Quality Installation and Retrocommissioning of High-Efficiency Condensing Boilers

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Executive Summary

Background and Overview

Although high-efficiency condensing boilers have been available to consumers for a long time, they have yet to fully penetrate the market. Consumer acceptance continues to be a barrier, as well as lack of confidence by many contractors and utilities related to energy savings, cost-effectiveness, and quality installation.

To address these uncertainties, our research team monitored thirteen condensing boilers in Minnesota homes to characterize installed performance. Six of these boilers were installed up to seven years before the project began and seven were installed during it, using a project-developed Quality Installation protocol. The team collected data on supply and return water temperature, flow rates, incidence of condensing, and energy use across all thirteen systems – which represent a wide range of single-family installations with different brands, emitter types, zone set-ups, and outdoor reset control installation and set points. In addition, the team conducted interviews with contractors/distributors and homeowners, and performed an economic analysis.

Key Findings

Field Monitoring

The project's field research was conducted in two phases: (Phase I) in six homes where a non-condensing boiler had been replaced with a condensing boiler within the last seven years, and (Phase II) for seven customers with an interest in replacing their non-condensing boiler with a condensing boiler. The project team developed site selection criteria to identify and select sites that were representative of Minnesota homes and boiler systems. Data from both phases was used to determine annual energy consumption and seasonal operating efficiency. Annual performance between operation modes and phases was compared and an estimated baseline boiler established. In addition, annual energy performance, runtimes, and installed efficiencies were also examined.

Overall the as-found operation had better than expected space heating performance. The vast majority of days had space heating efficiencies of 85% and above. Table 1 shows the annual performance of as-found operation for the previously installed boilers in Phase I. The space heating efficiencies were between 86% and 95%, with an average annual efficiency of 90%. While slightly lower than the rated AFUE (average AFUE was 94%), these installed efficiencies are in line with the expected efficiencies of well-installed systems. Actual measured efficiencies are different than ratings specifications that are measured in controlled laboratory environments (Hoeschele and Weitzel 2013). Based on these findings, the as-found condensing boilers would expect to save 14% annual heating energy consumption over a baseline boiler installation.

Table 1. Summary results from as-found performance of existing condensing boiler installations

Sites	Heating Load (therms/yr)	DHW Load (therms/yr)	Space Heating Efficiency	DHW Efficiency	Combined Efficiency	Operating Cost* ($/year)
exist_01	1111	135	86.2%	62.6%	83.6%	$1,001
exist_02	745	N/A	88.4%	N/A	N/A	$669
exist_03	485	85	90.5%	76.1%	88.0%	$429
exist_05	421	66	90.3%	74.6%	87.8%	$372
exist_06	636	N/A	95.1%	N/A	N/A	$535
exist_07	644	N/A	89.0%	N/A	N/A	$579

*This table assumes a natural gas cost of $0.80 per term

Table 2. Annual space heating efficiency for as-found and optimized sites

Site	As-Found Annual Heating Efficiency	Optimized Annual Heating Efficiency	Percent Improvement
Exist_01	86.2%	88.3%	2.1%
Exist_02	88.4%	90.2%	1.8%
Exist_07	89.0%	90.8%	1.8%
Average	87.9%	89.8%	1.9%

Space heating optimization was conducted at three of the seven as found sites. Site exist_6 had very high as-found efficiency and optimization was not possible. Two other sites were used to look at domestic water heating optimization instead. The final three sites were optimized for space heating. While difficult to do, the optimization did show improved efficiency and reduced energy consumption in all cases (Table 2). However, the effort, time, and measurements needed to make these optimizations did not justify the amount of energy savings they delivered. This was because the improvement was relatively small at an average of 1.9%, but also because these systems already had very good energy efficiency performance without optimization, limiting the opportunity for impact

Table 3. Annual performance results from Phase II monitoring (new installations)

Sites	Heating Load (therms/yr)	DHW Load (therms/yr)	Space Heating Efficiency	DHW Efficiency	Combined Efficiency	Operating Cost* ($/year)
new_01	1033	N/A	89.0%	N/A	N/A	$938
new_05	616	N/A	89.5%	N/A	N/A	$551
new_08	656	44	88.2%	76.8%	87.3%	$641
new_10	549	N/A	89.9%	N/A	N/A	$488
new_11	740	N/A	88.2%	N/A	N/A	$671
new_12	778	N/A	89.1%	N/A	N/A	$699
new_16	1259	N/A	91.1%	N/A	N/A	$1,106
Average	766	N/A	89.3%	N/A	N/A	$728

Phase II monitoring and results had nearly identical performance to Phase I boilers after retrocommissioning. For Phase II, the average annual space heating efficiency was 89.3% compared to 89.9% for Phase I after retrocommissioning. This characterization validates the QI measures developed in Phase I for ensuring installed performance capable of achieving the expected savings above baseline for new installations. Table 3 shows the measured results for each newly installed boiler. As expected, the operating costs increase proportionally with the homes' load, but efficiency remains consistent.

Interviews with HVAC Professionals and Homeowners

Barriers to widespread market adoption of condensing boilers as well as general practice and attitudes was examined through interviews with Heating Ventilation and Air Conditioning (HVAC) contractors and one distributor from across the Twin Cities metro area. About 2% to 30% of these companies' retrofit business was replacement hydronic systems ranging from 15 to 50 installations per year. These interviews focused on installation costs and individual opinions about system performance and reliability, operations, and maintenance. All the contractors interviewed reported that they make decisions about replacement equipment based on reliability, affordability, and installer familiarity.

All contractors stated the practice of using some form of whole house sizing calculation method, though only a few used an official Manual J. Most contractors cited use of outdoor reset control as an external control device installed on condensing boilers. In addition, most contractors stated some sort of adjustment to the reset curve at installation, either according to manufacturers' recommendations or their own experience. None of the contractors use emitter capacity calculations on a regular basis unless there is a capacity concern. No particular attempt was being made by installers to ensure condensing actually occurs most of the time.

In addition, thirteen participant homeowners were interviewed to assess their experience with installed condensing boilers. These homeowners had either replaced their non-condensing boiler within seven years of the project's start or as part of the project. Most systems were replaced at time of failure or as part of a larger remodel/retrofit. Some homeowners were motivated by energy savings potential while others were sold by contractors on advantages of condensing, including sealed combustion safety. Two participants had minor issues with performance, which were remedied after installation; other participants had no issues. For participants that had experience with the older systems, all had a sense that they are saving energy with the new system and that comfort was either improved or the same. Eleven of the 13 homeowners rated their satisfaction at 5 on a scale of 1-5 (with 5 being the most satisfied).

Economic Analysis

We analyzed costs for condensing boilers by looking at 73 boiler replacement bids/invoices (45 non-condensing, 38 condensing) for 32 different homes. We found that the average difference in cost between condensing and non-condensing boiler installation is around $2,300. This is taking all 73 bids/invoices and comparing the average non-condensing price, $6,658, and the average condensing price, $8,944. We also looked at the price difference when both were bid by the same contractor on the

same job (10 homes); this average price difference was around $2,500. However, the range in price difference when looking at cost comparison for these ten homes was between $550 and $5,000. We also looked at installations that included indirect water heaters. The average price for including domestic hot water (DHW) was around $2,800.

All of the monitored systems had space heating efficiencies near 90% and showed annual energy savings between 10% and 18% over a baseline non-condensing boiler with an assumed efficiency of 82%. The average heating savings for the participant households with condensing systems over non-condensing systems is 13%, with an average yearly cost savings of $97 (Table 4). In order to have a simple payback of 25 years or less (typical lifetime of boilers), the price difference between condensing and non-condensing boilers needs to be around $2,500. In order to have a 10-year payback, the price difference needs to be around $1,000.

Table 4. Summary of annual results

Site	Design Load (Outdoor Temp of -11 ^{0}F)	Annual Savings over Average Non-condensing Boiler($/year)	Percent Savings over Average Non-condensing Boiler
exist_01 – as found	49,123	$108	10%
exist_02 – as found	32,581	$95	12%
exist_03 – as found	23,606	$69	14%
exist_05 – as found	19,762	$59	14%
exist_06 – as found	29,490	$117	18%
exist_07 – as found	27,670	$82	12%
new_01	46,230	$122	12%
new_05	25,492	$81	13%
new_08	26,397	$88	12%
new_10	25,727	$74.	13%
new_11	31,746	$88	12%
new_12	32,354	$100	12%
new_16	43,332	$185	14%
Average	30,366	$97	13%

The cost analysis showed that, on average, the difference in installation price ($2,300) was close to the 23-year simple payback mark. However, equipment costs, contractor labor estimates, and national numbers demonstrate that increased market penetration can lower installation costs and in that scenario, a simple payback period of less than ten years is possible. This payback can be reduced further through rebate programs and other market incentives.

Program Recommendations

Based on the results above we have three recommendations for utility CIP programs:

1. Continue to provide a higher rebate tier for 90+% (condensing) boilers. Condensing boilers are operating at or near their rated efficiency and currently are or have the ability to achieve cost effectiveness.

2. Include a checklist on the submitted rebate form with the installation criteria listed above in order to ensure better performance. This could include a settings section for the contractor to report predominant emitter type and water temperature set points, and outdoor air temperature settings for minimum and maximum water temperatures.

3. Offer contractor training. These added criteria likely warrant some contractor training. We recommend that utilities sponsor training for HVAC contractors performing rebate work that is focused on condensing boiler installation protocols and the ways to obtain the additional savings results seen in this project.

Introduction

High-efficiency condensing boilers have been available in the residential market for many years, but consumer acceptance and market penetration has remained low. Furthermore, there is a lack of confidence by many contractors and utilities about the energy savings attributable to this technology over a non-condensing version-particularly in the retrofit market.

To address these concerns and uncertainty, our research team monitored thirteen condensing boilers in MN homes to characterize installed performance. Six of these were installed up to seven years prior to the project and seven were installed using a Quality Installation protocol developed during the project.

We have data on supply and return water temperature, flow rates, incidence of condensing, and energy usage for all thirteen systems. These systems represent a variety of single family residential installations with various brands, emitter types, zone set-ups, and outdoor reset control installation and set points. These homes also represent a range of house types and heating loads in MN.

In this report, we will discuss the usage and performance findings from this monitoring and the impact of installation and recommissioning procedures on boiler performance. We will show that condensing boilers in MN homes are generally achieving high performance without requiring a specialized site specific installation. We will discuss the results of our market analysis, including HVAC contractor and homeowner surveys, as well as cost comparisons on over 70 projects. We will also include our recommendations for easy-to-implement Quality Installation activities to improve system performance.

Background

There have been a few research projects aimed at understanding condensing boiler operation and optimization. These studies have examined several potential issues and industry concerns, and have provided a technical basis for condensing boiler optimization measures. Much of this work focuses on laboratory testing, house characteristics (including load and distribution designs), and system types that do not directly apply to Minnesota's residential market. This work was used as a starting point to identify potential solutions, test them under Minnesota conditions, and develop best practices.

Cost Effectiveness

One of the common concerns of HVAC contractors and potential customers is whether the large cost difference between condensing and non-condensing boilers is recouped in energy savings. This question requires an analysis of the efficiency of these systems as well as a look at the incremental cost difference between condensing and non-condensing boilers.

Installation costs for condensing boilers tend to vary significantly by home, contractor, and equipment manufacturers. This cost variability is far greater with boilers than it is with forced air furnaces. Since

cost effectiveness is a barrier to market transformation, we needed to look at both the efficiency of the equipment and the variables that go into the installation costs.

Condensing Boiler Operation

Understanding the market concerns for actual efficiency versus rated efficiency, and the potential opportunities for optimization, requires a discussion of the differences between condensing and non-condensing boilers.

Condensing boilers are more efficient because they transfer more heat out of the combustion gases and into the circulating water than non-condensing boilers. They do this by utilizing a secondary heat exchanger that harnesses and effectively handles the energy from the condensation process. Because of this design, it is optimal to have the combustion gases condense as much as possible. In order to do this, the return water coming back from the room emitters needs to be low enough to allow significant heat transfer out of the gases below the condensation point and into the circulating water.

Figure 1 shows the increase in boiler efficiency in relation to return water temperature. Efficiency slowly but steadily increases as the return water temperature goes down from 240˚ to about 130˚. At 130˚ return water temperature, you see an exponential jump in efficiency, and that has to do with the condensation of the combustion gases. This points to the 130˚ mark as quite an important threshold, and ideally we get return water temperatures as low as possible to maximize efficiency.

In order to ensure low return water temperatures (<130˚), there needs to be significant heat transfer from the emitters into the home and/or low enough supply water temperatures. This is not an issue in condensing forced air furnaces because the returning air temperature is always below 130˚. Much of the skepticism around the real energy efficiency of condensing boilers has to do with these details and whether or not the systems are set up in a way to allow condensation to occur on a regular basis.

In non-condensing boilers, it is very important to prevent condensation from occurring inside a heat exchanger that is not designed or equipped to handle condensate due to corrosion issues. Therefore most supply water temperatures are set very high (180˚F or more) in order to keep return water temperatures from bringing the combustion gases below the condensation point. This is in direct contrast to the goal for condensing boilers. Because of this, the theory is that if an installation contractor sets the supply water temperatures or flow for a condensing boiler the same as a non-condensing boiler (in other words, too high), the savings will be small or non-existent.

Many HVAC contractors have concerns that if they lower the supply water temperature of a condensing boiler system below the traditional 180˚F in a retrofit from a non-condensing system, the heating load won't be met by the existing radiators. To have confidence in meeting the heating load, it is much easier (as an installation contractor) to keep the supply temperature high and sacrifice efficiency, than it is to do calculations on emitter capacity and heat load.

Figure 1: Relationship of boiler performance to return water temperature
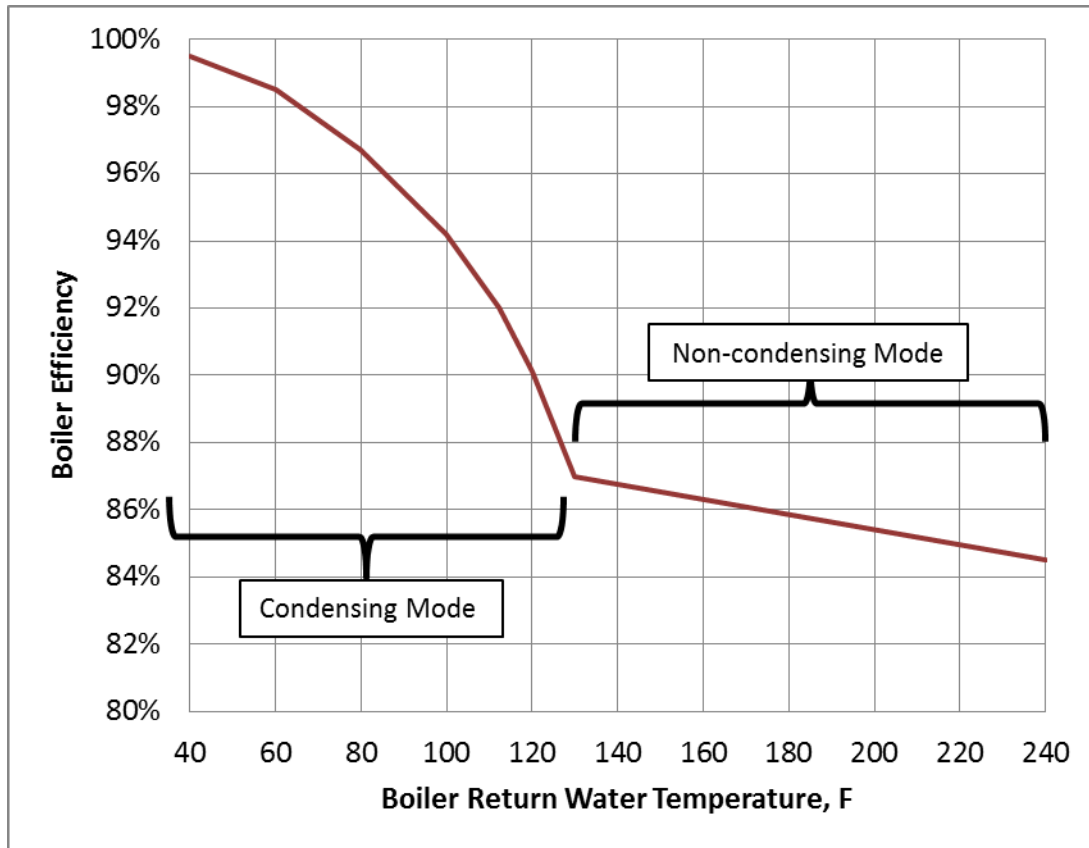
Methodology

First, we did market research to investigate barriers to wide market adoption. We did this through in-depth interviews with HVAC contractors/Distributors as well as homeowners. These interviews focused on installation costs, as well as individual perceptions regarding system performance, reliability, and operations and maintenance. In addition to the interviews, we also analyzed condensing boiler rebate data from utilities, and installation costs across multiple contractors and programs.

Next, we conducted field research in two phases.

1. The first phase included homes that had replaced their non-condensing boiler with a condensing boiler recently (Phase I).
2. The second focused on customers interested in replacing their current non-condensing boiler with a condensing boiler (Phase II).

Although the data collection and analysis for these two phases were very similar, we gleaned unique market insights and installation procedure details by conducting the two phases. It also allowed us to perform detailed monitoring of systems before and after optimization.

Field Research Site Selection

To solicit participants for this project, the Minnesota Department of Commerce sent out a notice in one of their newsletters to invite the general public to participate. We also used referrals from energy auditors and HVAC contractors.

The project team developed site selection criteria to identify a sample of field sites that was representative of Minnesota homes and boiler systems. These criteria were developed around seven specific areas that have been shown by prior research and CEE's residential experience to have the largest impact on boiler performance and savings from increased boiler efficiency. For each category listed below, an estimation of the demographics in Minnesota was determined and the criteria were set to ensure that typical conditions were represented. However, the criteria do not require that the sites selected for this project exactly match the demographics for Minnesota.

1. The heating load of the home
2. The domestic hot water (DHW) system
3. Emitter type
4. The installation contractor
5. The boiler manufacturer
6. Boiler controls
7. The sizing fit for the boiler, house load, and emitters

Field Characterization

During the first heating season, we monitored the as-found performance of existing condensing boilers in Phase I. This data helped determine the baseline performance of condensing boilers installed without specific requirements beyond the manufacturer's requirement and/or general installation practice.

Once the as-found condition was fully characterized, a trained contractor and/or project staff performed retrocommissioning on each boiler using a checklist based on existing research (Arena 2013) (Landry et al. 2016), the as-found data analysis, and engineering calculations (ASHRAE 2013, 2015), in order to optimize performance. The optimization focused on reducing the water temperature returning from the heating loop by optimizing the outdoor reset curve and lowering supply temperature set points, modifying the water flow rate (as applicable), and adjusting the supply water temperatures in the DHW loop, if present. We conducted the optimization at these sites with an "adjust and measure" approach and, as more optimization visits were conducted, the guide and checklist were finalized. The Results section of this report gives more detail about the findings and development of the document. The monitoring continued until we were able to fully characterize the impacts of the retrocommissioning visit.

During the second heating season, we worked with contractors to replace non-condensing boilers with condensing boilers (Phase II) using quality installation (QI) guidelines developed from the checklist in Phase I. These QI guidelines again focused on minimizing return water temperature through distribution set points and outdoor reset controls. Once installed following these guidelines, we monitored the replacement condensing boilers for at least one heating season. This phase allowed us to work with installation contractors more closely to implement a quality installation and set-up procedure as a way to test the protocol for ease of use. It also gave us the opportunity to look at multiple bids on the same home to see if there were trends based on contractor, equipment choice, or home details.

Once both phases were complete, we compared data from the sites in Phase II to the as-found and optimized conditions in Phase I sites.

Data Collection and Instrumentation

Each home was fully instrumented with a residential HVAC data acquisition system that was developed by CEE and successfully used on other field test projects. The system utilizes a Campbell Scientific acquisition system customized to collect energy use, temperature, water flow, runtime and other system data. A high resolution data collection interval was used (one second) to capture short time scale events. This logging interval strategy allows for efficient use of short-term storage on the data logger with daily transmission by cellular modem or internet connection each night. Table 5, Figure 2, and Figure 3 (below) detail the instrumentation and data collection system used at each site.

Figure 2. Instrumentation locations for a condensing boiler without DHW integration
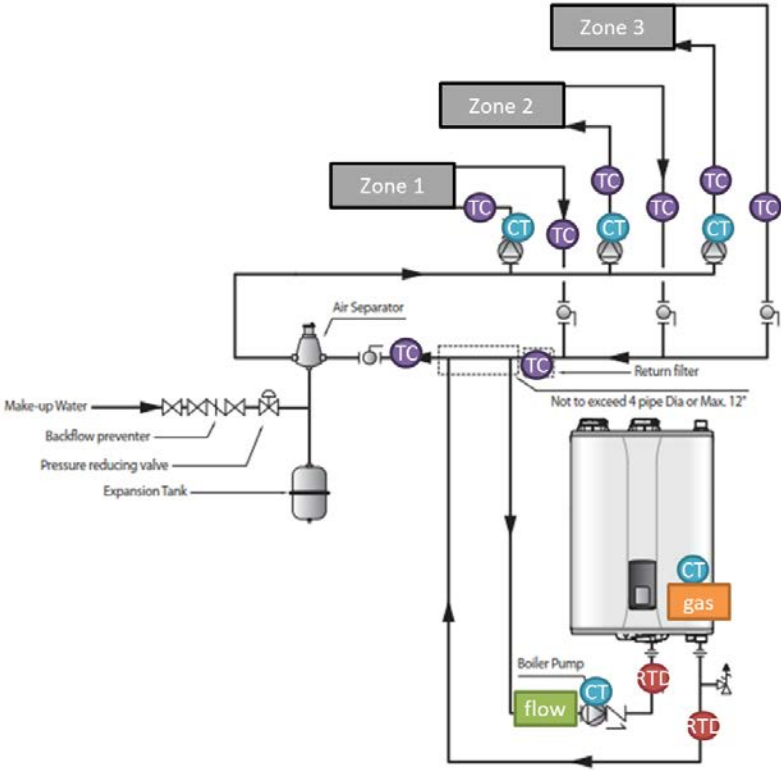
Figure 3. Instrumentation locations for a condensing boiler with DHW integration
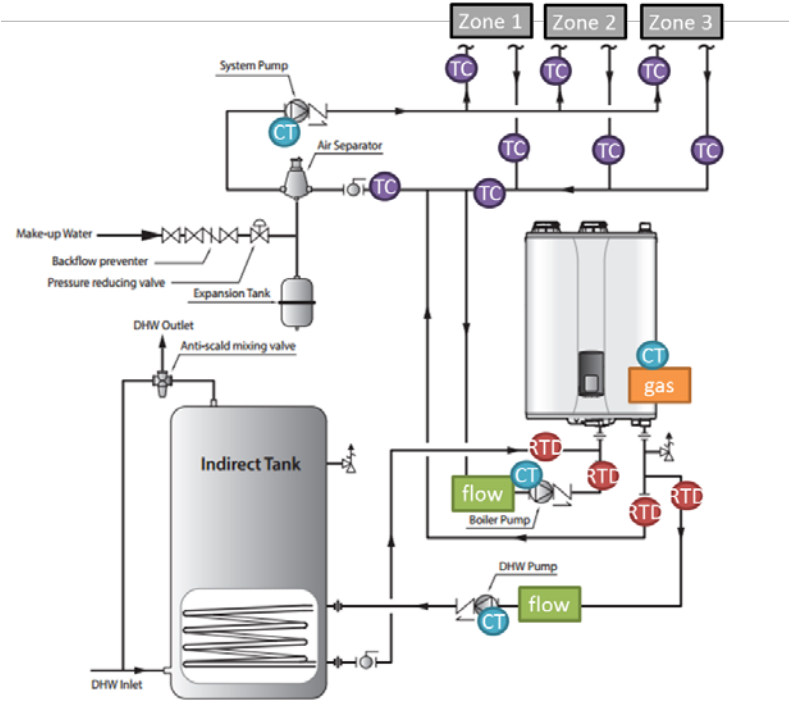
Table 5. Instrumentation deployed in field monitoring sites

Instrument	Measurement Type	Measurement Location
Immersion RTDs	Immersion water temperature	Heating supply water Heating return water DHW supply water (if applicable) DHW return water (if applicable)
Nutating disk flow meter	Water flow rate	Primary loop flow DHW loop flow (if applicable)
Diaphragm gas meter	Gas flow rate	Boiler gas inlet
Surface mount thermocouples	Hydronic pipe temperature (as an approximation of water temperature)	Individual zone supplies Individual zone returns Individual emitter supplies Individual emitter returns
Thermocouples	Air temperatures	Ambient near boiler Ambient in conditioned space Ambient outdoors (if possible)
Current Transformers	Runtime and Current measurements	Circulation pumps Boiler
Status switch	On/off status	Zone valves
NOAA weather data	Data collected from nearest weather station	Outdoor air temperature

Retrocommissioning of Condensing Boilers

In all sites in Phase I, a retrocommissioning process was used to identify opportunities in system installation or operation for improved performance. The commissioning process sought to identify operational settings that could lead to higher delivered capacities than necessary, which could then be modified. Increased capacities result in higher water temperatures and shorter run times, less condensing, lower efficiency, and increased energy usage.

Analysis

Data from both phases was analyzed to determine the annual energy consumption and the seasonal operating efficiency. Annual performance was compared between operation modes (as-found and optimized), between phases, as well as to an estimated baseline (80% AFUE) boiler. We also compared annual energy performance, runtimes, and installed efficiencies.

For the annual energy consumption analysis, we used an input/output method to compare the performance of the systems and modes of operation. CEE used this method in previous projects to compare annual energy use and the installed efficiencies of each system (Bohac et al. 2010; Schoenbauer 2013). See Appendix D for a detailed discussion of the analysis methodology.

The data collection included additional parameters, such as boiler water temperatures, outdoor air temperatures, and the temperature in the conditioned space. These parameters were analyzed and used to refine the retrocommissioning tune up and quality installation checklists, and to deterime the impacts of various factors (runtime, water temperature, outdoor air temperature, firing rate, etc.) on cycle efficiency.

Results

Market Assessment

Heating professional interview results

We conducted in-depth, in-person interviews with five HVAC contractors and one equipment distributor. The interviews were about distribution of forced air versus hydronic replacements, market trends, utility programs and current design, installation, and set-up procedures by contractors.

Table 6. Summary results of HVAC contractor/distributor interviews

Result	C1	C2	C3	C4	C5	D1
% of Business that is retrofit hydronic	10%	29%	19%	5%	2%	5% of total heating system sales
# of Retrofit hydronic annually	50	25	15	35	25	N/A
# of condensing boilers	25	10	5	5	2	80% of boilers sold
Whole house calc. method	Manual J	Spreadsheet Manual J "like"	Manual J	Estimates 50 BTUs/ft.^{2}	Supplier does Manual J	N/A
Use outdoor reset	Yes	Yes	Yes	Mostly	Mostly	N/A
Adjust reset curve	According to manufacturer's specs	According to manufacturer's specs	According to manufacturer's specs	No	No	N/A
Utility Service Territories Covered	Xcel, CPE, MERC, Dak. Elec., MVEC, Wright Hennepin	Xcel and CPE	Xcel and CPE	CPE, Xcel-MN/WI, Greater MN Gas	CPE, Xcel, MERC	N/A

The HVAC companies we interviewed primarily serve the Twin Cities metro area, with roughly 2% to 30% of the companies' retrofit business being replacement hydronic systems ranging from 15-50 installations

per year (Table 6). Condensing boiler replacements make up about 15% to 50% of all hydronic installations by HVAC companies interviewed. All contractors reported choosing replacement equipment brands based on reliability, affordability, and installer familiarity.

All contractors stated the practice of using some form of whole house sizing calculation method (only a few used an official Manual J). Most contractors cited use of outdoor reset control as an external control device installed on condensing boilers. In addition, most contractors stated some sort of adjustment to the reset curve at installation, either according to manufacturers' recommendations or their own experience. None of the contractors cited using emitter capacity calculations on a regular basis, unless there was a reason to be concerned about under capacitance. No particular attempt was being made by installers to ensure condensing actually occurs most of the time.

Four of the five contractors cited very little, if any, cost differences for clean and tunes for condensing versus non-condensing equipment. Regular maintenance was recommended by all contractors for both condensing and non-condensing systems. Two contractors recommend annual maintenance for all systems, and two contractors recommend annual maintenance for condensing, but two to three years for non-condensing. One contractor expressed some concern about dirty heat exchangers causing issues for condensing boilers over time.

Three contractors stated that they mostly encourage condensing boiler replacements on non-condensing equipment, but sometimes have concerns about payback and performance. The other two contractors are typically indifferent, so the lower priced non-condensing option often wins the customer over. The distributor encourages contractors to purchase condensing systems based on the current technology. When asked about customer satisfaction, four contractors stated a high level of customer satisfaction with condensing boiler replacements with only a few callback issues. All contractors stated concern/questions over the efficiency payback. One contractor stated that a lower price for condensing boiler installations would really help in their ability to sell this technology.

When asked about rebate program participation, all five contractors stated they often submit rebates on their customers' behalf. Four of the five contractors indicated that their customers are aware of the rebates available for boiler replacements. One contractor said few of their customers know about the rebates, so they work to educate the customers on the programs. Additionally all five contractors indicated that rebate programs offered for condensing boilers help their business. Three contractors expressed concern about the amount of paperwork involved, and two contractors suggested higher rebate amounts in order to justify the extra paperwork.

Homeowner interview results

In addition to the contractor surveys, all 13 homeowner participants completed an in-person or phone interview about their experience with the installed condensing boilers. These systems were all replaced either within five years of our project start or as part of our project.

Most systems were replaced at time of failure or as part of a larger remodel/retrofit. Some homeowners were motivated by energy savings potential while others were sold by contractors on advantages of

condensing, including sealed combustion safety. Most participants had expectations of energy/cost savings and improved comfort.

Two participants had minor issues with performance, and these have been remedied since installation, including an issue with a side arm tank sensor and a gas pressure issue. All other participants cited no issues with system performance.

Seven participants across both phases cited annual or semiannual maintenance practices, while six participants cited no maintenance activities at all. In addition, three participants in Phase I stated that they are doing less maintenance on the current condensing boiler than the old non-condensing system, and only two participants from Phase II said they were planning on doing more maintenance on their new system. The planned maintenance on the new systems was more about being proactive on maintenance as opposed to the sense that the new systems would require more maintenance.

All participants that had experience with the older system said they had a sense that they are saving energy and money with the condensing boiler. Four participants stated they've analyzed their bills and have experienced savings of 10%, 20%, 33% and 40%.

Comfort was either improved or the same as the previous system in all sites where participants had experience with both systems. Ten of the participants rated their overall satisfaction at 5, on a scale from 1-5 (5 being the most satisfied). Of the other three, one rated satisfaction at 6, one at 4.5 and one at 3 (because of a pressure valve issue). In addition, all the participants stated they would recommend a condensing boiler to others based on the energy savings, home re-sale value, reliability, and safety.

Installation cost analysis

We looked at 73 boiler replacement bids/invoices (45 non-condensing, 38 condensing)for 32 different homes, including internal CEE loan data and research project bids, and found that the average difference in cost between condensing and non-condensing boiler installation is around $2,300. This is taking all 73 bids/invoices and comparing the average non-condensing price, $6,658, and the average condensing price, $8,944.

We also looked at the price difference when both were bid by the same contractor on the same job (10 homes of the 32); this average price difference was around $2,500. However, the range in price difference when looking at cost comparison in this way was between $550 and $5,000.

We found that the price ranges were spread more widely for boilers than that of their forced air counterparts. The installation cost range for non-condensing boilers was $3,700-$13,000, and for condensing boilers it was $5,700-$17,000. In examining these cost ranges, we excluded additional costs for asbestos abatement, additional radiator installs, and indirect water heater tanks. By comparison, the price range for condensing forced air systems is typically between $3,000 and $4,500.

Additionally, we investigated just the difference in equipment costs between non-condensing and condensing boilers. We did this by searching online for supplier product cost data on equipment bid for

four of the homes by six different contractors where non-condensing and condensing boilers were both bid. This showed that the average equipment cost difference was around $1,000 (Table 7).

Table 7 Results of equipment only cost analysis

Site	Contractor	Non-Condensing Boiler model	Non-Condensing Equipment Cost	Condensing Boiler model	Condensing Equipment Cost	Equipment Cost Difference
H1	Co1	Slant Fin VSPH90	$ 1,900.00	Triangle Tube Prestige Solo	$ 3,200.00	$1,300.00
-	Co2	Weil McLain CG13	$ 2,100.00	Weil McLain Ultra	$ 2,900.00	$ 800.00
H2	Co3	Buderus GA124-23	$ 2,500.00	Bosch ZWB28-3	$ 2,900.00	$ 400.00
H3	Co4	Weil McLain CGi4	$ 2,100.00	Triangle Tube Prestige Solo	$ 3,200.00	$ 1,100.00
-	Co5	Peerless MIH-II	$ 1,400.00	Triangle Tube Prestige Solo	$ 3,200.00	$ 1,800.00
H4	Co6	Peerless MIH-II	$ 1,400.00	Navian NHB80	$ 1,800.00	$ 400.00
Avg. Cost			$ 1,900.00		$ 2,866.67	$ 966.67

We also looked at installations that included indirect water heaters. The average price for including DHW was around $2,800. However, this price may be less in the future. The side-arm tanks in this analysis were all double-walled tanks, which have been required by code in Minnesota until recently. Single-wall-tanks are now being allowed in most Minnesota cities. Interviewed contractors stated that double-walled tanks are about $1,000 more than single walled tanks.

This analysis leads us to believe that pricing for boiler replacements is highly irregular from contractor to contractor, system to system, and household to household — whether or not the bid is for condensing or non-condensing, but especially for condensing replacements. It also indicated that the bulk of the average price difference is not in equipment costs.

Test Sites

Recruitment and Selection Criteria

Using the recruitment methodology described in the methodology section, we were able to recruit twenty-three potential participants. This number was narrowed down to six for Phase I and seven for Phase II, based on the selection criteria described below.

We used multiple methods to determine representative sampling including household information from CEE's database, utility rebate information, and HVAC contractor feedback. Below are the results of each site selection category listed in the methodology section.

Heating Load

The heating load criterion was designed to select houses that represented the typical range of heating loads of hydronic homes in Minnesota. The range of typical heating loads was determined by performing a utility billing analysis on Minnesota homes in existing CEE databases. The database was a random sample of over 70 homes. These homes were located in or near the Twin Cities metro area with a mixture of suburban and urban homes. The majority of natural gas boilers in Minnesota fall within this demographic. Figure 4 shows the range of heating loads from this database. These quartile ranges were used to define four heating load bins (less than 728, 728 to 914, 914 to 1189, and greater than 1189 therms per year).

Figure 4. The range of heating loads for Minnesota homes
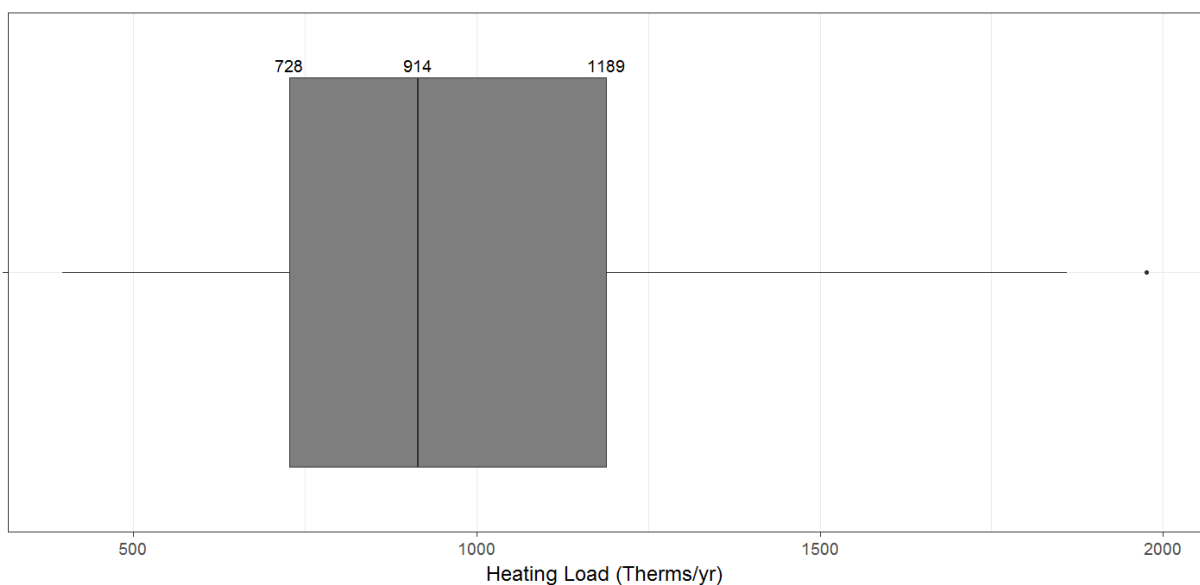
We also collected natural gas utility bills as part of the site selection process and analyzed the bills to determine the heating load of each potential home. Homes were selected for each phase (existing

boilers and new installations) so that each bin had at least one site and no bin had more than three sites.

Domestic Hot Water Integration

Hydronic heating systems can be used to meet the domestic water heating needs of a home. Indirect water heaters, tankless coils, or integrated tanks can all be used with a boiler as part of a combined space and water heating system. These systems add additional load and complexity to the performance of a boiler. Data collected from over 130 Minnesota homes with condensing boilers showed that about 37% had integrated water heating. Therefore the selection criteria required that at least one home in each phase have integrated domestic hot water (DHW), with a minimum of three homes total.

Emitter Type

Emitter type has the potential to have a large impact on total system performance. Previous research (Landry et al. 2016; Schoenbauer 2013; Arena 2013) has shown that the temperature of the water returning to the boiler from the distribution system has the biggest impact on system efficiency — the effectiveness of an emitter to transfer heat from the hydronic loop to the space is a major factor in determining this return water temperature. This project targeted system selection that would allow for characterization of all common emitter types. According to interviewed HVAC contractors as well as CEE's staff observations over 30 years, cast iron radiators are by far the most common emitter type in Minnesota homes. Phase I recruitment data showed that 87% of homes had at least one zone with cast iron radiators. In order to increase emitter diversity, the selection criteria was to include at least two homes with some emitters other than cast iron radiation in each phase.

Installation Contractor

A large component of this research project was to assess the current installation practices and characterize the potential for improving existing condensing boiler performance as well as ensuring quality installation of new systems. Therefore, a large range of contractors and installers was desirable. The selection criteria required that the same contractor install no more than three boilers across both phases of the project.

Boiler Model and Manufacturer

For many HVAC systems, the performance, set up, and operational best practices can differ by manufacturer due to differences in design and control. Because of these differences, we deemed it important to include a wide variety of boiler manufacturers. Contractor interviews and utility rebate data were used to determine which boilers had the largest market share in Minnesota. Boiler manufacturers were grouped into four tiers of qualitative market share (Table 8). Ideally, the boilers included in this study would be representative of the market share, with at least four of the tier one and tier two manufacturers, and no more than three of any one product included in each phase of the project.

Table 8. Boiler product market share in Minnesota

Tier level	Boiler Manufacturers
Tier 1 (most sold)	Triangle Tube Well-McLain
Tier 2	U.S. Boiler (Burnham) Slant/Fin Lochinvar
Tier 3	Navien NY Thermal (NTI)
Tier 4 (smaller, but significant)	Bosch (Buderus) HTP (Munchkin) Peerless

Controls

A March 2015 study conducted by CADMUS evaluated utility heating system programs in Massachusetts utilities (Tabor et al. 2015). The study documented that over 50% of the rebated condensing boilers either had no outdoor reset installed or the reset was installed in a manner that resulted in ineffective control. Initial screening and recruitment visits showed this was not the case in Minnesota. Only one of the recruited homes for Phase I had a condensing boiler and no outdoor reset. While this home was included in the study, a 50/50 split of homes was not feasible for recruitment and would not have been representative of the Minnesota marketplace.

It is possible that the large range of temperatures in Minnesota, very cold design conditions, and moderate shoulder seasons make outdoor resets more common in Minnesota than other locations with more moderate heating climates.

Outdoor resets have become standard for new condensing boilers, especially in colder-climates where they have been commonly installed since around 2014. Due to this requirement, all Phase II boilers were installed with resets.

Emitter Sizing

Older emitters, such as baseboards and cast iron radiators, were designed to work with lower efficiency systems that did not require low return water temperatures. Homes with oversized emitters have the potential to reduce the emitter capacity by lowering water temperatures while still meeting the heating load of the home. Reduced water temperatures could improve system efficiency. For each potential field site, we estimated the design condition capacity of each emitter. Old cast iron radiators and hydronic baseboard capacities were based off of thermodynamic calculations and industry rules of thumb. Some newer baseboards and radiation panels had model numbers and product specifications that we used to determine actual rated capacities. All emitter capacity estimations required assumptions on water temperatures and flow rates in the system. While in some cases these temperatures and flow rates could be determined in the field, in many cases we assumed industry standards. See Appendix C for more details on this procedure.

We then compared the emitter capacities to the design heating load of the home. This ratio ranged from 1.1, where the emitters had a design capacity of 45,000 Btu/hour and the design heating load of the home was 40,400 Btu/hour, up to 3.6 in a home, where the emitter capacity was almost four times the design heating load. The selection criteria attempted to select a range of sizing ratios. Figure 5 shows the ratios from the selected sites in both phases of field research.

Figure 5. Ratio of design heating load and emitter capacity for selected field sites
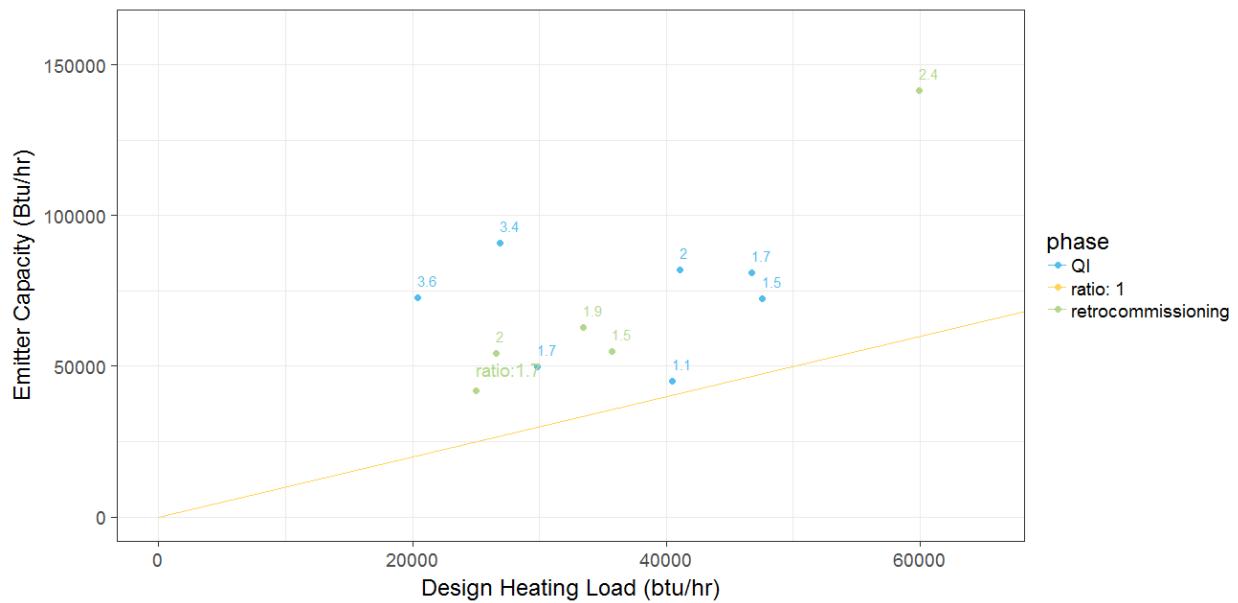
Table 9 lists the criteria, targets, and actual selections made for this project.

Table 9. Boiler site selection

Desired Criteria	Target Selection	Actual Selection
Heating loads	Select sites from a mix of the heating load range expected in Minnesota	1st Quartile: 5 homes (38%) 2nd Quartile: 3 homes (23%) 3rd Quartile: 4 homes (31%) 4th Quartile: 1 home (8%)
DHW integration	Minimum of 4 homes with integrated DHW	Phase 1: With 3 of 6 (50%) Phase 2: With 1 of 7 (14%)
Emitter types	A mix of cast iron radiators, in-floor heating, low-mass radiators, and baseboards	4 of 13 cast iron radiator only 9 of 13 mix of emitters
Installers	No more than 3 sites per installer, max installers for phase I	Phase I: 5 installers Phase II: 4 installers Max 3 sites for a single installer
Major manufacturers	At least 4 of the top 5 manufacturers	All tier 1 manufacturers 2 of 3 tier 2 All of tier 3

Desired Criteria	Target Selection	Actual Selection
Controls	Sites without outdoor resets (if possible)	1 of 13 sites (phase I)
Sizing	Sites with a range of emitter to design load sizing ratios	Ratios selected were between 1.1 and 3.6 (none with capacities below 1)

System Age (Phase I):

In addition to the seven criteria listed above, we also wanted to include systems for Phase I that were not brand new. This allowed us to observe any signs of pre-mature degradation. However, if there was major degradation from age, we didn't want to skew our results with such a small sample size. With this in mind, we wanted an age mix of previously installed condensing boilers. Our sample included boilers installed up to seven years old at the start of this project in 2015.

Site Characteristics

The characteristics for chosen sites in Phase I and II are listed below in Table 10 and Table 11 respectively.

Table 10. Phase I site characteristics

Sites	Design Heating Load (Btu/hr)	House Built	Floor Area (Ft.^{2})	Water Heating	Condensing Boiler Brand	Emitter Types	Emitter Capacity at 180˚F supply water temp.
Exist_1	49,123	1925	3000	Indirect Tank (Amtrol WH41)	Triangle Tube Prestige Solo 110	Cast Iron, New Panels, In Floor	141,300
Exist_2	32,581	1919	1500	Independent	Triangle Tube Prestige Solo 110	Cast Iron, Baseboards, In Floor	54,910
Exist_3	23,606	1912	977	Indirect Tank (Amtrol WH41ZDW)	Buderus GB 142 wall hung	Cast iron radiators	41,997
Exist_5	19,762	1918	1400	Indirect Tank (Triangle Tube SMART 40)	Bunham Alpine, ALP080-L02	Cast iron radiators	54,179
Exist_6	29,490	1931	2009	Independent	Weil-McClain Ultra 105	Cast iron radiators, in-floor in basement	52,000
Exist_7	27,670	1926	2188	Independent	TriangleTube Prestige Trimax Solo	Cast iron and modern radiators, one electric baseboard unit (rarely used)	62,932

Table 11. Phase II site characteristics

Sites	Design Heating Load (Btu/hr)	House Built	Floor Area (Ft.²)	Water Heating	Non-Condensing Existing Boiler	Condensing Boiler	Emitter Types	Emitter Capacity at 180°F supply water temp.
New_1	46,230	1912	1800	Independent	Burnham P-XG2004-W	Weil McClain	Cast iron radiators & Baseboard	72,445
New_5	25,492	1925	2880	Independent	Weil Mclain CG-4-SPON	Slant Fin CHS-110	all cast iron, one cast iron baseboard, and a couple electric baseboards that are used very sparingly	90,930
New_8	26,397	1930	1531	Indirect Tank	Unknown-Owner removed boiler before project start	Navien NHB80	All Cast Iron	72,758
New_10	25,727	1914	1952	Independent	Burnham P-204-W	Triangle Tube cc85S	cast iron radiators + electric baseboard upstairs	45,041
New_11	31,746	1939	1531	Independent	Weil Mcclain P-CGM-4	Triangle Tube cc85S	cast iron radiators + electric baseboard upstairs	45,041
New_12	32,354	1931	2681	Independent	Slant Fin GG 125 HE	NTI N1 TFT	cast iron	82,013
New_16	43,332	1913	1881	Independent	Slant Fin SX-150 EDP	NTI VM110 V-Max	Cast iron radiators & Baseboard	80,982

You can see the variety of house sizes, product brands, design heating load and emitter types in selected homes based on the selection criteria listed above. It also includes the calculated emitter capacity at 180˚F supply water temperature. Comparing the design heating load to the emitter capacity at different supply water temperatures helped us determine the amount we could lower the supply water temperature set-points on the re-set curve. As you can see in these tables, the emitter capacity at 180˚F is, in many cases, more than twice the amount of capacity needed to heat the homes on the coldest

days of the year. This showed us that we had plenty of room to lower the supply water set-point at outdoor design temperature.

Field Study Phase I: As-Found Performance

The system performance was continuously calculated from the measured data throughout the entire monitoring period. The first analysis of the project was to determine the as-found performance of the Phase I boilers. Figure 6 shows the daily efficiencies from each of the phase I boilers in the as-found condition. Each of the six sites had daily data collected through a full calendar year. All boilers provided heat for space heating in each home and sites exist_01, exist_03, and exist_05 also provided heat for domestic hot water (DHW) through the use of indirect water heaters.

Figure 6. Daily efficiency of as-found boilers (Phase I)
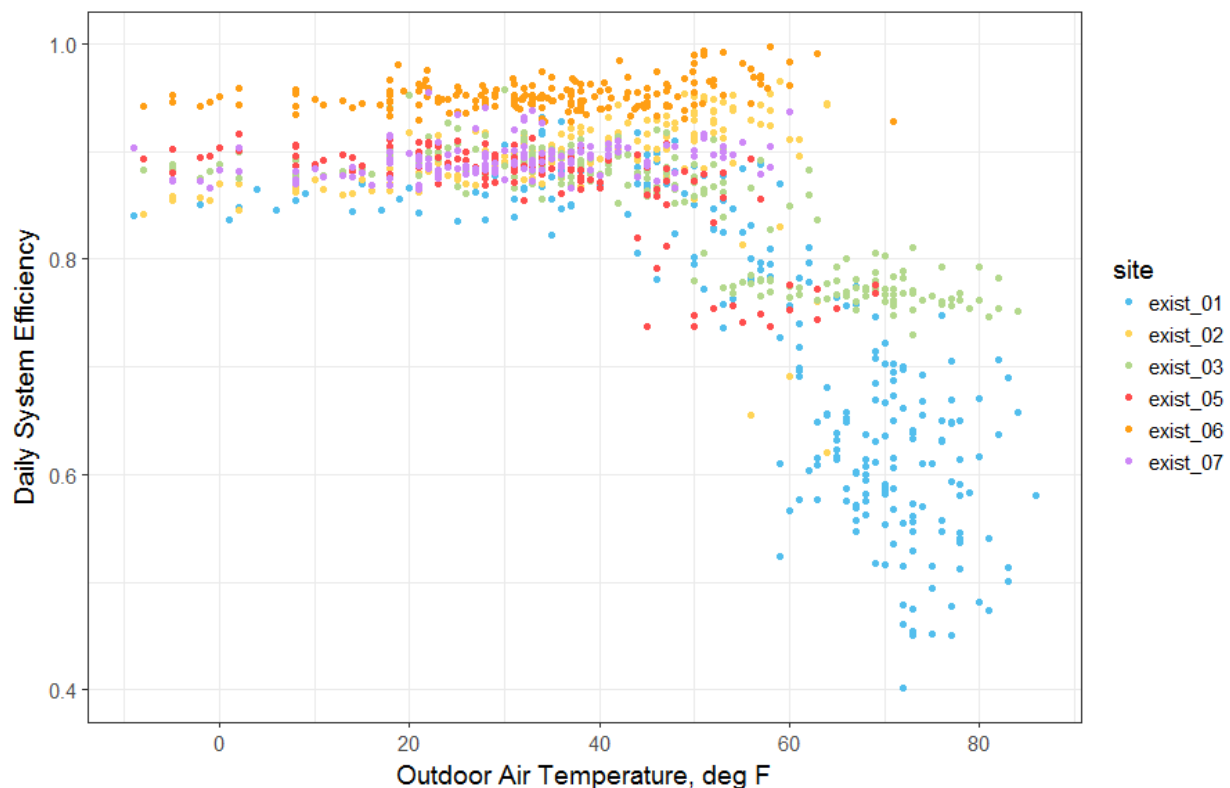
Operation for DHW had significantly lower efficiencies than the space heating operation. DHW efficiency was lower than space heating operation due to higher water temperatures and flow rates. DHW systems were designed to ensure maximum capacity with simple systems, which increased the return water temperature. Figure 7 shows the difference in the supply water temperatures for space and DHW heating at one site. The boiler controls for the space heating side have been designed to deliver only the needed capacity to the space heating distribution. This minimizes temperatures throughout the heating season. For DHW, the system delivers maximum heat and maximum capacity at all times, resulting in

DHW efficiencies that were never greater than 78%, while space heating efficiencies never dropped below 87%.

Figure 7. Daily supply water temperatures for DHW and space heating at site exist_03
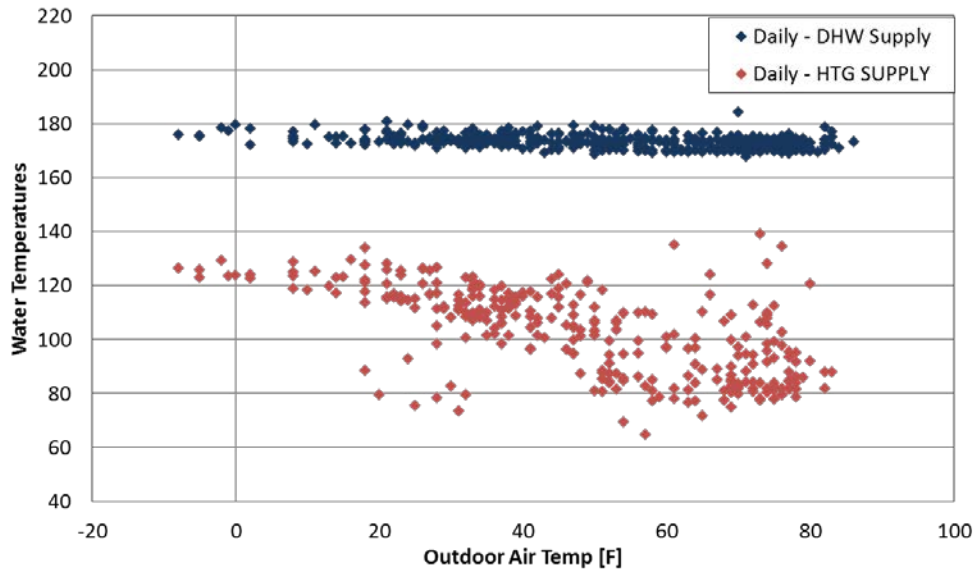
Sites with combined space and water heat had daily efficiencies that dropped below 80% when outdoor temperatures were warm enough that no space heating was required. DHW loads are smaller than design heating conditions. So, on very cold days, lower DHW efficiencies had only a small impact on the overall system efficiency, while in the warmer weather the impact was greater.

Table 12. Summary results from as-found performance of existing condensing boiler installations

Sites	Heating Load (therms/yr)	DHW Load (therms/yr)	Space Heating Efficiency	DHW Efficiency	Combined Efficiency	Operating Cost* ($/year)
exist_01	1111	135	86.2%	62.6%	83.6%	$1,001
exist_02	745	N/A	88.4%	N/A	N/A	$669
exist_03	485	85	90.5%	76.1%	88.0%	$429
exist_05	421	66	90.3%	74.6%	87.8%	$372
exist_06	636	N/A	95.1%	N/A	N/A	$535
exist_07	644	N/A	89.0%	N/A	N/A	$579

*This table assumes a natural gas cost of $0.80 per term

Overall the as-found operation had better than expected space heating performance. The vast majority of days had space heating efficiencies of 85% and above. Table 12 shows the annual performance of as-found operation for the previously installed boilers in Phase I. The space heating efficiencies were between 86% and 95%, with an average annual efficiency of 90%. While slightly lower than the rated AFUE (average AFUE was 94%) these installed efficiencies are in line with the expected efficiencies of

well-installed systems. Actual measured efficiencies are different than ratings specifications that are measured in controlled laboratory environments (Hoeschele and Weitzel 2013). Based on these findings, the as-found condensing boilers would expect to save 14% annual heating energy consumption over a baseline boiler installation.

Site exist_06 was the most efficient boiler in the entire field study with an annual space heating efficiency of 95.1%. This high efficiency was due to the site consistently having a very low return water temperature. Daily average return water temperatures were always below 110 $^\circ$F, even on days with outdoor temperatures well below 0°F. These low return water temperatures were due to a large fraction of in-floor radiant heat at this home, which required a much lower supply water set point than other emitter types. Less than 5% of all heating events at exist_6 required the boiler to deviate from the low in-floor supply temperature settings.

Further analysis of the as-found boilers identified three main contributing factors to the energy efficient operation. Those factors were:

1.   Emitter types and sizes,
2.   Outdoor reset, and
3.   Boiler water temperature control.

Emitters

Most boiler installations occur in existing homes with hydronic heating systems that were designed to work before condensing boilers were available. These systems typically relied on high water temperatures to achieve the necessary heating capacities. In the Minnesota metro areas, these distribution systems typically depend on large cast iron radiators. Newer hydronic distribution systems typically have emitters that rely on lower water temperatures, such as radiant panels and in-floor heat (Figure 8).

High-efficiency boiler operation requires return water temperatures to be less than 130°F. Emitter characterization for this project found that the older cast iron radiators were typically sized with a large safety factor to ensure they could meet the heating needs of the home. Additionally, homes with hydronic heating are typically older. Therefore, when the distribution was designed, it relied on less efficient equipment. Over time, rising equipment efficiencies, improvements to the home, and the conservative design resulted in the radiator systems being oversized. For these reasons, the water temperatures can reliably be reduced and still meet the load of the home.

In addition, newer emitter types (radiant panels and in-floor heating) are designed to work at lower operating temperatures, allowing the boiler to operate at higher efficiency.

a)   b)
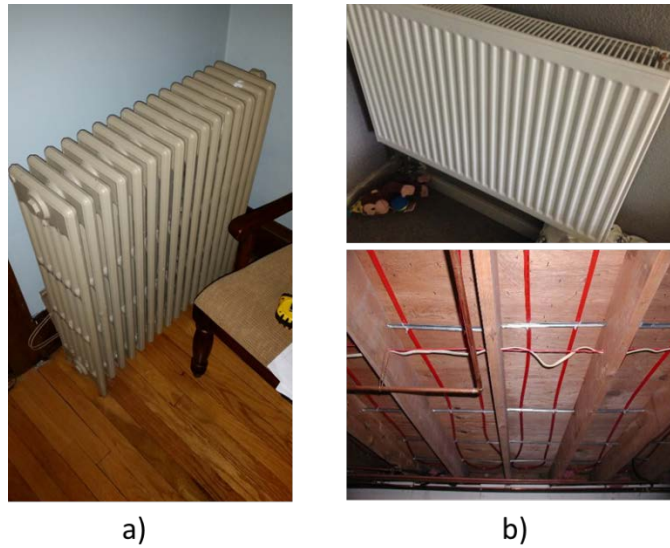
Outdoor reset control

The reset is a control strategy for condensing boilers that reduces the target boiler supply temperature based on the outdoor air temperature measured by the system. With an outdoor reset, the capacity of the boiler automatically scales with the house heating load. Reducing the target supply water temperature also reduces the return water temperature, increasing boiler efficiency.

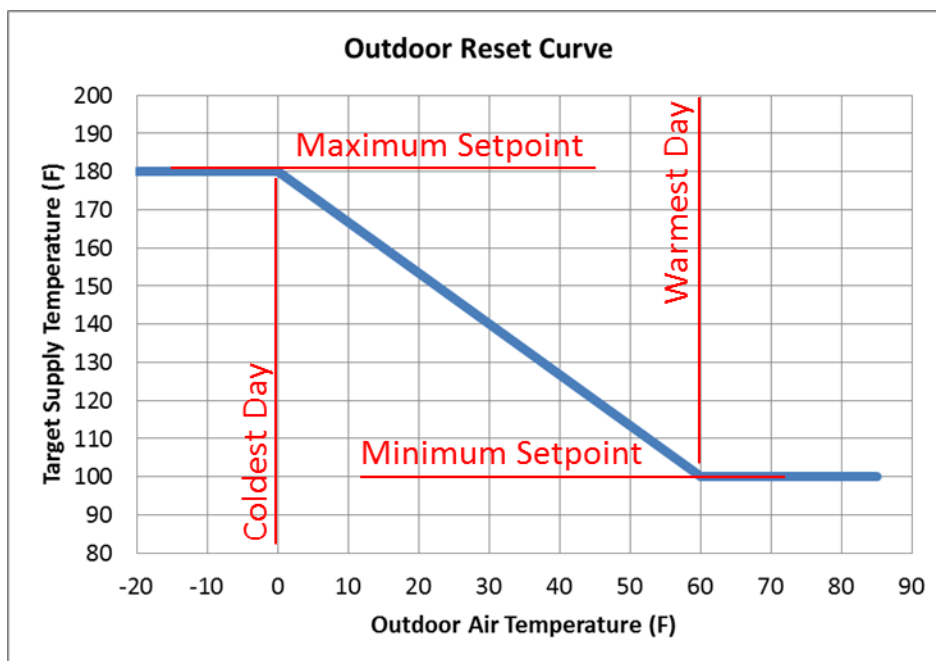**Figure 9. Typical boiler reset curve**

Figure 9 shows a typical reset curve and the four operational parameters that can be changed and optimized for individual installations. The four control points allow the installer to set the coldest and warmest days as well as the corresponding target water temperature at those outdoor temperatures.

Water temperature control

The analysis also showed that condensing boilers had operational controls and methodologies that helped ensure high performance. Figure 10 shows a time-series plot of the supply water temperature for individual heating cycles at site exist_7. The plot shows that for each heating cycle the supply water temperature started at temperatures below 100 °F and then slowly ramped up to the target set point temperature. At an outdoor temperature of 30°F, the boiler took about 30 minutes to reach the target temperature. At 0°F, it took over 100 minutes to reach the target. Additionally, the chart shows that for lots of events the boiler turned off before reaching the target temperature. This control strategy means that the system was meeting the load of the home at lower water temperatures than if the temperatures quickly went to the target. This strategy results in lower return water temperatures and high efficiencies.

Figure 10. Time-series plot of the supply water temperature for each heating event of one boiler
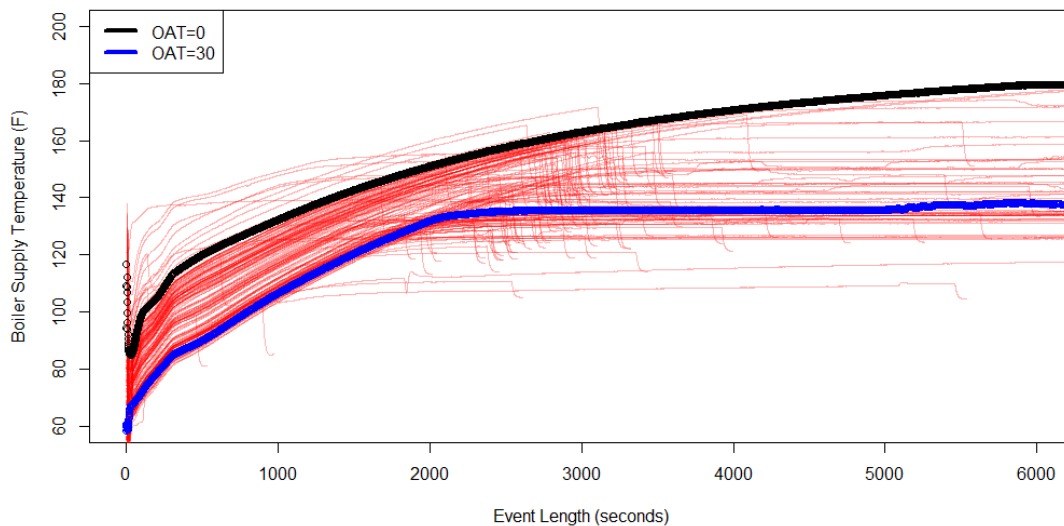
The combination of the emitter sizing, outdoor reset, and supply water control led to low return water temperatures in each of the as-found Phase I boilers. The low water temperatures resulted in the high space heating efficiencies shown in Figure 6 and Table 12. Figure 11 shows the average performance across the range of return water temperatures for exist_7, a typical site. At the lowest return temperatures, between 80˚F and 90˚F, the boiler saw its highest efficiencies of 97.5%. These low heating return water temperatures were found across all of the Phase I boilers (Figure 12).

Figure 11. Average heating efficiency per return water temperature bins at Site exist_7
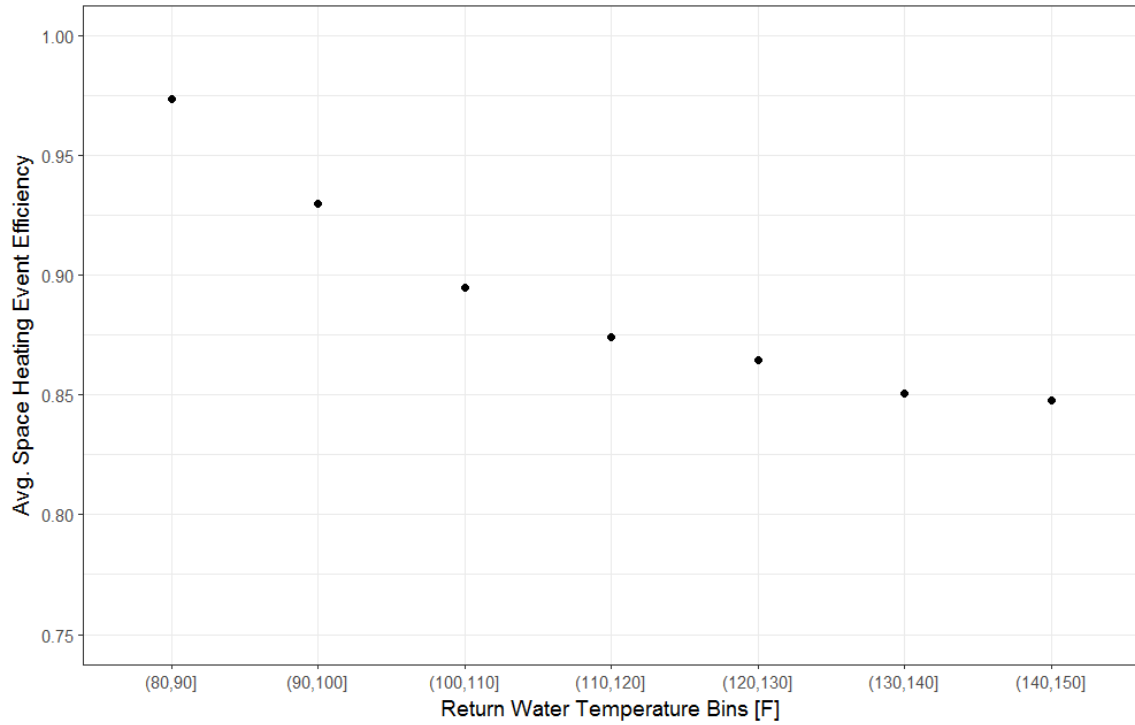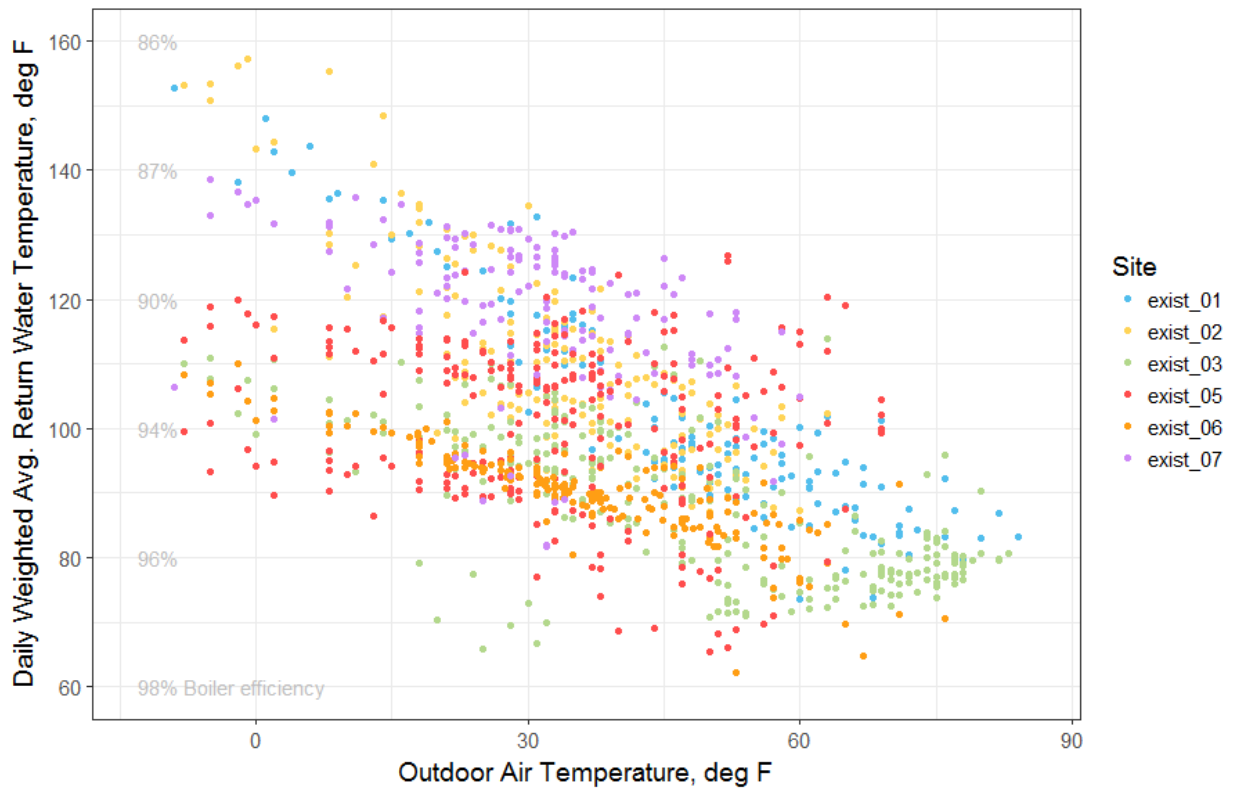

Figure 12. Outdoor air temperature and its impact on heating water temperatures

Field Study Phase I: Optimization Performance

Opportunities for both space heating and water heating performance improvements were evaluated as part of Phase I of this project. The goal was to minimize supply water temperatures as much as possible while ensuring house heating loads and DHW loads (where applicable) were still met over the full range of outdoor air conditions.

In general, the identification and optimization process were time consuming and required specific knowledge or measurement of parameters in each system. For example, the space heating optimization required a full measurement and calculation of the emitter capacity at a range of operating conditions. These measurements and calculations are not difficult, but are time consuming. This was true for both space and water heating optimization.

Space heating optimization focused on minimizing the supply water temperature through a four-step methodology.

1. The home's heating load was characterized over the full range of outdoor temperatures in the heating season. This characterization was done through detailed monitoring, for this project, but could be done through a simple utility bill analysis.

2. The home's emitter capacities were estimated over a range of water temperatures. This process included careful measurement and visual inspection of each emitter, noting type of emitter, model information (if available), as well as the physical size and style of the emitter. If model information was available, as is often the case for newer equipment, the specifications for the exact emitter was looked up. When no manufacturing information was available, industry standard performance curves were used for the capacity estimation. For more detail discussion of this step, see Appendix C.

3. The home's heating load and outdoor air temperature relationship was compared to the total emitter capacity and water temperature relationship. This comparison was used to set the lowest supply water temperatures necessary for the emitters to deliver the necessary capacity to meet the home's heating load at any outdoor air temperature. This was used to set the supply water temperatures at the coldest and warmest day conditions. These settings are shown at the factory defaults in Figure 9.

4. The set-points identified in step 3 were used to change the reset curve parameters of the boiler.

For example, Figure 13 shows the reset curve optimization for site exist_7. The emitter capacity and heating load comparison allowed for a significant reduction in the supply water temperature. The solid black line in Figure 13 represents the as-found outdoor reset curve set points. We determined this to be the factory default. After optimization, the coldest day outdoor air temperature was changed from the factory default of 0°F to -11 °F (the design outdoor air temperature for the home). Additionally, the

maximum temperature of the supply water at the design outdoor air temperature was set to be 135°F based on the emitter capacity calculated to meet the heat load. This was a considerable reduction from the factory set point of 180 °F. The figure also shows the average supply water temperature of each event. The optimization resulted in reduced supply water temperatures, especially in very cold conditions. The solid red line in the figure represents the optimized reset curve set points.

Figure 13. Outdoor reset curve optimization and impact on supply water temperature at site exist_7
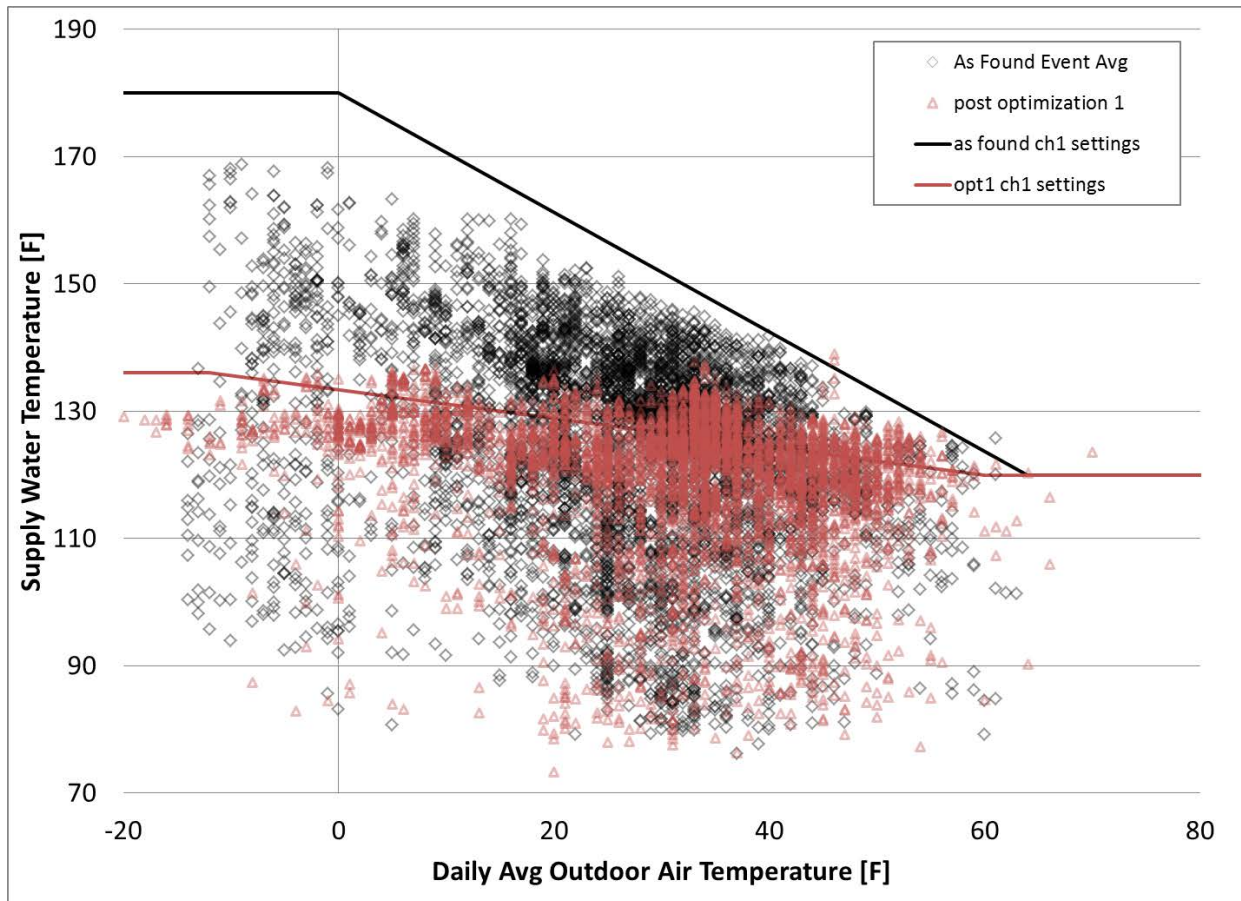
The optimization was effective at reducing supply water temperatures in extreme weather conditions. However, the reductions were much smaller in the more moderate temperatures where the majority of the heating hours occur. This fact limits the overall improvements in efficiency of the system over the course of a year. Additionally, for many of the heating events before optimization, the set supply water temperature was never met. This was due to the water temperature controls situation mentioned above. Therefore, despite optimizing the reset curve, the daily efficiencies were not drastically increased (Figure 14).

Figure 14. Daily efficiency of the space heating system before and after optimization at exist_7
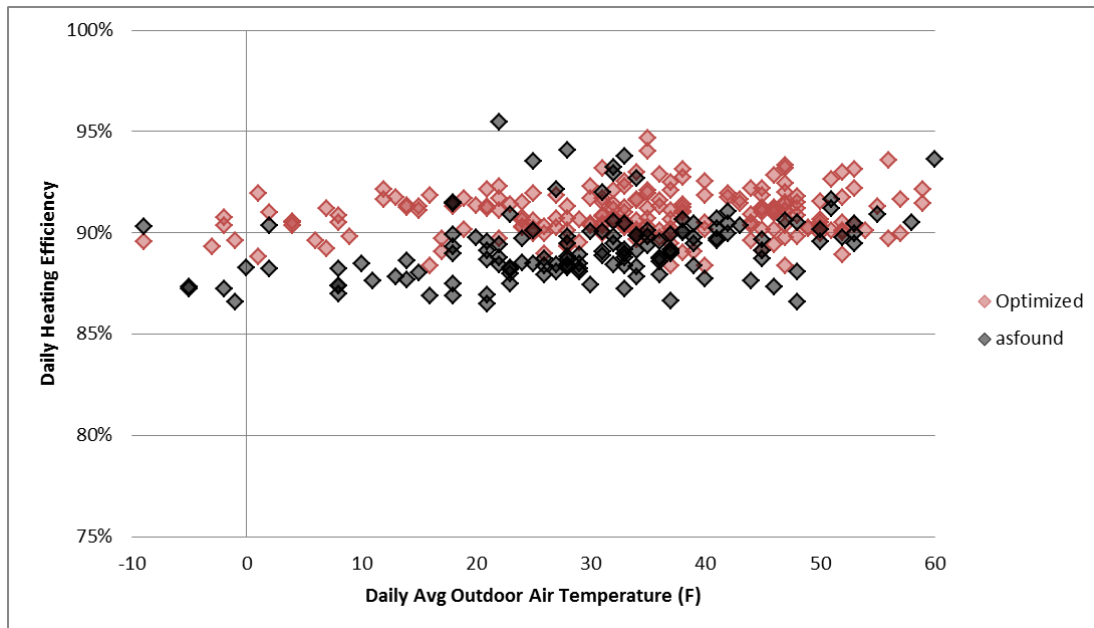
Space heating optimization was conducted at three of the seven as found sites. Site exist_6 had very high as-found efficiency and optimization was not possible. Two other sites were used to look at domestic water heating optimization instead. The final three sites were optimized for space heating. While difficult to do, the optimization did show improved efficiency and reduced energy consumption in all cases (Table 13). However, the effort, time, and measurements needed to make these optimizations did not justify the amount of energy savings they delivered. This was because the improvement was relatively small at an average of 1.9%, but also because these systems already had very good energy efficiency performance without optimization, limiting the opportunity for impact.

Table 13. Annual space heating efficiency for as-found and optimized sites

Site	As-Found Annual Heating Efficiency	Optimized Annual Heating Efficiency	Percent Improvement
Exist_01	86.2%	88.3%	2.1%
Exist_02	88.4%	90.2%	1.8%
Exist_07	89.0%	90.8%	1.8%
Average	87.9%	89.8%	1.9%

In systems designed to meet heating and DHW loads with an indirect or integrated DHW tank, DHW efficiencies were much lower than space heating efficiencies, due to the maximum capacity design. Lower efficiencies meant a better potential for optimization. Two of the as found sites (exist_01 and exist_03) had DHW systems and optimization was attempted at both sites.

Similar to the space heating optimization, water heating optimization focused on minimizing the return water temperature while still meeting the DHW and heating needs of the system and the home. The first step of DHW optimization was to look at the current capacity and determine if there was enough

capacity to make any adjustments. Then, if there was an opportunity for optimization, the DHW set point temperature and flow rate were reduced. Adjustments were made in small increments, checking the impact on the DHW system capacity after each adjustment.

DHW optimization yielded only minimal impacts. The effectiveness of optimization was limited due to the equipment installed at both sites and the maximum capacity design of the systems. Both boilers were found to be delivering very hot water to the DHW systems. Site exist_01 was supplying 155°F water to the indirect DHW tank and exist_03 was supplying 173°F water. However, despite these high water temperatures, the delivered capacities to the indirect tanks at both sites were not dramatically oversized. Both sites had 40 gallon indirect water heaters. Site exist_01 was delivering approximately 36,000 btu/hr and exist_03 had a median capacity of 53,500 btu/hr as shown in Figure 15.

Figure 15. Delivered heating capacity for DHW heating at site exist_03
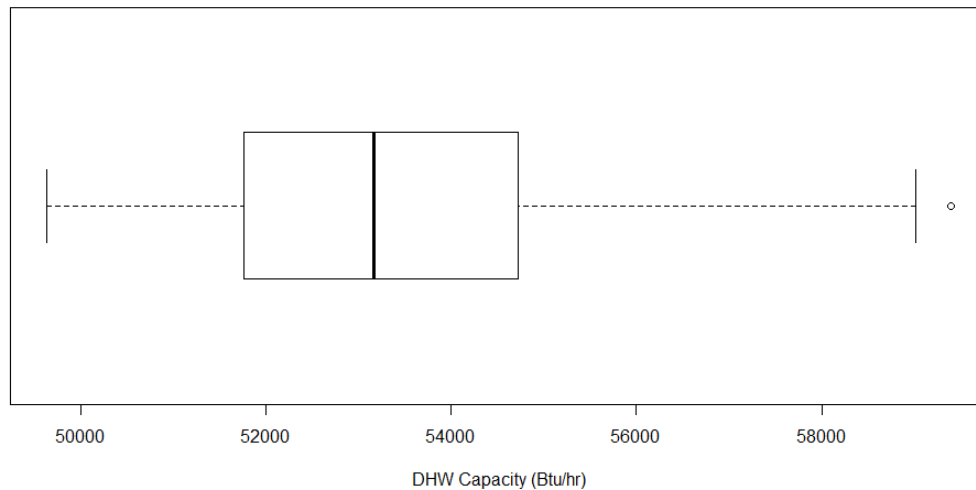
A typical 40 gallon residential gas water heater has about 30,000 btu/hr heating capacity delivered to the water inside the tank (40,000 btu/hr input capacity and an estimated 75% burner thermal efficiency). Exist_01 had only limited room for adjustment, which limited the potential impact of optimization without risk of an undersized DHW system.

Exist_03 had more opportunity for adjustment of the DHW supply water temperature and the DHW flow rate. Figure 16 shows the DHW efficiency for site exist_03 in the as-found condition, two optimization attempts, and an ideal condition. These efficiencies are the thermal efficiencies of the water heater and do not include the storage tank loses to ambient conditions. Therefore the ideal performance would be comparable to that of a condensing tankless water heater (Bohac et al. 2010) as shown in the figure. Both attempts at optimization (opt1 and opt2) yield only marginal improvements in annual efficiencies. Opt1 increased the as-found efficiency (76.1%) by 0.8 percentage points to 77.3%, and opt2 increased the annual performance slightly more to 77.9%.

Figure 16. Optimization attempts on the DHW system at exist_03
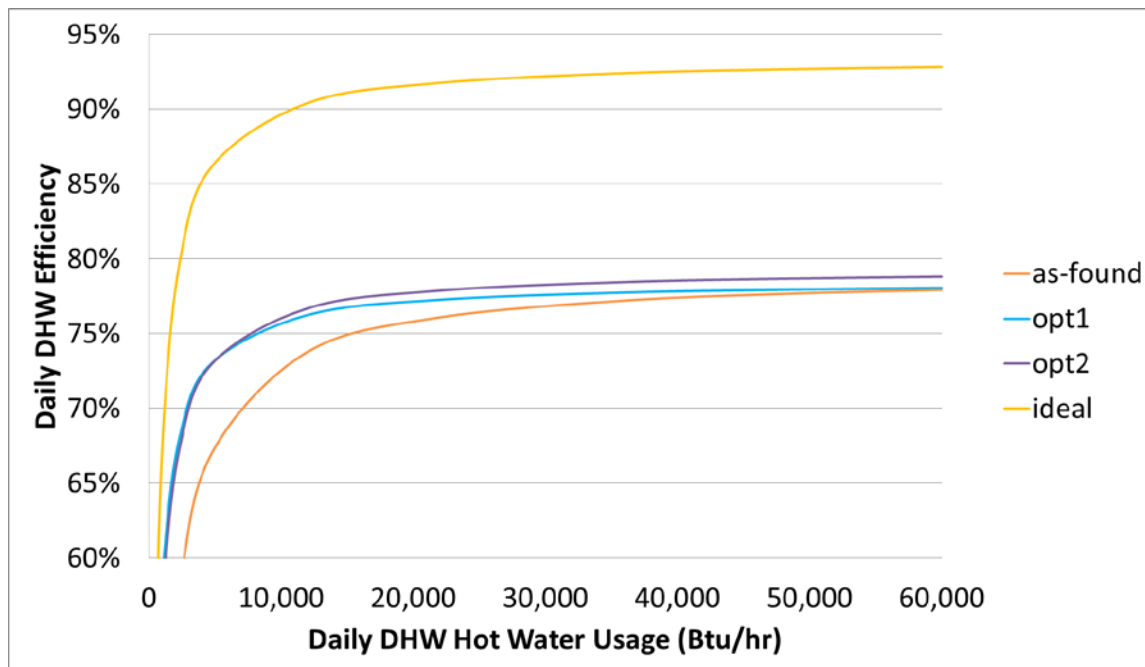
Field Study Phase II: Quality Installation Performance

Seven sites were selected and had condensing boilers installed following a QI procedure based on the lessons learned from Phase I of this project. The same instrumentation and data collection package used for Phase I was also used in Phase II. Data was collected and analyzed for one full heating season and the performances of the newly installed boilers were compared to the results from Phase I and baseline systems.

The quality installation procedure was developed based on the as found and optimized performance of the boilers from Phase I. The project team found that the best practice would be to follow the manufacturer's installation requirements and ensure that:

1. The maximum firing rate of the boiler was sized according to ACCA Manual J (Rutkowski and Air Conditioning Contractors of America 2006), while minimizing the minimum firing rate. This was achieved by selecting a boiler with a reasonable turn-down rate.
2. The outdoor reset control had been installed to the manufacturer's specifications. This specifically ensured that the exterior temperature sensor had the required clearances and was installed so that it would take a reasonable measurement of the outdoor temperature (e.g. in a sheltered location outside of direct sunlight).
3. The outdoor reset curve was set for the appropriate distribution system in the home (e.g. the emitter type). Figure 17 shows a generic version of the outdoor reset guidance used for this project. The coldest day set point was based on the installation location and design temperatures. Then the minimum and maximum supply water temperatures were set according

to the emitter type. Most manufacturers provide specific guidance in their installation documentation.

Figure 17. Generic outdoor reset curve guideline
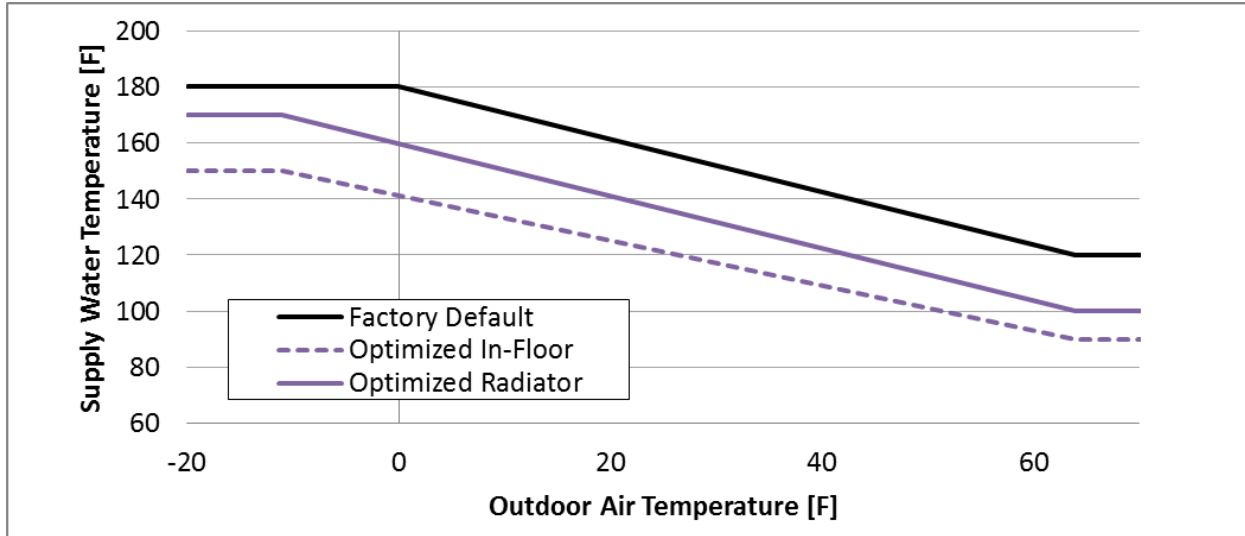
Phase II monitoring and results had nearly identical performance to Phase I boilers after retrocommissioning. For Phase II, the average annual space heating efficiency was 89.3% compared to 89.9% for Phase I after retrocommissioning. This characterization validates the QI measures developed in Phase I for ensuring installed performance capable of achieving the expected savings above baseline for new installations. Table 14 shows the measured results for each newly installed boiler. As expected, the operating costs increase proportionally with the homes' load, but efficiency remains consistent.

Table 14. Annual performance results from Phase II monitoring (new installations)

Sites	Heating Load (therms/yr)	DHW Load (therms/yr)	Space Heating Efficiency	DHW Efficiency	Combined Efficiency	Operating Cost* ($/year)
new_01	1033	N/A	89.0%	N/A	N/A	$938
new_05	616	N/A	89.5%	N/A	N/A	$551
new_08	656	44	88.2%	76.8%	87.3%	$641
new_10	549	N/A	89.9%	N/A	N/A	$488
new_11	740	N/A	88.2%	N/A	N/A	$671
new_12	778	N/A	89.1%	N/A	N/A	$699
new_16	1259	N/A	91.1%	N/A	N/A	$1,106
Average	766	N/A	89.3%	N/A	N/A	$728

Comparing All Modes

Both as-found and optimized boiler space heating performance was compared to the installed performance of the Phase II newly installed systems. Figure 18 compares the efficiency for all these systems. The figure shows that all the measured efficiencies were fairly consistent, ranging from 86% to 96% with an average annual efficiency of 90%. Additionally the performance of a typical baseline system was also included for comparison. This baseline was created from the average estimated performance of the typical baseline system and validated against a billing analysis for the systems prior to the Phase II installations.

Only three of the as-found systems were optimized. Both Exist_05 and Exist_06 were already set up for the lowest return water temperatures possible. Exist_06 had the highest annual efficiency (95.1%) measured across all sites. Exist_05 had slightly higher return water temperatures than Exist_06, but emitter capacity, existing supply temperature settings and house load were such that further optimization was not likely to result in significant changes in system performance. Exist_03 was optimized for DHW performance and not space heating performance.

Figure 18. Space heating efficiency for all sites
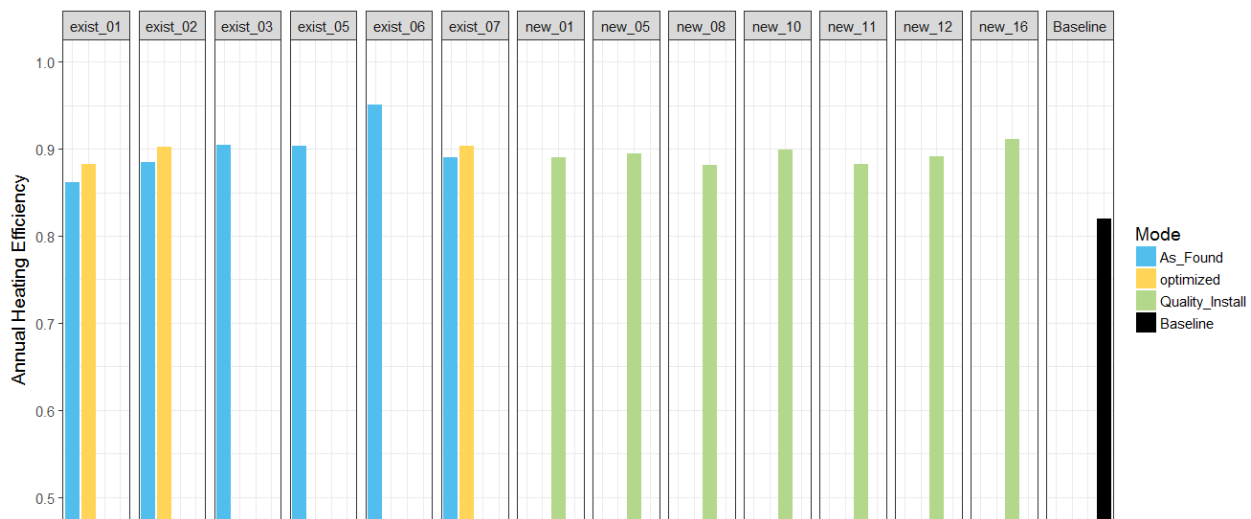
Savings Results

All of these systems had space heating efficiencies near 90% and showed annual energy savings between 10% and 18% over a baseline non-condensing boiler with an assumed efficiency of 82% (about 78% actual efficiency). Table 15 shows the annual cost and percentage savings.

Table 15. Summary of annual results

Site	Design Load (Outdoor Temp of -11 ^{0}F)	Annual Savings over Average Non-condensing Boiler($/year)	Percent Savings over Average Non-condensing Boiler
exist_01 – as found	49,123	$108	10%
exist_02 – as found	32,581	$95	12%
exist_03 – as found	23,606	$69	14%
exist_05 – as found	19,762	$59	14%
exist_06 – as found	29,490	$117	18%
exist_07 – as found	27,670	$82	12%
new_01	46,230	$122	12%
new_05	25,492	$81	13%
new_08	26,397	$88	12%
new_10	25,727	$74.	13%
new_11	31,746	$88	12%
new_12	32,354	$100	12%
new_16	43,332	$185	14%
Average	30,366	$97	13%

Cost Effectiveness

According to our savings analysis, the average heating savings for the participant households with condensing systems over non-condensing systems is 13%, with an average yearly cost savings of $97. In order to have a simple payback of 25 years or less (typical lifetime of boilers), the price difference between condensing and non-condensing boilers needs to be around $2,500. Similarly, for a 10-year payback, the price difference needs to be around $1,000.

The cost analysis showed that, on average, the difference in installation price ($2,300) was close to the 23-year simple payback mark, but an individual bid for a particular homeowner may prove to be a shorter or longer payback due to the wide range of price differences in the market.

Our savings results for side arm or integrated DHW over a baseline power vented DHW unit is quite small, or non-existent. So, this does not appear to justify the higher average cost ($2,800 for the side arm vs. $2,000 for a power vented unit). However, if a side arm or integrated tank installation cost was similar to a power vented unit (around $2,000 installed) it would likely be cost-effective. We see some potential for this based on the recent code change allowing single wall tanks as discussed in the Installation Cost Analysis section.

Conclusions and Recommendations

Conclusions

Condensing boilers installed to provide space heating are achieving the energy savings and performance expected based on their ratings and specifications. There should not be any concerns about the ability of these systems to achieve condensing performance due to high return water temperatures in Minnesota's typical housing stock, as return water temperatures in these test sites were all low enough to allow condensing to occur. The as-found condition of previously installed condensing boilers in homes participating in Phase I of this project had an average annual space heating efficiency of 89.9%, which represented a 13% energy savings over a baseline non-condensing boiler.

The optimization work in Phase I and quality installation work in Phase II of this project showed that detailed emitter and DHW capacity calculations in order to set supply water temperature as low as possible may yield small increases (approximately 2%) in efficiency and performance, but are unnecessary to achieve the good efficiencies already found in the measured baseline of the condensing boilers in the first phase of the project.

However, there are three simple installation criteria that should be considered for any condensing boiler program in order to ensure good performance from condensing boilers:

1. **Boiler sizing**. The boiler should be sized according to ACCA Manual J to prevent oversizing.

2. **Manufacturer's specifications for outdoor reset control installation**. Results from this study indicate that outdoor resets are regularly being installed with new condensing boiler installations in residential applications. However, contractors should make sure they are following the specifications of the manufacturer for installation of the reset control, including locating the outdoor sensor in a sheltered location away from direct sunlight.

3. **Matching reset control settings to on-site conditions**. The outdoor reset temperature control settings should reflect the design temperature conditions for the home as well as the emitter types used by the home. Lowering supply water temperatures and adjusting design day set points from factory defaults based on emitter type and location can help ensure more incidence of condensing through lower return water temperatures. Emitter based temperature settings can typically be found in the manufacturer's installation specifications. In the absence of manufacturer's guidelines, refer to Figure 17 of this document.

The project saw a wide range of incremental installation costs for condensing boilers. However, equipment costs, labor estimates from contractors, and national numbers indicate that with increased market penetration, installation costs can be reduced to a point where the simple paybacks will be less than 10 years. Rebate programs and other market incentives can reduce these paybacks further or increase market penetration more quickly.

Recommendations for Conservation Improvement Programs (CIP) in Minnesota

Based on the conclusions above we have three recommendations for utility CIP programs:

1. Continue to provide a higher rebate tier for 90+% (condensing) boilers. Condensing boilers are operating at or near their rated efficiency and currently are or have the ability to achieve cost effectiveness.

2. Include a checklist on the submitted rebate form with the installation criteria listed above in order to ensure better performance. This could include a settings section for the contractor to report predominant emitter type and water temperature set points, and outdoor air temperature settings for minimum and maximum water temperatures.

3. Offer contractor training. These added criteria likely warrant some contractor training. We recommend that utilities sponsor training for HVAC contractors performing rebate work that is focused on condensing boiler installation protocols and the ways to obtain the additional savings results seen in this project.

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Appendix A: Questionnaires

Note: The same survey was used for both contractors and distributors. When appropriate (e.g. the questions were geared more toward installation), we asked the distributor about what they knew about what their customers do, as opposed to what they themselves do. When a question did not apply to the distributor, it was marked NA.

HVAC Contractor and Distributor Survey

Opening Script

Hello I am Rebecca Olson with the Neighborhood Energy Connection. We are working on a study for the MN Department of Commerce on residential HVAC contractor opinions, and installation and maintenance practices for condensing boilers, as well as frequency of installation. Your company is one of 3-5 MN contractors we want to interview. Are you the right person (1st service manager, 2nd boss, 3rd technician) to talk with regarding your business' installation and maintenance practices?

(If yes) Would you be willing to speak with me for 45-60 minutes, now or sometime in the next week or so, to share information about your procedures?

(If no) Could you refer me to the right person? What is the best time to reach him/her?

Confidentiality. The information we gather will be grouped and analyzed, without linking it to specific businesses (i.e., your name or the name of your business will not be included in the report or shared with anyone — we will assign your responses a number once the interview is over). The results will help utility program designers better understand the conditions HVAC contractors are working under and how their programs might be more effective.

(If refused): I understand. Thank you for your time and have a nice day.

(If needed) Project background. Part of this study involves talking with residential HVAC contractors in MN regarding condensing boiler installation frequency, set up conditions and any concerns about equipment to provide insight and tools to increase the effectiveness of the utility Conservation Improvement Program. We are looking to characterize how things are currently being done, and you are being interviewed as representative of a typical contractor business. The information you share will be aggregated and used for statistics; not identified with your particular business or with you by name, so please speak freely. Your opinions and information are very important in this effort.

Do you have any questions for me before we get started?

Firmographics (some background about your business)

1. First can you tell me what your title or position is with your company?
2. How long have you been with the company? (Or if appropriate e.g., is it his/her business?)
3. How long has the company been in this business (i.e., doing residential boiler installations)?
4. What region or territory does your business cover?
5. Do you know which utility territories you work within?
6. How many installers and service techs do you employ? How many residential boiler installations do you do in a typical year?
7. What is the split between forced air heating systems and hydronic? How many of these are condensing boilers?
8. Do any of your technicians have certifications for gas boiler installation? If yes, which certifications?
9. What proportion of those installations is for new construction versus retrofits?
10. What brands of condensing boilers do you install? If more than one, about what percentage of each?
11. What factors influence which brand is installed?
12. Are there any fundamental installation differences between brands that made you choose the brand/s you install?
13. Are there any performance characteristics that influenced your brand choice? If so, elaborate.
14. What percentage of installations include an indirect water heater installation as part of the boiler replacement?
15. Do you typically suggest/recommend indirect water heaters?
    If so, how do you decide to recommend them (i.e. what situations do you recommend indirect water heaters)?
16. If you do not suggest indirect water heaters, why are they typically installed?

Pricing

17. What factors influence your bid price for replacement of a traditional boiler with a condensing unit?
18. In a typical replacement (uncomplicated), what is your price range for this retrofit?
    With and without an indirect water heater?
19. In a more complicated retrofit (i.e. asbestos, primary loop/secondary loop installation, any other factors?), based on your answers above, what would the high end of this cost be?
20. What complications cause this higher price?
21. Based on the brand/s listed earlier, what are the equipment costs of the installation versus labor costs?

Installation Practices

Now I have some questions about how you do installations. We are not suggesting that any practices are right or wrong, we are just trying to get an idea how things are actually done in Minnesota.

22. How do you go about sizing systems? (a. Use ACCA Manual J —
heat loss/heat gain calculations — lots of data to be considered, b. based on what was there before,
c. sq. footage/home size, d. other)
    o Does it matter whether it is new construction or retrofit?
    o (*If not clear from first part of the question*) Do you do heat loss and heat gain
      calculations to size systems? (*Probe on Manual J if appropriate*.)
    o *(If use Manual J)* Do you do whole house calculations, room by room, or both? Do you
      do modeling in-house or have your supplier do this for you? If in house, what software
      package do you use?
    o *(If use Manual J sometimes)* What types of homes or what characteristics prompt you to
      use these energy models? Do you do modeling in-house or have your supplier do this for
      you?
23. Do you ever install any control devices external to the boiler?
    o If so, what do you install, how often, and what factors led you to install them?
    o Outdoor reset follow-up: How do you decide where to place the outdoor sensor? Do
      you change the factory settings?
    o If so, why and how?
24. Thermo-stat follow-ups: How often do you replace t-stats?
    o How do you choose what t-stat to install?
    o Do you do any programming or setting of the t-stat?
25. Any other controls:
    **Prompt them about thermostats and outdoor resets if they do not provide that info.
26. When is primary/secondary loop configuration used?
    o When isn't it used?
    o Does the presence of an indirect water heater impact the decision?
    o Are choices different for condensing and non-condensing boilers?
    o Which loop do you call primary and which secondary?
27. Do you ever replace convectors as part of your condensing boiler retrofits?
    o If so, what determines the need for convector replacement?
28. Do you do any calculations on the output rates of the convectors (emitters) in the home?
29. What types of emitters do you typically see (cast Iron radiators, baseboards, in-floor, low mass
    panels)?
30. What is the frequency of each type?
31. When installing new emitters or re-plumbing the system, are individual emitters usually
    plumbed in parallel or in series?
    o What impacts that decision?
32. When just replacing the boiler and not emitters, what is the typical plumbing configuration;
    parallel, series, combination of the 2, other?
33. How do you typically set the supply temperature for the boiler?
    o What is the typical maximum supply temperature?
    o When would this vary?
34. Are there installation techniques you employ to ensure that condensing occurs as often as
    possible?
    o If so, what are those techniques?

Tune-up/Maintenance Procedures

Now I have some questions about your tune-up or maintenance call procedures

35. What does your company typically charge for a routine maintenance or tune-up call for condensing boilers?
    o Does this differ from a traditional boiler?
    o What frequency do you recommend?
    o Again, does this differ from traditional boilers?

36. What does the tune up/maintenance visit include for condensing boilers?

Maintenance/Tune-up - $	Comments
Check all thermostat settings	
Tighten all electrical connections	
Lubricate all moving parts	
Check and inspect the condensate drain	
Check controls of the system	
Heating	
Check safety switches	
Gas pressure	
Combustion analysis	
CO level	
Test primary heat exchanger	
Inspect/clean secondary heat exchanger	
Others?	

Utility Program Participation

Now I have questions about MN utility HVAC programs:

37. Have you participated in any utility condensing boiler equipment rebate programs?
    o (If yes) How many of these rebates are you involved with per year?
    o (If yes) Which program(s)?
    o (If they have not participated in utility programs) Why weren't you interested in these programs?

Notes on utility programs (for interviewer)

Utility	Program
Xcel Energy	
CenterPoint	
MN Energy Resources	

38. What do you think of the condensing boiler equipment rebate programs?
39. Do you feel the utility HVAC programs help or hurt your business in any way?
40. Do you have any suggestions for changes in these programs?
41. What would that change mean for your business?
42. Do your customers typically know about utility rebates for condensing boiler replacement?
    o About what percentage of your customers know about it?
    o If they know about the programs, are they usually interested in participating?
43. What percentage would you say want to participate?

General Opinion

I just have a couple of questions about your overall opinion of condensing boiler installation:

44. Do you encourage or discourage customers to replace a traditional boiler with a condensing unit?
    o Why?
45. What feedback, if any, do you get from customers about satisfaction with this equipment?
46. Do you or your customers have concerns or questions about the energy efficiency of this equipment as related to cost?

Participant Survey

Phase I Participants:

The following questions will be asked in person or on the phone by Rebecca Olson, project manager. This way, we can clarify any confusing questions and also take more elaborate answers than if we sent it via email or survey tool.

47. What motivated you to install a high efficiency condensing boiler?
48. Did you have any expectations about the performance of this new equipment?
49. Did you have any specific brand in mind or did you rely on the installing contractor to choose the product?
50. Did you get multiple bids from contractors?
    o Did you meet resistance from any contractors about installing a high-efficiency system?
    o If so, did they give any reasons?
51. What was the installation cost?
52. Were any modifications made to the heating system or home to account for the new boiler installation (i.e., new radiators, gas line change out, etc.)?
53. Have you had any issues with the installation or performance of the system?
54. What, if any, maintenance activities do you do for your boiler?
    o Are these different than your previous system?
55. Have you noticed a reduction in energy bills since installing the condensing boiler?

56. Do you do anything other than adjust your thermostat to change operation of the boiler? Set-back?
57. What are your thermostat set points?
58. On a scale of 1-5, 1 being very uncomfortable and 5 being very comfortable, how would you rate you/your family's comfort in the home?
    o Did your comfort level improve, stay the same or get worse, with the condensing boiler vs. the non-condensing boiler (if applicable)?
    o If the thermostat is set back at any times (night or day), does the system recover in a timely manner? Do you have a sense of how long this takes?
59. On a scale of 1-5, 1 being very dissatisfied and 5 being very satisfied, how would you rate your overall experience with this system?
60. Would you recommend this type of system to others?
    o Why or why not?

Phase II Participants:

The following questions will be asked in person or on the phone by Rebecca Olson, project manager. This way, we can clarify any confusing questions and take more elaborate answers than if we sent it via email or survey tool.

61. What motivated you to participate in this research project and to install a high-efficiency condensing boiler?
62. Did you have any expectations about the performance of this new equipment?
63. Have you had any issues with the installation or performance of the system?
64. What, if any, maintenance activities did you do for your old boiler?
    o Are these different than your plan for your new system?
65. Have you noticed a reduction in energy bills since installing the condensing boiler?
66. Do you do anything other than adjust your thermostat to change operation of the boiler? Set-back?
67. What are your thermostat set points?
68. On a scale of 1-5, 1 being very uncomfortable and 5 being very comfortable, how would you rate you/your family's comfort in the home?
    o Did your comfort level improve, stay the same or get worse, with the condensing boiler vs. the non-condensing boiler (if applicable)?
    o If the thermostat is set back at any times (night or day), does the system recover in a timely manner? Do you have a sense of how long this takes?
69. On a scale of 1-5, 1 being very dissatisfied and 5 being very satisfied, how would you rate your overall experience with this system?
70. Would you recommend this type of system to others?
    o Why or why not?

Appendix B: Tune-up and Quality Installation Guides

Quality Maintenance Retrocommissioning Guides

This project showed that a detailed retrocommissioning (RCx) or optimization process was not necessary to achieve the desired performance and savings from a condensing boiler. However, a detailed retrocommissioning process will achieve some level of additional savings. As such, this appendix provides two separate guides. The Basic RCx guide focuses on some simple steps to achieve the desired performance. The Advanced RCx guide lists the more detailed optimization process followed in this project.

Basic

1. Ensure that outdoor reset installation location is within manufacturer specifications
   a. Optimal outdoor temperature sensor location will depend on sensor type and sensor shielding. It is important to consult the documentation for specific sensors, installation requirements may contain items such as: locate outdoor sensor on the north wall, limit exposure to direct sunlight, avoid placing sensor in close proximity of heat sources, prevent sensor from being covered by snow, etc. Most boiler installation manuals or subliminal documentation provide these requirements (Navien 2017; Weil-McLain 2011).
2. Check supply water temperature versus outdoor air temperature reset curve settings
   a. Check for manufacturer recommended temperatures based on emitter type (see example in Table 16
      1. Use the correct curve for emitter type
      2. Do NOT use factory default

Table 16. Example outdoor reset control temperatures from a condensing Navien boiler(Navien 2017)

Emitter Type	Max Supply Setting	Min Supply Setting
Finned Tube Baseboard (default)	180 ^{o}F	120 ^{o}F
Fan Coil	180 ^{o}F	140 ^{o}F
Cast Iron baseboard	170 ^{o}F	100 ^{o}F
Low Mass Radiant	140 ^{o}F	80 ^{o}F
High Mass Radiant	120 ^{o}F	80 ^{o}F
Radiators	170 ^{o}F	120 ^{o}F
Custom	180 ^{o}F	104 ^{o}F

   b. Change design heating temperature to the correct number for your location (Table 17)

**Table 17. Heating design temperatures for Minnesota (ASHRAE 2017)**

City	Heating Design Temperature (°F)
Anoka	-9
Duluth	-17
Mankato	-12
Minneapolis/St Paul	-11
St. Cloud	-17

3. Check flow rates, if practical.

Advanced Tune-up

71. Calculate household heating load
    o Using ACCA Manual J
    o Using utility bill analysis (for sample methodology see Agnew and Goldberg 2013)
72. Calculate emitter capacity (methodology in Appendix C)
73. Adjust the set points on the outdoor reset curve to meet ideal operating conditions (Figure 19)
    o For the coldest day setting (red circle in Figure 19)
        ▪ Determine the homes heating load at the design heating temperature
        ▪ Compare that design load to the emitter capacity and determine the water temperature necessary to deliver the necessary capacity
        ▪ Adjust the boiler reset curve to meet these calculations with the design heating temperature as the coldest day reset parameter, and the necessary emitter water temperature as the max water temperature reset parameter
    o For the warmest day setting (green circle in Figure 19)
        ▪ Set warmest day reset parameter to 60 °F.
        ▪ Set the minimum boiler supply temperature to the boiler recommended min. or 100°F.

Figure 19. Figures and relationships used to relate emitter capacity, house load and outdoor reset curve
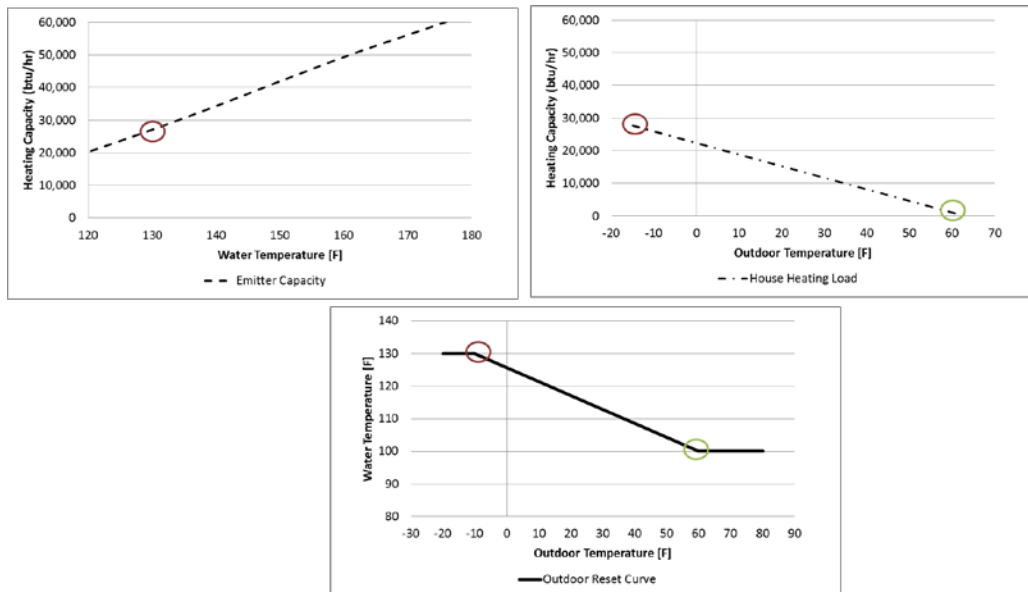
74. Indirect tank water heating
    o Set supply water temperature and DHW flow rate so that delivered capacity is at least 40,000 Btu/hr and the supply temperature is minimized
        ▪ Use indirect heat exchange characteristics, if available
        ▪ If there are no equipment characteristics, estimate delivered capacity by forcing the DHW system to reheat and counting the energy consumption on the gas meter.

Quality Installation Guide

75. Follow ACCA Manual J and S equipment sizing and selection guidelines
76. Install outdoor reset control in a location recommended by manufacturer
    o Optimal outdoor temperature sensor location will depend on sensor type and sensor shielding. It is important to consult the documentation for specific sensors, installation requirements may contain items such as: locate outdoor sensor on the north wall, limit exposure to direct sunlight, avoid placing sensor in close proximity of heat sources, prevent sensor from being covered by snow, etc. Most boiler installation manuals or subliminal documentation provide these requirements (Navien 2017; Weil-McLain 2011).
77. Follow manufacturer recommended specifications, including:
    o Outdoor reset conditions for supply water temperature based on emitter type
        ▪ If none are provided, use Table 16
    o Design heating temperature setting of the outdoor reset to reflect the design conditions for the location of the installation (see Table 17).
    o Space heating recirculation flow rates
78. For systems with DHW loops

- Internal DHW systems, including small internal tanks and low or no-mass heat exchangers:
  - Follow manufacturer specifications
  - Minimize recirculation temperatures where possible
  - Reduce supply DHW set point to minimum possible. Do not reduce below 120 F, to prevent issues related to water borne pathogens
- For indirect tanks:
  - Reduce return water temperature
    - Set supply water temperature and DHW flow rate so that delivered capacity is at least 40,000 Btu/hr and the supply temperature is minimized
      - Use indirect heat exchange characteristics, if available
      - If there are no equipment characteristics, estimate delivered capacity by forcing the DHW system to reheat and counting the energy consumption on the gas meter.
    - Oversize indirect DHW heat exchanger, where possible
    - Install single-wall tank where code allows

Appendix C: Emitter Capacity Calculations

Emitter capacity calculations need to be made in order to adjust the outdoor resect curve for the Advanced RCx tune-up guide for condensing boilers. The methodology for this tune-up is described in Appendix B. The outdoor reset curve settings are used by the boiler to determine the supply water temperature at any given outdoor air temperature. The boiler performance is optimized by selecting the minimum supply water temperature necessary to achieve the heating load of the home at that outdoor temperature. Characterizing the delivered capacity of a home's emitters at various water temperatures will ensure that the heating load can be met, while minimizing the system supply water temperature.

The emitter characterization process can be broken down into the following steps:

1. Identify the type of each individual emitter.

2. Measure the size and record the defining characteristics of each emitter

3. Look up the capacities of each emitter based on type and size. When possible, manufacturer specifications for specific emitters should be used. Manufacturer specifications will not be available for many (especially older) emitters. In these cases, industry rules-of-thumb or standard values should be used.

Emitter Capacity Examples and Standard Values

Many of the most common emitter types have standard capacity information available. This section will discuss examples and standard values for common emitter types. This information can be used as a starting place if no emitter specific data is available.
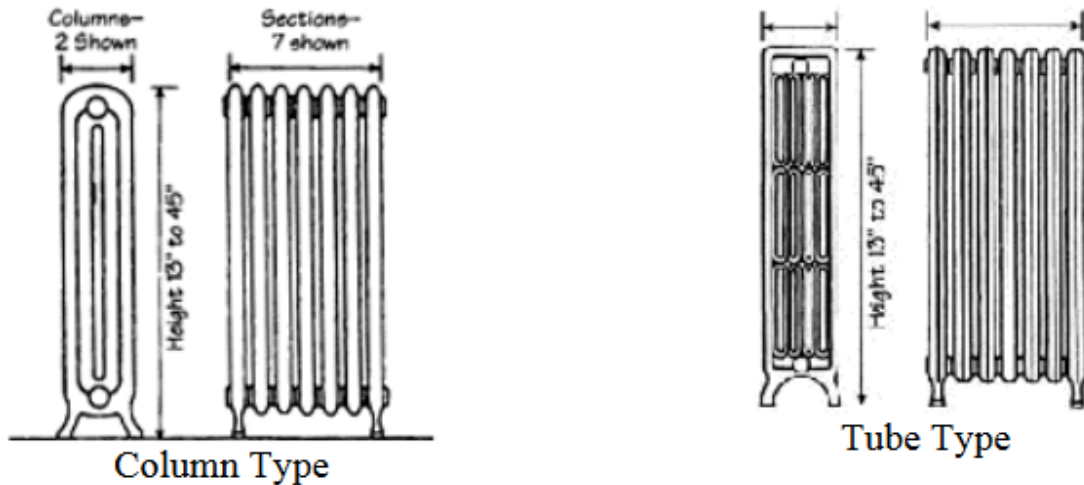
Cast Iron Radiators

According to interviewed HVAC contractors as well as CEE's staff observations over 30 years, cast iron radiators are the most common emitter type discovered in Minneapolis and St Paul metro area homes. There are a few different types of cast iron radiators and many available resources for estimating the heat emission capacity. This example looks at data from Columbia Heating Products ((Columbia Heating Products Company 2014)), but many other sources exist and provide similar information and estimates ((Burham by US Boiler Company 2013; Stelrad 2014)). The process for calculating the radiator capacity has several steps.

Radiator Type

There are two main types of Cast iron radiators. These are column type and tube (or slenderized) type (Figure 20). There is a third type of cast iron radiator, a wall type, but these are uncommon in Minnesota and none were observed in this project. The radiator's capacity is estimated by the temperature of the

ambient surrounding air, which can be assumed to be 70°F; the temperature of the water flowing through the radiator that determines the radiator's surface temperature; and the surface area of the radiator. Using a multiple step process, the capacity can be estimated through simple measurements and look up tables.

Figure 20. Images of the two main types of cast iron raditors.

The first step is to determine the type of radiator. Traditional cast iron radiators are made up of columns or tubes and sections. When standing in front of a radiator and facing the wall the iron slices are the radiator sections. The sections make up the slices in the "loaf of bread" of the radiator. When looking at the narrow end of the radiator, the tubes or columns that make up each section are visible. The vertical slices, or sections, are made of one or more vertical tubes or columns. Very old radiators typically have larger columns about 2.5 inches wide. More recent radiators were made from cast iron pipes about 1.5 inches wide, these are the tube type. Column type radiators, also referred to as classic radiators, may have a number of columns, typically between two and five. Figure 21 shows a 2 column unit, and Figure 22 shows a three column version. Tube radiators included in this project typically had between four and six tubes. Figure 23 shows a six tube radiator.

Figure 21. Two column cast iron radiator

Figure 22. Three column cast iron radiator

Figure 23. Tube style radiator, also called slenderized radiators

The second step in estimating the capacity is to measure the height in inches and count the number of sections and tubes/columns of the radiator.

The radiator surface area can now be determined using the type and size. The radiator surface area is expressed in square feet of "Equivalent Direct Radiation (EDR)" as directly measuring the surface area of the irregularly shaped radiators would be very time consuming. Table 18 can be used to look up the EDR square footage per section for these radiators based on the number of tubes or columns. Then multiplying the section EDR by the total number of sections will determine the total EDR square footage for each radiator.

Table 18. EDR per section for tradiational radiators, based on the height and number of tubes or columns of the radiator

	13"	16"	18"	20"	22"	23"	26"	30"	32"	36"	38"	45"
3 Tubes	-	-	-	1.72	-	2.00	2.33	3.00	-	3.50	3.50	-
4 Tubes	-	-	-	2.25	-	2.50	2.75	-	3.50	4.25	-	-
5 Tubes	-	-	-	2.67	-	3.00	3.50	4.33	4.33	5.00	6.00	-
6 Tubes	-	-	-	3.00	-	3.50	4.00	-	5.00	-	-	-
7 Tubes	2.60	3.50	-	4.20	-	-	4.75	-	-	-	-	-
1 column	-	-	-	1.50	-	1.67	2.00	-	2.50	-	3.00	-
2 cols	-	-	-	2.00	-	2.33	2.67	-	3.33	-	4.00	5.00
3 cols	-	-	2.25	-	3.00	-	3.75	-	4.50	-	5.00	6.00
4 cols	-	-	3.00	-	1.00	-	5.00	-	6.50	-	8.00	10.00
5 cols	3.00	3.75	4.50	5.00	-	6.30	7.00	-	8.50	-	10.00	-

Heat transfer calculations have been used to determine the relationship between room temperature, water temperature, surface area, and the radiators capacity. The calculations have been used to create charts and look up tables. Figure 24 shows this relationship and can be used with the radiator measurements to determine the total energy output over a range of water temperatures. Table 19 shows an example of emitter output calculated for Exist_3, one of the sites in this project.

Figure 24 . Traditional radiator capacity at 70˚F room temperature
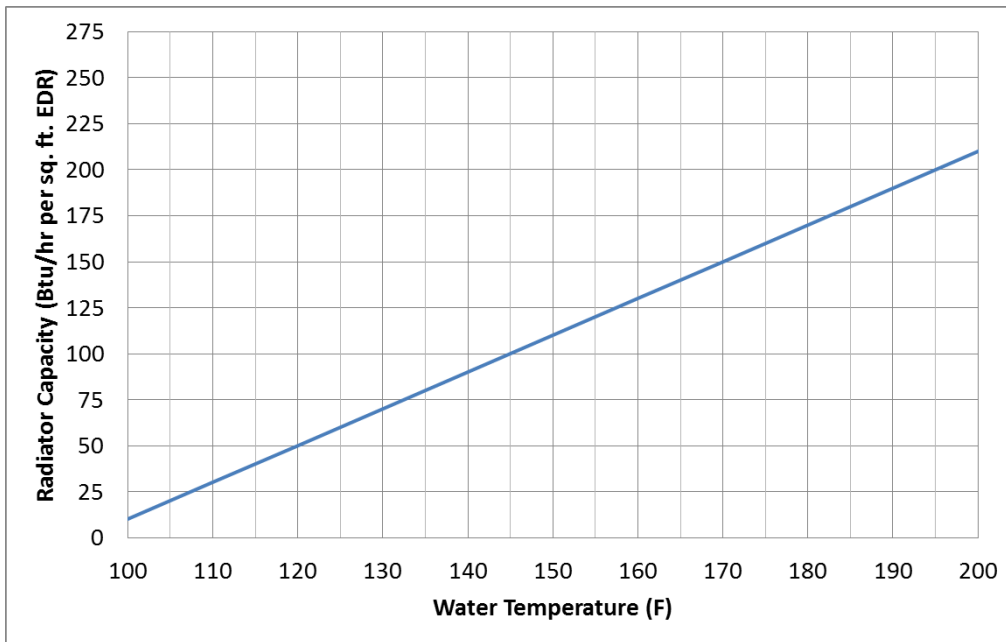
Table 19. Emitter capacities at site exist_3 based on this calculation process

location	height (in.)	Column or Tube	No. Col. or tubes	No. Sections	EDR per section	Total EDR	Output at 180F	Output at 140F
Dining	22	Column	2	16	2.22	35.52	6,038	3,197
living	22	Column	2	16	2.22	35.52	6,038	3,197
kitchen	38	Column	2	10	4	40	6,800	3,600
bedroom 1	38	Column	2	12	4	48	8,160	4,320
bedroom 2	38	Column	2	12	4	48	8,160	4,320
bathroom	38	Column	2	10	4	40	6,800	3,600

Hydronic Baseboard

Hydronic baseboard capacity is dependent on water flow rate, water temperature and emitter design. In a process similar to that for cast iron radiators, capacity estimation has multiple steps.

1. Determine the type of baseboard. The main design considerations are the number of pipe passes, the type and size of pipe, and the fin style.

2. Measure the size of the baseboard in linear feet.

3. Use manufacturer specific data or industry standard to determine the capacity of the baseboard over a range of operational characteristics. Table 20 shows the capacities for a single pipe baseboard radiator with fins.

Table 20. Capacity ratings for residential single-pipe and fin baseboard

Water flowrate	Delivered capacity (btu/hr-linear foot) based on hot water temperature (^{o}F)							
	110°F	120°F	130°F	140°F	150°F	160°F	170°F	180°F
1 GPM	160	210	260	320	380	450	510	580
4 GPM	170	220	270	340	400	480	540	610

Modern Radiators

Modern panel radiators no longer conform to typical styles and types. This makes standard rules of thumb or calculation methodologies difficult. However, these modern systems are much more likely to be stamped with manufacturer and model information. As building science has gotten more specific and advanced over time, the sizing and design of these systems has become more sophisticated. As such manufacturers provide detailed specifications for individual radiators. Figure 25 shows an example of one model of panel radiator.

Figure 25. Manufacturer specifications for a modern radiator panel (Bosch Thermotechnology Corp 2010)

Dimensions (H x W x D)	BTU @ 180° F
12" x 24" x 2½"	1,970
12" x 36" x 2½"	2,960
12" x 48" x 2½"	3,950
12" x 59" x 2½"	4,940
12" x 71" x 2½"	5,920
20" x 24" x 2½"	2,920
20" x 36" x 2½"	4,380
20" x 48" x 2½"	5,840
20" x 59" x 2½"	7,300
20" x 71" x 2½"	8,750
24" x 24" x 2½"	3,370
24" x 36" x 2½"	5,060
24" x 48" x 2½"	6,740
24" x 59" x 2½"	8,420
24" x 71" x 2½"	10,110

Household Emitter Capacity

Once the individual capacity of each radiator is determined over a range of water temperatures, the capacity of the entire house can be analyzed. This can be calculated by adding each radiator capacity together at a given water temperature. During the advanced RCx tune-up (Appendix B), these capacities will be compared with a home's heating load to determine the optimized outdoor reset conditions. Figure 26 and Figure 27 show the individual emitter capacities and the total house capacity over a range of operating temperatures for the Exist_7 site.

Figure 26. Individual emitter capacities at site Exist_7 over a range of water temperatures
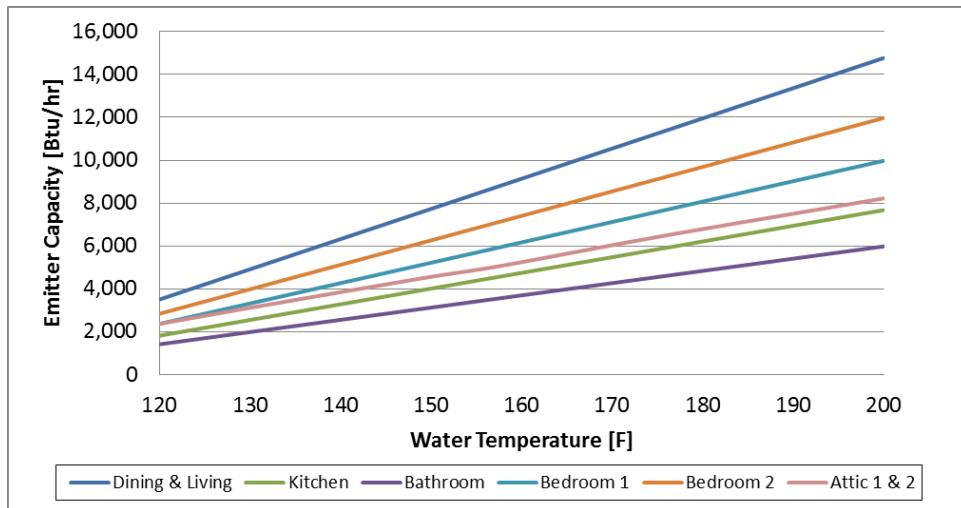
Figure 27. Total household emitter capacity at site Exist_7 over a range of water temperatures
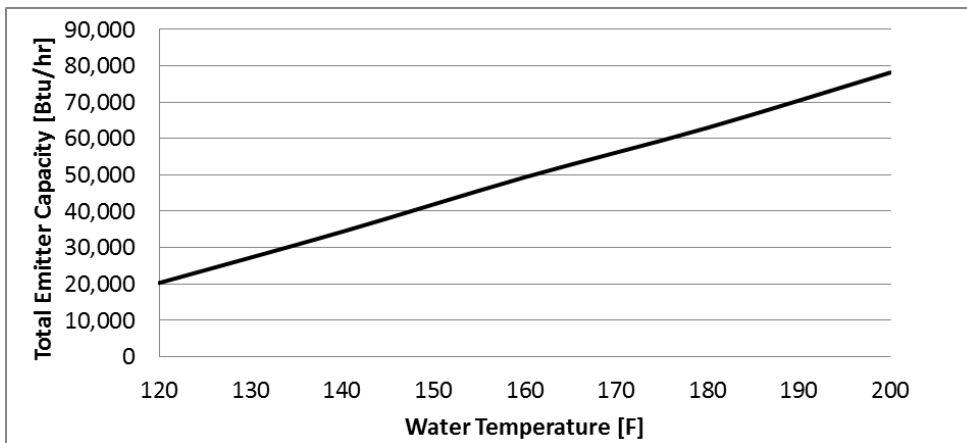
Appendix D: Detailed Discussion of Analysis

Data from both phases of the project were analyzed to determine the annual energy consumption and seasonal operating efficiency. Annual performance was compared between operation modes (as-found and optimized), between Phase I and Phase II, as well as to an estimated baseline (80% AFUE) boiler. We also compared annual energy performance, runtimes, and installed efficiencies.

For the annual energy consumption analysis we used an input/output method to compare the performance of the systems and modes of operation. CEE used this method in previous projects to compare annual energy use and the installed efficiencies of each system (Bohac et al. 2010; Schoenbauer 2013).

The first step in data analysis was to process the measured data from each field site. The energy consumption or input to the boiler was calculated following equation (1).

$$Q_{in} = Gasmeter_{pulse} * C_{in} * HF, \tag{1}$$

Where Q_{in} was the energy consumption of the boiler, $Gasmeter_{pulse}$ was the volumetric measurement from the gas flow meter, C_{in} was a conversion constant to convert pulses from the meter to cubic feet of natural gas (typically 40 pulses was 1 cubic foot of natural gas), and HF was the heat factor of the natural gas reported by the gas utility (typically around 1020 BTU per cubic foot).

The next calculation was to calculate the real time delivered energy or output from the boiler. The output was calculated by the water flow rates and temperatures in the distribution system which characterized the energy delivered to the home as heat. Equation (2) was used for the calculation.

$$Q_{out} = C_{out} * Flow_{dist} * \left(T_{Supply} - T_{Return}\right) \tag{2}$$

In equation (2) the energy delivered by the boiler was represented as Q_{out}. C_{out} was a combination of the properties of water, the density and specific heat at the measured temperature, and a conversion constant. The water flow rate into the distribution system was represented as $Flow_{dist}$, and the boiler supply and return water temperatures from the boiler were T_{supply} and T_{return} respectively.

The energy input (equation (1)) and energy output (equation (2)) were used for the majority of the analysis performed for this project.

The household heating load was characterized from the measured data and calculated output of each boiler. Because no significant supplemental heating was present in any of the sites, the boiler output energy was the energy necessary to maintain comfort at any specific outdoor air temperature. This energy output, or the energy required to heat the conditioned space of each home, was compared on a daily basis to the outside temperature. A least squares linear regression was fit to the data at each site. This fit, or heating load maps (shown for one site in Figure 28), were used to estimate the heating requirement of the home at any specified outdoor air temperature. The heating load maps were used to characterize each home, including the heating load at design conditions and the balance point temperature where heating was no longer required. For the Twin Cities metro area, the design heating

Figure 28. Measured heating load data and the regression model for site Exist_06
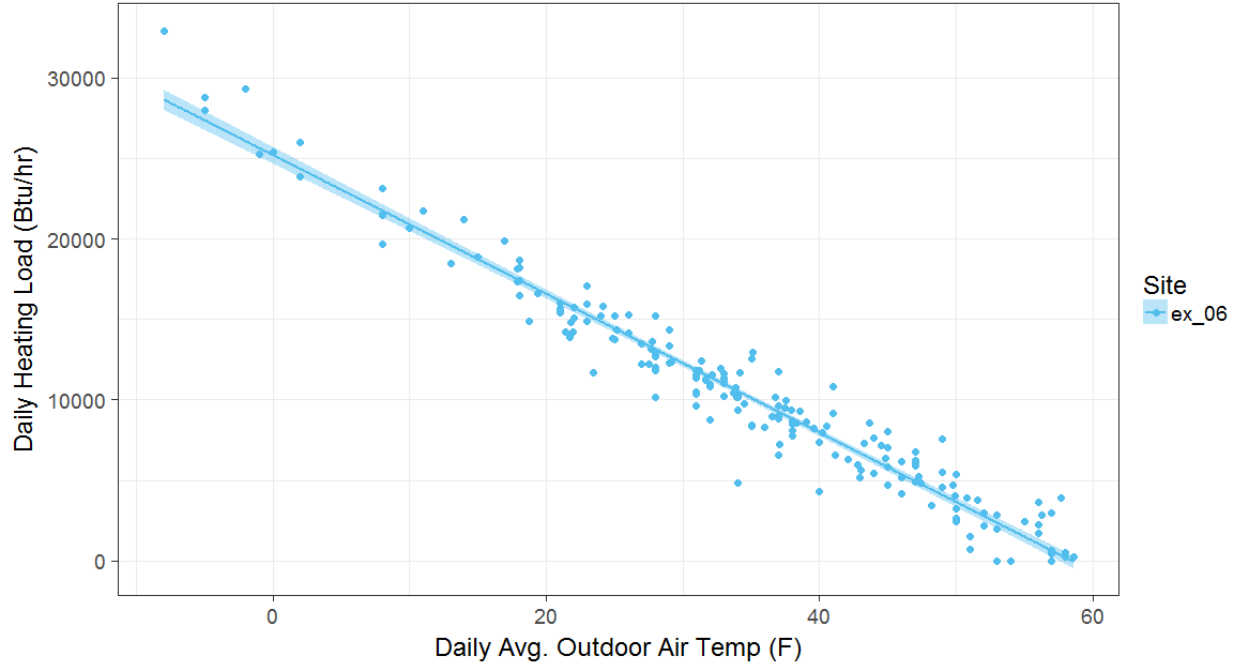
The energy input (equation 1) was then used with the energy output (equation 2) to create a field data based performance map for each boiler. This map showed the amount of energy consumption or input in natural gas required to deliver an amount of energy to the home. This relationship between boiler input and output also defined the efficiency of the system.

The boiler performance maps were created for each site. For Phase I sites, a separate performance map was created from the field data collected during each mode of operation (as-found and optimized). The quality installed sites (Phase II) had one performance map based on the QI operation for the new boiler. The daily energy consumption (input) was fit to daily energy delivered from the boiler (or output). Typically the relationship between the input and output would have been linear, but with condensing boiler performance there could be a non-linear relationship. The condensing boiler efficiency was impacted by the return water temperature and the outdoor reset of the controller changed the water temperatures in the system based on the outdoor air temperature. These changes to performance and efficiency were not necessarily linear with respect to system output, and because of these non-linear effects, a binned analysis approach was used. Daily energy delivered data was binned by 5,000 BTU intervals, and data in each bin was fit to a linear regression. Figure 29 shows the as-found boiler performance model for site Exist_06. The performance map was then used to compute the energy consumption necessary for the boiler to deliver the necessary output to heat the home.
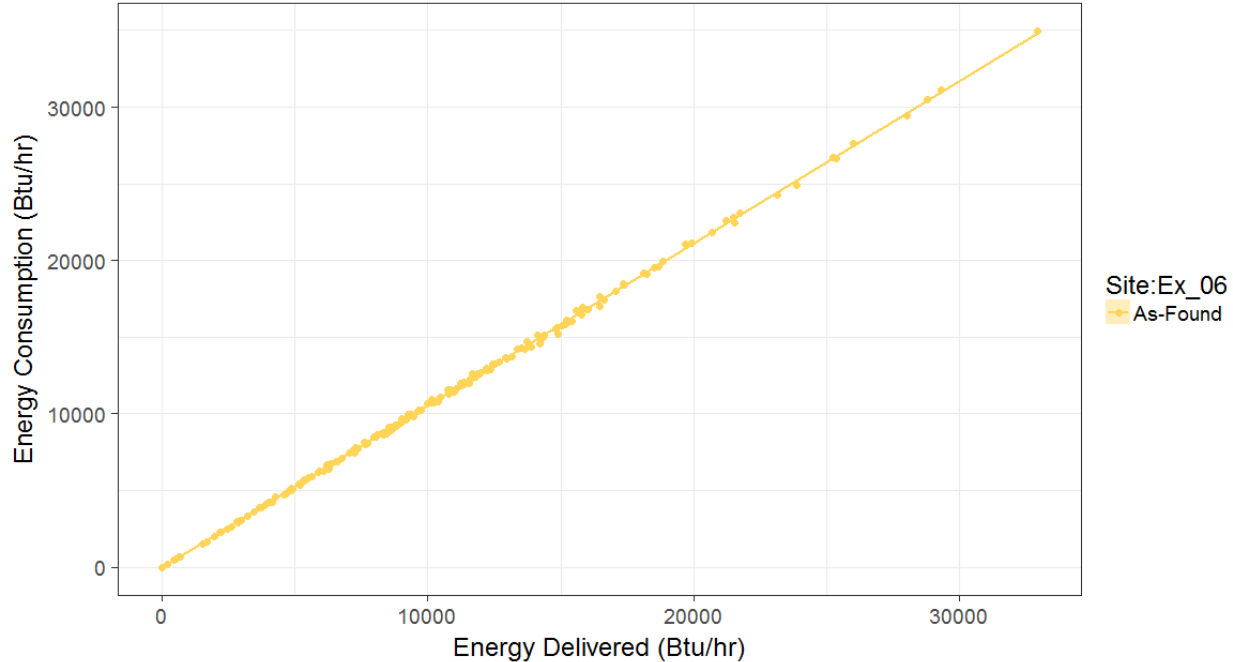
Figure 29. Boiler perfomance model for site Exist_06 as found operation

Table 21 shows the daily calculations for some days of as-found boiler operation at site Exist_6. To calculate this we took the outdoor air temperature (OAT) from the TMY3 outdoor dry-bulb air temperature at the nearest weather station and calculated the daily heating load from the OAT, the heating load data map, and equation (5). The daily heating load and the boiler performance map were then used to calculate the energy consumption (input) for each day with heating. We summed the daily energy consumption to compute the annual energy use and performed a daily analysis due to the non-linearity of the input/output boiler performance relationship.

Table 21. Example energy calculations for daily analysis at site Exist_06

Date	OAT[1] (°F)	Heating Load[2] (Btu/hr)	Energy Consumption[3] (Btu/hr)
1/1	23	15,265	16,092
1/2	23	15,265	16,092
7/10	75	0	0
7/11	75	0	0
12/30	25	14,428	15,208
12/31	26	14,009	14,766

[1] Daily OAT was taken from the TMY3 outdoor dry-bulb air temperature.

[2] The daily heating load was calculated from TMY3 OAT, the house heating load data (Figure 28), and Equation (5).

[3] The daily energy consumption was calculated from the daily heating load and the boiler performance map (Figure 29)

Additional analyses included evaluation of system performane by heating cycle, and analysis of actual install efficiency. The high resolution data collection method allowed for data to be processed so that each individual heating cycle could be analyzed. We used this analysis to refine the retrocommisioning tune up and quality installation checklists, and to deterime the impacts of various factors (runtime, water temperature, outdoor air temperature, firing rate, etc.) on cycle efficiency.