.g. utility rebates)
- Other

Condensing Boiler Observations

4. In the commercial condensing boiler installations that you deal with, how often do they achieve their rated efficiency?

Rarely	Sometimes	Often	Almost Always	*Do not know*
○	○	○	○	○

5. In the commercial condensing boiler installations that you deal with, how often do you see the following features?

a. Variable speed drive control of the main building loop pump(s)

Rarely	Sometimes	Often	Almost Always	*Do not know*
○	○	○	○	○

b. Primary/secondary piping of boilers

Rarely	Sometimes	Often	Almost Always	*Do not know*
○	○	○	○	○

c. Control of boiler(s) is primarily via on-board boiler controllers that were packaged with the boiler(s)

Rarely	Sometimes	Often	Almost Always	*Do not know*
○	○	○	○	○

d. Control of boiler(s) is primarily via a building automation system (BAS)

Rarely	Sometimes	Often	Almost Always	*Do not know*
○	○	○	○	○

e. Control of boiler(s) is primarily via a separate, dedicated boiler system controller, that is not specific to a certain brand of boiler

Rarely	Sometimes	Often	Almost Always	*Do not know*
○	○	○	○	○

6. For condenser boiler systems that you deal with, what is the most typical boiler system supply temperature (°F) at each of the following conditions?
(Please leave blank if you do not know).

50°F Outside __________

0°F Outside __________

Summertime __________

7. Please indicate if you have observed any of the following issues that may be negatively impacting the efficiency of the condensing boiler installations you deal with.

- ☐ Piping arrangements circulate water through an idle, non-condensing boiler
- ☐ Turning off and on frequently (short cycling)
- ☐ Difficulties coordinating control between a BAS and the boiler(s)
- ☐ Difficulties coordinating operations of multiple boilers
- ☐ There is no control that can lower the boiler temperature in mild weather
- ☐ Outdoor reset control does not lower temperature as much as it could in mild weather
- ☐ Boiler minimum temperature limited by the need to heat service hot water
- ☐ Boiler system controls are too complex for operations staff to optimize settings based on occupant feedback and observations
- ☐ Other

8. Please rate how important each item is to the efficiency of condensing boiler systems you deal with.

a. Piping design and pump controls

Unimportant	Of Little Importance	Moderately Important	Important	Very Important
○	○	○	○	○

b. Boiler staging and firing rate controls

Unimportant	Of Little Importance	Moderately Important	Important	Very Important
○	○	○	○	○

c. Boiler temperature controls

Unimportant	Of Little Importance	Moderately Important	Important	Very Important
○	○	○	○	○

d. Operator usability of controls

Unimportant	Of Little Importance	Moderately Important	Important	Very Important
○	○	○	○	○

e. Type and sizing of hot water coils or radiators served by the boiler system

Unimportant	Of Little Importance	Moderately Important	Important	Very Important
○	○	○	○	○

f.

Other

Solutions for Future Installations

9. For **future installations**, how useful would each item be to increase the operating efficiency?

a. The piping design is reviewed by a third-party expert to identify common problems

Not at all Useful	Of Little Use	Moderately Useful	Useful	Very Useful
○	○	○	○	○

b. The control sequences are reviewed by a third-party expert to identify common problems

Not at all Useful	Of Little Use	Moderately Useful	Useful	Very Useful
○	○	○	○	○

c. A more accurate savings estimate (compared to boiler efficiency ratings) based on the unique system and operating plan

Not at all Useful	Of Little Use	Moderately Useful	Useful	Very Useful
○	○	○	○	○

d. A bonus rebate (above and beyond a high-efficiency boiler rebate) for installations that meet a set of stricter system design requirements

Not at all Useful	Of Little Use	Moderately Useful	Useful	Very Useful
○	○	○	○	○

e. Bonus rebates for incorporating individual design features that can increase the boiler's efficiency (e.g. specific boiler control capabilities)

Not at all Useful	Of Little Use	Moderately Useful	Useful	Very Useful
○	○	○	○	○

f. A commissioning agent verifies proper installation and control during and after installation

Not at all Useful	Of Little Use	Moderately Useful	Useful	Very Useful
○	○	○	○	○

g. New training options for engineers and contractors on how to maximize the efficiency of condensing boilers

Not at all Useful	Of Little Use	Moderately Useful	Useful	Very Useful
○	○	○	○	○

10. Which of the items presented in the previous question (Q8) would be most worth having a building owner pay a portion of the cost for?

a. Piping Design Review
b. Control Sequence Review
c. Site-Specific Savings Estimate
d. Bonus Rebate for Quality Design
e. Bonus Rebates for Individual Design Features
f. Commissioning of Installation and Controls
g. New Training Options for Designers & Installers

Solutions for Existing Installations

11. For **existing installations**, how helpful would each item be to increase the operating efficiency?

a. A specialized on-site engineering review and consultation of system optimization opportunities

Not at all Useful	Of Little Use	Moderately Useful	Useful	Very Useful
○	○	○	○	○

b. A gas utility rebate for variable speed drive control that increases boiler efficiency

Not at all Useful	Of Little Use	Moderately Useful	Useful	Very Useful
○	○	○	○	○

c. Rebates for control equipment upgrades

Not at all Useful	Of Little Use	Moderately Useful	Useful	Very Useful
○	○	○	○	○

d. Rebates for changing settings of existing controls to optimize efficiency

Not at all Useful	Of Little Use	Moderately Useful	Useful	Very Useful
○	○	○	○	○

e. Technical resources that provide guidance on optimal condensing boiler control and operation (e.g. graphs, online tools)

Not at all Useful	Of Little Use	Moderately Useful	Useful	Very Useful
○	○	○	○	○

f. An expert prepares a site-specific guide for control settings and adjustment

Not at all Useful	Of Little Use	Moderately Useful	Useful	Very Useful
○	○	○	○	○

g. New training options for operators on how to maximize the efficiency of condensing boilers

Not at all Useful	Of Little Use	Moderately Useful	Useful	Very Useful
○	○	○	○	○

12. Which of the items presented in the previous question (Q10) would be most worth having a building owner pay a portion of the cost for?

a. Specialized Engineering Review
b. Gas Rebate for Variable Speed Drive
c. Rebates for Control Upgrades
d. Rebates for Optimizing Control Settings
e. Resources on Optimal Control & Operation
f. Site-Specific Guide for Controls
g. New Training Options for Operators

Closing

13. Please provide any other suggestions or comments you would like on possible ways of improving the installed operating efficiency of condensing boilers.

14. Please check if you are interested in either or both options.

- ☐ I have ideas or concerns that I would like to talk about with the engineer managing this project.
- ☐ I would appreciate the chance to provide further feedback or direction to project staff or utilities regarding the issues.

Appendix E: Full Results of Industry Contact Survey

Survey Summary Report

Are Your Commercial Condensing Boiler Installations Living up to Expectations?

2. What is your primary role of your company related to condensing boilers? (Please select one of the following.)

Value	Count	Percent
Mechanical Contractor	2	9.5%
Controls Contractor	0	0.0%
Design Firm	2	9.5%
Manufacturer's Representative	7	33.3%
Equipment Distributor	3	14.3%
Facility Owner or Operator	3	14.3%
Utility	1	4.8%
Other	3	14.3%

3. What is your primary responsibility related to condensing boilers? (Please select one of the following.)

Value	Count	Percent
System Design	6	33.3%
Boiler Installation	1	5.6%
Boiler Service	0	0.0%
Operation of Boilers	2	11.1%
Facility Owner or Administrator	1	5.6%
Boiler Sales	3	16.7%
Technical Support	3	16.7%
3rd Party Efficiency Program or Fi	1	5.6%
Other	1	5.6%

4. In the commercial condensing boiler installations that you deal with, how often do they achieve their rated efficiency?

Value	Count	Percent
Rarely	1	5.9%
Sometimes	6	35.3%
Often	6	35.3%
Almost Always	3	17.7%
Do not know	1	5.9%

5. In the commercial condensing boiler installations that you deal with, how often do you see the following features?

a. Variable speed drive control of the main building loop pump(s)

Value	Count	Percent
Rarely	1	5.6%
Sometimes	5	27.8%
Often	3	16.7%
Almost Always	9	50.0%
Do not know	0	0.0%

b. Primary/secondary piping of boilers

Value	Count	Percent
Rarely	0	0.0%
Sometimes	1	5.9%
Often	8	47.1%
Almost Always	6	35.3%
Do not know	2	11.8%
	15	

c. Control of boiler(s) is primarily via on-board boiler controllers that were packaged with the boiler(s)

Value	Count	Percent
Rarely	0	0.0%
Sometimes	2	11.1%
Often	8	44.4%
Almost Always	8	44.4%
Do not know	0	0.0%
	18	

d. Control of boiler(s) is primarily via a building automation system (BAS)

Value	Count	Percent
Rarely	2	11.1%
Sometimes	7	38.9%
Often	7	38.9%
Almost Always	1	5.6%
Do not know	1	5.6%
	17	

e. Control of boiler(s) is primarily via a separate, dedicated boiler system controller, that is not specific to a certain brand of boiler

Value	Count	Percent
Rarely	8	44.4%
Sometimes	8	44.4%
Often	0	0.0%
Almost Always	1	5.6%
Do not know	1	5.6%
	18	

7. Please indicate if you have observed any of the following issues that may be negatively impacting the efficiency of the condensing boiler installations you deal with.

Value	Count	Percent
Piping arrangements circulate water through an idle, non-condensing boiler	8	44.4%
Turning off and on frequently (short cycling)	12	66.7%
Difficulties coordinating control between a BAS and the boiler(s)	11	61.1%
Difficulties coordinating operations of multiple boilers	6	33.3%
There is no control that can lower the boiler temperature in mild weather	3	16.7%
Outdoor reset control does not lower temperature as much as it could in mild weather	7	38.9%
Boiler minimum temperature limited by the need to heat service hot water	8	44.4%
Boiler system controls are too complex for operations staff to optimize settings based on occupant feedback and observations	4	22.2%
Other	4	22.2%
Boiler minimum temperature is limited by need to provide enough heating from radiators, baseboard heat, convectors, or other heat sources without a fan	1	5.6%

8. Please rate how important each item is to the efficiency of condensing boiler systems you deal with.

a. Piping design and pump controls

Value	Count	Percent
Unimportant	0	0.0%
Of Little Importance	0	0.0%
Moderately Important	2	11.8%
Important	6	35.3%
Very Important	9	52.9%
	17	

b. Boiler staging and firing rate controls

Value	Count	Percent
Unimportant	0	0.0%
Of Little Importance	0	0.0%
Moderately Important	0	0.0%
Important	9	52.9%
Very Important	8	47.1%

c. Boiler temperature controls

Value	Count	Percent
Unimportant	0	0.0%
Of Little Importance	0	0.0%
Moderately Important	0	0.0%
Important	8	47.1%
Very Important	9	52.9%

d. Operator usability of controls

Value	Count	Percent
Unimportant	2	11.8%
Of Little Importance	3	17.7%
Moderately Important	5	29.4%
Important	4	23.5%
Very Important	3	17.7%

e. Type and sizing of hot water coils or radiators served by the boiler system

Value	Count	Percent
Unimportant	0	0.0%
Of Little Importance	0	0.0%
Moderately Important	6	35.3%
Important	4	23.5%
Very Important	7	41.2%

9. For future installations, how useful would each item be to increase the operating efficiency?

a. The piping design is reviewed by a third-party expert to identify common problems

Value	Count	Percent
Not at all Useful	2	11.1%
Of Little Use	2	11.1%
Moderately Useful	4	22.2%
Useful	8	44.4%
Very Useful	2	11.1%
	18	

b. The control sequences are reviewed by a third-party expert to identify common problems

Value	Count	Percent
Not at all Useful	1	5.6%
Of Little Use	4	22.2%
Moderately Useful	4	22.2%
Useful	7	38.9%
Very Useful	2	11.1%

c. A more accurate savings estimate (compared to boiler efficiency ratings) based on the unique system and operating plan

Value	Count	Percent
Not at all Useful	1	5.6%
Of Little Use	2	11.1%
Moderately Useful	9	50.0%
Useful	5	27.8%
Very Useful	1	5.6%

d. A bonus rebate (above and beyond a high-efficiency boiler rebate) for installations that meet a set of stricter system design requirements

Value	Count	Percent
Not at all Useful	2	11.1%
Of Little Use	0	0.0%
Moderately Useful	2	11.1%
Useful	10	55.6%
Very Useful	4	22.2%

e. Bonus rebates for incorporating individual design features that can increase the boiler's efficiency (e.g. specific boiler control capabilities)

Value	Count	Percent
Not at all Useful	2	11.1%
Of Little Use	0	0.0%
Moderately Useful	5	27.8%
Useful	10	55.6%
Very Useful	1	5.6%

f. A commissioning agent verifies proper installation and control during and after installation

Value	Count	Percent
Not at all Useful	1	5.6%
Of Little Use	0	0.0%
Moderately Useful	6	33.3%
Useful	7	38.9%
Very Useful	4	22.2%

g. New training options for engineers and contractors on how to maximize the efficiency of condensing boilers

Value	Count	Percent
Not at all Useful	0	0.0%
Of Little Use	1	5.6%
Moderately Useful	0	0.0%
Useful	11	61.1%
Very Useful	6	33.3%

10. Which of the items presented in the previous question (Q8) would be most worth having a building owner pay a portion of the cost for?

Value	Count	Percent
a. Piping Design Review	2	11.1%
b. Control Sequence Review	2	11.1%
c. Site-Specific Savings Estimate	1	5.6%
d. Bonus Rebate for Quality Desig	2	11.1%
e. Bonus Rebates for Individual D	1	5.6%
f. Commissioning of Installation ar	8	44.4%
g. New Training Options for Desig	2	11.1%

11. For existing installations, how helpful would each item be to increase the operating efficiency?

a. A specialized on-site engineering review and consultation of system optimization opportunities

Value	Count	Percent
Not at all Useful	0	0.0%
Of Little Use	1	5.6%
Moderately Useful	7	38.9%
Useful	7	38.9%
Very Useful	3	16.7%

b. A gas utility rebate for variable speed drive control that increases boiler efficiency

Value	Count	Percent
Not at all Useful	0	0.0%
Of Little Use	0	0.0%
Moderately Useful	5	27.8%
Useful	9	50.0%
Very Useful	4	22.2%

c. Rebates for control equipment upgrades

Value	Count	Percent
Not at all Useful	0	0.0%
Of Little Use	2	11.1%
Moderately Useful	6	33.3%
Useful	8	44.4%
Very Useful	2	11.1%

d. Rebates for changing settings of existing controls to optimize efficiency

Value	Count	Percent
Not at all Useful	0	0.0%
Of Little Use	1	5.9%
Moderately Useful	2	11.8%
Useful	11	64.7%
Very Useful	3	17.7%

e. Technical resources that provide guidance on optimal condensing boiler control and operation (e.g. graphs, online tools)

Value	Count	Percent
Not at all Useful	0	0.0%
Of Little Use	2	11.1%
Moderately Useful	6	33.3%
Useful	8	44.4%
Very Useful	2	11.1%

f. An expert prepares a site-specific guide for control settings and adjustment

Value	Count	Percent
Not at all Useful	1	5.6%
Of Little Use	2	11.1%
Moderately Useful	4	22.2%
Useful	7	38.9%
Very Useful	4	22.2%

g. New training options for operators on how to maximize the efficiency of condensing boilers

Value	Count	Percent
Not at all Useful	2	11.1%
Of Little Use	1	5.6%
Moderately Useful	3	16.7%
Useful	9	50.0%
Very Useful	3	16.7%

12. Which of the items presented in the previous question (Q10) would be most worth having a building owner pay a portion of the cost for?

Value	Count	Percent
a. Specialized Engineering Reviev	2	11.1%
b. Gas Rebate for Variable Speed	1	5.6%
c. Rebates for Control Upgrades	1	5.6%
d. Rebates for Optimizing Control	3	16.7%
e. Resources on Optimal Control &	2	11.1%
f. Site-Specific Guide for Controls	1	5.6%
g. New Training Options for Opera	8	44.4%

14. Please check if you are interested in either or both options.

Value	Count	Percent
I have ideas or concerns that I wo	7	77.8%
I would appreciate the chance to p	9	100.0%