



Improving Installation and Maintenance Practices for Minnesota Residential Furnaces, Air Conditioners and Heat Pumps

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Executive Summary

This report summarizes a study intended to look at savings potential and program strategies associated with quality installation and maintenance of residential central air conditioners, air-source heat pumps and natural-gas furnaces in Minnesota. The study included market research activities as well as field research into savings from adjustments to both new and older systems to improve their operating efficiency. To carry out the study, interviews were conducted with residential heating contractors, distributors of residential equipment, utilities and other stakeholders; a telephone survey of more than 700 homeowners was implemented; field tests were made on more than 100 residential systems; and, the operation of nearly 60 central heating and cooling systems was monitored for about a year.

Key findings:

- Program activity related to quality installation and maintenance of central heating and cooling systems is largely focused on quality installation of *new* high-efficiency air conditioners and heat pumps. Incentives for proper installation of standard efficiency equipment and maintenance for existing systems are not particularly attractive to contractors (Page 8).
- Consumers shop for new heating and cooling systems mainly on the basis of price and reputation, and have little awareness of—or concerns about—installation issues that affect the performance of the systems they purchase (Page 22).
- Professional service calls for heating and cooling systems are surprisingly common: more than half of surveyed households report having their heating and/or cooling system serviced in the last five years. About one in every four households has a service contract for annual maintenance of their system (Page 18).
- Field testing reveals that more than nine out of ten air conditioners and heat pumps have an installation or maintenance issue that, when corrected, would improve the operating efficiency of the system. Measurements suggest that the average improvement in efficiency from addressing these opportunities is 12 ± 3 percent; however, this represents a blend of many systems with minor improvement opportunities and about one in six systems with a potential performance improvement of 25 percent or more (Page 27).
- For systems in climates similar to the Twin Cities area, the average savings potential for addressing installation and maintenance issues with central cooling systems is about 100 ± 30 kWh per year in seasonal electricity consumption, and about 185 ± 40 watts' worth of diversified peak demand reduction. (Page 35 and Page 38).
- Most of the improvement opportunities in cooling systems are related to refrigerant charge and airflow adjustments. Routine maintenance activities such as filter replacement and coil cleaning account for about 20 percent of the savings potential (Page 30).

- The average Minnesota air conditioner or heat pump in climates similar to the Twin Cities area operates for 340 ± 70 hours per year, and uses 800 ± 175 kWh. These estimates include the fact that households do not always operate their air conditioners on warm summer days, which reduces seasonal energy consumption by about 20 percent compared to what it would be if all households left their thermostats set in cooling mode for the entire summer.
- On a typical hot weekday afternoon and early evening in the summer, about a quarter of all Minnesota central cooling systems are running flat out, half are cycling on and off, and a quarter are not operating at all (Page 35).
- Air conditioners in new homes appear to run about 50 percent more hours and use nearly 70 percent more energy on average than air conditioners in older homes. The higher energy consumption is mainly due to the fact that new homes are, on average, larger and have bigger cooling systems than older homes. The higher operating hours may reflect the fact that new homes are less likely to be shaded, or may simply indicate a greater propensity for occupants of new homes to use their cooling systems (Page 38).
- The savings potential related to installation and maintenance of natural gas furnaces appears to be limited. Most new and existing furnaces are high-efficiency, condensing units with little to adjust, and all of those tested in this project were operating in condensing mode when tested. Manifold-pressure (which affects firing rate) was the most frequent adjustment, at about a 25 percent incidence rate. No statistically significant improvement in combustion efficiency was observed for adjusted systems (Page 40).
- The average single-stage gas furnace in a Minnesota home operates for 900 ± 100 hours per year, and consumes 670 ± 80 therms of gas. Multi-stage and modulating furnaces operate for about 50 percent more hours than single-stage furnaces on average, albeit at lower input rates (Page 48).
- Air-source heat pumps appear to have the same incidence of opportunities for refrigerant-charge, airflow adjustment, coil cleaning and filter change as central air conditioners. All ten of the heat pumps encountered in this study used a fuel-fired heating system as back-up in cold weather. One of the five systems monitored over the course of a year had a significant number of days where the unit operated in both heating and cooling mode on the same day, suggesting that there may be savings potential from better control and operation of these systems (Page 48).
- Nearly half of households practice continuous air circulation at some point during the year; some only because their installer recommended it (Page 49).
- Measurement of system airflow by different methods do not always agree. (Page 52)

Recommendations (Page 55):

- Utilities should maintain installation standards for central cooling systems that are eligible for high-efficiency incentives. However, these represent only about five percent of annual installation and service visits.
- To address the much larger market of service calls to existing systems and installations of new standard-efficiency systems, utilities could consider an enhanced program based on recent advances in the capabilities of diagnostic equipment to supplement current program offerings. These advances could form the basis for a cloud-based “instant-incentive” program for contractors who invest in this equipment and use it in Minnesota homes. This model could dramatically reduce contractor transaction costs for meeting utility program requirements – thereby facilitating wider participation – and would work best if it were offered statewide or at least as a coordinated regional effort among multiple utilities. Any such effort should be piloted first.
- Utilities could do more to engage with Minnesota HVAC equipment distributors, whose interests intersect with those of the utilities in key ways. A tighter partnership with distributors could be especially fruitful if an enhanced program model involving advanced diagnostic equipment is implemented.
- Utility quality-installation and -maintenance programs related to central cooling systems should focus on refrigerant-charge and airflow adjustment, as these represent the majority of the potential savings. Additional contractor training and guidance related to measuring system airflow may be needed, and additional research on appropriate approaches to measuring airflow would be helpful.
- Utilities could do more to promote contractors who use good installation and maintenance practices, and to raise public awareness that improper installation of central cooling systems can be an issue.

Introduction

This report summarizes the findings of market and field research on savings opportunities from improving the installation and maintenance practices for residential central air conditioners, air-source heat pumps and forced-air furnaces. All of these pieces of equipment share the characteristic that they are custom-installed in each home, and require certain adjustments in order to achieve their top efficiency. Past research (which we discuss later in this report) has shown that these adjustments are not always performed, resulting in sub-par system performance. In addition, if the systems are not properly maintained, their performance may degrade over time.

The primary objective of this project is to provide insight and tools to increase the effectiveness of utility Conservation Improvement Program (CIP) efforts related to proper installation and maintenance of these systems. We tackle this objective through the following activities:

- a review of the literature on installation and maintenance practices for central residential heating and cooling systems;
- a review of programs in Minnesota and elsewhere for encouraging quality installation and maintenance of central heating and cooling systems;
- interviews with Minnesota heating and cooling contractors, equipment distributors and others to better understand current technology and practices;
- a survey of Minnesota homeowners to gain insight into operating and maintenance practices, satisfaction with their heating and cooling equipment, and decision-making related to purchase of new systems; and,
- field testing of a variety of systems in Minnesota homes to better understand the potential savings from improved installation and maintenance practices.

Throughout this report we assume some basic familiarity with how furnaces, central air conditioners and air-source heat pumps work. Readers who are unfamiliar with this equipment (or who want a quick refresher) are encourage to read [Appendix A](#), which provides a primer on the subject.

Background

Literature on Savings from Quality Installation and maintenance

Residential furnaces, central air conditioners and heat pumps are unlike other appliances that consumers purchase. For one, they are typically responsible for the greatest share of energy bills in the home. In addition, unlike, say, a refrigerator, which just needs to be plugged in to start working as intended by the manufacturer, these systems require installation adjustments that vary from home to home in order to operate at peak efficiency. Two key examples of this are refrigerant charge and airflow (often referred to in shorthand as simply RCA). The amount of refrigerant needed for a cooling system varies with the distance between the indoor and outdoor coils, which itself varies from home to home. Similarly, differences in duct sizing and layout affect the blower speed settings needed to achieve proper system airflow and depend on the nature of the duct system to which the equipment is attached.

Moreover, to perform as intended, filters and coils need to be kept clean, creating a maintenance requirement that homeowners may or may not meet.

Evidence for the impact of improper installation on the performance of air conditioners and heat pumps dates back to the early 1990s. One early laboratory experiment showed that refrigerant charge errors can significantly affect system efficiency, depending on the type of expansion device used (Farzad and O'Neal, 1993). Around the same time, evidence began to emerge from the field that many systems were in fact sized and installed sub-optimally (e.g. Blasnik, 1995; Xenergy, 2001). A widely-cited 1999 report estimated that improved installation practices could save 24 percent in existing homes and 35 percent in new homes nationally (Neme et al., 1999).

Findings such as these led to the first utility programs to address quality installation and maintenance of residential HVAC systems, focusing primarily on cooling systems in hot-dry parts of the country, particularly southern California. While these programs indeed showed a high incidence of systems requiring adjustments (Downey and Proctor, 2002), Hunt et al. (2010) report that by the mid to late 2000s, evaluations of these large California programs had raised questions about their impact and cost effectiveness – though not without controversy surrounding the evaluations themselves. As Hunt et al. state,

“It's unclear whether the current programs' disappointing results were due to ineffective program design, overly optimistic projections, or inaccurate pre- and/or post-implementation evaluation techniques. What is clear is that the DSM industry needs a sound strategy for designing programs and evaluating their effectiveness.”

Interestingly, Hunt et al. (see also Heinemeier, 2012), point out that instrument uncertainty associated with measuring refrigerant line temperatures and pressures are high enough that technicians may typically be doing no better than a coin flip in terms of the chances of leaving a system properly charged.

In the late 2000s, utilities in other parts of the country began to show interest in quality-installation and maintenance programs. We (Seventhwave, then the Energy Center of

Wisconsin) undertook a field study of installation quality and savings opportunities for central air conditioners in Wisconsin on behalf of the statewide energy efficiency program administrator (Pigg, 2008). Among other things, that study estimated the efficiency improvement from proper installation of new systems and tune-ups of older systems at 5±4 percent. In the Northeast, Wirtschafter et al. used simulations to analyze the likely impact of installation issues on air conditioners in New England, and concluded that programs targeting quality installation could only be justified if systems have excess cooling capacity at system peak, because peak demand reductions were needed to make the effort cost effective (Wirtschafter et al., 2007).

These studies demonstrated that regional differences need to be accounted for in estimating the potential for correcting installation defects. For example, while the prior hot-climate field research revealed that *low* system airflow was a common problem, the Wisconsin study showed that *high* airflow was more likely in that state. This is most likely a result of the fact that in cold climates, homes tend to have larger-capacity furnaces (with bigger blowers) paired with smaller-capacity air conditioners, which is the reverse of the situation in hot climates. Similarly, duct sealing – which is often lumped into estimates of quality-installation savings potential – has been shown to have significant savings potential in warm climates where slab-on-grade construction forces ductwork and air handlers into unconditioned attics, but much less potential in cold climates like Minnesota’s where most ductwork runs inside the thermal envelope of the building.

Moreover, products have changed over time in ways that affect the savings potential from proper installation. In particular, the federal Seasonal Energy Efficiency Ratio (SEER) 13 standard that came into force in 2006 appears to have dramatically increased the share of equipment with thermostatic expansion valves, which have been shown to be able to compensate for moderate refrigerant charge errors (Farzad & O’Neal, 1993; Pigg, 2008; Kim and Braun, 2010). Similarly, Domanski et al. (2014) argue that federal efficiency standards and test procedures have prompted manufacturers to reduce cycling losses to the point that oversizing no longer carries the same energy penalty for air conditioners and heat pumps that it once did. Indeed, Sonne et al. (2006) saw mixed results from an experiment involving air conditioners in four Florida homes in which oversized units were replaced with properly-sized (but otherwise identical) equipment. We conducted a similar experiment around the same time in two Wisconsin homes, and saw no difference in energy consumption (Pigg, 2008).

Another notable market trend has been the introduction – and increasing market share – of high-end, variable-speed furnaces, particularly in northern climates like Minnesota’s. An important feature of these units is that they are not only capable of a much wider airflow range than traditional furnaces, but many can dynamically sense and maintain desired airflow. In theory, these units should be less likely to show airflow issues than standard furnaces. Nonetheless, in our 2008 study, we found no difference in the proportion of variable-speed versus standard furnaces with proper airflow in cooling mode (Pigg, 2008), suggesting that contractor attention to installation settings is still important even for advanced units.

Technology advances may also be helping ease the time and hassle associated with diagnosing and correcting refrigerant and airflow issues with cooling systems. Sophisticated gauge sets can automatically store (and even transmit) measurements, as well as diagnose issues and provide

suggested solutions (Murphy, 2016).¹ There have been recent efforts to introduce this technology in the context of quality installation and maintenance programs (Meisegeier, 2016).

Nationally, most of the attention and research has been devoted to performance issues related to air conditioners and heat pumps, and little is devoted to the potential for proper installation and maintenance of gas furnaces. However, some recent work has been conducted in the Midwest in this regard. Brand et al. (2013) looked at the efficiency of nine furnaces in Iowa that were replaced at end of life, and found no reduction from their rated efficiency when tested in the same manner as federal test procedure for Annual Fuel Utilization Efficiency (AFUE) ratings, suggesting that once a furnace is installed, there is little propensity for performance degradation over time. Brand and Rose (2012) tested three furnaces in a laboratory setting and concluded that furnace efficiency is insensitive to oversizing for high-efficiency equipment.

The testing reported by Brand and Rose also demonstrate how temperature rise – which is the difference between supply- and return-air temperatures affects gas efficiency. At an expert’s meeting in 2012, one manufacturer’s representative stated that gas efficiency increases about 1 percentage point for every 15F decrease in temperature rise (Brand, 2012b). Since most furnaces have a nameplate temperature rise range of about 30F, this suggests that there can be a 2 percentage point swing in gas efficiency across the nameplate temperature-rise range, and possibly more for furnaces that are improperly installed and have temperature rise outside the nameplate range.

In that vein, Yee et al. (2013) used as-found test data for 48 gas furnaces in Iowa to estimate that on average the units were failing to deliver about 9 percent of heating energy that they were rated for. The primary cause was listed as low airflow due to overly restrictive return ductwork and filters. This estimate is considerably higher than the above analysis would suggest, and would imply that many systems operate at very low airflow in heating mode. Some of the discrepancy may be attributable to the fact that the estimates were based on field-measurements of system temperature rise, which has been demonstrated to be an imperfect indicator of system output (Francisco, 2003).

These sources also generally demonstrate the somewhat complex relationship between heating-mode airflow, gas efficiency, furnace electricity consumption and comfort, which can be summarized thusly: as system airflow is increased, gas efficiency increases, but blower electricity consumption also increases and the delivered air temperature decreases. An effort to maximize gas efficiency by taking a furnace to the bottom of the temperature-rise range thus has the downside consequence of higher furnace electricity consumption and possibly adverse occupant comfort because the unit delivers air that feels cool.

Overall, the current body of literature shows a wide range of estimates for the savings potential from proper installation and maintenance of furnaces, central air conditioners and heat pumps, and highlights the importance of grounding these estimates in the appropriate housing stock and HVAC equipment of interest.

¹ See, for example, imanifold.com

Quality Installation and Maintenance Programs in Minnesota and Elsewhere

We reviewed Minnesota's utility programs as well as some in other parts of the country in order to characterize the program offerings and to note their differences.

Minnesota Programs

Minnesota utility programs related to quality-installation or maintenance of residential heating and cooling systems can be placed into three categories:

- **Incentives for tune-ups of existing equipment** – Incentives for tune-ups of existing heating and cooling systems are generally in the range of \$25 to \$30. Utilities require the tune-up to be done by a licensed contractor, but do not require additional contractor certification. These incentives are limited to Minnesota's two largest gas-only utilities and some municipal and co-op utilities, and tune-up incentives are the only type of quality installation/maintenance program offerings for gas furnaces in Minnesota.
- **Incentives for quality-installation of new standard-efficiency systems** – Xcel Energy, Minnesota Power and some co-op and municipal utilities in the state offer an incentive for contractors to document proper installation of standard efficiency (SEER 13) cooling systems. These incentives are typically in the range of \$30 to \$50 for air conditioners, and require the installing contractor to be certified with the utility for this work.
- **Quality-installation requirements for rebates on high-efficiency equipment** – Xcel Energy, Minnesota Power, the Great River Co-ops and some municipal utilities in Minnesota require that quality-installation protocols be followed in order to receive incentives for installing a high-efficiency air conditioner or air-source heat pump. Depending on the type and efficiency level of the equipment involved, these incentives can be for several hundred dollars or more.

Table 1 summarizes utility program offerings related to quality-installation and maintenance of residential heating and cooling systems.

Table 1. Minnesota utility incentives for quality installation or maintenance.

Utility		Incentive for tune-up of existing system?	Incentives for quality installation of standard efficiency system?	Quality installation required for high-efficiency system incentives?
Xcel Energy	Elec/Gas	No	Yes*	Yes*
Centerpoint Energy	Gas	Yes	No	No
Great River Co-ops	Elec	Some	Some	Yes
Minnesota Power	Elec	No	Yes	Yes
Minnesota Energy Resources	Gas	Yes	No	No
Ottertail Power	Elec	No	No	No
Municipals	Elec	Some	Some	Some

*for central air conditioners and heat pumps only; not offered for furnaces

Xcel Energy and Great River have coordinated contractor certification requirements for contractors who wish to participate in their quality installation programs. Training and certification to meet this requirement are delivered by HVACRedu.net. Together these utilities list about 1,100 certified contractors. Minnesota Power has a similar, but separately administered, requirement.

Contractors claiming quality installation and maintenance incentives are generally required to provide paper documentation of key installation parameters, such as the results of superheat or subcooling tests for refrigerant charge. Xcel Energy subjects a sample of these applications to third-party desk review, but to our knowledge, no Minnesota utilities conduct field quality-control activities.

Based on standard methodologies set forth by the State of Minnesota, utilities may claim 29 percent energy savings for quality installation of new central air conditioners or heat pumps in existing homes and 33 percent for quality installation activities in new homes (TRM, 2015).² These values include proper sizing and addressing duct leakage. Energy savings for tune-ups of existing systems are assumed to be two percent for furnaces and five percent for central air conditioners and heat pumps.

² These values are based on the assumption that improper installation reduces system efficiency by an average 25 percent, compared to 3.75 percent loss associated with proper installation of equipment in existing homes and zero percent loss in new homes. Annual energy and peak demand impacts depend on the size and efficiency level of the unit being installed, as well as the climate zone where it is installed.

Programs in Other States

While programs similar to Minnesota's exist in other parts of the country, there are also quality-installation and quality-maintenance program approaches that differ in some noteworthy aspects. In particular, California utilities have been aggressive in pursuing proper installation of residential HVAC equipment, both through regulatory means (Title 24) and through utility incentive programs.

The dominant program model in California is what has come to be known as a Verification Service Provider (VSP) approach (Mowris, n.d.; Hunt et al., 2010). Under this model, utilities contract with third party entities, which then train contractors, verify system performance improvements, and track program activity on behalf of the utilities. Notably, contractors are not limited to installation and tune-up visits, but can make system corrections as part of any service call to a home, provided that they document that appropriate system improvements were made.

The longest-running such program is the [CheckMe®](#) program implemented by the Proctor Engineering group. Under this program model, contractors make system measurements regarding airflow and refrigerant charge, and then phone these readings in to a central hotline, where they are entered into a database and evaluated by a combination of technical staff and an expert computer system (Downey and Proctor, 2002). If adjustments are authorized, the post-adjustment data are also phoned in to document the improvements. Other VSPs use an approach in which on-site technicians directly enter data into a tablet or laptop computer, which then provides guidance about improvements, as well as tracking system measurements and improvements.³ All of these programs are focused primarily on ensuring that refrigerant charge and system airflow are correct for air conditioners and heat pumps.

Closer to home, the [Midwest Energy Efficiency Alliance](#) (MEEA) has designed and operates a VSP-based HVAC quality-installation program called [HVAC SAVE](#) that is used by several utilities in Iowa and Illinois.⁴ The approach generally mirrors that taken by VSPs in California in that trained and certified technicians record system measurements to a tablet or laptop. However, rather than evaluating airflow and refrigerant charge *per se*, the HVAC SAVE system focuses on a score that is determined by comparing the measured heating and/or cooling output of the system to its rated values.⁵ Systems that receive a passing score are eligible for utility incentives. Notably, the HVAC SAVE program addresses furnaces as well as air conditioners and heat pumps. Participating utilities provide incentives for HVAC SAVE-based tune-ups of existing systems, and also require the HVAC SAVE protocol for incentives for high efficiency new systems.

³ See for example, [Verified® Refrigerant Charge and Airflow System](http://www.verified-rca.com/software.htm) (<http://www.verified-rca.com/software.htm>).

⁴ See [HVAC SAVE website](http://hvacsave.com/) (<http://hvacsave.com/>), and Yee et al. (2013).

⁵ For furnaces, the measured system output (determined by measuring temperature rise and airflow) is compared to the measured gas input, adjusted by the system's rated efficiency. For cooling systems, measured output is compared to rated input.

The U.S. Environmental Protection Agency has an [ENERGY STAR Verified Installation](#) (ESVI) program that is targeted at building awareness among consumers about HVAC installation quality and providing a seal of approval in the form of ENERGY STAR certificates for good installations (von Schrader, 2016). Currently, eight utilities (in New England, southern California and Oregon) have programs that link to ESVI. To our knowledge, no utilities in Minnesota or other Midwestern states have programs that tie to ESVI, perhaps because the program's standards require addressing duct leakage, which is less of an issue in Midwestern homes where ducts are typically located within the thermal envelope of the home.

Methods

Primary data collection for this study included interviews with various market actors, a survey of Minnesota homeowners and field testing of heating and cooling equipment for a sub-sample of survey respondents. We summarize these activities below. Additional details can be found in the appendices to this report.

Interviews

The study scope included interviewing individuals involved in residential heating and cooling system installation and maintenance, or involved in training people who do this work. These interviews were designed to better understand current technology and practices, and to explore barriers and motivators for improving installation and maintenance practices. The interviews included:

- Six Minnesota HVAC equipment distributors
- 22 Minnesota residential heating and cooling contractors
- Residential HVAC program staff for six Minnesota utilities
- Individuals with three organizations involved in training and certification for residential HVAC contractors
- Staff for three organizations that deliver residential HVAC programs with quality-installation or quality-maintenance components in Minnesota or elsewhere.
- One individual with a research and development organization involved in testing furnaces

The interviews were mostly conducted by telephone, except for HVAC distributor interviews, which were more effective to conduct in person. Interview guides for equipment distributors and heating and cooling contractors are provided in [Appendix B](#).

Homeowner Survey

The homeowner survey was designed to accomplish two goals: (1) to gather information about heating and cooling equipment, maintenance practices and homeowner attitudes related to selecting a contractor; and, (2) to serve as a recruitment vehicle for the on-site testing.

The survey was confined to homeowners in the Twin Cities, St. Cloud, Rochester and Duluth areas, and was limited to households in homes with a central air conditioner or air-source heat pump.⁶ Most of these homes also had a forced-air furnace.

⁶ The Twin Cities metro area is here defined as Anoka, Carver, Dakota, Hennepin, Ramsey, Scott, and Washington counties.

We stratified the survey sample to produce useful results for three groups:

1. New replacement system in an older home – these were households that had recently (within the past five years) installed a new furnace, air conditioner or central, air-source heat pump;
2. New system in a new home – these were households living in a home that had been built in the past five years, and that presumably had new HVAC equipment as well; and,
3. Older system – these were households in homes with heating and cooling systems that were more than five years old.

The survey sample came from a combination of purchased random samples of households (from [InfoUSA](#)) in the above geographic areas and HVAC permits obtained from the cities of Minneapolis, Duluth and Rochester.⁷ We used the permit data to help boost the number of respondents with new replacement systems. More details about the sampling and weighting for the survey can be found in [Appendix C](#).

The survey was implemented by telephone by [Leede Research](#) in waves between April and August, 2014, and yielded 729 responses, with an overall response rate of about 7 percent, which is fairly typical of current telephone survey efforts (Pew, 2012).⁸ The complete survey instrument can be found in [Appendix D](#).

As with any survey effort, non-response is a concern: households who decline to participate in the survey may differ systematically from those who do participate. Based on the limited demographic and housing data we collected for the study, the weighted study sample appears to be comparable to Census data for age of home and number of people in home, but skews towards older homes and households who have lived in their home for a long time (see [Appendix C](#) for details).

Field Testing

Survey respondents were asked if they would be interested in participating in the field-test component of the study (28% expressed interest). From this pool, we recruited and completed field testing for 116 households during the summers of 2014 and 2015. The field testing was meant not only to gather more detailed information about the systems in the home, but – more importantly – to look for tune-up opportunities, and to measure the performance improvement from addressing these.

To implement the field testing, technicians hooked up a customized instrumentation rig designed to measure various parameters of the heating and cooling system, and recorded data while making various tune-up adjustments. Measured parameters included:

⁷ Available permit data for St. Cloud did not allow for isolating households that had installed HVAC equipment.

⁸ A small number of additional survey responses were gathered in 2015 as part of recruiting for the 2015 fieldwork phase of the study.

- electrical power consumption;
- supply and return air temperature and humidity;
- airflow through the system;
- static pressure at various points in the system;
- refrigerant-line temperatures and pressures;
- condensate production rate.

The measurements allowed us to assess the operating efficiency of the system before and after the adjustments, and thus to measure how much the system efficiency was improved. More detail about the test rigs and testing protocol is provided in [Appendix E](#).

In consultation with Seventhwave technical staff (who were able to remotely view live data from the test rigs), technicians evaluated the systems for a number of tune-up opportunities:

- Airflow was assessed for both heating and cooling operation. For cooling operation, we established a target of 350 cfm per nominal ton of cooling capacity, and adjusted airflow if it was found to be below 300 or above 400 cfm per ton. For heating-mode airflow, the protocol called for measuring the temperature rise between supply and return air while the furnace was operating, and making an airflow adjustment if the measured rise was outside of the manufacturer's nameplate range.
- Refrigerant charge was checked and adjusted following the manufacturer's charging instructions, and generally involved measuring either the superheat or subcooling temperatures, and comparing this to the manufacturer's target value for given ambient conditions.⁹ Our protocol called for adjusting refrigerant if superheat was more than 3 F° (for subcooling) or 5 F° (for superheat) off from the manufacturer's target value.
- Filters were replaced at the technician's discretion if they were visibly fouled and a replacement was available.
- Similarly, air conditioner and heat pump outdoor unit coils were cleaned if they were visibly fouled.¹⁰
- For forced-air furnaces, gas manifold pressure was checked and adjusted to the manufacturer's specifications.

We measured the impact of adjustments to air conditioners and heat pumps sequentially, meaning that we recorded system performance data before and after each adjustment. Because of time constraints, we were only able to measure the combined impact of the heating-system adjustments on system performance.

⁹ In a few cases involving older systems, no manufacturer's charging instructions were available: these were assessed using a generic superheat chart.

¹⁰ Although we initially considered also inspecting and cleaning *indoor* coils, the protocol did not allow enough time for this, given the difficulty inspecting and cleaning these, which are often hidden inside of ductwork with no ready access.

Results

Following are the results from our interviews with residential HVAC stakeholders, our survey of households and our field research.

Market Research

Our market research involved interviews with equipment distributors, residential heating and cooling contractors, utility program staff and surveys of households.

Equipment Distributors

We interviewed six Minnesota distributors of residential HVAC equipment about market trends, utility programs and current specification and installation practices by contractors.¹¹ Findings from these interviews are summarized below.

SEER 13 equipment dominates the cooling market overall. Most distributors estimated about 80 percent market share for SEER 13 cooling equipment, with SEER 14-16.5 units making up most of the rest – though two larger distributors estimated that close to 50 percent of their air conditioner sales were for high efficiency equipment. Distributors thought that utility rebates were responsible for most of the higher SEER air conditioners sales. Those with knowledge of markets in both Wisconsin (where air conditioner incentives are more limited) and Minnesota said that there is a stark contrast between the two states when it comes to higher SEER CAC equipment sales, which are more prevalent in Minnesota. Most thought that there would always be high-efficiency sales, even without the rebates, but that it would be closer to five percent of sales.

Cooling systems with thermostatic expansion valves (TXVs) dominate the market. All distributors said that most evaporator coils on the market have integrated TXVs. This is likely a consequence of the 2006 federal SEER 13 standard.

High-efficiency condensing units make up 90 percent or more of furnace sales, and high-end multi-stage equipment is gaining market share. It is rare for a new furnace to have an efficiency of less than 90%, and the market for high-end, multistage furnaces with variable-speed air handlers is more than 50 percent of most distributors (and more than 75 percent for some). One reason for this may be the introduction of constant-torque (commonly called by the trade name “X13”) blower motors that offer some of the benefits of an electronically-commutated motor (ECM) variable-speed blower at a lower price point. Another reason may be that manufacturers have made it possible to replace just the control board for fully-variable ECM blowers when they fail instead of having to replace the entire motor assembly.

The majority of current equipment sales are for replacement systems rather than for new construction. All but one distributor said that sales of equipment for new homes is less than 25 percent of their sales. Some said that before the recent recession it had been significantly higher, but those sales have not returned. An overarching trend mentioned by all distributors was that

¹¹ The complete interview guide can be found in [Appendix B](#)

high efficiency cooling systems are rarely installed in new homes: the typical new home gets a SEER 13 air conditioner and a single-stage condensing gas furnace with a conventional permanent-magnet, split-capacitor (PSC) air-handler motor.

The market for air-source heat pumps varies geographically and over time. Air-source heat pumps tend to have higher market share in rural areas where natural gas is not available, and sales are rare in bigger cities. Some (especially municipal and co-op) utilities aggressively market dual-fuel rates that encourage the installation of heat pumps. Nonetheless, various distributors pegged heat pumps at between 1 and 20 percent of their sales.

Distributors have their eye on inverter-driven compressor technology for air conditioner and heat pump compressors in the high end of the market. All distributors thought that inverter technology for compressors (which is the same technology used in ductless minisplit systems) was going to be the biggest market disruptor moving forward for high-end central air conditioners and heat pumps, although some thought it would be 5-10 years before these units attain significant market share. Major brands are in the process of releasing new ducted inverter units within the year, although distributors weren't particularly clear about price points. Because this technology allows for full modulation of cooling capacity, it is likely to displace two-stage compressor systems, which currently account for perhaps 10 percent of sales.

Larger contractors drive the market for high efficiency systems. Distributors generally spoke about their dealer network as two distinct groups: small-scale operators and mid- to large-sized dealers. The latter are more likely to participate in utility rebate programs, exhibit the ability to sell equipment with a range of features and to have factory- or [NATE-certified](#) technicians. Mid- to large-scale contractors are actively courted by distributors, while smaller outfits are generally just "city-desk" customers.

Utility quality-installation requirements for high-efficiency systems have affected the market, but incentives for quality installation of standard efficiency systems have not. Some distributors thought that Xcel's program lost a lot of contractors as participants in their rebate programs when they changed requirements to require quality installation of high-SEER equipment about four years ago – but also that installation practices have improved for those who remained. This may have incentivized other contractors to improve practices so that they could participate in this program. Distributors thought that quality-installation procedures and related behavior would likely spill over to installation of non-rebated product for the dealers that participate in these rebate programs. However, distributors generally felt that smaller dealers aren't participating in these programs, primarily because they mainly install SEER 13 equipment, and the incentives associated with quality-installation of standard-efficiency equipment is not worth the effort.

Distributors see quality-installation requirements and incentives as complementary to their own goals. Distributors have a vested interest in having the products they sell installed correctly, since they are often on the receiving end of technical support calls when issues arise. Several of the distributors provided targeted quality-installation training several years ago, but have since stopped. Descriptions and review of training marketing material provided during the interviews left the impression that most distributors were offering training on topics relevant to quality installation (e.g. proper refrigerant charge and air flow), but no distributor was offering quality-installation trainings per se. Distributors do provide training and certification for contractors to achieve a "factory-authorized dealer" certification, which is

generally thought to provide some competitive advantage in the market. Some require such training in order to be able to purchase high-end equipment.

Heating and Cooling Contractors

The large majority of contractors whom we interviewed (20 of 22) were qualified by one or more utilities to provide quality installation or maintenance services. The interview pool is also dominated by contractors who primarily do retrofit work: more than half (12 of 22) of the contractors reported that new construction work makes up 10 percent or less of their business, and only five interviewees reported that new construction makes up half or more of their business.

Key findings from these interviews are as follows.

Utility Programs

Contractors are mainly focused on utility incentives for high-efficiency systems. About half see utility incentives as helping their business, and half were ambivalent about whether these programs do much to drive the market. Several were unhappy with what they see as onerous reporting requirements to meet the utilities' quality-installation requirements for high-efficiency systems, though two specifically called out the need for this type of reporting to keep things honest.

Contractor awareness of utility quality-installation incentives is fairly low, even among this group of contractors who are active with utility incentive programs. As noted above, while contractors are generally well aware of the utility quality-installation requirements for high efficiency systems, only about a third (7 of 20) showed awareness of quality-installation incentives for standard-efficiency air conditioners or heat pumps. Several of those who were aware of these incentives said that they do not participate in these because of the paperwork involved and the fact that the incentive goes to the homeowner.

Contractors did not express much enthusiasm for utility quality-maintenance programs. While contractors were generally aware of utility incentives for tune-ups of older systems, awareness was about as far as it went: only one reported doing a significant number of these, and several stated that it was just not worth the hassle.

Installation practices

All contractors state that they routinely do load calculations to determine equipment size. Several mentioned that municipalities like the City of Minneapolis require these calculations. Many, but not all, follow the Air Conditioning Contractors of America (ACCA) Manual J for determining design heating and cooling loads; others use simpler procedures or software from, for example, equipment manufacturers.

All state that they routinely assess refrigerant charge for new installations using superheat/subcooling methods. When asked what they do when the unit is installed when it is too cold outside to conduct these tests, all stated that they return when the weather is warmer to test charge. There is some variation in opinion as to the minimum outdoor temperature needed to test charge, however: temperatures from 55 to 75°F were cited.

Total system airflow at the furnace or air handler is seldom measured. Some contractors measure static pressure drops in the system, many measure furnace temperature rise (which is an indirect indicator of heating-mode airflow), and some measure airflow at registers when there is an issue with uneven heating throughout the house. But few routinely measure airflow through the central furnace or air handler in heating, cooling or fan-only modes. When total system airflow *is* assessed, it is most commonly implemented by adding up anemometer-based measurements at individual registers or (less frequently) by using the pressure drop across the evaporator coil along with a table provided by the manufacturer to translate pressure drop into airflow.

Homeowner Telephone Survey

We conducted a telephone survey of single-family owner-occupied households in four geographic areas in Minnesota. The survey asked a range of questions covering satisfaction with HVAC equipment to purchase practices. Following are results from the survey.

Satisfaction with heating and cooling equipment

The survey results show that most people are satisfied with their heating and cooling equipment (Table 2).

Table 2. Homeowner satisfaction with cooling and heating systems.

	Older system	New replacement system	New system in new home	Overall (weighted)
How satisfied would you say you are with your current <u>cooling</u> system?				
Would you say you are...				
...very satisfied	70%	83%	71%	73%
...somewhat satisfied	22%	16%	22%	20%
...neither satisfied nor dissatisfied	5%	1%	6%	4%
...somewhat dissatisfied	3%	1%	2%	3%
...very dissatisfied	0%	0%	0%	0%
	(n=294)	(n=293)	(n=138)	(n=725)
How satisfied would you say you are with your current <u>heating</u> system?				
Would you say you are...				
...very satisfied	73%	82%	67%	75%
...somewhat satisfied	18%	15%	25%	18%
...neither satisfied nor dissatisfied	7%	2%	5%	5%
...somewhat dissatisfied	2%	1%	2%	2%
...very dissatisfied	0%	0%	1%	0%
	(n=280)	(n=251)	(n=131)	(n=662)

"Don't know" and refusals omitted.

Satisfaction is highest among those with new replacement systems and somewhat lower for those living in new homes. Areas of dissatisfaction reported by respondents included: uneven

temperatures, newer system needing repairs and not running efficiently (e.g., system running too much or not enough warm/cool air).

Service and Maintenance Practices

We asked survey respondents about their maintenance practices on their heating and cooling systems. Overall, respondents reported that more than three in every four heating systems and more than half of cooling systems had been professionally serviced within the past five years (Table 3 and Table 4) with about three quarters of these service calls being for regular maintenance, and a quarter being because the unit was not operating properly. Unsurprisingly, service calls are less frequent among owners of new systems than they are among owners of older systems. Additionally, 95 percent of respondents report changing their furnace filter annually or more frequently (Table 3).

About one in four survey respondents report that they have a service agreement to provide regular maintenance for their heating and/or cooling system (Table 5), and these are a mix of contracts with heating and cooling contractors and contracts with the local electric or gas utility. The average reported cost of such contracts was about \$200 per year, though this ranged from zero for a few cases where regular service was included in the installation price for the system to more than \$700 per year. Higher-cost service agreements often included plumbing or other appliances in addition to the heating and cooling systems.

Table 3. Heating system service and maintenance.

	Older system	New replacement system	New system in new home	Overall (weighted)
When is the last time you had your heating system professionally serviced?				
within the last year	41%	36%	24%	39%
1-2 years ago	31%	24%	23%	29%
3-5 years ago	9%	10%	8%	9%
more than 5 years ago	8%	1%	2%	6%
never	12%	29%	42%	17%
	(n=275)	(n=235)	(n=130)	(n=640)
Did you have it serviced then because it wasn't operating properly or just for regular maintenance?*				
Not operating properly	29%	11%	36%	24%
Regular maintenance	68%	87%	62%	74%
Both	3%	2%	2%	2%
	(n=222)	(n=176)	(n=66)	(n=464)
How often do you usually replace your furnace filter? Is it...				
...more often than monthly	1%	1%	1%	1%
...about monthly	29%	26%	27%	28%
...every couple of months	37%	27%	44%	34%
...a few times a year	20%	22%	18%	20%
...annually	9%	17%	6%	11%
...less than annually	1%	3%	1%	1%
...by some other schedule	2%	1%	2%	2%
...never	1%	3%	1%	2%
	(n=285)	(n=236)	(n=127)	(n=648)

"Don't know" and refusals omitted.

*If serviced in last 5 years.

Table 4. Cooling system service.

	Older system	New replacement system	New system in new home	Overall (weighted)
When is the last time you had your cooling system professionally serviced?				
within the last year	24%	30%	16%	25%
1-2 years ago	25%	20%	16%	24%
3-5 years ago	11%	4%	4%	10%
more than 5 years ago	8%	0%	2%	6%
never	31%	45%	62%	35%
	(n=264)	(n=286)	(n=137)	(n=687)
Did you have it serviced then because it wasn't operating properly or just for regular maintenance?*				
not operating properly	22%	24%	30%	22%
regular maintenance	77%	75%	70%	77%
both	1%	1%	0%	1%
	(n=167)	(n=162)	(n=44)	(n=373)

"Don't know" and refusals omitted.
*If serviced in last 5 years.

Table 5. Service contracts.

	Older cooling system	New replacement cooling system	New system in new home	Overall (weighted)
Do you have a service contract that includes regular maintenance for your [heating and cooling systems]?				
cooling system	1%	1%	2%	1%
heating system	6%	3%	1%	6%
both	19%	14%	8%	17%
neither	74%	81%	90%	76%
	(n=291)	(n=285)	(n=135)	(n=711)
Who is that contract with? Is it with...				
...a private heating and cooling contractor	30%	49%	39%	34%
...and electric or gas utility	69%	48%	50%	65%
...someone else	1%	3%	11%	1%
	(n=78)	(n=81)	(n=12)	(n=171)

"Don't know" and refusals omitted.

Purchase Criteria

We asked households that had purchased a new heating or cooling system within the last five years how many bids they obtained, and we asked all respondents how they would go about finding an installer – as well as what qualities they would look for in an installer.

Among those who had recently installed a replacement heating or cooling system, the survey results indicate that a large majority of households obtained more than one bid, with an overall average of about two bids (Table 6). This suggests that the purchase decision for these systems is typically a fairly careful one, and not, for example, a rushed emergency replacement.

Table 6. Number of bids obtained when purchasing a new system.

How many different bids did you get when you bought your...?	...furnace	...air conditioner or heat pump
zero	15%	6%
one	22%	38%
two	17%	26%
three	38%	23%
four	7%	4%
five	1%	4%
mean number of bids:	2.0	1.9
	(n=212)	(n=270)

"Don't know" and refusals omitted.

Results limited to households who installed a replacement heating or cooling system in the past five years)

Respondents were generally more inclined to choose an installer who was known to them – or who came by way of a recommendation from someone they know – than they were to search for an installer with an internet search or other means (Table 7).

Table 7. How survey respondents would find an installer.

If you needed to replace your [cooling system], how would you go about finding someone to install a new one?	1st response	2nd response	Any mention
Call an installer I know/have used before	53%	15%	57%
Word of mouth – get recommendations of people I know	17%	35%	25%
Internet search (Angie's List, Consumers Report, BBB, etc.)	14%	17%	19%
Yellow pages	5%	14%	9%
Use (or contact) local utility company	3%	6%	5%
Look for someone who carries a particular brand or feature	3%	6%	4%
Other	4%	7%	6%
	(n=680)	(n=230)	

"Don't know" and refusals omitted.

The question was asked open-ended, and coded into the categories above. Up to two responses were recorded per respondent.

Reputation and price are clearly at the forefront of what people look for in choosing an installer. Explicit mentions of installation quality were infrequent at best, and suggests that people generally assume that systems will be correctly installed. This result is in line with a recent similar survey of California homeowners (Steiner and Malinick, 2015).

To make sure that installation quality wasn't implicitly embedded in other responses, we asked all respondents who mentioned "reputation" or "quality" what they meant by these terms. Most who mentioned reputation referred to the installer having references or positive recommendations from family or friends. Only about one in 10 of these respondents mentioned something to do with installation quality – and some of these responses had more to do with how well the installer cleaned up after themselves than with proper installation technique.

Similarly, among the few who mentioned "quality" as an attribute they sought in an installer, when asked to explain in more detail, only about one in three mentioned quality of the installation job; more often, it was the quality of the equipment itself that they were referring to.

Table 8. What survey respondents look for in choosing an installer.

What would you look for in choosing the installer who is going to get your business?	1st response	2nd response	3rd response	Any mention
<i>good reputation</i>	30%	28%	12%	43%
price	24%	18%	16%	38%
personal characteristics of the installer	9%	9%	3%	15%
reliability	8%	6%	4%	12%
past experience	7%	3%	7%	10%
availability (to get the work done quickly)	3%	7%	19%	9%
carrying a specific brand	4%	6%	3%	8%
<i>quality</i>	2%	6%	8%	7%
industry / manufacturer certification	3%	3%	5%	5%
equipment	1%	3%	8%	4%
experience	2%	2%	1%	4%
location	2%	1%	3%	4%
offering maintenance and repair service	1%	2%	0%	2%
customer service	1%	1%	5%	2%
knowledge	1%	1%	2%	2%
licensed	1%	1%	0%	2%
local company	1%	0%	1%	1%
warranty	0%	1%	3%	1%
having a showroom	0%	1%	0	<1%
	(n=666)	(n=411)	(n=127)	(n=666)

"Don't know" and refusals omitted.

The question was asked open-ended, and coded into the categories above. Up to three responses were recorded per respondent.

Field Research

Field testing was completed on 116 households to gather more detailed information about the heating and cooling systems in the home and to test for performance improvements from tune-up opportunities.

Cooling Systems

We conducted cooling-mode tests on 109 systems (99 central air conditioners and 10 air-source heat pumps). These were a mix of new replacement systems (n=50), new systems in new homes (n=21) and older systems in older homes (n=38).

Field technicians for the project performed the following adjustments on an as-needed basis for each system:

- **Filter change** – The filter was replaced at the technician’s discretion if a replacement was available, and the as-found filter was visibly fouled or showed a high pressure drop.
- **Condenser coil clean** – condenser coils were cleaned at the technician’s discretion if they appeared to be visibly fouled. Evaporator coil cleaning was also nominally within the scope of the study, but time constraints generally prevented opening ductwork to implement this measure.
- **Airflow adjustment** – Airflow at the central air handler was adjusted if it was measured to be outside a range from 300 to 400 cfm per nominal ton of cooling capacity. Technicians sought to achieve a target airflow of 350 cfm per ton.
- **TXV adjustment** – a small number of systems had add-on TXVs that were improperly mounted or adjusted. When observable – and at the technician’s discretion – these deficiencies were corrected.
- **Refrigerant charge adjustment** – Based on the type of metering device (TXV or fixed-orifice), refrigerant charge was adjusted – using either the measured subcooling (TXV) or superheat (fixed-orifice) – to manufacturer’s specifications. Refrigerant charge was generally adjusted if measured subcooling differed by more than 3F from the target value, or, for superheat, if the observed value was more than 5F off the target.

A Case Study

Before summarizing the overall results from the field testing, we present a case study of one site from the study. This site is instructive not because it was typical of the systems that we encountered, but rather because it illustrates just about everything that could possibly go wrong with a Minnesota central cooling system in terms of installation and maintenance. The site in question is a 1,750-ft² home in the Twin Cities area that was built in 1990 (Figure 1). It is served by a circa 2002, 3-ton, SEER-10 central air conditioner with a fixed-orifice expansion device. Cooled air is circulated via a new, 80 kBtuh, multi-stage, variable-speed condensing furnace with an ECM blower.

Figure 1. Cooling case-study site (Site ID 00171).



Upon arrival, the technician found a very dirty 16x25x1 inch MERV 7 furnace filter. The as-found testing revealed adequate airflow of about 410 CFM per ton, but with an astounding 0.86 inches water column (IWC) of pressure drop across the filter (typical values are less than $\frac{1}{4}$ of this level). One of the features of variable-speed furnaces like the one found in this home is that they automatically compensate for changing filter resistance by adjusting blower speed and power to maintain constant airflow. In this case, the furnace had responded to the situation by ramping up to over 750 watts of power draw, and had actually bent the filter in its effort to push air through it (Figure 2).

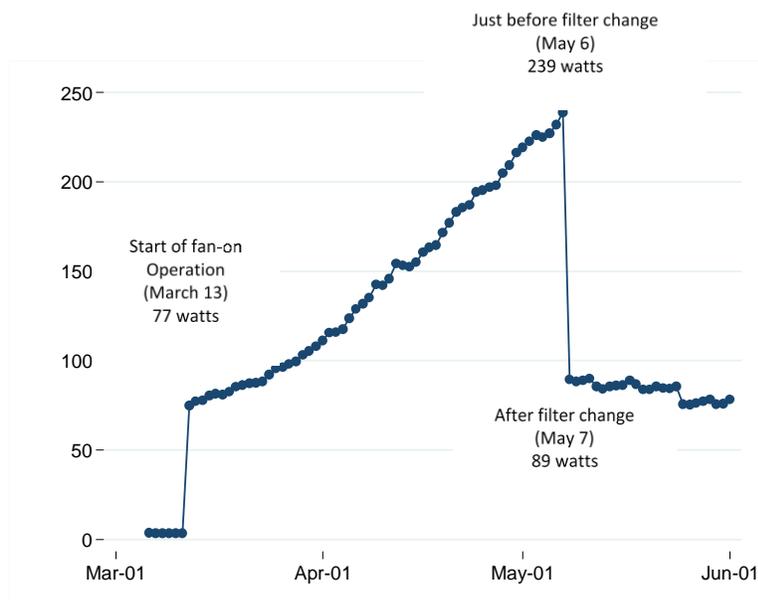
Figure 2. Furnace filter at Site 00171.



When the filter was replaced, the pressure drop decreased to a more manageable (but still high) 0.48 IWC, but airflow increased to almost 500 CFM per ton, and the blower power draw increased to almost 900 watts. The fresh filter thus revealed that the cooling-mode airflow setting on the furnace was too high, and that the initial indication of appropriate airflow was only due to the fact that the filter was so dirty that the system could not fully compensate for its resistance. The technician adjusted airflow to bring the system back to about 400 CFM per ton, at which point, the filter pressure drop was 0.34 IWC (still high, but reasonable, given the highly resistive type of filter used by the homeowner) and blower power had been reduced to 470 watts. The test data showed that these steps improved the system cooling Energy Efficiency Ratio (EER) from 6.3 to 7.2, or by about 13.5 percent.

Later, longer-term monitoring at this site revealed that even with regular filter maintenance, filter loading can be an issue, especially when households operate their system in fan-on mode for extended periods, as was the case for this household.¹² This particular household practiced fan-on operation from about mid-March through early June (and later also in August). Monitoring data showed the fan-only power draw for the furnace more than tripling in a 55-day period between the start of fan-on operation and an apparent filter change in early May (Figure 3), clearly indicating the need for more frequent filter changes for this system.

Figure 3. Air handler watts in fan-only mode at Site 00171.



Next, the technician observed that the outdoor unit coils were dirty (Figure 4). Cleaning the coils boosted the system’s cooling output by about 11 percent, and dropped the compressor power draw by about 2 percent, for an overall improvement in EER from 7.2 to 8.6 for this adjustment.

With these issues taken care of, the technician then checked refrigerant charge by measuring the system superheat, and comparing it to the unit’s charging instructions. The test showed superheat to be significantly low, indicating that the unit was undercharged. After charging the unit to achieve the target superheat, the cooling output of the system increased significantly, further boosting the system EER to the nameplate rating of 10.0.

¹² Fan-on operation means the air handler operates even when there is no call for heating or cooling. ECM furnaces like this one typically have lower fan-on airflow and power consumption than do PSC furnaces. See [Appendix A](#) for more details.

Figure 4. Outdoor-unit coil fouling at Site 00171.



Altogether, the combination of installation-related and maintenance-related adjustments improved the cooling output of the system from 6.4 to 10.0, a 57 percent improvement.

To be sure, the combination of issues found at this site was unusual. However, as we will show, individual issues like the ones found here were quite common among the tested systems, and occur with enough frequency that about one in six cooling systems could achieve a performance boost of 25 percent or more by addressing issues like the ones seen here.

Cooling-System Performance-Testing Findings

Among the 109 cooling systems that we tested, more than 90 percent received at least one adjustment (Table 9), with refrigerant-charge and airflow adjustments being the most common. Systems installed in new homes were the least likely to require an adjustment in our sample, but the differences are neither large nor statistically significant given the relatively small number of new homes included. Indeed, it is issues with airflow settings and refrigerant charge that are the most common adjustments, and it is plausible that the incidence of these should be relatively invariant with system age. Notably, there is no statistically-significant difference between the incidences of common adjustments required and whether the cooling system had been serviced in the previous five years or the homeowner had a service contract for regular service (Table 10). This suggests that service technicians do not routinely look at refrigerant charge and airflow when they service a cooling system.

Table 9. Summary of Cooling-mode adjustments.

		New replacement system (n=50)	New home (n=21)	Older system (n=38)	Overall (n=109)
Type of adjustment (in descending order of incidence)	No Adjustments	6%	14%	5%	7%
	Refrigerant charge	64%	71%	76%	70%
	Airflow	54%	48%	53%	52%
	Filter replacement	34%	33%	32%	33%
	Condenser coil clean	18%	24%	29%	23%
	TXV	8%	0%	0%	4%
Number of adjustments	0	6%	14%	5%	7%
	1	32%	24%	32%	30%
	2	42%	38%	39%	40%
	3	18%	19%	16%	18%
	4	2%	5%	8%	5%

Table 10. Incidence of cooling-system adjustments versus recent service or service contract.

Adjustment type at site visit	Cooling system serviced in last five years? (n=90)			Service contract for cooling system? (n=93)		
	No	Yes	p-value ^a	No	Yes	p-value ^a
Refrigerant adjustment incidence	65%	71%	0.65	70%	62%	0.53
Airflow adjustment incidence	61%	46%	0.20	56%	31%	0.13
Filter change incidence	27%	34%	0.49	31%	31%	1.00
Condenser coil clean incidence	27%	22%	0.63	24%	31%	0.73
Incidence of any adjustment	92%	90%	1.00	91%	92%	1.00

^aFischer’s exact, two-sided test. Values <0.05 indicate statistical significance at a 95% confidence level.

Individually, the adjustments made during the site visits yielded an average of about a seven percent improvement in system efficiency (Table 11), though measured changes at individual sites were sometimes much larger (Figure 5). Given an average of about two adjustments per site, the total change in system efficiency for all adjustments averaged 13.8 percent among sites that received at least one adjustment. When weighted to reflect the estimate proportion of systems among existing older systems, new replacement systems and new systems in new homes, the average EER improvement among adjusted systems is 12.8 percent, which is further reduced to 12.1 percent if the 8 sites where no adjustment was needed are included.

Table 11. Average impact of cooling-mode adjustments.

		n	Average % change in EER^a	95% confidence interval
Incremental effect of common individual adjustments	Refrigerant	72	+8.6	±3.8
	Airflow	52	+7.1	±2.5
	Filter	36	+2.9	±2.0
	Condenser coil clean	25	+7.4	±2.5
Any individual adjustment		195	+6.9	±1.7
Overall system effect of all adjustments among...	...adjusted new replacement systems	50	+14.1	±4.6
	...adjusted systems in new homes	21	+12.4	±10.7
	...adjusted older systems	38	+11.3	±4.3
	...all adjusted systems (unweighted)	101	+13.8	±3.4
	...all adjusted systems (weighted) ^b	101	+12.8	±3.3
...all systems (weighted)^b		109	+12.1	±3.2

^aAdjusted for differences in indoor and outdoor temperature during testing.

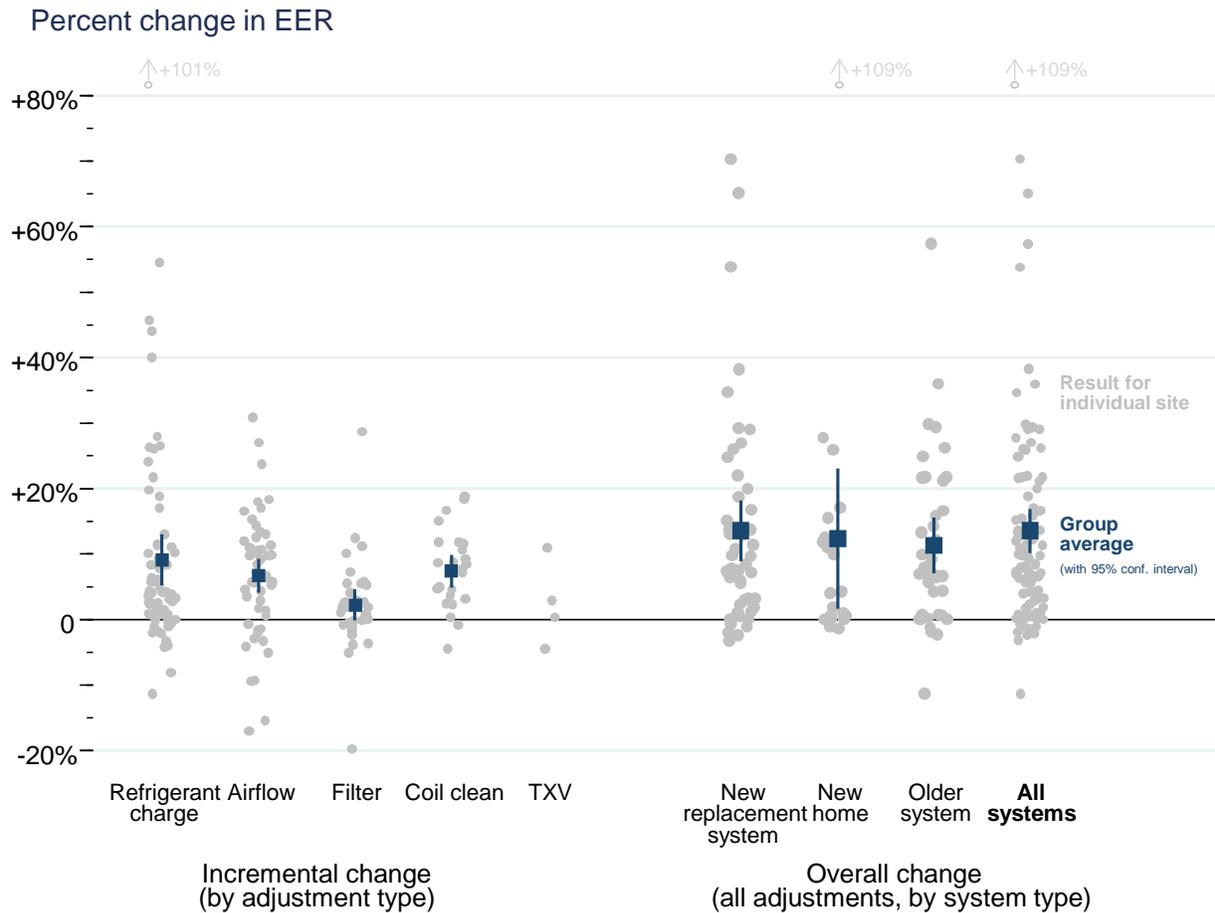
^bWeighted to reflect estimated population proportions: 23% new replacement systems; 2% new homes; 75% older systems

Note that the EER improvements reported here are corrected to account for the fact that indoor and outdoor temperatures typically changed slightly over the course of the testing, and this alone would be expected to affect the efficiency of the systems, because air conditioner and heat pump efficiency is sensitive to temperature “lift” (i.e. the difference between outdoor and indoor air temperature that the unit sees). On average, outdoor temperatures tended to increase over the course of the testing (by 1.5F on average) and indoor temperatures tended to decline due to the operation of the system (by an average of 1F). All else being equal, and in the absence of any cooling-system modifications, this increase in temperature lift alone (which averaged about 2.5F from as-found to the final post-adjustment test) would be expected to result in a decrease in measured system efficiency over the test period.

To compensate for this, we applied a generic correction factor to normalize the measured post-adjustment EERs to conditions at the time of the as-found test.¹³ Without this correction factor, the observed changes in system efficiency would generally be lower and therefore inaccurately measure the actual improvement due to the technician’s cooling-system modifications. For example, the 12.1 percent overall average change in EER among all systems is reduced to 6.0 percent if the temperature-correction factor is excluded.

¹³ The correction factor that we used is 0.2 EER per F, and is derived from an analysis of the difference in rated EER at 82F and 95F for central air conditioners found in the [California Appliance Efficiency Database](http://www.energy.ca.gov/appliances) (www.energy.ca.gov/appliances). For the approximately 6,000 systems that we examined, the median change in EER between the two rated temperatures was 0.2 per F, with 90 percent of systems falling between 0.15 and 0.25.

Figure 5. Impact of adjustments on cooling-system efficiency.



The efficiency improvement from the adjustments can also be separated into installation-related opportunities (airflow, refrigerant-charge and TXV adjustments) and maintenance-related opportunities (filter change and coil cleaning). The former were more prevalent in the study sample, occurring across about 85 percent of the sample, while the latter opportunities were found among 44 percent of the sample (37 percent of the sites had both types of opportunities, and 7 percent had no opportunities).

When present, the average performance improvement from addressing installation-related opportunities (12 ± 3 percent) was also twice that from addressing maintenance-related opportunities (6 ± 2 percent). Combined with the higher incidence of installation-related opportunities, the data suggest that installation-related opportunities account for about 80 percent of the total aggregate potential.

It is also noteworthy that while, on average, efficiency improvements were fairly modest, about one in six tested systems (18 of 109) showed an overall efficiency improvement of 25 percent or more. Refrigerant charge adjustments played the largest role among these systems, with 14 of the 18 systems showing a significant improvement in EER following refrigerant charge adjustment. Airflow adjustments played a significant role in about half of these sites (8 of 18 systems), and three systems showed a significant improvement following condenser coil cleaning.

Refrigerant charge adjustment

While charge was adjusted for about three of every four systems, in some cases the adjustments were minor. However, more than half of systems involved an adjustment of more than five percent of the system's listed factory charge, the majority of which were corrections to undercharged systems (Table 12). These results are consistent with other field research results looking at the incidence and type of charge errors, which have generally found undercharging to be more common than overcharging (e.g., Downey and Proctor, 2002; Pigg, 2008).

Table 12. Refrigerant adjustment incidence.

Category	Subcategory	Incidence	
Undercharged	Adjustment of 20% or more	20%	48%
	Adjustment of 5-19%	28%	
Charge OK or minor adjustment	No adjustment needed	30%	42%
	Adjustment of <5%	12%	
Overcharged	Adjustment of 5% or more	10%	

For 109 systems

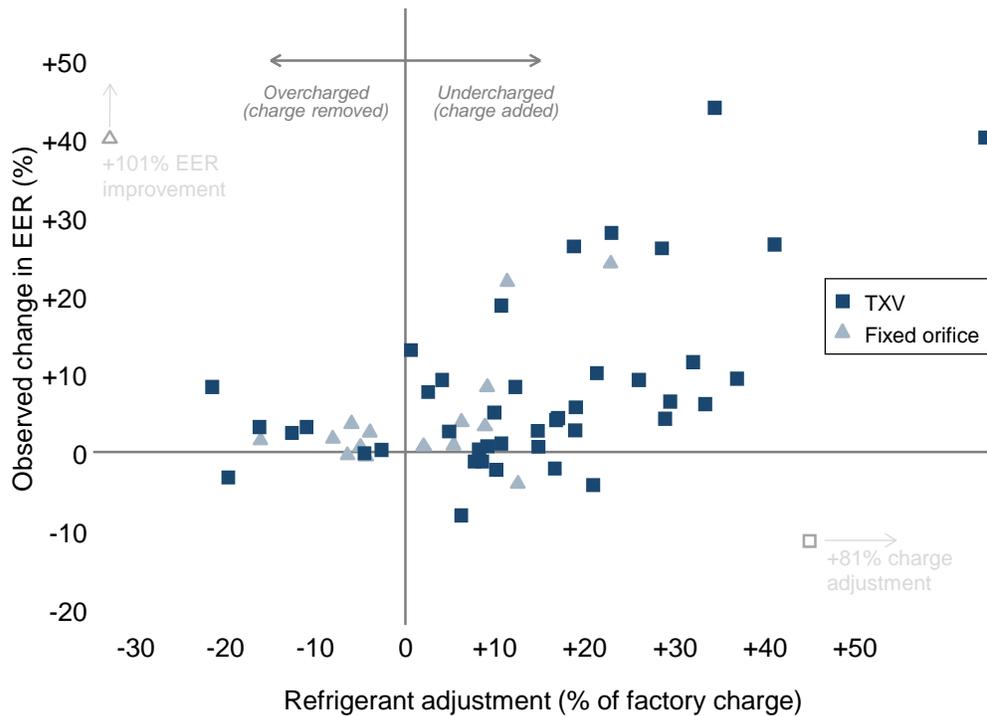
Adjustment values are percent of factory charge

A commonly-cited explanation for the high incidence of under-charged systems is that while condenser units are typically shipped with a factory charge that assumes a 15- to 20-foot length for the refrigerant lines that connect the indoor and outdoor units, actual line lengths tend to be longer. If the system charge is not adjusted to account for the longer line length, the system will be undercharged. Indeed, among the systems we investigated, line length ranged from 10 to 75 feet, with an average of about 30 feet. However, we found no difference in average line length (or line volume) for systems that were undercharged, overcharged or correctly charged.

Among the systems where refrigerant charge was adjusted, larger relative adjustments tended to be associated with a larger impact on measured system efficiency (Figure 6), but the relationship is not particularly strong.

Moreover, much of the overall 5 percent average improvement in EER stems from seven sites with efficiency improvements that exceeded 15 percent: if these cases (and the above outlier) are excluded, the average impact of charge adjustment on EER drops to 2 percent. This suggests that efficiency improvements from charge adjustments is a blend of many systems where the impact is small and a minority of systems with significant improvements. This may be increasingly the case in the future as the population of residential systems shifts to a higher proportion with TXVs, which have been shown to be more tolerant of charge errors than fixed-orifice systems (Farzad & O'Neal, 1993; Pigg, 2008; Kim and Braun, 2010).

Figure 6. Change in EER versus refrigerant charge adjustment.

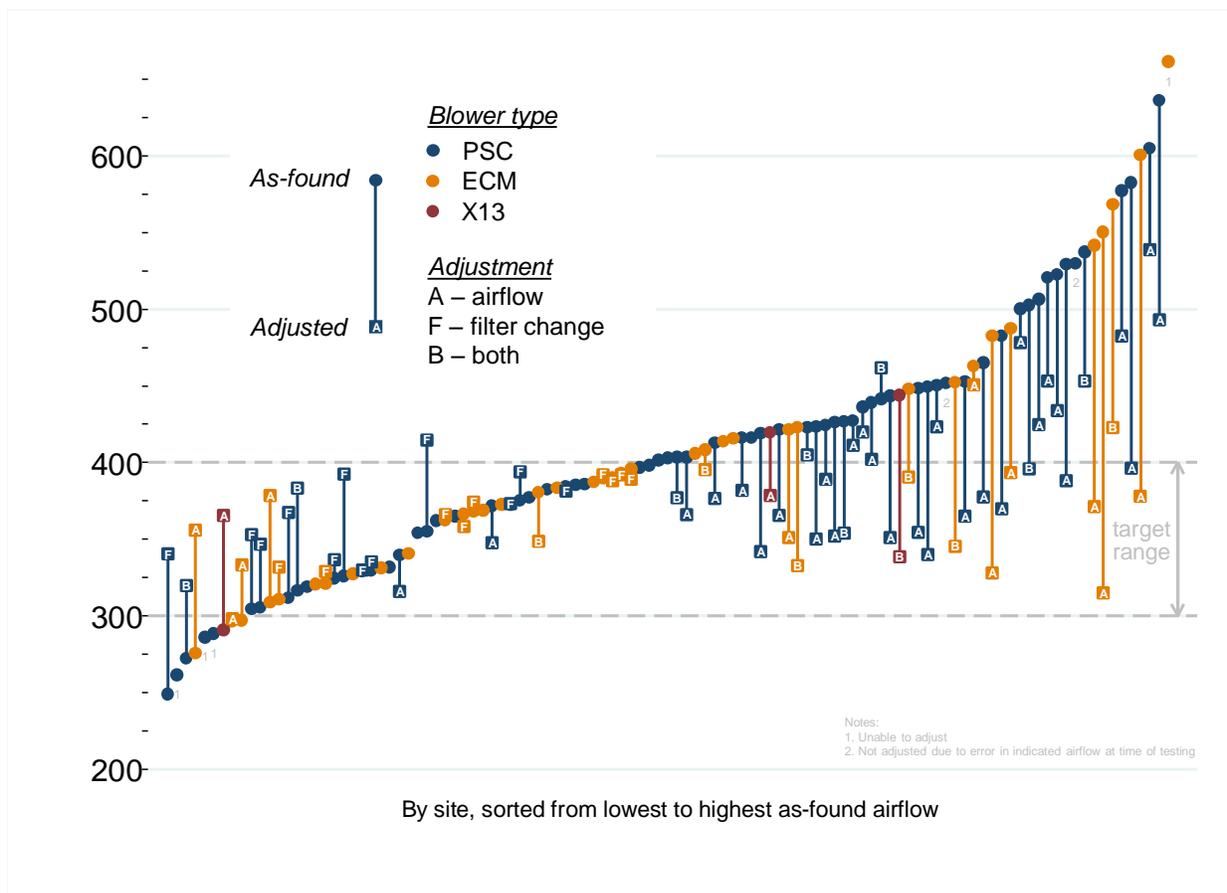


Filter replacement and airflow adjustment

Recommended airflow settings for residential air conditioners are generally in the range of 300 to 400 cfm per ton of cooling capacity. High airflow increases noise and air handler power, and reduces the dehumidification capacity of the system. Low airflow has the opposite effect – but very low airflow also risks having the temperature of the evaporator coil drop below freezing, causing ice to form, and severely compromising the performance of the system.

As-found airflow ranged from about 250 to 660 cfm per ton for the 109 systems, with an average of 408 cfm per ton (Figure 7). High airflow was much more common than low airflow: more than half of the tested systems had airflow that exceeded 400 cfm per ton, but fewer than 10 percent had airflow below 300 cfm per ton. This is likely a consequence of the fact that Minnesota’s cold climate typically pairs higher-capacity furnaces – that have commensurately larger blowers – with lower-capacity cooling systems.

Figure 7. As-found and adjusted cooling airflow.



About two-thirds of the systems had PSC type blower motors, and a third had ECM blowers.¹⁴ ECM blowers are capable of producing a wider range of airflow, and cooling airflow is typically set with switches on the furnace control board for furnaces that use this technology.¹⁵ It is therefore not surprising that within the field-study sample, ECM-based systems were somewhat more likely to be found with cooling airflow within the target range – and were more likely to be able to be adjusted to be within the range (Table 13). However, these differences are not statistically significant, so we cannot be confident that they are not simply luck of the draw for this particular set of systems.

¹⁴ Two sites had a hybrid type known as “X13” blowers.

¹⁵ See [Appendix A](#) for more detail.

Table 13. Incidence of proper airflow.

	n	Percent of sites with cooling-mode airflow between 300 and 400 cfm per ton ^a	
		As-found	After adjustments
All sites	107	41%	74%
PSC air handler	66	38%	68%
ECM air handler	38	50%	82%

^aOmits two sites where an airflow calibration issue resulted in incorrect airflow readings at the time of testing (correct airflow values were later calculated for these sites).

About two-thirds of the systems used a one-inch disposable filter, and about a third used a thicker replaceable filter (typically four or five inches thick). Only about one in 20 systems had an electrostatic filter. There was no difference in the replacement incidence between thin and thick filters, but the pressure drops were noticeably higher for the thin filters, both before and after filter replacement (Table 14). Thicker filters typically have deep folds that substantially increase the total face area of the filter, and can thus allow for high filtration efficiency without excessive overall resistance to airflow. However, one-inch filters with high particulate efficiency are also on the market, and these can have substantial flow resistance because of the combination of resistive media and limited total surface area. The aforementioned case study involved a filter of this type.

Table 14. Filter pressure drop.

Filter type	n	Mean filter pressure drop (IWC)						
		As-found (all sites)	Sites receiving filter change			Final ^a (all sites)		
			n	Before	After	Change		
Replaceable media	≤2" thick	70	0.32	23	0.39	0.20	-0.19	0.24
	>2" thick	30	0.19	9	0.19	0.15	-0.04	0.15
Electrostatic		5	0.28	2	0.23	0.11	-0.12	0.16
Any		105	0.29	34	0.33	0.19	-0.14	0.21

^aIncludes effect of any airflow adjustment

Condenser coil clean

A total of 25 systems received a condenser coil clean, which was based on visual inspection by the technician. Measured EER improvements ranged from a -4 percent to +19 percent, with a mean of 7 percent. The 95 percent confidence interval for the average efficiency improvement from this measure ranges from 5 to 10 percent.

These results are consistent with results from our earlier Wisconsin study (Pigg, 2008), which found EER improvements that ranged from -4 to +25 percent, with a mean of 7 percent.

TXV adjustment

As Mowris et al. (2004) have documented, add-on TXVs are sometimes installed or adjusted incorrectly. Here, four sites required adjustments to add-on TXVs: three to relocate the position

of the bulb, and one to adjust the TXV superheat setting.¹⁶ Three of these adjustments resulted in less than a 5 percent change in EER, and one resulted in an 11 percent improvement.

Cooling-System Monitoring Results

Data loggers installed on about half of the systems allowed us to track cooling-system operation over the course of a year. We modeled the relationship between cooling system operating hours and energy consumption and outdoor temperature and then developed weather-normalized estimates of season use and savings from quality-installation and maintenance adjustments (see [Appendix F](#) for details). We also estimated the impacts of these adjustments on summer peak electricity demand.

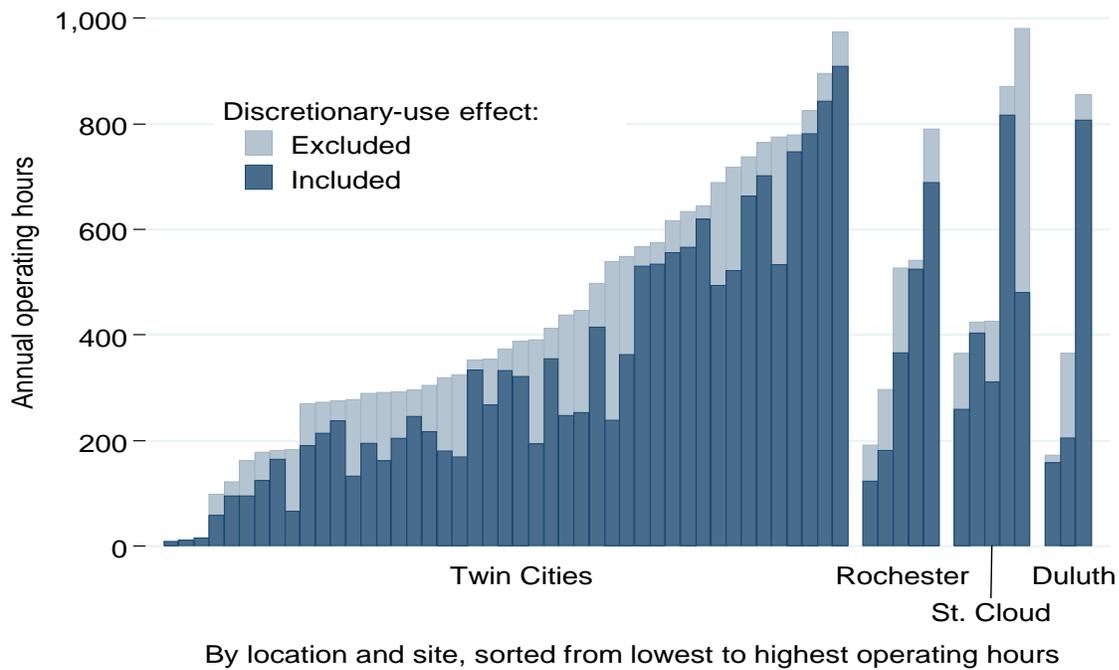
Annual Operating Hours and Electricity Consumption

On a weather-normalized basis, the 58 monitored cooling systems in the study ranged from fewer than 10 to nearly 1,000 hours of seasonal operation (Figure 8).¹⁷ Obviously, households vary in their setpoint temperatures, and systems may be sized differently relative to the cooling load of the home. But there are also signs that air conditioning use in a climate like Minnesota's has a healthy discretionary component to it: many of the sites have days with similar weather with no operating hours on some and significant hours on others.

¹⁶ Two thirds of the tested systems had a TXV, and of these, about one in six was an add-on TXV. An add-on TXV is one that is installed by the contractor at the time of installation; an integral TXV is built into the evaporator coil unit.

¹⁷ We define the cooling season as the months of May through September. Temperature and humidity loggers in the homes showed an average first-floor temperature of 75F and relative humidity of 54% on days when the cooling system operated for at least an hour. Second-floor temperatures averaged about 2F higher in the 9 homes where this was tracked.

Figure 8. Seasonal weather-normalized operating hours for monitored sites, by location and site.

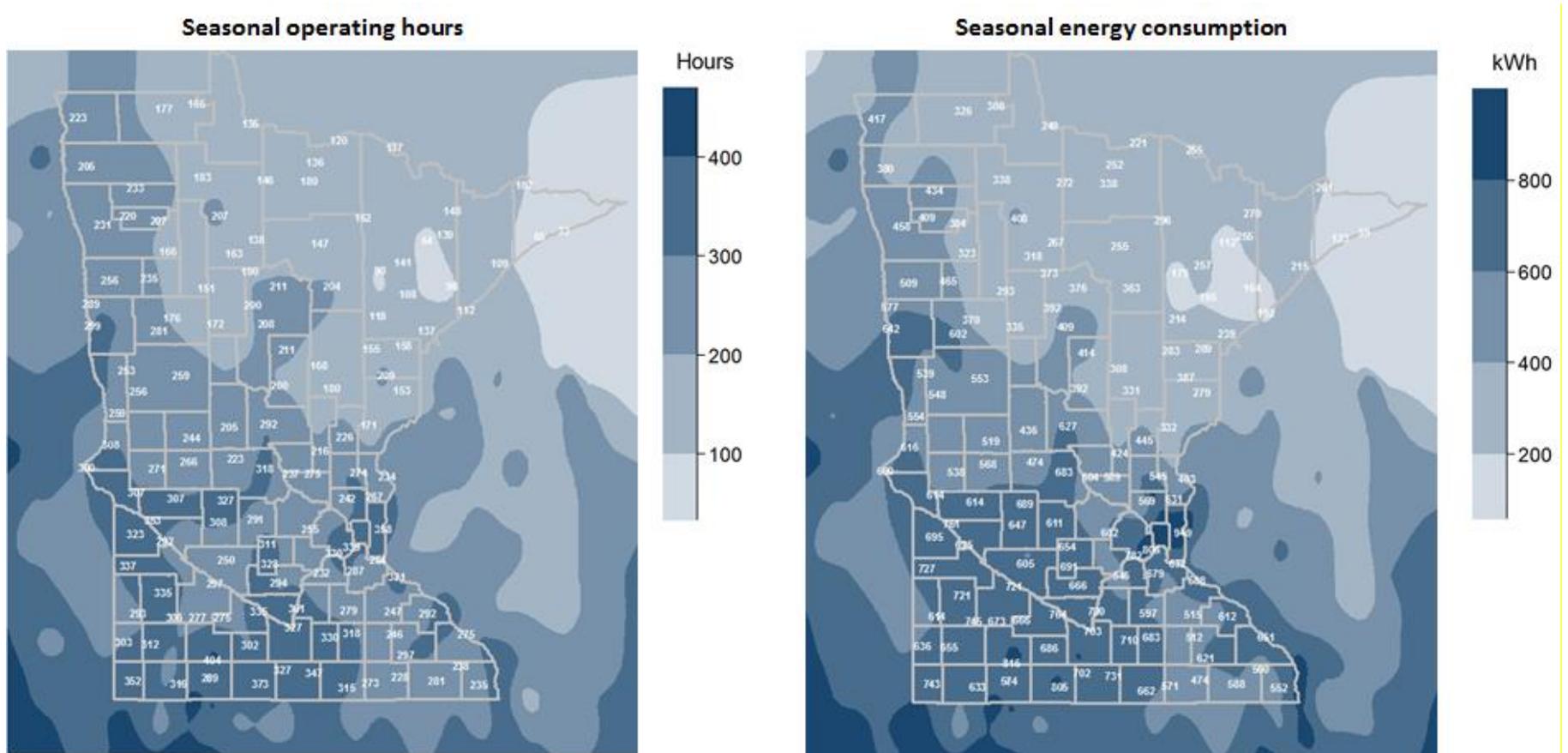


To account for this phenomenon, we developed two estimates of seasonal hours for each site: the first includes the fact that many households did not operate their cooling systems at all on some warm days that would otherwise indicate a need for cooling; the second excludes this discretionary-use effect, and effectively models a situation where households simply leave their cooling system enabled for the entire summer. On average, the monitoring data suggest that discretionary use of cooling systems reduces weather-normalized, seasonal operating hours by about 20 percent, from about 450 hours to 350 hours in our monitoring sample. Discretionary use has a similar impact on estimated seasonal electricity consumption for the systems in the sample, reducing it from about 950 kWh to 750 kWh per year on average.

To get a better estimate of regional variation in cooling-system operating hours and electricity consumption, we projected our 58 site-specific models to 140 locations around the state where long-term average temperature data were available.¹⁸ The results of this exercise are shown in Figure 9 in the form of contour maps and numeric values with the estimated average value for each weather station location. On average, the analysis suggests about 30 minutes of seasonal cooling system operation and 1.1 kWh per seasonal cooling degree day (Base 65F).

¹⁸ See [Appendix G](#) for details.

Figure 9. Estimated average seasonal hours of operation and energy consumption for central cooling systems, by location.



A notable finding from the monitoring is that cooling systems in newer homes (five years old or less) run more hours and use considerably more energy than those in older homes. When modeled for typical cooling-season weather in Minneapolis, the 11 monitored systems in new homes averaged about 490 hours of operation and 1,300 annual kWh, compared to 340 hours and 770 kWh for the 47 systems in older homes. Part of this difference is related to home size: the new homes in the sample average more than a third larger than the older homes (2,070 versus 1530 ft²), and are served by cooling systems that average almost half a ton more cooling capacity (2.85 tons for new homes, versus 2.37 for older homes). The two groups are roughly comparable in terms of square feet of floor area per ton of cooling capacity, however (700 ft²/ton for new homes, versus 631 ft²/ton for older homes). This would seem to indicate that all else being equal, cooling systems in new and old homes should have comparable operating hours – or even that systems in new homes should run *fewer* hours, since they are likely better insulated.

That cooling systems in new homes appear to run more *hours* than systems in older homes, could simply reflect a higher propensity for occupants of new homes to use their cooling system. The logistic models that calculate probability that the cooling system is used (as a function of outdoor temperature) support this notion, suggesting that, for typical Minneapolis weather, occupants of newer homes have their cooling system enabled for about 14 more days per year than occupants of older homes on average. Another possible explanation is that new homes are much less likely to be shaded by mature trees. Since solar gain is a significant contributor to summer cooling loads, this could also contribute to an increased need for cooling

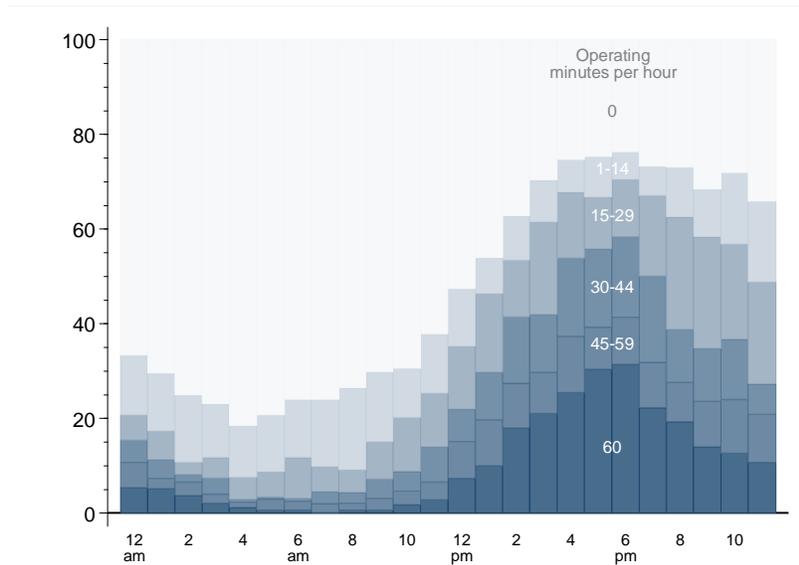
Peak Demand Impacts

Cooling systems in buildings are obviously a key contributor to summer peak electricity demand, which partly drives the need for generation capacity. Here we explore what the study data can tell us about cooling-system electricity consumption on hot summer days, and the potential impact that addressing installation and maintenance issues with central cooling systems could have on summer peak demand.

Figure 10 shows the distribution of hourly cooling-system duty cycle for the monitoring sample on hot weekdays. During the late-afternoon and early evening peak period (4pm to 8pm), about 25 percent of air conditioners are not operating at all, about 50 percent are operating and cycling on and off during the hour, and about 25 percent are running flat out over the entire hour. The average impact of performance improvements from quality-installation and maintenance improvements on system peak electrical demand is a weighted average of these three cycling categories: i.e., no impact for systems that aren't operating at all, impact proportional to the EER improvement for systems that are cycling; and, impact proportional to the reduction in power draw for systems that are running at 100 percent duty cycle.¹⁹

¹⁹ On a diversified basis, a 10 percent improvement in EER should result in an average 10 percent reduction in average system power draw for systems that are cycling on and off during the peak period. Diversified peak demand for units that are running at 100 percent duty cycle is affected only insofar as performance improvements reduce the power draw by the system: improvements that increase the cooling output but do not reduce power consumption will have no impact for these systems – unless they are large enough to cause the system to begin cycling, which we assume not to be the case here.

Figure 10. Hourly cycling behavior of 54 monitored systems on 10 days where the outdoor temperature exceeded 87F.



The test data from the cooling-mode performance adjustments indicate an average EER improvement of about 12 ± 3 percent across all systems, and an average system power-draw reduction of about 4 ± 1.5 percent. Combining these results with the cycling proportions above suggests about a 7 ± 1.5 percent average diversified reduction in cooling-system power consumption from resolving installation- and maintenance-related issues. Applied to the average peak-period power consumption from the monitoring sample of about 2,650 watts, this suggests that addressing installation and maintenance issues with central cooling systems will reduce system peak demand by about 185 ± 40 watts per system on average. Scaled up across the 1.76 million single-family homes in Minnesota, about 80 percent of which we estimate to have a central cooling system, the total technical statewide potential peak reduction from addressing installation and maintenance issues is about 260 ± 60 MW.²⁰

Gas Furnaces

We tested heating-mode operation at 84 sites with gas furnaces.²¹ Technicians made steady-state efficiency measurements before and after checking and adjusting several key parameters of the furnaces. These included:

- gas manifold pressure;
- temperature rise (airflow);

²⁰ The number of single-family (attached and detached) homes in Minnesota comes from Census 2014 estimates from the American Community survey. Our estimate of the proportion of single-family homes with central cooling comes from the 2009 [Residential Energy Consumption Survey](http://www.eia.gov/consumption/residential/) microdata (<http://www.eia.gov/consumption/residential/>), restricted to 585 single family homes in the West North Central Census division with between 90 and 900 annual cooling degree days.

²¹ Three furnaces were fueled by propane.

- blower-off delay; and,
- air-shutter adjustment.

We also monitored 55 gas furnaces over the course of the 2014/2015 heating season.

Gas-Furnace Performance-Testing Findings

As Table 15 shows, nearly all of the adjustments made were to gas manifold pressure. Technicians adjusted temperature rise at a small number of sites, but made no adjustments to blower-off delay or air shutters. Adjustments were somewhat less likely among households that had had their furnace serviced in the last five years or had a service contract, but the differences are not statistically significant given the sample size (Table 16).

Table 15. Summary of gas furnace adjustments.

		New replacement system (n=30)	New home (n=14)	Older system (n=40)	Overall (n=84)
Type of adjustment (in descending order of incidence)	No Adjustments	83%	50%	67%	70%
	Manifold pressure	13%	50%	28%	26%
	Temperature rise	3%	7%	5%	5%
	Blower-off delay	0%	0%	0%	0%
	Air-shutter adjustment	0%	0%	0%	0%
Number of adjustments	0	83%	50%	67%	70%
	1	17%	43%	33%	29%
	2	0%	7%	0%	1%
	3	0%	0%	0%	0%
	4	0%	0%	0%	0%

Table 16. Incidence of Furnace adjustment incidence versus recent service or service contract.

(n=71)		Furnace adjustment incidence	p-value ^a
Furnace serviced in last 5 years?	No	41%	0.209
	Yes	25%	
Service contract for furnace?	No	37%	0.196
	Yes	15%	

^aFischer’s exact, two-sided test. Values <0.05 indicate statistical significance at a 95% confidence level.

Manifold Pressure

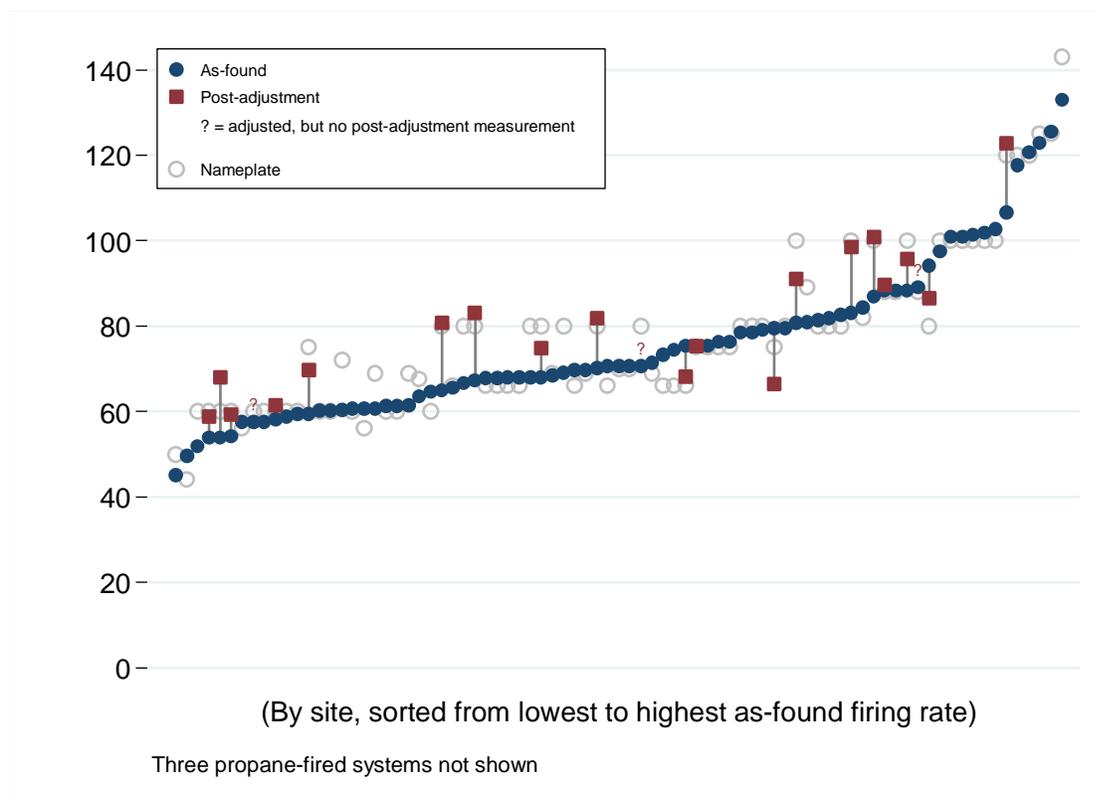
The furnace manifold connects the gas valve to the main burners, and manifold pressure is thus the pressure of natural gas delivered to the burners. For proper flame and firing rate, it is important that this pressure be set to the manufacturer’s specifications. Furnaces are typically

designed for a manifold pressure of about 3.5 inches of water column (in high-stage operation for multi-stage units). If the manifold pressure is below this target, the furnace will be under-fired; severe under-firing can result in condensation in the primary heat exchanger, causing it to fail prematurely. Conversely, manifold pressure above the target will result in an over-fired unit, which will run hotter than designed, and compromise efficiency.

As-found manifold pressure was recorded for 49 sites, and adjusted for 22 sites.²² The large majority of the adjustment cases (n=18) were sites where the measured manifold pressure was below the specified setting; only four sites had measured manifold pressure above the nameplate specification. The typical adjusted site had an as-found pressure of 2.6 IWC, or 1 IWC below the typical nameplate specification of 3.5 IWC.

Increasing the manifold pressure, increases the gas flow to the furnace and thus its firing rate. As Figure 11 shows, because most of the manifold pressure adjustments were increases, these adjustments mostly resulted in increases to the firing rate of the units.²³

Figure 11. As-found, adjusted and nameplate furnace firing rate, by site.



²² The heating-system tests came at the end of the overall site-visit protocol, and there was not always time to complete the full protocol.

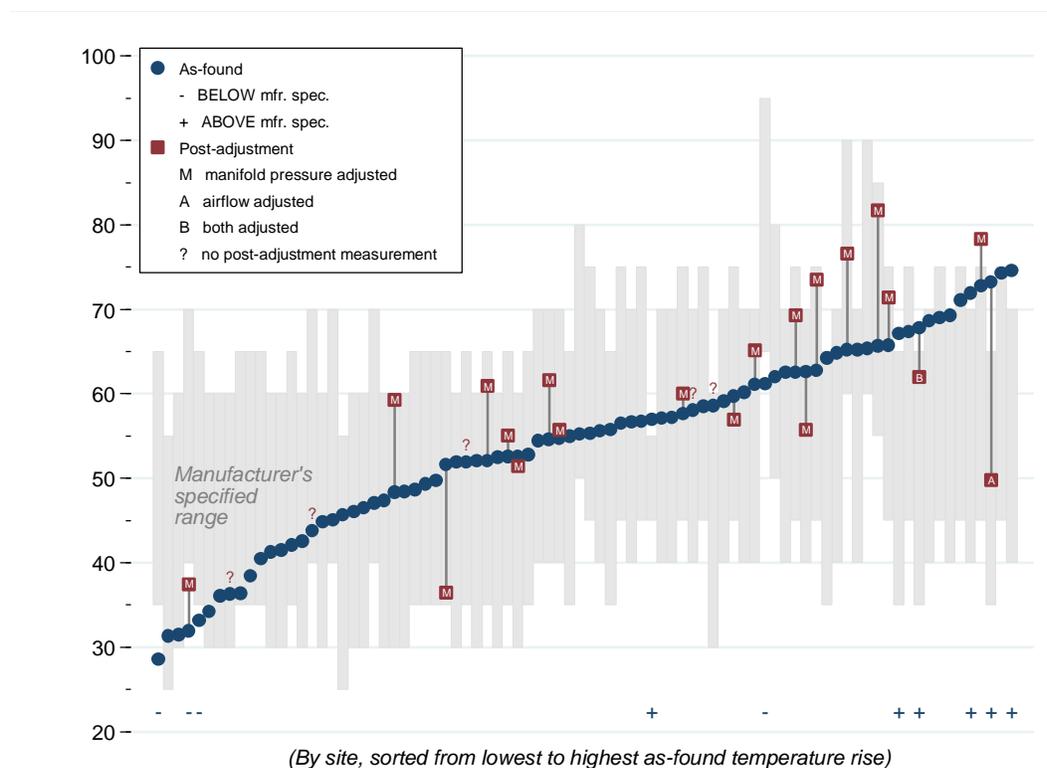
²³ To estimate the firing rate of each system, we measured the gas flow rate to the furnaces by clocking the home's gas meter, and converted this to an estimated firing rate using a conversion factor of 1,046 Btu per cubic foot, which is the average heating value for natural gas in Minnesota between July and September 2014, as reported by the federal Energy Information Agency.

Temperature Rise

Furnace temperature rise is simply the difference between supply and return air temperature, and is determined by the combination of firing rate and airflow. For a given firing rate, lower airflow results in higher temperature rise and vice versa. Gas efficiency suffers somewhat with high temperature rise, because a smaller proportion of the heat created by the furnace is transferred to the air stream that is delivered to the house.²⁴ On the other hand, more electricity is consumed by the furnace blower to deliver the higher airflow needed for a lower temperature rise.

In addition to efficiency implications, units with temperature rise above the nameplate range experience additional thermal stress, and could pose a safety concern (though all furnaces also have a high-limit switch to prevent severe overheating). Units with temperature rise below the nameplate range are at increased risk of condensation in the primary heat exchanger, which could cause it to fail prematurely. For these reasons, manufacturers specify the acceptable range of temperature rise for their units; this range typically spans 30°F, though with varying low- and high-end values, as Figure 12 shows.

Figure 12. As-found and adjusted heating-mode temperature rise for furnaces.



Ten of the 84 tested systems (12%) were found to be outside the manufacturer's specified temperature-rise range: four were below the manufacturer's range, and six were above (Figure

²⁴ One manufacturer has stated that furnace efficiency declines by about one percentage point for every 15 degrees of increased temperature rise (Brand, 2012).

12). Airflow adjustments were made at only four sites; the others presumably could not be corrected due to limited ability to adjust airflow.²⁵ Most of the changes to temperature rise came about as result of adjustments to manifold pressure, and most of these resulted in an increase in temperature rise as a result of increasing the firing rate of the furnace – though most remained within the desired range. However, at one site, the manifold pressure adjustment pushed the temperature rise slightly above the manufacturer’s range.

The blower-off delay is the amount of time that the unit continues to operate the main blower after the thermostat is satisfied and combustion has ceased. This delay helps scavenge heat from the unit, and deliver it to the living space. A longer blower-off delay scavenges more heat, but also results in a longer period of relatively cool air being distributed to the house. All but two of the sites had blower-off delays of at least 90 seconds, and some had delays of up to three minutes. We made no adjustments to these settings.

Adjustable air shutters are present on older furnaces, and allow for changing the fuel-to-air ratio for combustion. Most new furnaces do not have adjustable shutters, and no adjustments were needed for any of the systems that we tested. We did encounter one new furnace that appeared to have been damaged at some point (perhaps in shipment) where the entire burner assembly was bent. This was corrected separately under warranty by the homeowner.

Change in heating efficiency

As part of the test protocol, we measured the steady-state efficiency of the heating systems before and after adjustments using standard combustion analyzers. However, these combustion analyzers are not well-suited for accurately measuring the efficiency of condensing heating systems, which constituted three quarters of the tested systems.²⁶ We therefore attempted to improve on these values by calculating an adjusted steady-state efficiency that used the combustion-analyzer indicated stack temperature and oxygen concentration, but incorporated the condensate-production data directly collected by the test rigs.²⁷

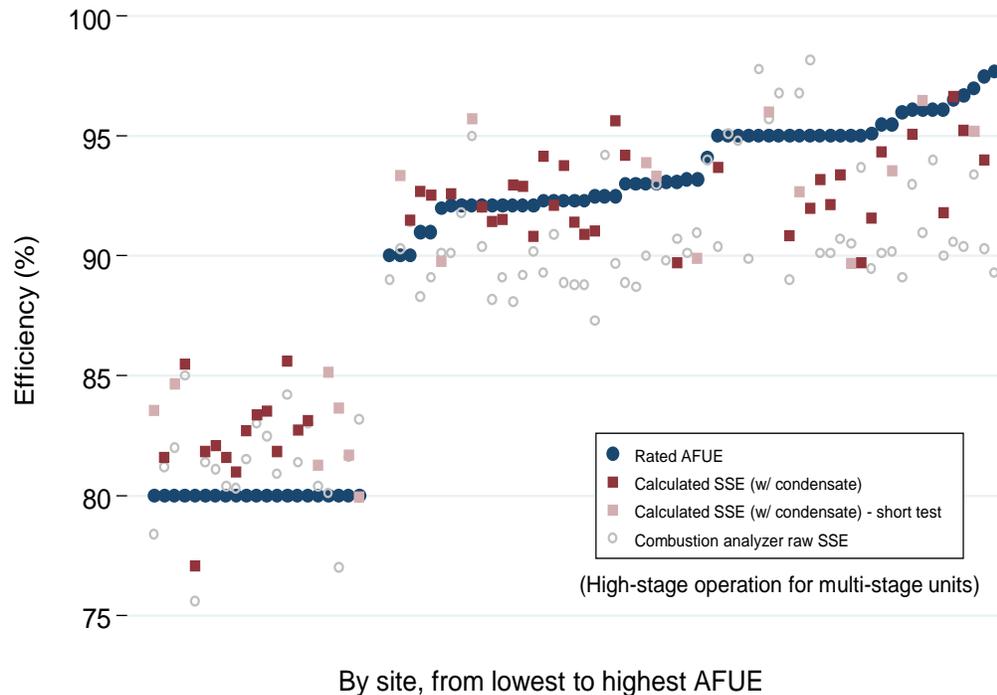
Figure 13 compares the measured as-found steady-state efficiency (SSE) to each furnace’s AFUE, the latter being the rated seasonal efficiency of a furnace based on a federal test procedure. Strictly speaking, the two are not directly comparable, because AFUE is measured under prescribed and controlled conditions, while SSE is simply a measure of combustion efficiency under the conditions found at the time. But generally speaking, one can expect to obtain an SSE that is within a few percentage points of AFUE for a properly operating furnace.

²⁵ Furnaces with PSC blowers have a limited number of speeds to choose from, and there may not be a speed that produces temperature rise in the required range. Also, some multi-stage furnaces with ECM blowers self-regulate airflow, and do not allow for adjustments.

²⁶ See Pigg and Parkhurst (2007) for a discussion of issues with using combustion analyzers on condensing systems.

²⁷ This was not possible for some systems due to issues with the condensate data collection.

Figure 13. Furnace rated AFUE and as-found measured efficiency (SSE).

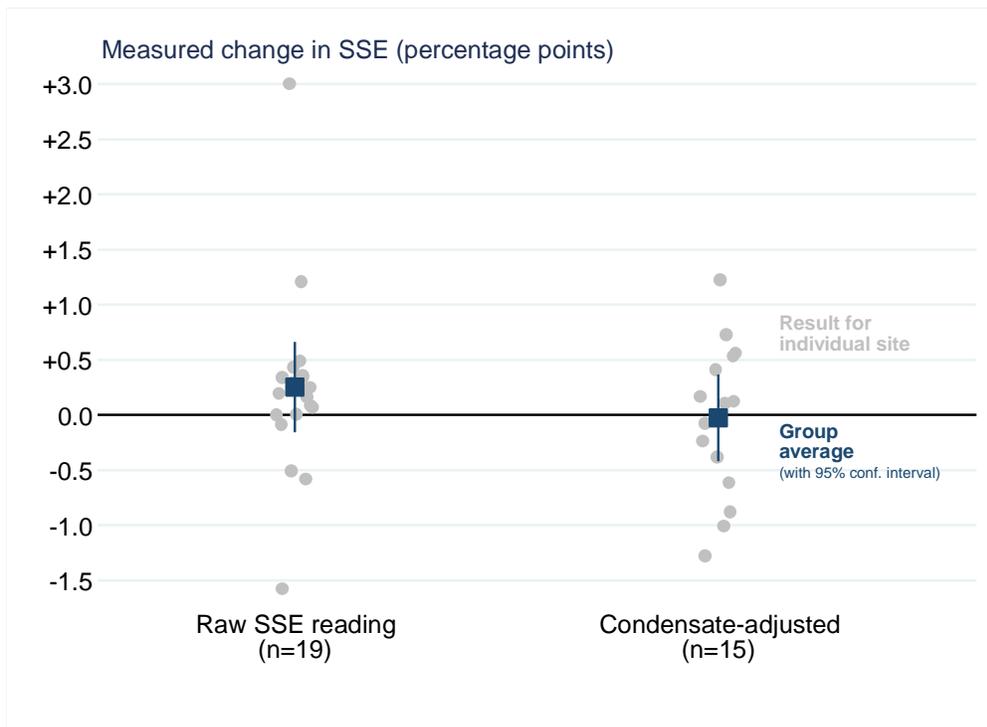


In general, the results show measured efficiencies that are somewhat higher than AFUE for the non-condensing furnaces (AFUE of 80), about the same as AFUE for condensing furnaces with AFUEs in the range of 90 to 94, and somewhat lower measured efficiency for furnaces with AFUE ratings of 95 or higher. The scatter in the measured values suggests inherent uncertainty in these measurements, and later review of the data suggests that some systems were not fully at steady-state when tested (these are denoted as “short test” in the figure). On the whole, however the data suggest that the condensing furnaces were operating in high-efficiency condensing mode.

Among the 19 systems that were adjusted, the combustion analyzers indicated an average 0.2 (\pm 0.4) percent increase in combustion efficiency after adjustment, with a range of observed values from -1.5 percent to +3.0 percent (Figure 14). The change in condensate-adjusted SSEs show a wider spread – and higher incidence of negative efficiency impacts – than the raw combustion-analyzer data would suggest: these ranged from -1.2 percent to +1.3 percent with an average of close to zero, and a 95 percent confidence interval around the average of \pm 0.4 percentage points.

Overall, while inherent uncertainty in these measures clouds the analysis somewhat, the results suggest that if there were improvements in combustion efficiency from the adjustments they are small on average.

Figure 14. Measured change in gas heating efficiency for furnaces.



Furnace Monitoring Findings

We installed monitoring equipment to track burner operating time on 55 gas furnaces in the field-study sample. For the nearly half of the study sample that comprised multi-stage furnaces, we monitored operating time by stage.²⁸ Combined with firing-rate measurements made at the time of the field visits, this allowed us to calculate daily operating hours and gas consumption, which in turn formed the basis for site-specific linear models of furnace operation versus outdoor temperature (see [Appendix F](#)).

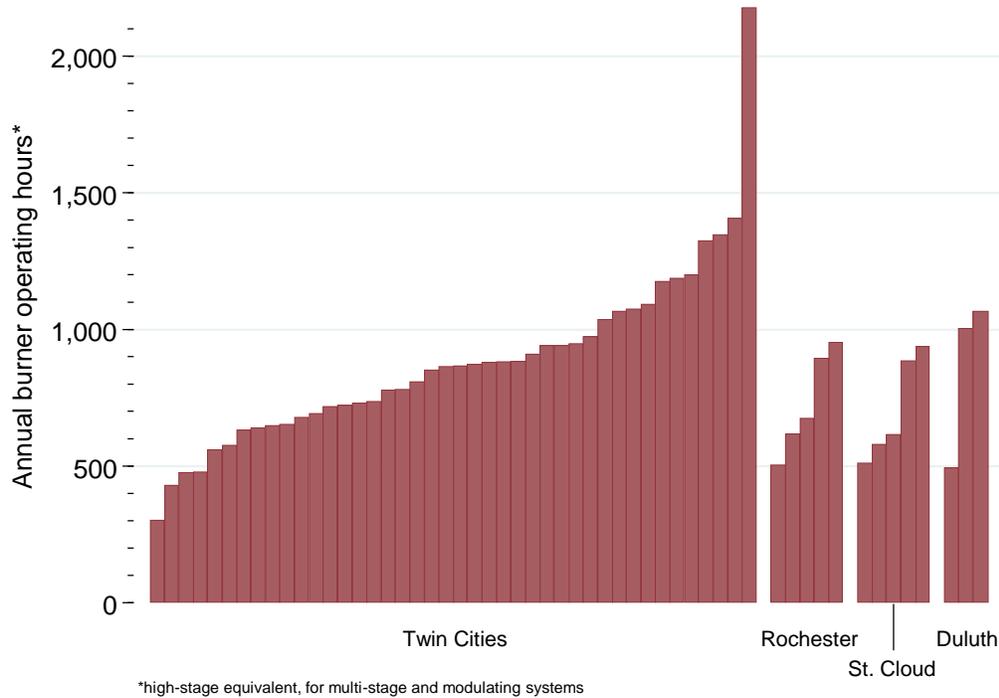
On a seasonal, weather-normalized basis, annual burner operating hours for the monitored furnaces ranged from about 300 to more than 2,000, though most fall between 500 and 1,200 hours (Figure 15).²⁹ Note that for multi-stage and modulating furnaces, burner hours are defined here (and shown in Figure 15) in high-stage equivalent terms; in other words, the number of hours that the unit would operate if it fired only in high stage. Actual operating hours for multi-stage furnaces are considerably higher, because most operate a significant amount of the time at a lower firing rate: on average, the monitoring data indicate that total

²⁸For the four monitored study sites with fully modulating furnaces, we used one-minute data on current draw for the unit to infer modulation level, on the assumption that airflow – and hence blower power – is reasonably proportional to firing rate.

²⁹ We define the heating season as spanning from September through May. Average indoor temperatures (on the first floor) for the monitored sites during the heating season ranged from 59 to 75F with a mean of 68F.

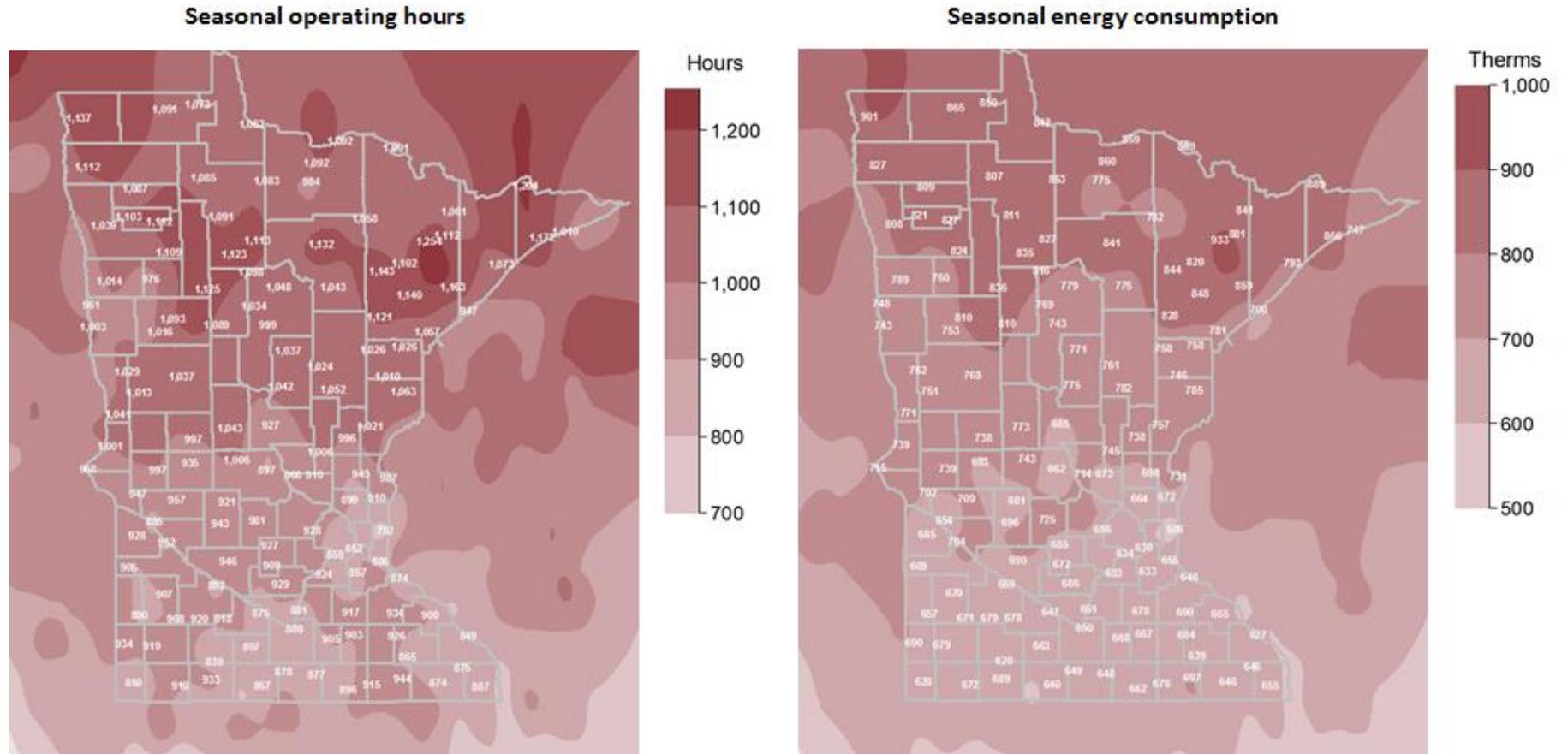
operating hours for these units is about 50 percent higher than would an otherwise equivalent single-stage furnace.

Figure 15. Seasonal weather-normalized operating hours for monitored furnaces, by location and site.



In a manner similar to that for cooling systems, we projected the results for the monitoring sample across the state in order to estimate how average heating system operating hours and gas consumption varies geographically. Figure 16 shows the distribution of these values across Minnesota. On average, the data suggest about 0.11 annual operating hours and 0.08 therms of gas consumption per heating degree day (Base 65°F). For the Twin Cities area, this works out to about 850 annual hours and 630 annual therms in a typical heating season.

Figure 16. Estimated average seasonal hours of operation and energy consumption for gas furnaces, by location.



(High-stage equivalent for multi-stage furnaces)

Heat Pumps

The study field sample included 10 central, air-source heat pumps. All of these homes also had gas or propane heating systems for space heating in cold weather when a heat pump typically cannot meet the home's heating load.³⁰

Although the number of heat pumps in the sample was small, the performance testing generally revealed similar incidence rates of refrigerant charge adjustments, airflow adjustments, filter changes and condenser-coil cleaning as for the central air conditioning systems in the study, and the average performance improvement from these is reasonably comparable (Table 17).

Table 17. Summary of Cooling-mode adjustments for heat pumps and air conditioners.

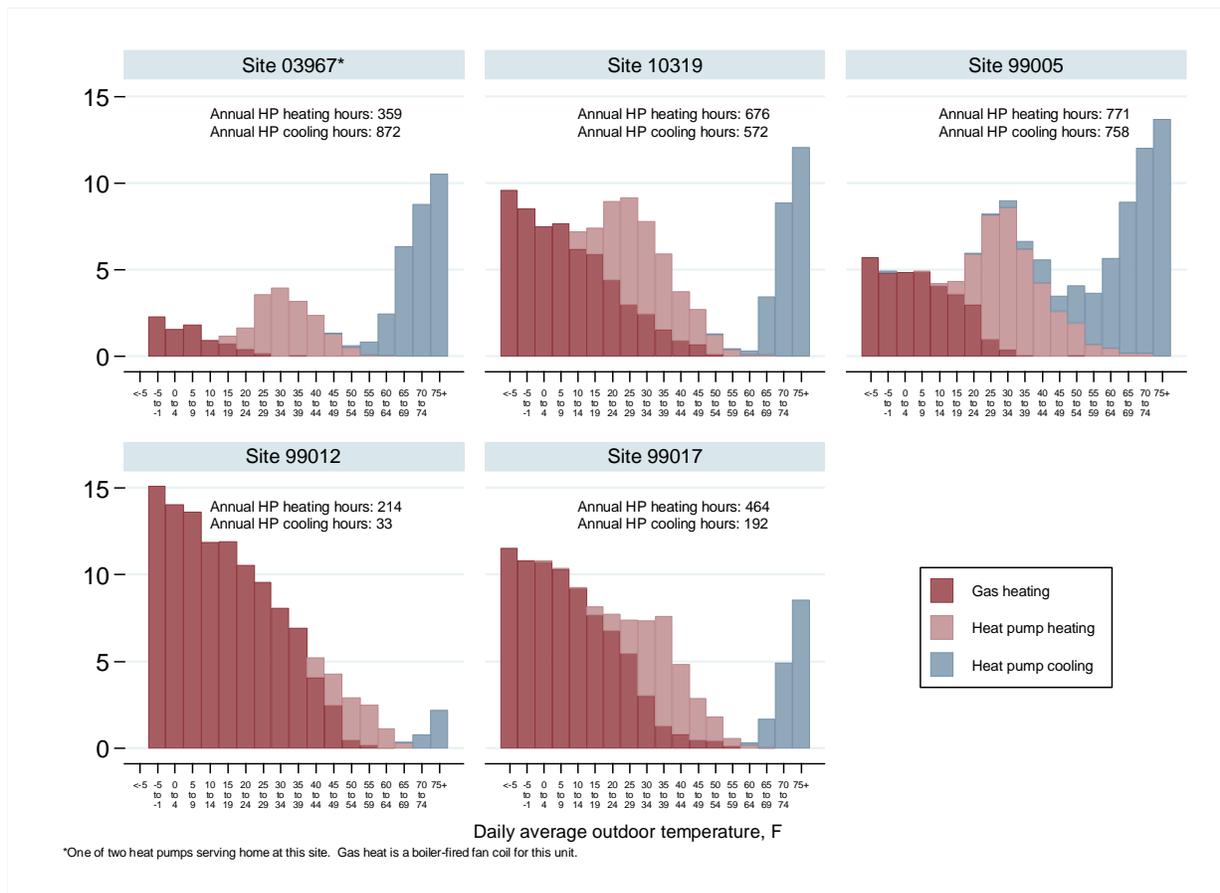
		Heat Pump (n=10)	Air Conditioner (n=99)
Type of adjustment (in descending order of incidence)	No Adjustments	0%	14%
	Refrigerant charge	80%	69%
	Airflow	40%	54%
	Filter replacement	40%	32%
	Condenser coil clean	10%	24%
	TXV	10%	3%
Mean % change in EER		9.5 ± 7.2	13.2 ± 3.4

Five of the heat pump sites received longer-term monitoring. Analysis of these data show that in addition to supplying cooling in the summer, the heat pumps shouldered much of the mild-weather heating load for the homes (Figure 17). Weather-normalized annual heat pump operating hours in heating mode ranged from about 200 to 800 for these five sites.

One site (Site 99005) is notable in the fact that it shows a considerable range of heating *and* cooling at similar outdoor temperatures. Closer examination of the data for this site show 87 days when the heat pump operated in both heating and cooling mode for at least 30 minutes each on the same day, with cooling operation occurring all the way down to freezing temperatures, and heating operation occurring well into the 70-degree range for outdoor temperature. We observed some periods where heating and cooling occurred in the same hour. Our best guess is that the thermostat for this system was set for auto heating/cooling operation. On the household survey, the occupants reported that they keep their thermostat set at a constant 72F year round.

³⁰ In all but one case, this was a gas furnace. The exception was a home with two heat pumps and hydronic in-floor radiant heat for the zone served by one of the heat pumps and a boiler-supplied fan coil for the other.

Figure 17. Operating hours for monitored heat pump systems.



Fan-Only Operation

Another aspect of central forced-air systems is power consumption in fan-only mode; i.e. times when the furnace or air handler operates but there is no call for heating or cooling. The homeowner telephone survey suggests that about half of all households practice fan-only operation at some point in the year, and about one in six households runs their air handler year round (Table 18). Some households choose to circulate air continuously for filtration purposes or to help equalize temperatures around the house. In other cases, the air handler may be interlocked with a heat recovery ventilator or other ancillary HVAC device, such that it is triggered whenever that device operates. Notably, about one in ten respondents to the telephone survey gave no reason other than that their installer had recommended it, a phenomenon that has been observed in at least one other study as well (Talerico and Winch, 2009). The practice is about twice as common among households with a furnace that is 15 years old or less, compared to those with older systems.

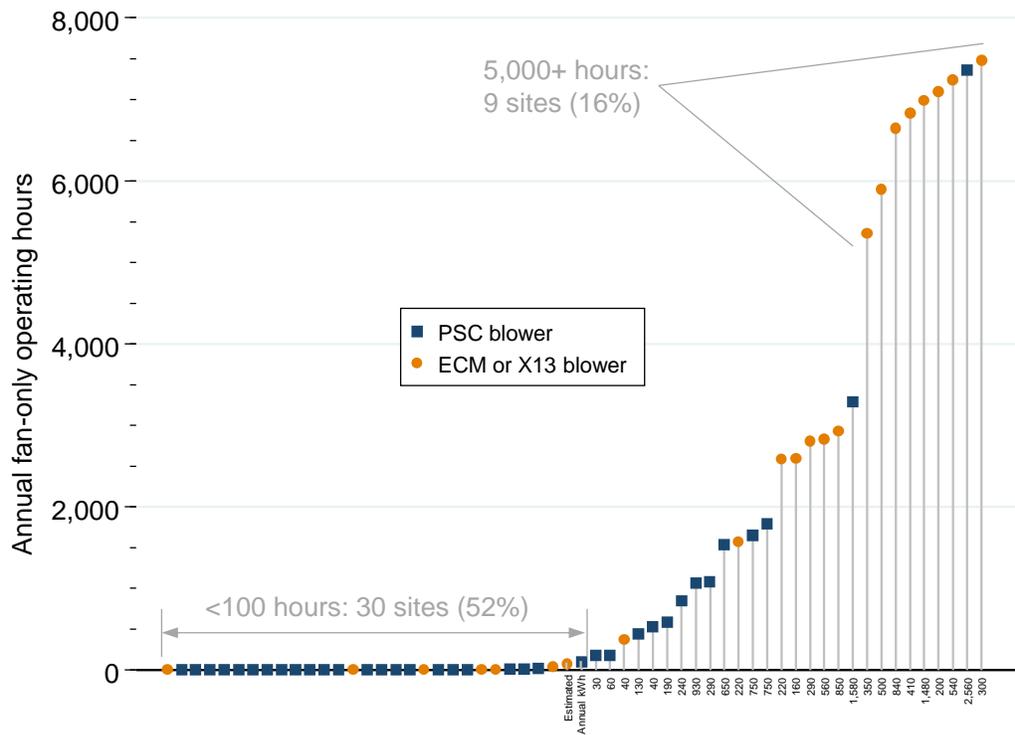
Table 18. Homeowner telephone-survey reported fan-only practices in winter and summer.

		Fan-only practiced in <u>Summer</u> ?			Total
		Yes	Sometimes	No	
Fan-only practiced in <u>Winter</u> ?	Yes	16%	2%	4%	22%
	Sometimes	2%	6%	3%	12%
	No	5%	13%	48%	66%
	Total	23%	21%	55%	100%

n=646 (weighted responses)

Data from the field-study sites with long-term monitoring reflect the survey results closely (Figure 18). About half of the sites showed little or no fan-only operation during the year of monitoring, and about one in six practiced year-round fan-on operation.³¹ The remainder fell somewhere between these extremes.

Figure 18. Fan-only operating hours for monitored sites.



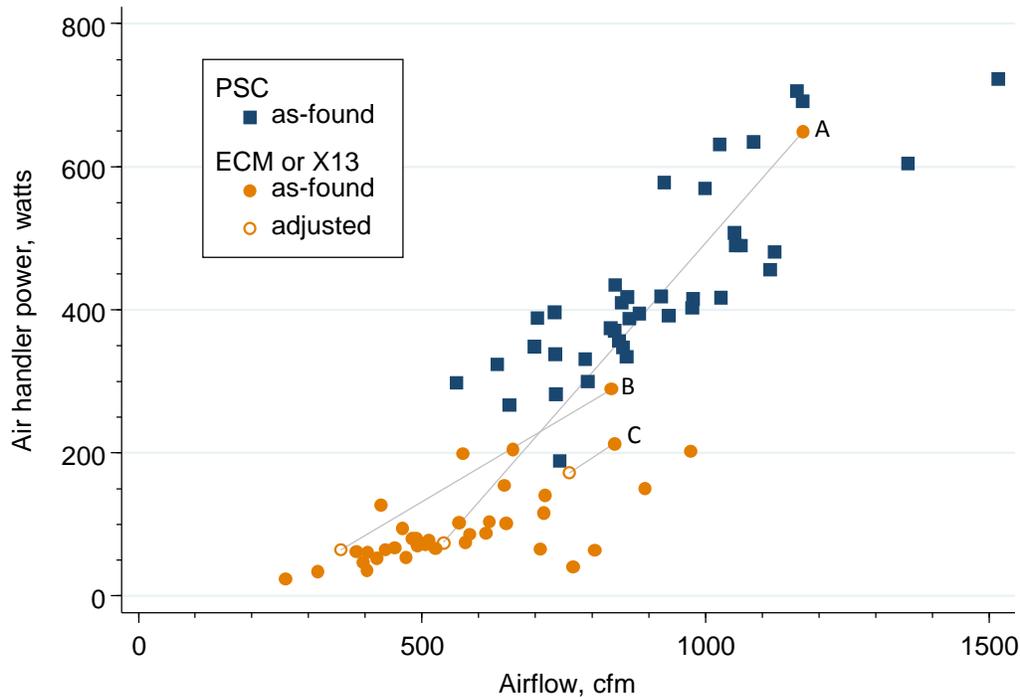
By site, sorted from lowest to highest fan-only hours

For assessing the energy implications of this practice, there is a fundamental distinction between variable-speed furnaces and air handlers, which have ECM or X13 type blower motors and conventional units with PSC blowers. The wide available airflow range of the former means that they can be configured to deliver gentle airflows at much lower power draw in fan-only

³¹ Practicing year-round fan-on operation typically results in between 6,000 and 8,000 fan-only hours; the remainder is made up of heating and cooling cycles.

mode compared to the latter. As Figure 19 shows, as-found power draw for the variable speed furnaces in the study were nearly all below 200 watts, and many were below 100 watts. In contrast, nearly all of the furnaces with PSC blowers drew more than 200 watts and delivered higher airflows.

Figure 19. Air handler power and airflow in fan-only mode.



Fan-only airflow for ECM furnaces can also typically be adjusted by way of jumpers or DIP switches on the furnace control board (as well as by the homeowner at the thermostat for owners of systems with matched proprietary thermostats). PSC-based air handlers on the other hand, typically have the fan-only blower speed tied to the same setting as heating-mode airflow, and the former cannot be adjusted without also affecting the latter.

This configurability of ECM furnaces can sometimes lead to trouble, however, as appears to be the case for two of the systems that we tested. These systems – which are labeled “A” and “B” in Figure 19 – were delivering much higher airflow – and drawing much more power – than is typical for an ECM-type blower. Since these furnaces are typically factory-shipped with fan-only airflow set to a low setting, we can only presume that the setting was changed for some reason in the field by the installers. When adjusted back to their lowest speed setting (along with a third system, “C,” which was adjusted by a more minor amount), power draw and airflow for these units came back in line with the other ECM air handlers.

Such misconfigured ECM fan settings, while uncommon, can have significant electricity-use implications if they occur in a household that incurs a significant amount of fan-only operation. The difference in power draw can easily be several hundred watts, playing out over several thousand hours of operation.

Investigation of Airflow Measurement Methods

As noted previously, we found that very few contractors make system airflow measurements when installing a new air conditioner or heat pump. This may partly be due to lack of a perceived need for fine tuning cooling airflow, but it may also be due to the difficulty (real or perceived) in doing so. There are a number of ways to measure airflow through the central air handler. To assess relative ease of use – and accuracy – of methods that are generally available to service technicians, we conducted a limited comparison of airflow-measurements methods as part of the study. Specifically, we looked at the following methods:

- **Flow plate** – this method replaces the filter with a calibrated flow plate (which is a flat plate with holes of known size and location in it), and uses the pressure drop across the flow plate to measure airflow, based on the known relationship between the two. The effect on airflow of having the plate (instead of the filter) in the airstream can be eliminated by measuring the static pressure in the duct system with and without the flow plate in place, and applying a correction factor.
- **Hot-wire anemometer** – a hot-wire anemometer uses a heated wire (typically mounted on an extendable probe) to measure air velocity. Velocity measurements at various points in the ductwork can be combined with the duct dimensions to estimate airflow. A similar approach is to use a pitot tube to measure the velocity pressure of the airflow (which can be converted to velocity) at various points in the system.
- **Evaporator-coil pressure drop** – most manufacturers of evaporator coils publish data relating pressure drop across the coil to airflow. The evaporator coil itself can thus be used in the same way as the flow plate method above – provided that the evaporator make and model are known, published pressure-drop versus airflow data are available, and the coil is clean.
- **Temperature-split method** – the temperature-split method does not measure airflow *per se*, but rather provides an indicator for whether airflow is too high or low. “Temperature split” refers to the temperature difference between return and supply air. To implement this method, the user measures the system temperature split and compares this to a table of target values. If the observed temperature split is outside a tolerance band around the target value, then either airflow is incorrect or another factor (such as improper refrigerant charge) is affecting the unit’s performance.

Table 19 provides a comparative summary of the above methods.

For the flow plate tests reported here, we used the [TrueFlow Air Handler Flow Meter](#), manufactured by [The Energy Conservatory](#), which is located in Minneapolis, and is the only commercially available product for this purpose that we are aware of. Because this device is estimated to be accurate to within ± 10 percent, we take it as our primary measurement of airflow here (and elsewhere in this report).³²

³² The manufacturer’s stated accuracy of the True Flow is ± 7 percent, but we estimate its accuracy at slightly less than this, given the instrumentation and protocol that we used. See [Appendix E](#).

Table 19. Key features of airflow test methods.

	Flow plate	Hot-wire anemometer (or pitot tube)	Evaporator-coil pressure drop	Temperature-split
Equipment required	Flow plate and manometer	hot-wire anemometer (or pitot tube and pressure gauge)	manometer	insertion thermometer capable of measuring dry-bulb and wet-bulb temperatures
Approximate equipment cost	\$900-\$1,700 (depending on type of manometer**)	\$300 - \$1,000	\$75 - \$850 (depending on type of manometer**)	\$75 - \$500
Approximate time required for test*	10-15 minutes	10-15 minutes	~5 minutes	~5 minutes
Basic steps for testing	(1) Drill hole, and measure system operating pressure. (2) Mount flow plate in filter slot. (3) Measure flow-plate pressure drop (airflow) and re-measure system pressure (4) remove flow plate and replace filter	(1) Drill holes in return plenum. (2) Conduct velocity traverse for each hole using hot-wire anemometer (or pitot tube). (3) Combine with duct dimensions to estimate airflow.	(1) Drill two holes for static pressure probes. (2) Measure static pressure drop across coil. (3) Relate to published table to estimate airflow.	(1) Drill holes for supply and return temperature measurements. (2) Measure return dry-bulb and wet-bulb temperatures. (3) Determine target temperature split. (4) Measure supply dry-bulb temperature, and calculate observed temperature split. (5) Compare observed temperature split to target value.

*Assumes (for tests that require cooling-mode operation) that the system is already operating at steady-state.

**Assumes \$75 for an analog magnehelic gauge with less precision, and \$850 for a digital manometer designed to directly

Overall, we found mixed results from this exercise. On the one hand, all of the alternative methods agreed with the flow plate airflow values *on average*, indicating that they do not tend to systematically under- or over-estimate airflow. On the other hand, they sometimes produced airflow estimates that varied substantially from the flow-plate based value. Typically, the hot-wire anemometer and coil-pressure-drop methods yielded values that were within 15 to 20 percent of the flow plate value; but in about one in 10 cases there was a 40 percent or higher discrepancy. Even a 20 percent difference can be important, since most of the airflow adjustments that we made were in the range of 20 to 30 percent.

The temperature-split method does not provide a measure of airflow *per se*, but rather provides a diagnostic for whether airflow is too low or too high. In our comparison, we found about 80 percent agreement in diagnosing airflow problems, but with the proviso that other performance issues (especially refrigerant charge) need to be dealt with first – otherwise low refrigerant charge can be mistaken for high airflow when using the temperature-split method. Since both low refrigerant charge and high airflow are common among Minnesota cooling systems, caution needs to be exercised when using this method.

More details on the comparison of airflow measurement methods can be found in [Appendix G](#).

Discussion and Recommendations

The results presented in this report lead to several important conclusions. First, the field findings indicate pervasive – though diffuse – savings opportunities related to properly tuning and maintaining central cooling systems, making these systems a potentially good target for utility CIP programs. It is especially striking that the field study revealed virtually the same incidence of opportunities for older and newer cooling systems, as well as for systems installed in both newer and older homes. This suggests that the large majority of air conditioners and heat pumps, regardless of age or efficiency level, present efficiency-improvement opportunities. These findings suggest that there is considerable remaining potential for addressing central cooling system field performance issues, largely through once-per-system-lifetime adjustments to refrigerant charge and airflow settings.

Current utility-program activity in this area is mainly concentrated on a small proportion of systems, namely, new high-efficiency cooling systems. Owing to their high nameplate efficiencies, utilities can offer attractive incentives for these units, which consumers, contractors and equipment distributors all find attractive. This in turn provides leverage for utilities to establish quality-installation standards for these systems. Utilities can and should maintain quality-installation standards for new high efficiency equipment that they incentivize.

However, these systems represent only about five percent of all installation and service calls that contractors make to Minnesota single-family homes.³³ This leaves on the table the majority of new standard-efficiency system installations and a very large stock of existing older systems, of which about a quarter receive a service visit each year.

But since homeowners have no awareness of how system performance can be compromised by poor installation practices, installers have little incentive to try to differentiate themselves in this regard--and service technicians have no compelling reason to take the time to assess important parameters like refrigerant charge and airflow. Although utilities can and do offer small incentives for addressing these systems, our interviews suggest that installers mostly do not find it worthwhile to go through the hassle of meeting utility reporting requirements for these. The end result is little program attention to performance improvements among the large majority of Minnesota central cooling systems.

Given the level of per-unit savings involved, utilities cannot simply increase incentives to try to address these untapped opportunities. Utilities thus need to focus on reducing the transaction costs associated with quality-installation and maintenance work for systems that do not qualify for high-efficiency incentives--as well as increasing consumer awareness and demand for these services.

Recent advances in test-equipment technology could make the process of validating and incentivizing good installation and maintenance activities almost entirely frictionless for

³³ This is a rough estimate based on: (a) 1.76 million single-family homes in Minnesota, 80% of which are estimated to have a central air conditioner or heat pump, and (from survey data collected for this study) 25% of which receive a service call in a given year; and, (b) an estimated 60,000 new system installations annually, 75% of which are estimated to be standard efficiency systems and 25% of which are high-efficiency models.

contractors. Technology is already on the market (for less than \$1,000) that streams time-series data about critical system parameters to a central server.³⁴ These devices not only make the technician's job of diagnosing and correcting defects easier, they also provide a track record of system performance throughout the service call, thus automatically providing the documentation utilities need to verify that the work was done, as well as a reasonable basis for on-going assessment of collective energy and peak-demand impacts from incentivized activities.

With a modest upfront investment in an appropriate platform, utilities could create a new program model in which a participating contractor simply registers the address of a home on a smartphone app at the time of an installation visit or service call, and the app then automatically geolocates the home within the appropriate utility service territory, as well as archiving system performance data during testing and adjustment. The contractor simply receives a check each month that corresponds to the number of jobs performed with the advanced equipment, without having to fill out any forms.³⁵ For their part, utilities receive documentation of the number of jobs performed in their service territory, and have access to valuable system performance data for regularly assessing savings and performing quality control checks.

In essence, this represents the next logical step in the verification-service-provider model, which currently requires technicians to phone in—or key into a tablet—information about system parameters. The difference is that advanced diagnostic equipment and cloud computing do the heavy lifting of both diagnosing defects and documenting important system parameters.

Notably, such a program model does not need to replace current program offerings, it could simply be offered as an enhancement to make life easier for contractors who choose to invest in advanced diagnostic equipment. Contractors who prefer to keep using their existing equipment could still participate via the existing model.

An enhanced program like this would be most successful if it was coordinated across utilities, or perhaps even implemented as a joint statewide program. This would increase the effort's overall visibility and leverage, and provide for a more robust quality-control process. Most importantly, a joint effort would make the program easier for contractors, who frequently work in multiple service territories. An upfront market-research effort with contractors to gauge interest and potential pitfalls, followed by a limited pilot program would help determine the viability of this concept.

Minnesota utilities could increase the reach of these programs by better engaging with HVAC equipment distributors in the state, whose interests mostly naturally align with those of the utilities. Distributors have a vested interest in having their product properly installed, because poorly-installed equipment can increase technical support calls and warranty claims. Distributors also often have existing contractor training programs and facilities, which could provide a platform for both promoting program efforts and providing hands-on training with

³⁴ See, for example, [imanifold](#).

³⁵ Since much of the savings potential is associated with once-in-a-system-lifetime adjustments of refrigerant charge and airflow, the app could also provide instant feedback regarding whether the system in question is eligible for incentivized testing and adjustment.

advanced diagnostic equipment for the type of enhanced program discussed above. Since distributors and manufacturers of advanced diagnostic equipment also stand to make money off sales of these devices, utilities could negotiate for cost-sharing associated with such trainings.

Regardless of the training provider and platform, contractors should continue to be certified with the type of training that several utilities already employ, and utilities could consider subsidizing the cost of the advanced test equipment. The pitch to contractors could be something along the lines of: “Join our Committed Contractor team. You’ll get a discount on the latest and greatest test equipment – which will save you time on every job – plus we’ll pay you every time you use it, with no forms to fill out.”

We also recommend that utilities focus on adjustment items that are: (a) commonly encountered; and, (b) result in demonstrable energy savings. Toward that end, we recommend that Minnesota utilities place most of their emphasis on refrigerant charge and airflow testing and adjustment. These two parameters not only make up the lion’s share of the total potential savings encountered in this study, but they are also system parameters that, once adjusted, should provide savings over the life of the equipment. We recommend *less* emphasis on load calculations and proper sizing, mainly because there is little field evidence that proper sizing has a substantial impact on energy consumption for new systems.

This brings up the notion of linking Minnesota programs to EPA’s [ENERGY STAR Verified Installation Program](#) (ESVI), which seeks to apply the widely-recognized ENERGY STAR label to cooling-system installation quality. Minnesota utilities should assess whether ESVI could provide increased visibility and consumer demand for quality-installation practices without imposing a significant reporting burden on contractors to document, for example, load calculations.

In addition to potentially using ESVI to increase consumer demand for these services, Minnesota utilities could do more to provide visibility and promotion for contractors who participate, thus leveraging a quality that both consumers and installers care first and foremost about – reputation. Installer reputation was the most-mentioned attribute that households told us they look for in choosing a contractor to install a new system, and contractors are keenly aware of this fact. Since utilities are generally regarded as one of the most trustworthy sources of information on household-energy related topics, this sets the stage for utilities to be able to provide a significant reputation boost for installers who meet their programmatic standards.

Increased utility promotion of “Committed Contractors” who participate in quality-installation and maintenance programs could translate into more business for these contractors, and thus lead to wider participation. Of course, utilities rightfully need to avoid implying any warranty related to the work that contractors perform. The websites for several Minnesota utilities go out of their way to make that point crystal clear – perhaps to the point of nullifying any potential promotional benefit. Utilities could do more to promote contractors who are indeed committed to their programs while still maintaining clarity that they (the utility) are not legally warranting the work that these contractors perform.

Minnesota utilities could help stimulate the demand for proper installation and maintenance of central cooling systems by taking steps to inform the public that installation practices matter, and that improper installation can increase cooling bills. For example, utility educational

materials could emphasize the finding from this study that one in six cooling systems in Minnesota is operating at less than 75 percent of its rated efficiency.

Fan-only practices also present an educational opportunity. The incidence of fan-only operation from our homeowner survey and monitoring sample is surprisingly high, and this practice can increase electricity consumption by several thousand kWh a year. Homeowners need to be made more aware of the energy costs associated with this practice, and utilities should take steps to mitigate the extent to which installers recommend that homeowners run their furnace fans constantly because it is more efficient that way (not true) or simply to provide more even temperatures throughout the home. Some households do have legitimate desire to operate their air handler continuously for ventilation, filtration or temperature-distribution reasons: for these households, a variable-speed furnace or air handler is a clear winner, given its ability to continuously circulate air at much lower power draw than conventional equipment. But the evidence from this (and at least one other) study suggests that at least some households that purchase a variable-speed furnace choose to operate the fan continuously for no reason other than the installer said it would be a good idea.

On the technical side, this study reveals a need for more emphasis on airflow measurement for cooling systems. High airflow is relatively common among Minnesota air conditioners and heat pumps, but most contractors do not measure airflow at all – and when they do, it is more typically measured at individual room registers, which is helpful for diagnosing air-distribution issues, but less useful for gauging whether total airflow at furnace or air handler is correct. Utilities could both boost the training emphasis on airflow settings for cooling systems, and, as noted above, perhaps provide subsidies to participating contractors to invest in the equipment to do so. Also, more research is needed to establish appropriate means for measuring system airflow: our preliminary investigation suggests that not all approaches are equal in this regard.

In terms of installation and maintenance of gas furnaces, this study suggests limited opportunities. The large majority of new and existing furnaces in Minnesota are high-efficiency condensing units that have little to adjust and, as best we can tell, appear to largely be performing as intended. That much said, this study was not optimized for a full investigation of gas-furnace field efficiency: because it included cooling systems, which can *only* be operated in warm weather, we were somewhat constrained in our ability to test furnaces, since many households were understandably reluctant to have their furnace running for an extended period on hot summer days.

Finally, the study included a small sample of air-source heat pumps, all of which were backed up by gas or propane heating systems in cold weather. Heat pumps appear to have the same incidence of opportunities for refrigerant charge, airflow adjustment and coil-cleaning as central air conditioners. One of the five units that we monitored over the course of a year showed a significant amount of heating *and* cooling operation on the same days, suggesting that there are some available opportunities to improve how these systems are controlled and operated.

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Glossary

AFUE	Annual Fuel Utilization Efficiency. This is the rated seasonal efficiency of a furnace, based on mandated federal test procedures.
Air handler	The blower and associated motor and cabinetry used to circulate air through a duct system. For homes with forced-air heat, the air handler is typically integrated with the forced-air furnace.
BTU (British thermal unit)	A measure of heat. 1 BTU is the equivalent of warming one pound of water by 1°F.
CIP	Conservation Improvement Program. Minnesota's statewide energy-efficiency program funded by ratepayers and administered by electricity and natural gas utilities.
Compressor	The part of a refrigerant system that compresses refrigerant in vapor form.
Condenser coil	The outdoor coil for a residential cooling system. Heat from indoors is rejected to the environment in the condenser coil, as gaseous refrigerant changes to liquid form.
ECM	Electronically Commuted Motor. A type of motor used in forced-air furnaces and central air handlers, characterized by higher electrical efficiency and wider airflow range than traditional PSC blower motors (see PSC).
EER	Energy Efficiency Ratio. EER is a measure of the efficiency of a cooling system, and is calculated as the ratio of cooling output (in Btu/hr) to energy input (in watts). EER varies with outdoor temperature and indoor conditions. Manufacturers report EER at a 95°F outdoor temperature, an 80°F indoor temperature and an indoor relative humidity of 50%.
EIA	Energy Information Administration.

Evaporator coil	The indoor coil for a residential cooling system. Heat from indoor air is absorbed by circulating refrigerant as it changes from liquid to gaseous form in the evaporator coil.
Fixed-orifice expansion device	A type of refrigerant-system expansion device that meters refrigerant at a constant rate. (See also TXV .)
IWC (Inches of water column)	A measure of pressure. 1 IWC is approximately 0.036 pounds per square inch of pressure.
PSC	Permanent-magnet, Split Capacitor motor. The type of blower motor used in many forced air-furnaces. This type of motor has a limited number of fixed operating speeds (see ECM).
R-22	A type of refrigerant commonly found in older residential cooling systems. Systems that use R-22 are no longer allowed to be manufactured.
R-410a	The dominant type of refrigerant currently used in new residential systems.
RCA	Shorthand notation for Refrigerant Charge and Airflow.
SEER	Seasonal Energy Efficiency Ratio. The seasonal cooling efficiency of a central air conditioner or heat pump. SEER is determined by a federally-mandated test procedure. (See also EER).
Subcooling	A measure of refrigerant thermodynamic state on the liquid side of a refrigerant system. Subcooling is the difference between the saturation temperature and the observed temperature of the liquid refrigerant (typically just after it leaves the condenser coil). Refrigerant charge for systems with TXVs is typically assessed by comparing the observed subcooling with a target value specified by the manufacturer. (See also Superheat .)

Superheat	A measure of refrigerant thermodynamic state on the vapor side of a refrigerant system. Superheat is the difference between the observed temperature of the gaseous refrigerant (typically just before it enters the compressor) and the saturation temperature. Fixed-orifice system charge is assessed by comparing the observed superheat with a target value that depends on the outdoor air temperature and indoor humidity. (See also Subcooling .)
Ton	Measure of the capacity of a cooling system, equivalent to 12,000 BTU per hour. Derived from the fact that melting a ton of ice in a 24-hour period is equivalent to 12,000 BTU per hour of cooling.
TXV (Thermostatic expansion device)	A type of refrigerant-system expansion device that can adjust the flow of refrigerant in response to changing conditions. (See also Fixed-orifice expansion device .)
X13	A type of blower motor that has characteristics of both PSC (limited number of airflow choices) and ECM (wide range of airflows) motors.

Appendix A – A Primer on central air conditioner, air-source heat pump and furnace operation

Central Air Conditioners and Heat Pumps

A residential air conditioner moves heat by taking advantage of the fact that when a substance (in this case a special refrigerant) changes from a liquid to a gas, it absorbs heat from its surroundings; and, conversely, when it changes from a gas to a liquid, it releases heat to the environment. The components of an air conditioner are designed to make the former happen *inside* the home, and the latter happen *outside* the home, thereby moving heat from indoors to outdoors. A heat pump expands on this concept by allowing for the system to work in either direction, so that in the summer, it can move heat from indoors to outdoors, but in the winter it can run the system in reverse to move heat from outdoors to indoors.

How do these systems accomplish this? The key is to create large differences in pressure in the system so that the refrigerant boils from liquid to gas at the appropriate place and condenses from gas to liquid at a different spot in the system. In the case of an air conditioner, the liquid-to-gas change occurs in a so-called evaporator coil located inside the home's duct system (typically just above the furnace). There, liquid refrigerant under high pressure is sprayed through a small orifice that separates the high-pressure side of the system from the low-pressure side. The large reduction in pressure causes the refrigerant to flash rapidly into a vapor, and absorb heat from its surroundings – which is the air flowing through the heat-transfer coils inside the ductwork. The refrigerant vapor then travels to the outdoor unit where it is compressed, and pumped into the outdoor (or condenser) coil. Here, the large increase in pressure from the compressor causes the refrigerant to condense back into a liquid where it releases heat to the outdoor surroundings, aided by heat-transfer coils and a fan that moves air through them.

An air conditioner or heat pump thus has five key components:

- **Expansion device** – the expansion device is nothing more than a restriction in the refrigerant circulation system that separates the high- and low-pressure sides of the system. It limits the rate at which liquid refrigerant under high pressure can pass into the low-pressure side of the system. Most older residential air conditioners have fixed-orifice expansion devices, allow refrigerant to pass at a fixed rate. In recent years, thermostatic expansion valves (TXVs) have become popular: these devices use a feedback loop to adjust the flow of refrigerant as conditions change.
- **Evaporator coil** – The evaporator coil sits inside the home's ductwork (typically on top of the home's furnace), and receives refrigerant from the expansion device. As the liquid refrigerant sprays through the expansion device, it encounters a low-pressure environment inside the evaporator coil, causing it to flash into vapor. In the process, the refrigerant absorbs heat from its surroundings, which makes the evaporator coil cold. Indoor air that is being simultaneously circulated through the ductwork is thus cooled. The air is also dehumidified whenever the temperature of the evaporator coil surface is below the dew point of the indoor air. In this case, by the same principle that cause

moisture to accumulate on the outside of a glass of ice water on a humid summer day, water condenses on the surface of the evaporator coil and drips into a collection pan and drain system to be removed from the home.

- **Compressor** – the job of the compressor is to move refrigerant through the system, and to create the high and low pressure needed on the two sides of the system. As the name implies, the compressor receives low-pressure refrigerant in vapor form from the evaporator coil, compresses it, and delivers high pressure vapor to the outdoor condenser coils. Most residential air conditioners have compressors that operate at a single capacity, but two-stage systems have been on the market for some time, and fully-modulating central systems are beginning to enter the market.
- **Condenser coil** – The condenser coil receives high-pressure vapor from the compressor. The increase in pressure caused by the compressor, reduces the boiling point of the refrigerant to the point that it can no longer remain in gaseous form at normal ambient temperatures. As the refrigerant condenses into a liquid, heat that was absorbed indoors at the evaporator coil is released to the environment through the condenser coil. A small fan in the condensing unit assists in moving air across the coil to facilitate this heat transfer.

Indoor air handler – though not a part of the refrigerant system *per se*, the indoor air handler – which is most commonly the blower in the home’s forced-air furnace – is an important part of the cooling system. In cooling operation, the indoor air handler circulates air through the home’s duct system and thus past the evaporator coil. Residential cooling systems are designed to operate most effectively in a range of about 300 to 400 cubic feet per minute of airflow per ton of cooling capacity. At very high airflow, dehumidification is compromised (as we discuss below), and system efficiency may suffer due to high air-handler power. At very low airflow, there is risk of ice forming on the evaporator coil, which in turn severely compromises the performance of the system. Since most central air conditioners in Minnesota use a forced-air furnace for air circulation, we discuss airflow settings and blower-motor technology in more detail in the next section.

Air conditioners (and heat pumps running in cooling mode) perform two tasks: they cool the indoor air and they remove humidity from it.³⁶ It is easy to see how the former is accomplished simply by placing a cold evaporator coil in the middle of a circulation airstream, but what about the latter? The answer is that an air conditioner’s evaporator coil behaves in the same way that a glass of ice water on a hot summer day: its cold surface collects moisture from the surrounding air. Evaporator coils are specifically designed to create this effect, and drain away the moisture that condenses out of the circulating air. The amount of dehumidification provided by an air conditioner depends on how much moisture is in the air that it circulates and also on the temperature of the evaporator coil, which in turns depends on whether it is properly charged with refrigerant and the rate of airflow over its surface. Typically, between and quarter and a third of the cooling energy for an air conditioner goes to dehumidification and the rest goes to cooling the temperature of the air.

³⁶ For reasons that make sense mainly only to mechanical engineers, these two functions are called *sensible* and *latent* cooling, respectively.

Forced-Air Furnace

At its most fundamental level, a forced-air furnace simply burns natural gas (or less frequently, propane or fuel oil) to heat air that is circulated through the home's duct system by a blower in the furnace cabinet. This is chiefly accomplished in the primary heat exchanger, where hot combustion products flow on one side of the heat exchanger, while the air to be warmed flows on the other side.

So-called condensing furnaces have a secondary heat exchanger to further cool the combustion products and improve the efficiency of the system. The efficiency boost derives from the fact that the two primary products of combustion are carbon dioxide and water vapor; when the latter is condensed back into a liquid by cooling it below the dew point of the combustion products – which is around 130°F for natural gas – additional heat is released. Condensing furnaces thus require a means of collecting and draining away the condensate that is produced.

Modern forced-air furnaces need few adjustments. Two important ones, however, are the gas manifold pressure and the blower speed. The gas manifold pressure setting essentially controls the rate at which gas is fed into the combustion chamber, and thus the firing rate of the furnace. Manifold pressure that is too low results in a lower firing rate, and cooler combustion products, with potential risk of condensation in – and consequent corrosion of – the primary heat exchanger. Manifold pressure that is too high can result in overheating and damage to the primary heat exchanger from thermal stress. Manifold pressure is checked in the field using a manometer, and adjusted by turning a set screw on the gas valve.

Blower speed (or more accurately, airflow) affects both the efficiency and delivered temperature of the air that is heated by the furnace. Airflow is indirectly specified by manufacturers in the form of specifying the required temperature rise range, temperature rise being the difference between the supply- and return-air temperatures. A typical nameplate temperature rise for a new furnace is 30 to 60F, meaning that the air coming out of the furnace should be between 30 and 60F warmer than the air entering it. Assuming that the firing rate is correct a high temperature rise means that airflow is low; conversely low temperature rise means that airflow is high. Even within the nameplate temperature rise range, a low temperature rise (high airflow) results in slightly higher gas efficiency but cooler delivered supply air, and high temperature rise (low airflow) delivers warmer supply air, but at somewhat reduced efficiency.

Airflow and Blower Type

Airflow setting (in heating or cooling mode) also affects the electricity use of the furnace. The power required to move air through the system increases with the cube of airflow, so higher airflow can mean dramatically higher electricity consumption by the furnace. Because the air handler motor actually sits in the unit's airstream, the electricity that it uses is converted to heat. In heating mode, this slightly reduces the amount of heat needed from natural gas combustion, but in cooling mode, blower-motor heat must be removed by the cooling system, and thus induces an additional efficiency penalty.

System airflow and power requirements are also affected by the airflow resistance of the system, which includes the ductwork, filter and indoor cooling coil, and can be measured in the field by examining the static pressures induced in the system at various points for a given

airflow. All else being equal, it takes more blower-motor power to move air through a system with restrictive ducts and filter at a given rate than it does to achieve the same airflow in a less restrictive system.³⁷ However, in practice, the relationship between airflow resistance, actual system airflow and air handler power depends on a third factor: the type of blower motor that is involved.

Until fairly recently, the large majority of furnaces and air handlers used an inexpensive blower motor known as a permanent-magnet, split capacitor motor, or PSC. The important characteristic of these motors is that they come with three or four available operating speeds, which are selected by the installer by physically plugging wires into appropriate connectors on the furnace control board. For example, the technician might select a Medium-Low speed for heating operation and High for cooling mode. Once these speeds are selected, the blower motor will run at one speed whenever the furnace is providing heat and at a different speed when the air conditioner is running.

The key to PSC blower operation, though, is that while the installer selects blower speeds, actual airflow rates depend on the flow resistance of the system: for a given air handler operating at a given speed, airflow (and electrical power consumption) will be higher for a system with less airflow resistance (i.e. large ducts and a non-restrictive filter), and lower for a system with higher airflow resistance. Also, the range of available speeds is not particularly wide for most PSC motors. Taken together, these attributes mean that it is impossible to fine-tune airflow for PSC-based systems, and, depending on the airflow resistance of the system, it may not even be possible to achieve airflow within a desired range. Moreover, for homeowners who fail to practice regular filter changes, airflow for PSC systems tends to drop as the filter becomes dirtier and more resistive to airflow.

However, in recent years, high-end furnaces with two or more stages of heating output have gained considerable market share in cold climate regions like Minnesota's. These furnaces are popular both because they have higher rated efficiency and because they operate much of the time at a reduced output rate that provides gentler heat with less noise and airflow. Because these furnaces need to be able to modulate airflow to match their firing rate, manufacturers have incorporated a more advanced (and expensive) blower-motor technology known as an electronically commutated motor, or ECM.³⁸

The important attributes of ECMs are that they are inherently more electrically efficient than PSC motors, and, more importantly, they can provide a much wider range of airflows. Moreover, most ECMs have the built in capability to sense static pressure and determine at least approximately how much airflow is being moved by the system.

Manufacturers have taken advantage of these features by making airflow selection easier for the installer – and by making their furnaces dynamically responsive to changes in system static pressure. Instead of selecting a speed tap to set the cooling-mode airflow and being unsure of

³⁷ For ductwork, “restrictive” means smaller diameter ducts with more bends: essentially anything that increases the friction in the system. For filters, “restrictive” applies to the combination of small surface area and tight weave of the filter itself. Dirt and dust also affect how restrictive the filter (and to a lesser extent the ductwork) is.

³⁸ These motors are sometimes also referred to as brushless permanent magnet, or BPM, motors.

what actual airflow results, the installer may only need to select the tonnage of the air conditioner via dip switches on the furnace control board, and the system will automatically produce the desired airflow taking into account the flow resistance of the system.³⁹ In addition, as the system filter becomes loaded, ECM-based systems respond by increasing the blower power to maintain desired airflow.

To further complicate matters, in recent years a *third* type of motor has hit the marketplace that is something of a hybrid between a PSC and an ECM. These motors are sometimes referred to as constant-torque motors, but more commonly called by the trade name X13 motors. An X13 blower motor can be considered to be something of a dumbed-down ECM: it uses the basic ECM motor technology, and thus enjoys the higher electrical efficiency and potentially wide airflow range of ECMs, but it provides only a limited number of airflow settings (like a PSC) and lack the dynamic adjustment capabilities of a full ECM in a high-end furnace. The available airflow for these motors are dependent on how manufacturers choose to program the available settings. They are used both in new equipment and as drop-in replacements for PSC-based systems.

³⁹ Indeed, some matched system eliminate even this step by enabling the furnace, outdoor cooling unit and thermostat to all communicate. The furnace may thus automatically know what size air conditioner it is producing airflow for, and adjust the blower output accordingly.

Appendix B – Interview Guides

Distributor Interview Guide:

Pre-Interview Information (may have been collected during distributor recruitment and scheduling).

Distributor Name	<i>(fill in appropriate information)</i>
Branch Location	<i>(fill in appropriate information)</i>
Contact Name	<i>(fill in appropriate information)</i>
Contact Title	<i>(fill in appropriate information)</i>
Contact Phone	<i>(fill in appropriate information)</i>
Contact Email	<i>(fill in appropriate information)</i>
Visit Date	<i>(fill in appropriate information)</i>

Products / Services Advertised (to be gathered before interview)

Product/Service	Remarks/Detail
AC Lines	<i>(fill in appropriate information)</i>
Furnace Lines	<i>(fill in appropriate information)</i>
Trainings Offered	<i>(fill in appropriate information)</i>

Project Background (some of this may have been covered in initial conversations with the distributor).

Who we are:

The Energy Center of Wisconsin is a private non-profit organization that conducts research on all things energy related in the Midwest, with a particular focus on energy efficiency. We were awarded a grant by the Minnesota Department of Commerce to study the current state of installation and maintenance practices for residential split air conditioning equipment in Minnesota.

What we are doing:

Our research is multi-faceted. Part of the research involves speaking with folks like you to gain a better understanding of the state of technology in the Minnesota res AC market and to get your opinions about QI/QM practices. We're conducting similar interviews with heating and cooling contractors and homeowners to collect a wide variety of data; including information about QI/QM practices and attitudes, baseline equipment saturations, firmographics and equipment operation practices.

Next, we'll be doing some field testing on approximately 120 split systems located throughout Minnesota to get a better understanding of the potential for energy savings through the implementation of QI/QM practices. Approximately half of these systems will be metered and then monitored for a year to collect information about each unit's day-to-day operation.

What we intend to learn:

We will assess the energy savings potential associated with remedying problems related to refrigerant charge, airflow and coil cleaning opportunities through utility-run QI/QM programs.

What we need to know from you:

I'd like to stress that anything you say will be held in confidence

We'd like to hear your perspective on the state of residential HVAC technology in Minnesota, particularly split air conditioners.

Our questions mostly deal with residential HVAC market trends and the market share of a selected set of specific technologies. We'd also like to get your opinions about the current state of installation and maintenance practices for res split ACs/ASHPs in Minnesota.

Finally, we'd like to get your opinions about our proposed field research and whether or not we are overlooking any important factors we should consider that might affect the quality of the installation or maintenance of res split AC/ASHPs.

1. Now I'd like to confirm the lines of equipment that you carry.

(Share with them a list of product prepared before the interview)

- a. What are your most popular lines?
- b. Are there specific AC models that you've seen a big uptick in the past 5 years?
- c. What attributes have made them popular?
- d. Do you distribute furnaces with ECM or X13 blowers?
 - i. More X13 vs ECMs?
 - ii. Trend going forward?
- e. What AC lines have integral thermal expansion valves (TXVs)?
- f. What do you think have been the most important technological advancements in the past 5 years?
 - i. Splits, condensers

- ii. Splits, coils
 - iii. Furnace blowers
 - iv. Controls (t-stats, etc.)
- g. While conducting our field research, we will need to reference pressure-drop/airflow charts when assessing the performance of evaporative coils. (Prompt for info on consolidated resources). What do you think is the best way to find these?
 - 1. Major brands/manufactures.
 - 2. 3rd party manufacturers (e.g. ASPEN)
- h. We might also run into situations in the field where we'll need immediate access to technical information about a system. Do you have any recommendations for getting technical questions answered on an immediate/impromptu basis (who to call)?
 - 1. Major brands/manufactures.
 - 2. 3rd party manufacturers (e.g. ASPEN)
- 2. The following questions are geared toward understanding how various market trends are reflected in the equipment you distribute to your customers.
 - a. Regarding CAC systems...
 - i. Can you estimate how many of your splits go to new construction vs. replacing existing systems?
 - 1. How has this changed since the housing bust?
 - 2. What do you think the trend will be moving forward?
 - ii. Of the CAC you distribute, what share are SEER 13 vs SEER 14 vs SEER 15 and above?
 - 1. Past five years until now?
 - 2. Moving forward?
 - 3. Do you expect the southern 2015 SEER-14 std. to affect the northern market?
 - iii. Of the CAC you distribute, what share are R-22 (dry-charge) vs. R410a refrigerant?
 - 1. Past five years until now?
 - 2. Moving forward?
 - iv. Of the CAC you distributed, what share use multi-stage vs single-stage condensers?
 - 1. Past five years until now?
 - 2. Moving forward?
 - v. What share of CAC that you ship are ASHPs?
 - 1. Past five years until now?
 - 2. Moving forward?
 - vi. Can you estimate the share of units you sell annually that are paired with evap coils that have an integral TXV?

1. Past five years until now?
 2. Trend moving forward?
 - vii. Do you think that many contractors are selling after-market TXVs as a retrofit option for existing evap coils?
 1. Past five years until now?
 2. Trend moving forward?
 - viii. Any other trends in CAC related equipment that we haven't spoken about?
 - b. What about furnaces? What share of the equipment that you distribute is:
 - i. Condensing vs. non-condensing?
 1. Past five years until now?
 2. Moving forward?
 - ii. Has a PSC vs ECM vs X13 blower?
 1. Past five years until now?
 2. Moving forward?
 - iii. Is single-stage vs. multi-stage?
 1. Past five years until now?
 2. Moving forward?
3. Regarding contractor practices, do you know approximately what share:
 - a. Replace the evaporative coil (on install of new condenser)?
 - b. Use 3rd party evaporative coils?
 - c. Oversize evaporative coils do get a higher SEER rating?
 - d. Offer add-on TXVs as a retrofit option?
 4. Now I'd like to get your perceptions about whether or not current EE program rebates or incentives have affected the market for efficient heating and cooling equipment and practices.
 - a. Do you think that high-efficiency product rebates have had any effect on market share?
(Prompt for effect on AC, furnaces, blower motors)
 - b. Do you think that any of the QI program rebates that are in place have impacted QI/QM practices in the field?
(Prompt for why or why not).
 5. Training
 - a. What trainings to you offer?
 - b. Any trainings related specifically to QI/QM practices?
 - c. What fraction of dealers/contractors that you deal with have the following certifications?
 - i. NATE-certified techs
 - ii. HVACRedu-certified techs
 - iii. ACCA-certified techs
 - iv. Manufacturer certification

- d. Are you aware of QI certification requirements?
 - i. Do you think these complement or contradict your own trainings?
(If yes, prompt for which ways)

Field research

Our field testing will focus on measuring refrigerant charge, airflow and assessing coil fouling and system sizing. The field sample will be biased toward newer systems, since utility-run QI/QM programs are typically added onto the sale of a new system.

What we will be monitoring in the field (for reference during interview):

On-site monitoring (90 new, 30 older)	On-going monitoring (45 new, 15 older)
Refrigerant-line pressure and temp	Operating status (heating, cooling, fan-only)
System airflow and static pressure drop (measured several ways)	Heating/cooling cycle lengths
Observance of coil fouling	Seasonal operating hours (by mode)
Observance of system sizing relative to load/residence characteristics	NA
Air handler and compressor power draw	NA
Supply-air, return-air and outdoor temperatures	NA
Condensate production rate (to measure latent cooling)	NA
Component power draw	NA
Expected results: Sequential correction of found issues in the field will allow for calculation of as-found, intermediate and final EER, and thus efficiency improvements gained from QI or QM procedures can be quantified.	Expected results: Operating characteristics of monitored systems will be used to assess: incidence of mis-sizing equipment; to project seasonal operating hours and peak-day cycling behavior; to better inform deemed savings estimates for QI/QM programs, as well as other MN EE measures (ECM furnaces and high-SEER AC)

6. Can you think of any other things you might recommend us taking a look at during our field research?

Area	Remarks
<i>(list area)</i>	<i>(fill in remarks)</i>
<i>(list area)</i>	<i>(fill in remarks)</i>
<i>(list area)</i>	<i>(fill in remarks)</i>

Contractors

Interview Guide for Contractors Minnesota CARD QI/QM Services

Hello I am _____ with the Energy Center of Wisconsin. We are working on a study for the MN Department of Commerce on residential HVAC contractor opinions, and installation and maintenance practices. Your company is one of 30 MN contractors we have randomly drawn in our interview sample. 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 20-30 minutes sometime in the next week or so to share information on your opinions and procedures? We are interviewing 30 contractors and will have a drawing to win an iPad Mini from that group (i.e., a 1/30 chance). Is there a time we can set up in the next week or so that would work for you? Thanks, I'll call you then. (Confirm email address and send reminder with my contact info.)

(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 installation and maintenance practices to provide insight and tools to increase the effectiveness of the utility Conservation Improvement Program. We are specifically looking at practices related to central air conditioners, forced-air furnaces, and air-source heat pumps. We are looking to characterize how things are currently being done, and you are being interviewed representing 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.

Day of interview. Thank you again for agreeing to do this interview to help us with our study. Is this still a good time?

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., it is his/her business) How long has the company been in this business (i.e., doing residential HVAC)?

3. What region or territory does your business cover? Do you know which utility territories you work within?
4. How many installers and service techs do you employ? How many residential HVAC installations do you do in a typical year?
5. What proportion of those installations is for new construction versus retrofits?

The rest of my questions are focused on forced air furnaces, central air conditioners and air source heat-pumps.

6. What brands of these types of equipment do you most often install? (If more than one) About what percentage of each?
7. Do you use manufacturers' or third party evaporator coils? If both, what %?
 - a. *(If use 3rd party)* What advantages does this give projects (i.e., why use them)? (e.g., better SEER rating, qualify for state incentives, system cost, etc.)?
 - b. Do you oversize coils for efficiency purposes?
8. What types of filters do you typically install? (1" thick disposable, 2-4" pleated, electronic)

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.

9. 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.)
 - a. Does it matter whether it is new construction or retrofit?
 - b. *(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.)*
 - c. *(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?
 - d. *(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?

10. Do you measure total air flow across the whole system at the air handler?
 - a. Do you measure air flow at individual room registers?
 - b. How do you do it and in what situations? (new furnaces, new AC, tune-ups/routine maintenance?) (e.g., not measured, furnace heat rise, velocity – pitot tube, hot wire anemometer, AC coil pressure drop, flow plate – they might only have to set the dip switches to set air flow, and not need to measure esp. for newer models)
 - c. *(If not clear from previous question)* Do you measure air flow for both new construction and retrofits?

11. When do you do refrigerant charge checks? (e.g., new AC installation, service call). How do you do it? (e.g., beer can cold, weigh in, adjust to measured performance target – superheat, subcooling, Lennox)
 - a. *(If they use superheat, subcooling or Lennox)* What do you do when you install a system and it's too cold to use superheat, subcooling or Lennox?

12. What types of refrigerant gauges do you use? (digital/analog)

13. In the last year have you installed many R-22 systems (unit is not charged with refrigerant until installed)?
 - a. *(If they do some, ask)* Are those dry-charge systems? Is that much of your business?

14. How do you determine the duct sizing for new construction?

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

15. What does your company typically charge for a routine maintenance or tune-up call? What does that include?

Maintenance/Tune-up - \$	Comments
Check all thermostat settings	<i>(fill in comments)</i>
Tighten all electrical connections	<i>(fill in comments)</i>
Lubricate all moving parts	<i>(fill in comments)</i>
Check and inspect the condensate drain	<i>(fill in comments)</i>
Check controls of the system	<i>(fill in comments)</i>

Maintenance/Tune-up - \$	Comments
Cooling	<i>(fill in comments)</i>
Clean evaporator AC coils	<i>(fill in comments)</i>
Clean condenser AC coils	<i>(fill in comments)</i>
Check central AC refrigerant level	<i>(fill in comments)</i>
Clean and adjust blower components	<i>(fill in comments)</i>
Check gas/oil connections, gas pressure, burner combustion and heat exchanger	<i>(fill in comments)</i>
Heating	<i>(fill in comments)</i>
Check safety switches	<i>(fill in comments)</i>
Gas pressure	<i>(fill in comments)</i>
Temperature rise	<i>(fill in comments)</i>
Combustion analysis	<i>(fill in comments)</i>
CO level	<i>(fill in comments)</i>
Test primary heat exchanger	<i>(fill in comments)</i>
Inspect/clean secondary heat exchanger	<i>(fill in comments)</i>
Check air filters	<i>(fill in comments)</i>
Measure air flow	<i>(fill in comments)</i>
Others?	<i>(fill in comments)</i>

16. Some utilities offer rebates for tune-ups. Are you involved with those at all?

- a. *(If yes)* How many tune-ups with rebates do you do per year?
 - i. What utilities do you do this with?
- b. *(If yes)* What are the requirements for participation in these?

17. Do you offer a service contract? What is included, and what does it cost?

Now I have questions about MN utility HVAC programs

- 18. Have you participated in any utility high efficiency HVAC equipment rebate programs?
 - a. *(If yes)* How many of these rebates are you involved with per year?
 - b. *(If yes)* Which program(s)?

- 19. Do you do anything where you or the customer gets a rebate for a “quality install?”
 - a. *(If yes)* How many of these rebates are you involved with per year?
 - b. *(If yes)* Which utility program(s) are those for?
 - c. *(If yes)* How does that work (i.e., who gets the rebate)?
 - d. *(If they participated in one or more programs)* Is there some kind of qualification required for participation?
 - e. *(If some qualification required)* What was required, and how difficult was it to get?
 - i. Did it result in a change in your practices?
 - ii. Was it worth it?
 - f. *(If they have not participated in utility programs)* Why weren’t you interested in these programs?

Notes on utility programs (for interviewer)

Utility	Program	Trained?
Xcel Energy	HVAC quality installation assessment, must pass online test	<i>(fill in information)</i>
Minnesota Power	ASHP proper installation rebate program AC proper installation rebate program	<i>(fill in information)</i>
Otter Tail Power Company	<i>(fill in information)</i>	<i>(fill in information)</i>
Great River Energy	Contractors get certified and entered into sweepstakes to win \$500, must pass online test	<i>(fill in information)</i>

Utility	Program	Trained?
Municipals?	<i>(fill in information)</i>	<i>(fill in information)</i>
Other	<i>(fill in information)</i>	<i>(fill in information)</i>

- 20. What do you think of the energy efficient equipment and quality installation rebate programs?
- 21. Do you feel the utility HVAC programs help or hurt your business in any way?
- 22. Do you have any suggestions for changes in these programs? What would that change mean for your business?
- 23. Are any of your technicians NATE certified? (can be certified for CAC, ASHP, gas heating)

I just have a couple more questions on consumer awareness and demand for these programs

- 24. Do your customers typically know about utility rebates for **quality installation** of standard efficiency systems? About what percentage know about it?

If they know about the programs, are they usually interested in participating? What percentage would you say want to participate?

Appendix C – Survey Sample Development

The homeowner survey and subsequent field data collection were implemented in the Twin Cities area and three outlying locations: Duluth, St. Cloud and Rochester.⁴⁰ Data collection began with a telephone survey of homeowners, a subset of whom were then recruited for site visits. Both aspects of the study were stratified into three groups of interest:

1. New replacement system in an older home – these were households that had recently (within the past five years) installed a new furnace, air conditioner or central, air-source heat pump;
2. New system in a new home – these were households living in a home that had been built in the past five years, and that presumably had new HVAC equipment as well; and,
3. Older system – these were households in homes with heating and cooling systems that were more than five years old.

The survey sample came from a combination of purchased random samples of households in existing and new homes (from [InfoUSA](#)) in the above geographic areas and HVAC permit lists obtained from the cities of Minneapolis, Duluth and Rochester.⁴¹ The survey and site-visits were limited to single-family, owner-occupied homes with a central air conditioner or air-source heat pump.

Sample Weighting

Because of the way that it was stratified, the raw sample of survey respondents over-represented households with newer systems compared to the general population. We developed and used case weights for reporting overall survey results that were more reflective of the statewide population of single-family homes. These case weights took into account the estimated population proportions of single-family homes in Minnesota by age of home, location (Twin Cities area or not) and whether the home had a new cooling system. The population proportions for home age and location came from 2009-2013 five-year microdata from the [Census Bureau's American Community Survey](#) (ACS). Because we did not have an independent source for the proportion of homes with new cooling systems, we used the proportions from survey respondents in the random-sample pool to develop weights for the overall sample, which also included respondents gleaned from the permit lists who overwhelmingly had new cooling systems. Table 20 shows the strata and weights that we developed.

⁴⁰ The Twin Cities area is here defined as Anoka, Carver, Dakota, Hennepin, Ramsey, Scott, and Washington counties.

⁴¹ Available permit data for St. Cloud did not allow for isolating households that had installed HVAC equipment.

Table 20. Survey strata and weights.

Age of Home	Region	New A/C ?	Estimated population*	Survey respondents	Case weight
pre 1950	Twin Cities	No	88,000	30	2,933.33
		Yes	46,588	126	369.75
	Outlying	No	131,449	33	3,983.30
		Yes	49,294	21	2,347.33
1950-1969	Twin Cities	No	125,196	47	2,663.74
		Yes	41,732	36	1,159.22
	Outlying	No	99,982	38	2,631.11
		Yes	33,327	28	1,190.25
1970-1989	Twin Cities	No	151,092	34	4,443.88
		Yes	42,495	16	2,655.94
	Outlying	No	145,466	44	3,306.05
		Yes	24,836	24	1,034.83
1990-2008	Twin Cities	No	150,676	12	12,556.33
		Yes	62,781	6	10,463.50
	Outlying	No	164,197	58	2,830.98
		Yes	34,079	36	946.64
2009+	Twin Cities	Yes	13,649	109	125.22
	Outlying	Yes	11,168	29	385.10
Total			1,416,007	727	

*Based on 2009-2013 American Community Survey microdata for home age and region, and on non-permit survey sample for proportion of homes with new A/C.

Sample Representativeness

To assess the representativeness of the survey sample, we compared key demographic and housing characteristics that we collected as part of the survey to similar data that is gathered by the ACS. Specifically we compared the (weighted) survey data to 2013, five-year ACS microdata for Minnesota single-family homeowners in terms of the following characteristics:

- Age of home
- Number of people in household
- Length of residency in current home

The results (Table 21) show that the survey sample compares favorably to Census data in terms of age of home and number of people in the household, but skews towards households that have lived in their home for longer periods of time.

Table 21. Housing and demographic characteristics from Census data and for the study sample.

	Census* (n=16,329)	Study sample** (n=727)
Year built		
1939 or earlier	17.2%	16.8%
1940-1949	5.1%	5.5%
1950-1959	12.2%	13.4%
1960-1969	9.0%	7.8%
1970-1979	13.1%	12.1%
1980-1989	12.6%	13.6%
1990-1999	14.5%	17.0%
2000-2008	14.5%	12.1%
2009-present	1.8%	1.7%
TOTAL	100.0%	100.0%
Number of household members		
1	20.0%	20.9%
2	39.7%	44.1%
3	15.8%	11.8%
4	14.2%	15.7%
5	6.9%	6.1%
6	2.1%	1.0%
7	0.7%	0.2%
8 or more	0.6%	0.2%
TOTAL	100.0%	100.0%
Length of residency in current home		
Less than 1 year	5.4%	0.3%
1 to 4 years	15.5%	4.6%
5 to 9 years	19.6%	10.3%
10 years or more	59.5%	84.8%
TOTAL	100.0%	100.0%

*2013, 5-year microdata from American Community Survey, restricted to single-family homeowners in Minnesota.

**Weighted results. "Don't know" and refusals omitted.

Appendix D – Homeowner Survey Instrument

Screener to qualify for the study:

Q0. Hello, I'm calling from Leede Research on behalf of the State of Minnesota about a study of residential heating and cooling systems. We're conducting a survey of Minnesota households about their furnaces and air conditioners. I'm not selling anything; I'd just like to talk with an adult member of your household. All responses are completely confidential. Are you 18 years or older?

- 1 Yes
- 2 No → May I speak with an adult member of the household? Repeat introduction if necessary.
- 3 SOFT REFUSAL → [INTERVIEWER NOTE: If you can't convert a soft refusal into a full response, offer to ask just a very small number of questions to see if they qualify for a study that includes a cash incentive for participation in a field study of air conditioners.] ==>JUMP TO H1

[IF ASKED] This could take up to 10 minutes.

First, I have a few questions about your home.

Q1. Is your home a single family home?

- 1) Yes
- 2) No ==>TERMINATE
- 88) DON'T KNOW ==> TERMINATE
- 99) REFUSED ==> TERMINATE

Q2. Is your home a mobile home?

- 1) Yes ==>TERMINATE
- 2) No
- 88) DON'T KNOW ==> TERMINATE
- 99) REFUSED ==> TERMINATE

Q3. Do you own or rent your home?

- 1) Own
- 2) Rent ==> TERMINATE
- 88) DON'T KNOW ==> TERMINATE
- 99) REFUSED ==> TERMINATE

Q4. Do you have a central forced air furnace fueled by natural gas or propane?

- 1) Yes
- 2) No ==> JUMP TO Q6
- 88) DON'T KNOW ==> TERMINATE
- 99) REFUSED ==> TERMINATE

Q5. Do you use more than one forced air furnace to heat your home?

- 1) Yes ==> [READ: For the remainder of the survey questions about heating your home, please answer for the newest forced air furnace.]
- 2) No
- 88) DON'T KNOW
- 99) REFUSED

Q6. Do you have a central cooling system like a central air conditioner or a heat pump that also provides cooling during the summer?

[INTERVIEWER NOTE: IF THE RESPONDENT ONLY HAS ROOM AIR CONDITIONERS, PLEASE MARK NO]

- 1) Yes
- 2) No ==>TERMINATE
- 88) DON'T KNOW ==> TERMINATE
- 99) REFUSED ==> TERMINATE

Q7. Do you use more than one central air conditioner or heat pump to cool your home?

- 1) Yes ==> [READ: For the remainder of the survey questions about cooling your home, please answer for your newest cooling system.]
- 2) No

88) DON'T KNOW ==> TERMINATE

99) REFUSED ==> TERMINATE

Q8. Is your cooling system a/an...

1) Central air conditioner

2) Air-source heat pump

3) Geothermal or ground-source heat pump ==> TERMINATE

4) Something else ==> TERMINATE

88) DON'T KNOW ==> TERMINATE

99) REFUSED ==> TERMINATE

[IF Q4 <> 1 AND Q8 = 2]

Q9. Is the air source heat pump also your primary heating system, or do you have some other heating system you consider to be the primary way you heat your home?

1) Air source heat pump is primary

2) Have a different primary system

3 OTHER - SPECIFY: _____

88) DON'T KNOW

99) REFUSED

=====

1. Home type, age, size

A1. When was your house built? _____ [READ CATEGORIES IF NEEDED]

- 1) Before 1900
- 2) 1900-1919
- 3) 1920-1929
- 4) 1930-1939
- 5) 1940-1949
- 6) 1950-1959
- 7) 1960-1969
- 8) 1970-1979
- 9) 1980-1989
- 10) 1990-1999
- 11) 2000-2008
- 12) 2009-present
- 88) DON'T KNOW
- 99) REFUSED

A2. What is the finished square footage of your home? _____ [READ CATEGORIES IF NEEDED]

- 1) Below 1000
- 2) 1000-1499
- 3) 1500-1999
- 4) 2000-2499
- 5) 2500-2999
- 6) 3000-3499
- 7) 3500-3999
- 8) 4000-plus
- 88) DON'T KNOW
- 99) REFUSED

A3. How long have you lived in your current home?

- 1) Less than 1 year
- 2) 1 to 4 years
- 3) 5 to 9 years
- 4) 10 to 14 years
- 5) 15 years or more
- 88) DON'T KNOW
- 99) REFUSED

A4. How many people in each of the following age groups live in your home most of the year?

- ___ Children
- ___ Adults
- ___ Seniors

2. Heating and cooling fuel, type and age

Next I have some questions about the heating and cooling systems in your home.

[IF Q4 = 1]

B1. When was your furnace installed? [READ CATEGORIES IF NEEDED]

- 1) Pre-1950 ==> JUMP TO B2
- 2) 1950-1979 ==> JUMP TO B2
- 3) 1980-1989 ==> JUMP TO B2
- 4) 1990-1999 ==> JUMP TO B2
- 5) 2000-2008 ==> JUMP TO B2
- 6) 2009-present
- 88) DON'T KNOW ==> JUMP TO B2
- 99) REFUSED ==> JUMP TO B2

[If B1=6 and A3=3, 4 or 5]

B1a. How many different bids did you get when you bought your furnace?

[INTERVIEWER NOTE: RESPONDENT'S ESTIMATE IS FINE. KNOWING WHETHER IT WAS ONE OR MORE THAN ONE IS MOST IMPORTANT. BEYOND THAT, A ROUGH ESTIMATE OF HOW MANY BIDS IT WAS IS FINE.]

_____ [RECORD NUMBER]

88) DON'T KNOW

99) REFUSED

B2. When was your [INSERT RESPONSE FROM Q8] installed? [READ CATEGORIES IF NEEDED]

1) Pre-1950

2) 1950-1979

3) 1980-1989

4) 1990-1999

5) 2000-2008

6) 2009-present

88) DON'T KNOW

99) REFUSED

[If B2=6 and A3=3, 4 or 5]

B2a. How many different bids did you get when you bought your [INSERT RESPONSE FROM Q8]?

[INTERVIEWER NOTE: KNOWING WHETHER IT WAS ONE OR MORE THAN ONE IS MOST IMPORTANT. BEYOND THAT, A ROUGH ESTIMATE OF HOW MANY BIDS IT WAS IS FINE.]

_____ [RECORD NUMBER]

88) DON'T KNOW

99) REFUSED

3. Thermostat (type and use of programmable features / winter and summer setback practices)

C1. What type of thermostat do you use to control your heating and cooling systems? Is it a...

[INTERVIEWER NOTE: A DIGITAL PROGRAMMABLE THERMOSTAT ALLOWS PEOPLE TO SET TEMPERATURES THEY WANT THEIR HOME TO BE AT DIFFERENT TIMES OF THE DAY, AND THE THERMOSTATE ADJUSTS THE TEMPERATURE ACCORDINGLY, BUT PEOPLE CAN ALSO JUST INDICATE THE TEMPERATURE THEY WANT AT THE MOMENT. A MANUAL THERMOSTAT JUST BRINGS THE HOME TO THE TEMPERATURE SET AT ANY ONE TIME.]

- 1) Digital programmable thermostat (whether or not you use the programmable features)?
- 2) Manual-style thermostat ==>JUMP TO C3a
- 3) OTHER-SPECIFY:_____ ==>JUMP TO C3a
- 88) DON'T KNOW ==>JUMP TO C3a
- 99) REFUSED ==>JUMP TO C3a

C2a. Do you use the programmable features of your thermostat in the winter?

- 1) Yes
- 2) No
- 88) DON'T KNOW
- 99) REFUSED

C2b. Do you use the programmable features of your thermostat in the summer?

- 1) Yes
- 2) No
- 88) DON'T KNOW
- 99) REFUSED

C2c. Is your thermostat connected to the Internet?

- 1) Yes
- 2) No ==>JUMP TO C3a
- 88) DON'T KNOW ==>JUMP TO C3a
- 99) REFUSED ==>JUMP TO C3a

C2d. What brand of thermostat is it? [RECORD VERBATIM]

Now I have a few questions about how you set your thermostat at various times of day in the winter and summer.

C3a. During the winter, what temperature do you usually set your thermostat to when someone is awake and at home?

___ [RECORD TEMPERATURE]

888) DON'T KNOW

999) REFUSED

C3b. How about during sleeping hours in the winter?

___[RECORD TEMPERATURE]

888) DON'T KNOW

999) REFUSED

C3c. How about when no one is home in the winter?

___[RECORD TEMPERATURE]

888) DON'T KNOW

999) REFUSED

C4a. During the summer, what temperature do you usually set your thermostat to when someone is awake and at home?

___[RECORD TEMPERATURE]

000) cooling system is turned off

888) DON'T KNOW

999) REFUSED

C4b. How about during sleeping hours in the summer?

___[RECORD TEMPERATURE]

000) cooling system is turned off

888) DON'T KNOW

999) REFUSED

C4c. How about when no one is home in the summer?

___[RECORD TEMPERATURE]

000) cooling system is turned off

888) DON'T KNOW

999) REFUSED

4. Furnace-fan practices (Use of "fan-on" by season/ reasons for doing so)

[IF Q4=2 ==> JUMP TO D3a]

We are studying how people operate their furnace fans. This is the fan in your furnace that blows air through your ducts and vents. Let's first talk about how you operate the fan on your furnace during the heating season. This is the time of the year when temperatures are cold enough that you need to run your furnace to heat your home.

D1. Which of the following two statements best describes how you operate the fan on your furnace during the heating season?

1) The furnace fan is set to the ON setting so that it blows air through your ducts and vents 24 hours a day.

2) The furnace fan is set to the AUTO setting so that it blows air through your ducts and vents only when the furnace is heating the air. ==> JUMP TO D1b

88) DON'T KNOW ==> JUMP TO D1b

99) REFUSED ==> JUMP TO D1b

D1a. So, just to confirm, the fan moves air through your ducts and vents all the time during the heating system regardless whether your furnace is heating up the air at the moment. Is that correct?

1) Yes ==>JUMP TO D2

2) No

88) DON'T KNOW

99) REFUSED

D1b. Do you ever operate your furnace fan in the ON setting during the heating season so that it blows air through your ducts and vents when your furnace is not heating the air?

- 1) Yes
- 2) No ==>JUMP TO D3a
- 88) DON'T KNOW ==>JUMP TO D3a
- 99) REFUSED ==>JUMP TO D3a

D1c. Just to confirm, you sometimes set the furnace fan to circulate air through your ducts and vents in the winter even if the furnace is not heating the air, and you have the furnace fan operate only when your furnace is heating at other times in winter. Is that correct?

- 1) Yes
- 2) No ==>JUMP TO D3a
- 88) DON'T KNOW ==>JUMP TO D3a
- 99) REFUSED==>JUMP TO D3a

D2. Why do you operate the furnace fan this way? [PROBE FOR SPECIFIC REASONS; RECORD VERBATIM]

Now let's talk about how you operate your furnace fan [IF Q4 = 2: ADD: or other distribution fan connected with your [INSERT RESPONSE FROM Q8]] when temperatures are warm enough that you decide to cool your home.

D3. Which of the following two statements best describes how you operate the fan on your [INSERT RESPONSE FROM Q8] during the cooling season?

- 1) The fan is set to the ON setting so that it blows air through your ducts and vents 24 hours a day.
- 2) The fan is set to the AUTO setting so that it blows air through your ducts and vents only when the system is cooling the air. ==> JUMP TO D3B
- 88) DON'T KNOW ==> JUMP TO D3B
- 99) REFUSED==> JUMP TO D3B

D3a. So, just to confirm, the fan moves air through your ducts and vents all the time during the cooling season regardless whether your [INSERT RESPONSE FROM Q8] is cooling the air at the moment. Is that correct?

- 1) Yes ==>JUMP TO D4

- 2) No
- 88) DON'T KNOW
- 99) REFUSED

D3b. Do you ever operate the fan in the ON setting during the cooling season so that it blows air through your ducts and vents when your [INSERT RESPONSE FROM Q8] is not cooling the air?

- 1) Yes
- 2) No ==>JUMP TO D5a
- 88) DON'T KNOW ==>JUMP TO D5a
- 99) REFUSED ==>JUMP TO D5a

D3c. Just to confirm, you sometimes set the fan to circulate air through your ducts and vents in the summer even if your [INSERT RESPONSE FROM Q8] is not cooling the air, and you have the fan operate only when your system is cooling at other times in summer. Is that correct?

- 1) Yes
- 2) No ==>JUMP TO D5a
- 88) DON'T KNOW ==>JUMP TO D5a
- 99) REFUSED==>JUMP TO D5a

D4. Why do you operate the cooling system fan this way? [PROBE FOR SPECIFIC REASONS; RECORD VERBATIM]

[IF Q4=2 ==> JUMP TO D6a]

D5a. Next, I'd like to ask how satisfied you are with your current heating system. Would you say you are...

- 1) Very satisfied ==> JUMP TO D6A
- 2) Somewhat satisfied ==> JUMP TO D6A
- 3) Neither satisfied nor dissatisfied ==> JUMP TO D6A
- 4) Somewhat dissatisfied
- 5) Very dissatisfied
- 88) DON'T KNOW ==> JUMP TO D6A

99) REFUSED ==> JUMP TO D6A

D5b. In what ways are you dissatisfied? [RECORD VERBATIM]

D6a. How satisfied would you say you are with your current cooling system, would you say you are...

- 1) Very satisfied ==> JUMP TO E1
- 2) Somewhat satisfied ==> JUMP TO E1
- 3) Neither satisfied nor dissatisfied ==> JUMP TO E1
- 4) Somewhat dissatisfied
- 5) Very dissatisfied
- 88) DON'T KNOW ==> JUMP TO E1
- 99) REFUSED ==> JUMP TO E1

D6b. In what ways are you dissatisfied? [RECORD VERBATIM]

5. HVAC maintenance practices (Service contract / Regular professional tune-ups / Filter-change practices)

[IF Q4=2 ==> JUMP TO E5]

E1. Next I'd like to ask about your heating and cooling system maintenance. When is the last time you had your heating system professionally serviced? [DON'T READ]

- 1) Within past year
- 2) 1-2 years ago
- 3) 3-5 years ago
- 4) More than 5 years ago ==>JUMP TO E3
- 5) Never ==>JUMP TO E4
- 88) DON'T KNOW ==>JUMP TO E3
- 99) REFUSED ==>JUMP TO E4

E2. Did you have it serviced then because it wasn't operating properly or just for regular maintenance? [DON'T READ]

- 1) Not operating properly
- 2) Regular maintenance
- 3) Both
- 88) DON'T KNOW
- 99) REFUSED

E3. How often do you usually get your heating system serviced professionally? [DON'T READ]

- 1) More often than annually
- 2) Annually
- 3) Every couple of years
- 4) Every 3-5 years
- 5) Irregular schedule
- 6) NEVER
- 88) DON'T KNOW
- 99) REFUSED

E4. How often do you usually replace your furnace filter? Is it...

- 1) More often than monthly
- 2) About monthly
- 3) Every couple of months
- 4) A few times a year
- 5) Annually
- 6) Less than annually
- 7) By some other schedule
- 8) Never
- 88) DON'T KNOW
- 99) REFUSED

E5. When is the last time you had your cooling system professionally serviced? [DON'T READ]

- 1) Within past year
- 2) 1-2 years ago
- 3) 3-5 years ago
- 4) More than 5 years ago ==>JUMP TO E7
- 5) Never ==>JUMP TO E8
- 88) DON'T KNOW ==>JUMP TO E7
- 99) REFUSED ==>JUMP TO E8

E6. Did you have it serviced then because it wasn't operating properly or just for regular maintenance? [DON'T READ]

- 1) Not operating properly
- 2) Regular maintenance
- 3) Both
- 88) DON'T KNOW
- 99) REFUSED

E7. How often do you usually get your cooling system serviced professionally? [DON'T READ]

- 1) More often than annually
- 2) Annually
- 3) Every couple of years
- 4) Every 3-5 years
- 5) Irregular schedule
- 6) NEVER
- 88) DON'T KNOW
- 99) REFUSED

E8. Do you have a service contract that includes regular maintenance for your [INSERT RESPONSE FROM Q8] [IF Q4=1: ADD “, furnace, both, or neither”]?

[IF NEEDED: A SERVICE CONTRACT IS A PLAN YOU CAN THAT PROVIDES MAINTENANCE AND SOMETIMES REPAIR OF APPLIANCES AT A SUBSCRIPTION FEE RATHER THAN ON A PAY-AS-YOU-GO BASIS.]

- 1) Cooling system / yes
- 2) Furnace
- 3) Both
- 4) Neither / no ==> JUMP TO F1
- 88) DON'T KNOW ==> JUMP TO F1
- 99) REFUSED ==> JUMP TO F1

E9. How much does that contract costs on an annual basis?

_____ [RECORD APPROXIMATE ANNUAL COST (numeric)]

- 88) DON'T KNOW
- 99) REFUSED

E10. Who is that contract with? Is it with:

- 1) A private heating and cooling contractor
- 2) An electric or gas utility
- 3) Someone else - SPECIFY: _____
- 88) DON'T KNOW
- 99) REFUSED

6. Perceptions of HVAC QI

[MULTI-RESPONSE; UP TO 2 RESPONSES]

F1a-b. If you needed to replace your [INSERT RESPONSE FROM Q8], how would you go about finding someone to install a new one? [DO NOT READ; RECORD RESPONSE(S)]

- 1) Internet search
- 2) Word of mouth - get recommendations of people I know
- 3) Look for someone who carries a particular brand/model/features
- 4) Call an installer I know / have used before

- 5) Yellow pages
- 6) Other - SPECIFY: _____
- 7) Would not replace
- 88) DON'T KNOW
- 99) REFUSED

[MULTI-RESPONSE; UP TO 3 RESPONSES]

F2a-c. What would you look for in choosing the installer who is going to get your business?
[DO NOT READ; RECORD RESPONSES; ASK "ANYTHING ELSE?" BEFORE MOVING ON]

- 1) Quality
- 2) Good reputation
- 3) Price
- 4) Industry / manufacturer certification
- 5) Personal characteristics of the installer (friendliness, courtesy, hygiene, etc.)
- 6) Carrying a specific brand
- 7) Availability (to get the work done quickly or at a convenient time)
- 8) Location
- 9) Having a showroom
- 10) Offering maintenance and repair services for the units they sell
- 11) Other - SPECIFY: _____
- 88) DON'T KNOW
- 99) REFUSED

[IF F2 = 1]

F3. What do you mean by quality? Can you elaborate on that? [RECORD VERBATIM]

- 88) DON'T KNOW
- 99) REFUSED

[IF F2 = 2]

F4. What do you mean by good reputation? Can you elaborate on that? [RECORD VERBATIM]

88) DON'T KNOW

99) REFUSED

[IF Q0<>3 ==> JUMP TO H6]

8. On-site solicitation

H1. Do you have a central cooling system like a central air conditioner or a heat pump that also provides cooling during the summer? [INTERVIEWER NOTE: IF THE RESPONDENT ONLY HAS ROOM AIR CONDITIONERS, PLEASE MARK NO]

1) Yes

2) No ==>TERMINATE

88) DON'T KNOW ==> TERMINATE

99) REFUSED ==> TERMINATE

H2. Do you own or rent your home?

1) Own

2) Rent ==> TERMINATE

88) DON'T KNOW ==> TERMINATE

99) REFUSED ==> TERMINATE

H3. Is your home a single family home?

1) Yes

2) No ==>TERMINATE

88) DON'T KNOW ==> TERMINATE

99) REFUSED ==> TERMINATE

H4. Is your home a mobile home?

1) Yes ==>TERMINATE

2) No

88) DON'T KNOW ==> TERMINATE

99) REFUSED ==> TERMINATE

H5. Do you have a central forced-air furnace fueled by natural gas or propane?

1) Yes

2) No

88) DON'T KNOW ==> TERMINATE

99) REFUSED ==> TERMINATE

H6. We are also looking for households willing to participate in an in-home study to look more in-depth at furnaces and air conditioners. Households selected for this study will receive a \$35 Visa gift card and an air conditioner/heat pump tune up (a \$125 value). Participating households will have meters installed on their cooling system and will participate in an interview. Would you be willing to participate in this study if the research team needs additional households in your part of the state?

1) Yes

2) No ==> JUMP TO END

3) Perhaps, would need more information

99) REFUSED ==> JUMP TO END

H7. Record contact info.

Name: _____

Phone number: _____

Address: _____

Good time to reach you: _____ [INTERVIEWER NOTE: LOOKING FOR TIME OF DAY OR DAY OF WEEK; ANY INSTRUCTIONS OF WHEN WE WOULD HAVE THE BEST CHANCE TO REACH THE RESPONDENT AND NOT INTERRUPT WORK, SLEEP, ETC.]

[IF NEEDED: We will be recruiting willing homes for this study between May and August. Someone from the Energy Center of Wisconsin would call you then to schedule a time for the visit to your house if your home is selected.]

[IF NEEDED FOR WILLING RESPONDENTS WHO NEED MORE INFORMATION: We will be recruiting willing homes for this study between May and August. Someone from the Energy

Center of Wisconsin would call you then if your home is selected and can tell you more about the study before you decide whether you want to participate.]

Those are all the questions I have for you. Thank you for participating in this survey.

Appendix E – Field Data Collection Details

Most of the field data collected in the study was recorded using two identical rigs that were custom-built for the study. The rigs included components for measurement of air-side conditions, refrigerant conditions, outdoor air temperature, condensate production and electrical input. Table 22 provides details about the sensors that were used. Below we describe in more detail their placement, and The core of the monitoring system was a Campbell Scientific CR-1000 data logger. Software written for the project directed operation of the CR-1000; it measured and recorded the value of all inputs at two-second intervals throughout the site visit. Field technicians toggled a switch connected to the rig to mark two-minute test periods in the data stream before and after system adjustments (after appropriate run-out periods to establish steady-state operation): these were automatically flagged and numbered in the data stream. Most of the analysis for the study was based on average values captured during these two-minute test periods.

The rig communicated with a local laptop computer via Wi-Fi communications. Using the laptop, technicians were able to view live data readings from the rig, as well as enter key parameters such as the nominal system tonnage, refrigerant type and TrueFlow plate number. Figure 28 shows the five display screens available to the field technicians. Live data from the rig were also transmitted over cellular connections directly to a central server at Seventhwave, where technical staff were able to remotely view the same displays in real time. The general site visit protocol called for the technician to set up the system, initiate a call for cooling, and then record an as-found two-minute test period once the system reached steady-state. The technician then called technical support at Seventhwave to review the results of the as-found test, and discuss the sequence of adjustments.

Figure 20 through Figure 27 show typical installation examples. The field data collection form is included at the end of this appendix.

Air-side measurements included temperature and humidity at two return and four supply locations, using probes inserted into drilled holes in ducts. The probes had variable-length extensions to allow placement near the center of the ductwork, and magnetic bases to hold them in place during the testing. These sensors were directly connected with cables to the monitoring system. In a normal installation, the two return probes were mounted in the return plenum, each about a third of the way in from the edge of the duct, and positioned to be in the middle of the duct in the direction of probe insertion. On the supply side, most (but not all) Minnesota systems have a T-header above the air conditioner evaporator coil where the system splits into two trunk lines. For this arrangement, two supply probes were mounted in each trunk line close to the header, in a manner similar to how the return probes were mounted (1/3 of the way from the edges, in the center of flow). Some systems have multiple supply take-offs from the supply plenum: for these situations one of the supply probes was dedicated to each take-off.

Duct static pressures were measured in the return air duct (upstream of the typical filter location), at the blower inlet, at the furnace or air handler outlet just upstream of the indoor coil, and in the supply plenum above the coil. Static pressure probes were used for all of the locations except at the air-handler outlet where a straight piece of metal tubing was threaded in through the joint between the top of the furnace or air handler and housing for the indoor coil. Flexible plastic tubing was used to connect the probes at each location to a valving network in

the monitoring system. This allowed each pressure to be measured in a sequence by the same pressure sensor, thereby eliminating errors due to variability between sensors. Each rig contained two pressure sensors in parallel with different working ranges, thereby allowing for a wide range of pressures to be observed, as well as adding redundancy to these measurements. The rigs were programmed to sequentially step through six pressure-measurement stations at two-second intervals, taking a single snapshot reading at each. In addition to the four static pressure location above, the six stations included a zero reading and a pressure reading for the TrueFlow device described below. Differential static pressure drops were calculated by subtracting the independently measured static pressure values relative to the room.

Airflow was initially measured at each site with a TrueFlow air handler flow meter placed in the filter slot at the air handler.⁴² The TrueFlow is a calibrated flow plate, where airflow is proportional to the square root of the pressure drop across the filter. Early in the site visit, the system filter was replaced with the TrueFlow, and a calibration sequence was run, during which the rig both measured the airflow indicated by the TrueFlow and established the relationship between the airflow and the supply or return static pressure (whichever provided the larger signal). The TrueFlow was then removed, and the filter put back in place. Thereafter, airflow was based on the calibrated relationship to system static pressure.⁴³

Refrigerant pressure measurements were made through direct connection to refrigerant lines, with system sensors connected at the outdoor unit test ports in parallel with manual test gauges. Refrigerant temperature was measured with sensors designed for this use, housed in copper and offering curved surfaces for improved thermal contact with tubing, and were placed on the refrigerant tubing inside the compressor unit housing, with insulating tape placed over them. Signals from refrigerant pressure and temperature sensors, and outdoor air temperature sensor, were carried to the monitoring system through a cable.

Condensate production (in both heating and cooling modes) was captured by routing the system condensate to a bucket that sat atop an electronic scale. The system captured the scale weight at two-second intervals: condensate production rate was later calculated from the difference in cumulative weight across a known two-minute test interval.

Electrical power measurement was done at the main electrical distribution panel, where circuits for both the outdoor unit and indoor furnace/air handler are usually accessible. Measurements were made with a WattNode 3-channel metering device, with two channels dedicated to the two legs of the compressor circuit and the third to the air handler circuit. Voltage signals were carried through wires with alligator clip leads connected to the two voltage phases available in most residential systems. Current sensing was done with clamp-on current transducers. The

⁴² See information on the [TrueFlow Air Handler Flow Meter](http://products.energyconservatory.com/trueflow-air-handler-flow-meter/) on The Energy Conservatory Website (<http://products.energyconservatory.com/trueflow-air-handler-flow-meter/>).

⁴³ Later we discovered that the Supply and Return static pressure probes were sometimes temporarily removed and replaced during the course of testing, creating a potential concern about the accuracy of the indicated airflow after this disturbance. We manually reviewed the data for all sites, and made a post hoc switch to basing airflow from the alternative probe in cases where it was apparent that the main probe had been disturbed.

electrical metering device was connected to the main monitoring system through a cable. The system used Modbus communications.

For testing furnaces, in addition to the data natively collected by the test rigs, technicians recorded the firing rate of the system by clocking the gas meter, conducted steady-state efficiency tests with separate combustion analyzers, and measured the gas manifold pressure with a separate pressure gauge.

Table 22. Test-rig measurement parameter details.

Parameter	Sensor/Equipment	Measurement accuracy
Supply and Return air temperature and humidity (4 supply, 2 return)	Vaisala temperature and relative humidity sensors HMP110	Temperature: ± 0.75 F Humidity: $\pm 1.7\%$ RH
Outdoor temperature	Omega 10K Ohm thermistor TH-10-44006, mounted in radiation shield	± 1 F (including effects of bridge resistor)
Static Pressure (4 locations)	Honeywell analog differential pressure sensor, ± 2 IWC range, HSC-D-DR	± 1.25 Pa
	All Sensors analog differential pressure sensor 1-inch-D-4V	± 1 Pa
System airflow	True Flow air handler flow meter, calibrated to system operating pressure	$\pm 10\%$ (see Note 1)
Refrigerant line temperature	U.S. Sensors thermistor USP7881	± 1.2 F
Refrigerant line pressure	Setra 0 to 500 psi analog pressure transducer model 209	± 4.5 psi
Condensate production	Adam CPWPlus electronic scale (15 kg)	Estimated accuracy of differential weight: ± 0.05 lb. (see Note 2)
Electrical (accumulated kWh, power, volts, amps, power factor)	Continental Controls WattNode WNC-3Y-208-MB 3-channel power meter with Modbus interface, and Continental Controls Accu CT current transducers ACT-0750-020 and ACT-0750-030	Accumulated kwh: $\pm 1\%$ (including WattNode meter and current transducers). Voltage, current, and power factor accuracy not specified.

Note 1: Estimated, based on stated accuracy of the TrueFlow ($\pm 7\%$), plus uncertainty in system pressure measurement.

Note 2: Condensate data is based on differential scale readings over a test period, the stated accuracy is for differential scale readings. The absolute accuracy of the scale is estimated at ± 0.15 lb.

Also note: The conversion of analog sensor output voltages to digital values (performed by the Campbell Scientific CR-1000) may carry additional errors, but these are generally small compared to the underlying accuracy of the sensors.

The core of the monitoring system was a Campbell Scientific CR-1000 data logger. Software written for the project directed operation of the CR-1000; it measured and recorded the value of all inputs at two-second intervals throughout the site visit. Field technicians toggled a switch

connected to the rig to mark two-minute test periods in the data stream before and after system adjustments (after appropriate run-out periods to establish steady-state operation): these were automatically flagged and numbered in the data stream. Most of the analysis for the study was based on average values captured during these two-minute test periods.

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Figure 20. Test rig being unpacked.



Figure 21. Typical placement of return temp/RH sensors and return static pressure probe.



Figure 22. Typical placement of static pressure probe at air-handler inlet.

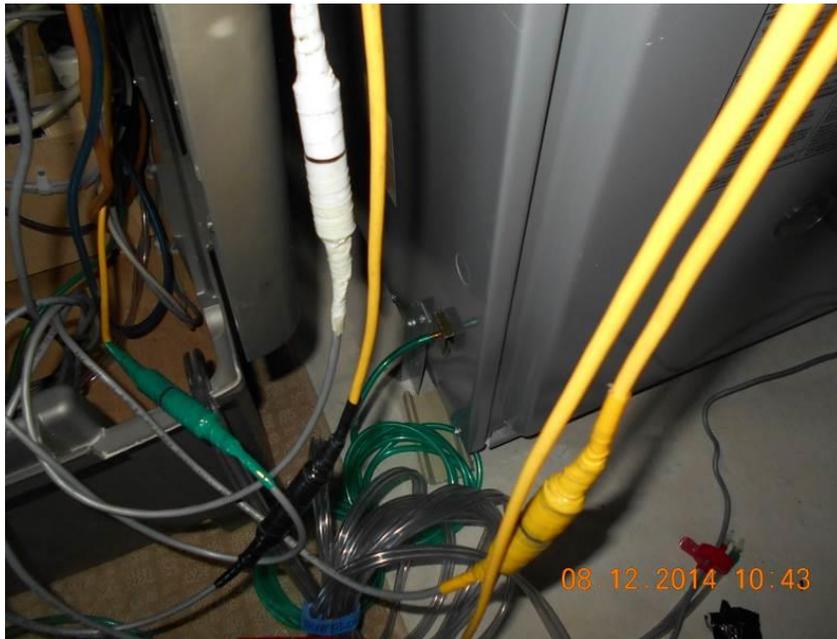


Figure 23. Typical placement of static pressure probe at the air-handler outlet.



Figure 24. Typical placement of supply temp/RH probes (two of four).



Figure 25. Atypical placement of supply temp/RH probes for a system with three supply trunks.



Figure 26. Rig installation example showing condensate collection and return probes.

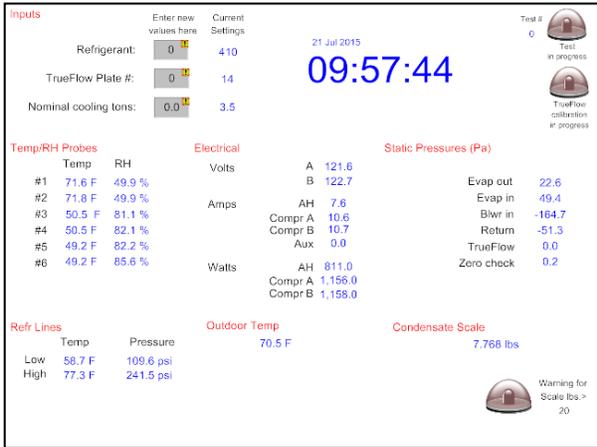


Figure 27. Typical electrical connections.

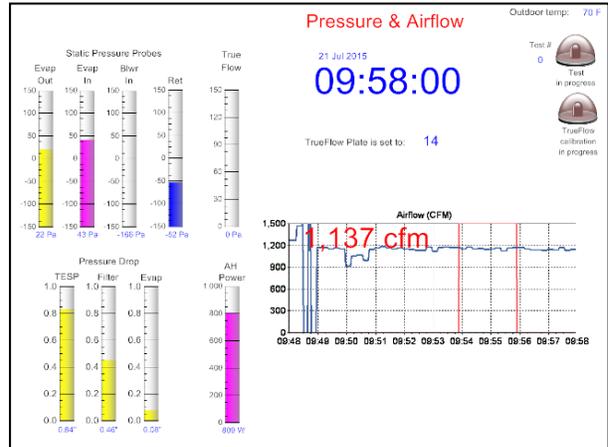


Figure 28. Example of test-rig display screens.

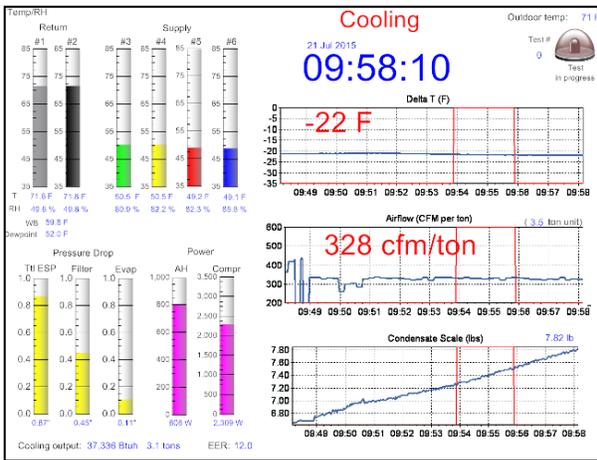
Screen 1



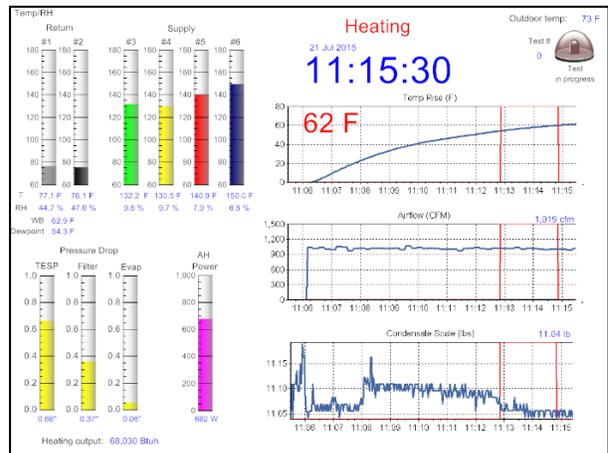
Screen 2



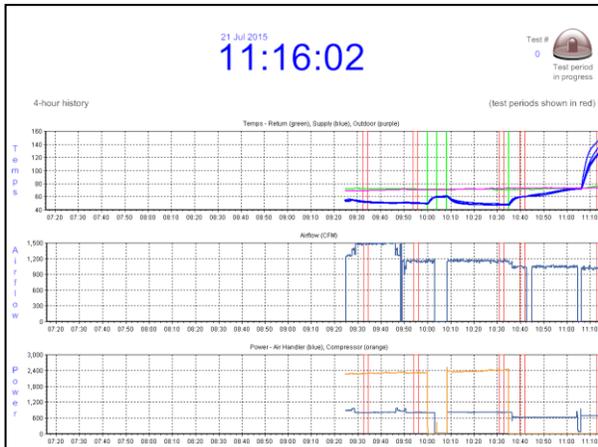
Screen 3



Screen 4



Screen 5



Site: _____ Rig#: _____ Date: _____

Rig Installation																																									
Initial connections																																									
<input type="checkbox"/> Wireless access point powered up (<i>must do this prior to powering up rig</i>) <input type="checkbox"/> Rig powered up <input type="checkbox"/> Cell modem powered up and connected to rig <input type="checkbox"/> Laptop powered up and connected to rig via access point in Loggernet <input type="checkbox"/> Synchronize laptop and rig clocks (<i>Click Check then Set on Connect screen</i>) <input type="checkbox"/> Create new data file (<i>Loggernet / Main-Setup / DataFiles tab, select QOut1</i>) <i>(Set to C:\Data\Q_XXXX.dat, where XXXX is Site ID)</i> <input type="checkbox"/> Initialize RTMC; check that on-screen clock is updating																																									
Electrical																																									
<input type="checkbox"/> Mount Wattnode at breaker panel, run cable and connect to rig <input type="checkbox"/> Furnace and A/C breakers identified <input type="checkbox"/> <i>Check here if furnace not in same breaker panel (use alternate CT in rig)</i> <input type="checkbox"/> Phases labeled (<i>furnace is "A"</i>) <input type="checkbox"/> 3 CTs installed (<i>labels face breakers</i>): Yellow (furnace), Red (Comp A), Black (Comp B) <input type="checkbox"/> 3 voltage clips installed: WHITE (<i>neutral</i>), RED (<i>Phase A</i>), BLACK (<i>Phase B</i>)																																									
Condensate collection																																									
<input type="checkbox"/> Condensate line routed to collection pan on scale <input type="checkbox"/> Collection pan and scale both free and clear (<i>nothing touching</i>) <input type="checkbox"/> Sensor cable attached to rig																																									
TrueFlow																																									
<input type="checkbox"/> Installed and secured (<i>logo faces upstream; no gaps around plate; holes not blocked</i>) <input type="checkbox"/> Trueflow hoses connected to rig <input type="checkbox"/> Plate # entered into laptop (" <i>14</i> " or " <i>20</i> ") Plate: <input style="width: 50px;" type="text"/>																																									
Temperature/RH probe holes																																									
<input type="checkbox"/> Drill 1/2" Supply/Return duct holes and install 6 temp/RH probes																																									
<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="width: 50%;"></th> <th colspan="2" style="text-align: center;">Duct sizing</th> <th colspan="2" style="text-align: center;">Probe</th> <th colspan="2" style="text-align: center;">Probe</th> </tr> </thead> <tbody> <tr> <td style="padding: 2px;">Return (3 equally-spaced holes in return plenum)</td> <td style="width: 20px; text-align: center;">x</td> <td style="width: 20px;"></td> <td style="width: 20px; text-align: center;">in.</td> <td style="width: 20px; text-align: center;">1</td> <td style="width: 20px; text-align: center;">2</td> <td style="width: 20px;"></td> </tr> <tr> <td style="padding: 2px;">Supply</td> <td style="text-align: center;">x</td> <td></td> <td style="text-align: center;">in.</td> <td style="text-align: center;">3</td> <td style="text-align: center;">4</td> <td></td> </tr> <tr> <td style="padding: 2px;"><i>(Modify assigned probe locations as needed, if direct take-offs are present. Note presence of round take-offs.)</i></td> <td style="text-align: center;">x</td> <td></td> <td style="text-align: center;">in.</td> <td style="text-align: center;">5</td> <td style="text-align: center;">6</td> <td></td> </tr> <tr> <td></td> <td style="text-align: center;">x</td> <td></td> <td style="text-align: center;">in.</td> <td></td> <td></td> <td></td> </tr> </tbody> </table>								Duct sizing		Probe		Probe		Return (3 equally-spaced holes in return plenum)	x		in.	1	2		Supply	x		in.	3	4		<i>(Modify assigned probe locations as needed, if direct take-offs are present. Note presence of round take-offs.)</i>	x		in.	5	6			x		in.			
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Supply	x		in.	3	4																																				
<i>(Modify assigned probe locations as needed, if direct take-offs are present. Note presence of round take-offs.)</i>	x		in.	5	6																																				
	x		in.																																						
Static pressure probes (<i>installed and taped down; tip facing upstream</i>)																																									
<input type="checkbox"/> BLUE - Return plenum (<i>upstream of filter; 24 in above elbow; not right below a connection</i>) <input type="checkbox"/> GREEN - Blower cabinet <input type="checkbox"/> PURPLE - Before evap coil <input type="checkbox"/> ORANGE - After evap coil (<i>24" downstream of header; on side w/o takeoffs, if possible</i>)																																									
Condenser and outdoor																																									
<input type="checkbox"/> Refrigerant gauges and pressure sensors installed <input type="checkbox"/> Refrigerant-line temperature probes installed and insulated <input type="checkbox"/> Outdoor ambient sensor installed <input type="checkbox"/> Sensor cable attached to rig <input type="checkbox"/> Refrigerant type entered into laptop (" <i>12</i> ", " <i>22</i> ", " <i>410</i> ") <input type="checkbox"/> Refrigerant-line details recorded at right:																																									
						Suction line dia. (in.)	<input type="text"/>																																		
						Liquid line dia. (in.)	<input type="text"/>																																		
						Line-set length (ft.)	<input type="text"/>																																		

Site: _____ Rig#: _____ Date: _____ Page 3

Cooling Test, As-Found													
Prep													
Metering device <i>(check one)</i> <input type="checkbox"/> Integral TXV <input type="checkbox"/> Add-on TXV <i>(Use subcool or approach method per mfr charging instructions.)</i>													
<hr/> <input type="checkbox"/> fixed-orifice piston <i>(Use superheat method per mfr charging instructions or generic superheat table.)</i> <input type="checkbox"/> fixed-orifice cap tube													
Test 1													
<input type="checkbox"/> Wait for steady-state <i>(minimum 10-minute run-out from call for cooling)</i> <input type="checkbox"/> Delta T steady <input type="checkbox"/> Condensate being produced at steady rate													
<input type="checkbox"/> <u>Initiate high/single-stage cooling test</u> Start time <input style="width: 100px;" type="text"/> Test # <input style="width: 50px;" type="text"/> <i>("Test" switch on rig)</i>													
<div style="display: flex; justify-content: space-between;"> <div style="width: 40%;"> (check one) <input type="checkbox"/> superheat <input type="checkbox"/> subcool <input type="checkbox"/> approach </div> <table border="1" style="width: 50%; border-collapse: collapse; text-align: center;"> <thead> <tr> <th style="width: 50%;">Measured</th> <th style="width: 50%;">Target</th> <th style="width: 10%;"></th> </tr> </thead> <tbody> <tr> <td><input style="width: 80%;" type="text"/></td> <td><input style="width: 80%;" type="text"/></td> <td>F</td> </tr> <tr> <td><input style="width: 80%;" type="text"/></td> <td><input style="width: 80%;" type="text"/></td> <td>F</td> </tr> <tr> <td><input style="width: 80%;" type="text"/></td> <td><input style="width: 80%;" type="text"/></td> <td>F</td> </tr> </tbody> </table> </div>		Measured	Target		<input style="width: 80%;" type="text"/>	<input style="width: 80%;" type="text"/>	F	<input style="width: 80%;" type="text"/>	<input style="width: 80%;" type="text"/>	F	<input style="width: 80%;" type="text"/>	<input style="width: 80%;" type="text"/>	F
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Refrigerant pressure: Liquid line <input style="width: 80px;" type="text"/> psi airflow <input style="width: 80px;" type="text"/> 300-400 cfm/ton Suction line <input style="width: 80px;" type="text"/> psi EER <input style="width: 80px;" type="text"/>													
Test 2													
<input type="checkbox"/> Test skipped (unit is single-stage)													
<input type="checkbox"/> Initiate call for low-stage cooling <i>(10-minute run-out)</i>													
<input type="checkbox"/> <u>Initiate low-stage cooling test</u> Start time <input style="width: 100px;" type="text"/> Test # <input style="width: 50px;" type="text"/> <i>("Test" switch on rig)</i>													
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Check-In													
<input type="checkbox"/> <i>Contact ECW Tech Support (608-210-7166) for data review</i> <i>(Alternative contact: Scott Pigg @ 608-210-7138)</i>													

CARD QI/QM ver. 11

Site: _____ Rig#: _____ Date: _____

Cooling Test, Post-Adjustment #1																			
Adjustment (check one) <input type="checkbox"/> No adjustment <input type="checkbox"/> New filter <input type="checkbox"/> Coil clean -----> <input type="checkbox"/> Condenser <input type="checkbox"/> Evaporator <input type="checkbox"/> Airflow adjustment describe: _____ <input type="checkbox"/> Refrigerant adjustment describe: _____ oz. (+/-) <input type="checkbox"/> Other describe: _____																			
Test 1 - High/Single-stage <input type="checkbox"/> Test skipped (no adjustment) <input type="checkbox"/> Initiate call for high/single-stage cooling (10-minute run-out) <input type="checkbox"/> <u>Initiate high/single-stage cooling test</u> Start time _____ Test # _____ ("Test" switch on rig)																			
(check one)																			
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<input type="checkbox"/> approach			F																
Refrigerant pressure:																			
Liquid line		psi																	
Suction line		psi																	
	airflow		300-400 cfm/ton																
	EER																		
Test 2 - Low stage <input type="checkbox"/> Test skipped <input type="checkbox"/> no adjustment <input type="checkbox"/> unit is single-stage <input type="checkbox"/> not final improvement test <input type="checkbox"/> Initiate call for low-stage cooling (10-minute run-out) <input type="checkbox"/> <u>Initiate low-stage cooling test</u> Start time _____ Test # _____ ("Test" switch on rig)																			
(check one)																			
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<input type="checkbox"/> superheat			F																
<input type="checkbox"/> subcool			F																
<input type="checkbox"/> approach			F																
Refrigerant pressure:																			
Liquid line		psi																	
Suction line		psi																	
	airflow		300-400 cfm/ton																
	EER																		

Site: _____ Rig#: _____ Date: _____ Page 5

Cooling Test, Post-Adjustment #2															
Adjustment (check one) <input type="checkbox"/> No adjustment <input type="checkbox"/> New filter <input type="checkbox"/> Coil clean -----> <input type="checkbox"/> Condenser <input type="checkbox"/> Evaporator <input type="checkbox"/> Airflow adjustment describe: _____ <input type="checkbox"/> Refrigerant adjustment _____ oz. (+/-) <input type="checkbox"/> Other describe: _____															
Test 1 - High/Single-stage <input type="checkbox"/> Test skipped (no adjustment) <input type="checkbox"/> Initiate call for high/single-stage cooling (10-minute run-out) <input type="checkbox"/> <u>Initiate high/single-stage cooling test</u> Start time _____ Test # _____ ("Test" switch on rig) <div style="display: flex; justify-content: space-between;"> <div style="width: 45%;"> <p style="text-align: center;">(check one)</p> <input type="checkbox"/> superheat <input type="checkbox"/> subcool <input type="checkbox"/> approach </div> <div style="width: 50%;"> <table border="1" style="width: 100%; border-collapse: collapse; text-align: center;"> <thead> <tr> <th style="width: 50%;">Measured</th> <th style="width: 50%;">Target</th> <th style="width: 10%;"></th> </tr> </thead> <tbody> <tr> <td>_____</td> <td>_____</td> <td>F</td> </tr> <tr> <td>_____</td> <td>_____</td> <td>F</td> </tr> <tr> <td>_____</td> <td>_____</td> <td>F</td> </tr> </tbody> </table> </div> </div> Refrigerant pressure: Liquid line _____ psi airflow _____ 300-400 cfm/ton Suction line _____ psi EER _____				Measured	Target		_____	_____	F	_____	_____	F	_____	_____	F
Measured	Target														
_____	_____	F													
_____	_____	F													
_____	_____	F													
Test 2 - Low stage <input type="checkbox"/> Test skipped <input type="checkbox"/> no adjustment <input type="checkbox"/> unit is single-stage <input type="checkbox"/> not final improvement test <input type="checkbox"/> Initiate call for low-stage cooling (10-minute run-out) <input type="checkbox"/> <u>Initiate low-stage cooling test</u> Start time _____ Test # _____ ("Test" switch on rig) <div style="display: flex; justify-content: space-between;"> <div style="width: 45%;"> <p style="text-align: center;">(check one)</p> <input type="checkbox"/> superheat <input type="checkbox"/> subcool <input type="checkbox"/> approach </div> <div style="width: 50%;"> <table border="1" style="width: 100%; border-collapse: collapse; text-align: center;"> <thead> <tr> <th style="width: 50%;">Measured</th> <th style="width: 50%;">Target</th> <th style="width: 10%;"></th> </tr> </thead> <tbody> <tr> <td>_____</td> <td>_____</td> <td>F</td> </tr> <tr> <td>_____</td> <td>_____</td> <td>F</td> </tr> <tr> <td>_____</td> <td>_____</td> <td>F</td> </tr> </tbody> </table> </div> </div> Refrigerant pressure: Liquid line _____ psi airflow _____ 300-400 cfm/ton Suction line _____ psi EER _____				Measured	Target		_____	_____	F	_____	_____	F	_____	_____	F
Measured	Target														
_____	_____	F													
_____	_____	F													
_____	_____	F													

Cooling Test, Post-Adjustment #3			
Adjustment (check one)			
<input type="checkbox"/> No adjustment			
<input type="checkbox"/> New filter			
<input type="checkbox"/> Coil clean ----->	<input type="checkbox"/> Condenser	<input type="checkbox"/> Evaporator	
<input type="checkbox"/> Airflow adjustment	describe:		
<input type="checkbox"/> Refrigerant adjustment		oz. (+/-)	
<input type="checkbox"/> Other	describe:		
Test 1 - High/Single-stage			
<input type="checkbox"/> Test skipped (no adjustment)			
<input type="checkbox"/> Initiate call for high/single-stage cooling (10-minute run-out)			
<input type="checkbox"/> <u>Initiate high/single-stage cooling test</u> Start time <input style="width: 100px;" type="text"/> Test # <input style="width: 50px;" type="text"/>			
("Test" switch on rig)			
(check one)			
		Measured	Target
<input type="checkbox"/> superheat	<input style="width: 60px;" type="text"/>	<input style="width: 60px;" type="text"/>	F
<input type="checkbox"/> subcool	<input style="width: 60px;" type="text"/>	<input style="width: 60px;" type="text"/>	F
<input type="checkbox"/> approach	<input style="width: 60px;" type="text"/>	<input style="width: 60px;" type="text"/>	F
Refrigerant pressure:			
Liquid line	<input style="width: 60px;" type="text"/>	psi	
Suction line	<input style="width: 60px;" type="text"/>	psi	
		airflow	<input style="width: 60px;" type="text"/> 300-400 cfm/ton
		EER	<input style="width: 60px;" type="text"/>
Test 2 - Low stage			
<input type="checkbox"/> Test skipped			
<input type="checkbox"/> no adjustment			
<input type="checkbox"/> unit is single-stage			
<input type="checkbox"/> not final improvement test			
<input type="checkbox"/> Initiate call for low-stage cooling (10-minute run-out)			
<input type="checkbox"/> <u>Initiate low-stage cooling test</u> Start time <input style="width: 100px;" type="text"/> Test # <input style="width: 50px;" type="text"/>			
("Test" switch on rig)			
(check one)			
		Measured	Target
<input type="checkbox"/> superheat	<input style="width: 60px;" type="text"/>	<input style="width: 60px;" type="text"/>	F
<input type="checkbox"/> subcool	<input style="width: 60px;" type="text"/>	<input style="width: 60px;" type="text"/>	F
<input type="checkbox"/> approach	<input style="width: 60px;" type="text"/>	<input style="width: 60px;" type="text"/>	F
Refrigerant pressure:			
Liquid line	<input style="width: 60px;" type="text"/>	psi	
Suction line	<input style="width: 60px;" type="text"/>	psi	
		airflow	<input style="width: 60px;" type="text"/> 300-400 cfm/ton
		EER	<input style="width: 60px;" type="text"/>

Site: _____ Rig#: _____ Date: _____ Page 7

Cooling Test, Post-Adjustment #4																													
Adjustment (check one) <input type="checkbox"/> No adjustment <input type="checkbox"/> New filter <input type="checkbox"/> Coil clean -----> <input type="checkbox"/> Condenser <input type="checkbox"/> Evaporator <input type="checkbox"/> Airflow adjustment describe: _____ <input type="checkbox"/> Refrigerant adjustment describe: _____ oz. (+/-) <input type="checkbox"/> Other describe: _____																													
Test 1 - High/Single-stage <input type="checkbox"/> Test skipped (no adjustment) <input type="checkbox"/> Initiate call for high/single-stage cooling (10-minute run-out) <input type="checkbox"/> <u>Initiate high/single-stage cooling test</u> Start time _____ Test # _____ ("Test" switch on rig) <div style="display: flex; justify-content: space-between;"> <div style="width: 45%;"> <p style="text-align: center;">(check one)</p> <input type="checkbox"/> superheat <input type="checkbox"/> subcool <input type="checkbox"/> approach </div> <div style="width: 50%;"> <table border="1" style="width: 100%; border-collapse: collapse; text-align: center;"> <thead> <tr> <th style="width: 50%;">Measured</th> <th style="width: 50%;">Target</th> <th style="width: 50%;"></th> </tr> </thead> <tbody> <tr> <td>_____</td> <td>_____</td> <td>F</td> </tr> <tr> <td>_____</td> <td>_____</td> <td>F</td> </tr> <tr> <td>_____</td> <td>_____</td> <td>F</td> </tr> </tbody> </table> </div> </div> <div style="margin-top: 10px;"> <p>Refrigerant pressure:</p> <table style="width: 100%;"> <tr> <td style="width: 30%;">Liquid line</td> <td style="width: 15%;">_____</td> <td style="width: 10%;">psi</td> <td style="width: 30%;">airflow</td> <td style="width: 15%;">_____</td> <td style="width: 10%;">300-400</td> <td style="width: 10%;">cfm/ton</td> </tr> <tr> <td>Suction line</td> <td>_____</td> <td>psi</td> <td>EER</td> <td>_____</td> <td></td> <td></td> </tr> </table> </div>				Measured	Target		_____	_____	F	_____	_____	F	_____	_____	F	Liquid line	_____	psi	airflow	_____	300-400	cfm/ton	Suction line	_____	psi	EER	_____		
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Suction line	_____	psi	EER	_____																									
Test 2 - Low stage <input type="checkbox"/> Test skipped <div style="margin-left: 20px;"> <input type="checkbox"/> no adjustment <input type="checkbox"/> unit is single-stage <input type="checkbox"/> not final improvement test </div> <input type="checkbox"/> Initiate call for low-stage cooling (10-minute run-out) <input type="checkbox"/> <u>Initiate low-stage cooling test</u> Start time _____ Test # _____ ("Test" switch on rig) <div style="display: flex; justify-content: space-between;"> <div style="width: 45%;"> <p style="text-align: center;">(check one)</p> <input type="checkbox"/> superheat <input type="checkbox"/> subcool <input type="checkbox"/> approach </div> <div style="width: 50%;"> <table border="1" style="width: 100%; border-collapse: collapse; text-align: center;"> <thead> <tr> <th style="width: 50%;">Measured</th> <th style="width: 50%;">Target</th> <th style="width: 50%;"></th> </tr> </thead> <tbody> <tr> <td>_____</td> <td>_____</td> <td>F</td> </tr> <tr> <td>_____</td> <td>_____</td> <td>F</td> </tr> <tr> <td>_____</td> <td>_____</td> <td>F</td> </tr> </tbody> </table> </div> </div> <div style="margin-top: 10px;"> <p>Refrigerant pressure:</p> <table style="width: 100%;"> <tr> <td style="width: 30%;">Liquid line</td> <td style="width: 15%;">_____</td> <td style="width: 10%;">psi</td> <td style="width: 30%;">airflow</td> <td style="width: 15%;">_____</td> <td style="width: 10%;">300-400</td> <td style="width: 10%;">cfm/ton</td> </tr> <tr> <td>Suction line</td> <td>_____</td> <td>psi</td> <td>EER</td> <td>_____</td> <td></td> <td></td> </tr> </table> </div>				Measured	Target		_____	_____	F	_____	_____	F	_____	_____	F	Liquid line	_____	psi	airflow	_____	300-400	cfm/ton	Suction line	_____	psi	EER	_____		
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Liquid line	_____	psi	airflow	_____	300-400	cfm/ton																							
Suction line	_____	psi	EER	_____																									

CARD QI/QM ver. 11

Site: _____ Rig#: _____ Date: _____

Airflow Tests		
Prep		
Blower type	# speed taps	
<input type="checkbox"/> ECM		[]
<input type="checkbox"/> X13 ----->		[]
<input type="checkbox"/> PSC ----->		[]
Fan-on as-found airflow test		
<input type="checkbox"/> Test skipped (<i>same as cooling-mode speed</i>)		
<input type="checkbox"/> Initiate fan-on call (<i>wait for full ramp-up</i>)		
<input type="checkbox"/> <u>Initiate fan-on as-found airflow test</u>	Start time []	Test # []
<i>("Test" switch on rig)</i>		
<input type="checkbox"/> Return anemometer test (<i>logged traverse in each of 3 return-plenum test holes; left to right</i>)		
Lowest-possible airflow test		
<input type="checkbox"/> Test skipped (<i>same as fan-on speed</i>)		
<input type="checkbox"/> Fan-on set to lowest-possible speed		
<input type="checkbox"/> Initiate fan-on call (<i>wait for full ramp-up</i>)		
<input type="checkbox"/> <u>Initiate lowest-speed airflow test</u>	Start time []	Test # []
<i>("Test" switch on rig)</i>		
<input type="checkbox"/> Return anemometer test (<i>logged traverse in each of 3 return-plenum test holes; left to right</i>)		
<i>(Leave fan-on set at lowest-possible speed if homeowner agrees)</i>		
<input type="checkbox"/> Left at lowest-possible speed		
<input type="checkbox"/> Adjusted back to as-found setting		
Completion		
<input type="checkbox"/> Continue to run Fan-on until coil is nearly dry ($\Delta T < 5F$)		
<i>(This is a good time to take photos and record system information. See Page 11.)</i>		

Gas Heating Test, As-found																			
Prep	<input type="checkbox"/> Count pilot lights in home _____ number <input type="checkbox"/> Install combustion analyzer <input type="checkbox"/> Disable water heater (if gas) and ensure other gas appliances are off																		
Test 1 - High/Single-stage	<input type="checkbox"/> Initiate call for low/single-stage heating (wait for steady condensate; min. 10-minute run-out) <input type="checkbox"/> Time from call-for-heat to gas-valve open: _____ sec <input type="checkbox"/> Clock gas meter (time for an integral number of revs over ~2-minute period) Dial size _____ cf Revs _____ Time _____ minutes _____ sec. BTUh _____ (calculated) <input type="checkbox"/> <u>Initiate low/single-stage heating test</u> Start time _____ Test # _____ <table style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 50%;"></td> <td style="text-align: center;">Measured Target range (nameplate)</td> </tr> <tr> <td>Temp. rise _____</td> <td style="text-align: center;">_____ F</td> </tr> <tr> <td>Stack temp. _____</td> <td style="text-align: center;">F</td> </tr> <tr> <td>O2 _____</td> <td style="text-align: center;">%</td> </tr> <tr> <td>CO _____</td> <td style="text-align: center;">ppm</td> </tr> <tr> <td>SSE _____</td> <td style="text-align: center;">%</td> </tr> </table>		Measured Target range (nameplate)	Temp. rise _____	_____ F	Stack temp. _____	F	O2 _____	%	CO _____	ppm	SSE _____	%						
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Temp. rise _____	_____ F																		
Stack temp. _____	F																		
O2 _____	%																		
CO _____	ppm																		
SSE _____	%																		
Test 2 - Low-stage	<input type="checkbox"/> Test skipped (unit is single-stage) <input type="checkbox"/> Initiate call for high-stage heating (min. 10-minute run-out) <input type="checkbox"/> Clock gas meter (time for an integral number of revs over ~2-minute period) Revs _____ Time _____ minutes _____ sec. BTUh _____ (calculated) <input type="checkbox"/> <u>Initiate high-stage heating test</u> Start time _____ Test # _____ <table style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 50%;"></td> <td style="text-align: center;">Measured Target range (nameplate)</td> </tr> <tr> <td>Temp. rise _____</td> <td style="text-align: center;">_____ F</td> </tr> <tr> <td>Stack temp. _____</td> <td style="text-align: center;">F</td> </tr> <tr> <td>O2 _____</td> <td style="text-align: center;">%</td> </tr> <tr> <td>CO _____</td> <td style="text-align: center;">ppm</td> </tr> <tr> <td>SSE _____</td> <td style="text-align: center;">%</td> </tr> </table>		Measured Target range (nameplate)	Temp. rise _____	_____ F	Stack temp. _____	F	O2 _____	%	CO _____	ppm	SSE _____	%						
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Blower-off delay	<input type="checkbox"/> Time from gas-valve off to blower off _____ sec																		
Adjustments (check all that apply)	<table style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 50%;"></td> <td style="text-align: center;">as-found</td> <td style="text-align: center;">adjusted</td> </tr> <tr> <td><input type="checkbox"/> Manifold pressure adjustment</td> <td style="text-align: center;">_____ in.</td> <td style="text-align: center;">_____ in.</td> </tr> <tr> <td><input type="checkbox"/> Airflow adjustment</td> <td colspan="2">describe: _____</td> </tr> <tr> <td><input type="checkbox"/> Burner air shutter adjustment</td> <td colspan="2"></td> </tr> <tr> <td><input type="checkbox"/> Blower-off delay</td> <td colspan="2">new setting: _____</td> </tr> <tr> <td><input type="checkbox"/> Other</td> <td colspan="2">describe: _____</td> </tr> </table>		as-found	adjusted	<input type="checkbox"/> Manifold pressure adjustment	_____ in.	_____ in.	<input type="checkbox"/> Airflow adjustment	describe: _____		<input type="checkbox"/> Burner air shutter adjustment			<input type="checkbox"/> Blower-off delay	new setting: _____		<input type="checkbox"/> Other	describe: _____	
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<input type="checkbox"/> Burner air shutter adjustment																			
<input type="checkbox"/> Blower-off delay	new setting: _____																		
<input type="checkbox"/> Other	describe: _____																		
	<input type="checkbox"/> Water heater re-enabled (if no adjustments)																		

Gas Heating Test, Post-Tune-Up																			
Test 1 - Low/Single-stage																			
<input type="checkbox"/> Test skipped (no adjustments)																			
<input type="checkbox"/> Initiate call for high/single-stage heating (until cond. appears; min. 10-minute run-out)																			
<input type="checkbox"/> Time from call-for-heat to gas-valve open:	<input style="width: 60px;" type="text"/> sec																		
<input type="checkbox"/> Clock gas meter (time for an integral number of revs over ~2-minute period)																			
Revs	<input style="width: 60px;" type="text"/>																		
Time	<input style="width: 30px;" type="text"/> minutes <input style="width: 60px;" type="text"/> sec.																		
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<input type="checkbox"/> Test skipped (no adjustments or unit is single-stage)																			
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Completion																			
<input type="checkbox"/> Water heater re-enabled (if disabled for clocking gas meter)																			

Site: _____ Rig#: _____ Date: _____

Photos																															
Exterior	<input type="checkbox"/> House exterior (2 views) <input type="checkbox"/> Condenser (distance) <input type="checkbox"/> Condenser faces (as-found and cleaned, if cleaned) <input type="checkbox"/> Condenser nameplate <input type="checkbox"/> Condenser charging instructions <input type="checkbox"/> Condenser Energy Guide label <input type="checkbox"/> Outdoor temperature sensor (distance) <input type="checkbox"/> Gas meter (faceplate)																														
Interior	<input type="checkbox"/> Thermostat (showing as-found settings) <input type="checkbox"/> Furnace/air handler (distance) <input type="checkbox"/> Furnace/air handler nameplate <input type="checkbox"/> Furnace/air handler Energy Guide label <input type="checkbox"/> Furnace/air handler service tags <input type="checkbox"/> Evap coil model sticker <input type="checkbox"/> Evap coil (as-found and cleaned, if plenum opened for inspection and/or cleaned) <input type="checkbox"/> Temp/RH probes; static pressure tap locations; condensate collection <input type="checkbox"/> Filter (as-found, showing upstream face; 2nd photo showing make/model) <input type="checkbox"/> Building Certificate (new home; typically near breaker panel)																														
System Information																															
Furnace/Air handler	<table style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 20%;">Mfr</td> <td style="width: 20%; border: 1px solid black;"></td> <td style="width: 20%;">Model</td> <td style="width: 20%; border: 1px solid black;"></td> <td style="width: 20%;">Year</td> <td style="width: 20%; border: 1px solid black;"></td> </tr> <tr> <td></td> <td style="text-align: center;">High/single</td> <td style="text-align: center;">Low</td> <td></td> <td></td> <td></td> </tr> <tr> <td>Input</td> <td style="border: 1px solid black;"></td> <td style="border: 1px solid black;"></td> <td>Btuh</td> <td></td> <td></td> </tr> <tr> <td>Rated temp-rise range</td> <td style="border: 1px solid black;"></td> <td style="border: 1px solid black;"></td> <td>F</td> <td></td> <td></td> </tr> <tr> <td>Blower</td> <td style="border: 1px solid black;"></td> <td>Hp</td> <td></td> <td></td> <td></td> </tr> </table>	Mfr		Model		Year			High/single	Low				Input			Btuh			Rated temp-rise range			F			Blower		Hp			
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Rated temp-rise range			F																												
Blower		Hp																													
Condenser	<table style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 20%;">Mfr</td> <td style="width: 20%; border: 1px solid black;"></td> <td style="width: 20%;">Model</td> <td style="width: 20%; border: 1px solid black;"></td> <td style="width: 20%;">Year</td> <td style="width: 20%; border: 1px solid black;"></td> </tr> <tr> <td>Nominal capacity</td> <td style="border: 1px solid black;"></td> <td>tons</td> <td></td> <td></td> <td></td> </tr> <tr> <td>Compressor type</td> <td style="border: 1px solid black;"></td> <td>scroll/recip</td> <td></td> <td></td> <td></td> </tr> <tr> <td>factory charge</td> <td style="border: 1px solid black;"></td> <td>lb.</td> <td style="border: 1px solid black;"></td> <td>oz.</td> <td style="border: 1px solid black;"></td> </tr> </table>	Mfr		Model		Year		Nominal capacity		tons				Compressor type		scroll/recip				factory charge		lb.		oz.							
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Mfr		Model																													
Bypass humidifier (check one)	<input type="checkbox"/> Present <input type="checkbox"/> Not present																														
HRV (check one)	describe HRV ducting: <input type="checkbox"/> Present <input type="checkbox"/> Not present																														
Wrap-Up																															
<input type="checkbox"/> Rig powered down and packed up <input type="checkbox"/> All test holes plugged <input type="checkbox"/> Breaker panel replaced; all breakers on <input type="checkbox"/> Furnace/air-handler functional <input type="checkbox"/> Condensate line reconnected	<input type="checkbox"/> A/C functional <input type="checkbox"/> HRV enabled (if present) <input type="checkbox"/> Test-summary report provided to homeowner <input type="checkbox"/> Gift card provided; receipt signature obtained Departure time: 																														

Appendix F – Monitoring and Modeling of Equipment Operation

Monitoring Equipment

About half of the sites in the field study had monitoring equipment installed to track operation of the equipment – and indoor conditions – over time. The monitoring equipment consisted of the following:

1. A data logger (Hobo UX-120) and current sensors (Hobo CTV-A) that recorded separate snapshots of amperage draw for the furnace (or other air handler) and cooling-system compressor once a minute was installed at the main breaker panel.
2. On/off status loggers (Hobo UX-90 or U-11) and current switches (Hawkeye H300) were attached to the energizing leads for furnace gas valves to record start/stop times for gas flow to the furnace.⁴⁴
3. Temperature and humidity loggers (Hobo U10 or UX100) recording 30-minute snapshots of indoor temperature and humidity were installed in the home. The number of loggers varied from one to eight, and included at least a logger at or near the main-floor thermostat.

Sixty homes were targeted for monitoring, but data were recovered for only 58. Other idiosyncratic issues with individual loggers further reduced the available data for some analyses for some sites. The total number of days of monitoring data per site averaged 343, with a range from 288 to 353. All of the sites had adequate data coverage in the heating and cooling seasons.

In most cases (42 homes), the monitoring was installed in 2014 *after* the on-site testing and any concomitant adjustments had been performed. However, 16 homes first had monitoring equipment installed in the fall of 2014, and then received performance testing and adjustments later in 2015.

Cooling Operation

Amperage data was converted to watts using the voltages and power factors recorded at the time of testing. These were then collapsed down to daily total operating hours and kWh of electricity consumption, and combined with daily average temperature data from nearby weather stations.

⁴⁴ For multi-stage furnaces, each stage was tracked separately via the separate gas-valve energizing leads for the stage. There were also four fully modulating furnaces in the monitoring sample. For three of the four, we were able to use the furnace amps data as a proxy for modulation level: airflow (and thus blower power) is generally proportional to firing rate for these systems. The fourth could not be deciphered in this manner, and is treated as a single-stage unit here.

The daily data were used as the basis for site-specific models of daily cooling-system operation. Three regression models were fit to the data for each site:

1. A logistic model of the probability that the system is used during the course of the day as a function of outdoor temperature;
2. A linear fit of daily operating hours to daily outdoor temperature, restricted to days when the system was used; and,
3. A linear fit of daily kWh to daily outdoor temperature, similarly restricted to days when the system was used.

(For the purposes here, a system was classified as being used on a given day if the compressor operated for 15 minutes or more.)

The first model accounts for the discretionary nature of space cooling in short-cooling-season climates like Minnesota's. Some households simply choose not to use their cooling system on some warm days (or they are perhaps away from home), though the likelihood of this generally decreases as outdoor temperature goes up. The logistic regression captures household-specific behavior in this regard.

The second and third models capture the site-specific load response of the cooling system as a function of outdoor temperature when the system is actually used. Factors such as outdoor humidity and solar gains at different times of the day can also affect system operation, but here we sought only to capture the temperature effect.

To estimate weather-normalized seasonal hours of operation and energy consumption, we combined the coefficients for each site with 30-year seasonal distributions of daily average temperature (in 1F bins) for the associated weather station.⁴⁵ The daily estimated cooling-system hours or kWh consumption for each day of the year is simply the predicted value from the fitted model at the long-term daily average temperature for that day. To incorporate discretionary use into the estimates, we multiply the predicted when-used daily hours of operation and kWh by predicted probability of use from the logistic model. Figure 29 and Figure 30 show thumbnail plots of the daily data points and fitted models for each site in the study.

⁴⁵ See National Centers for Environmental Information (NCEI) data on [Climate Normals](https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/climate-normals) on the National Oceanic and Atmospheric Administration website (<https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/climate-normals>). Our analysis used the 1981-2010 normals data. NCEI does not publish temperature distributions, but these can be estimated using data on published means and standard deviations of daily average temperature for each day of the year. The temperature distributions that we calculated match published normal heating and cooling degree days values quite closely (generally within one percent).

Figure 29. Modeled hours of operation in cooling mode.

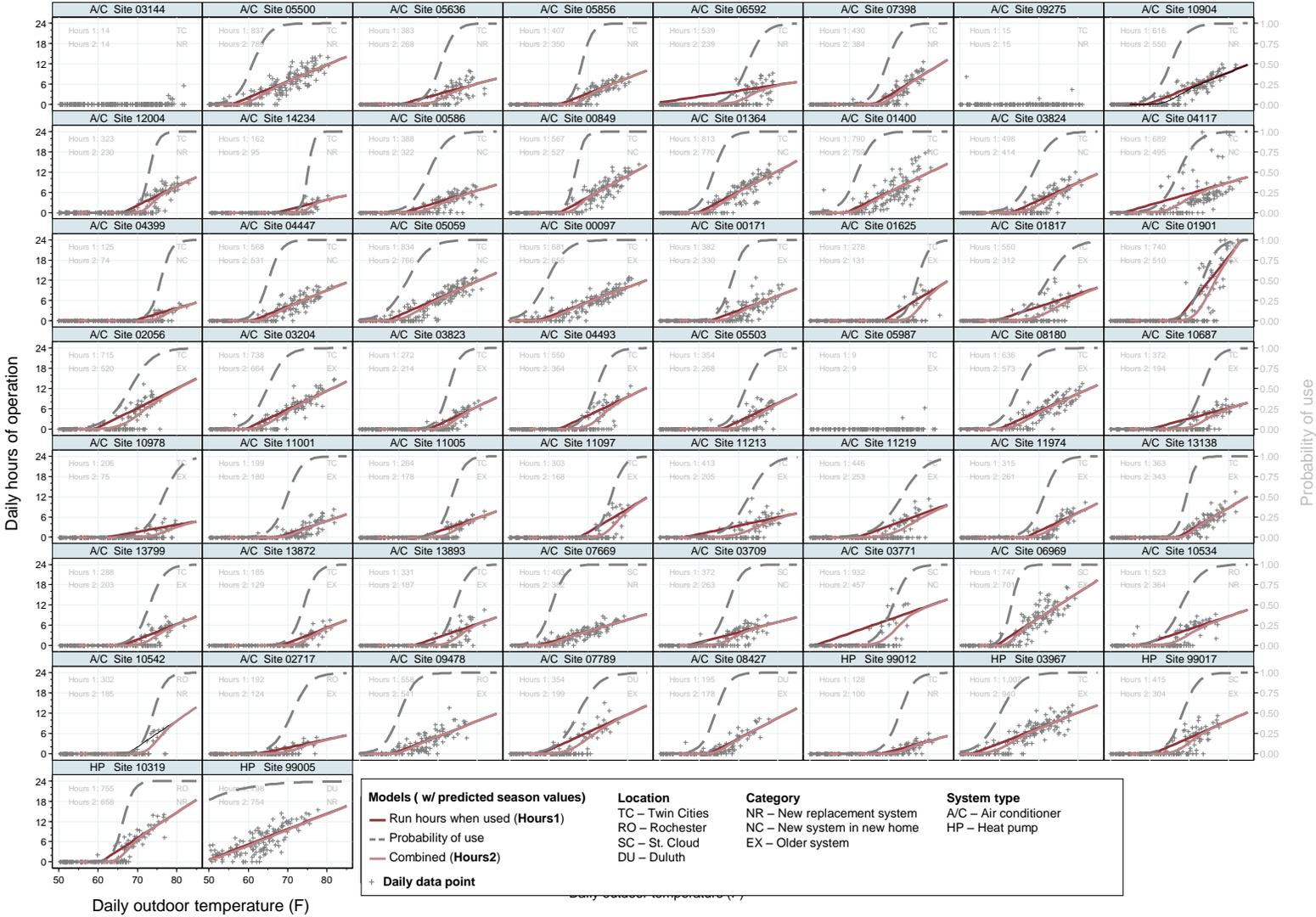
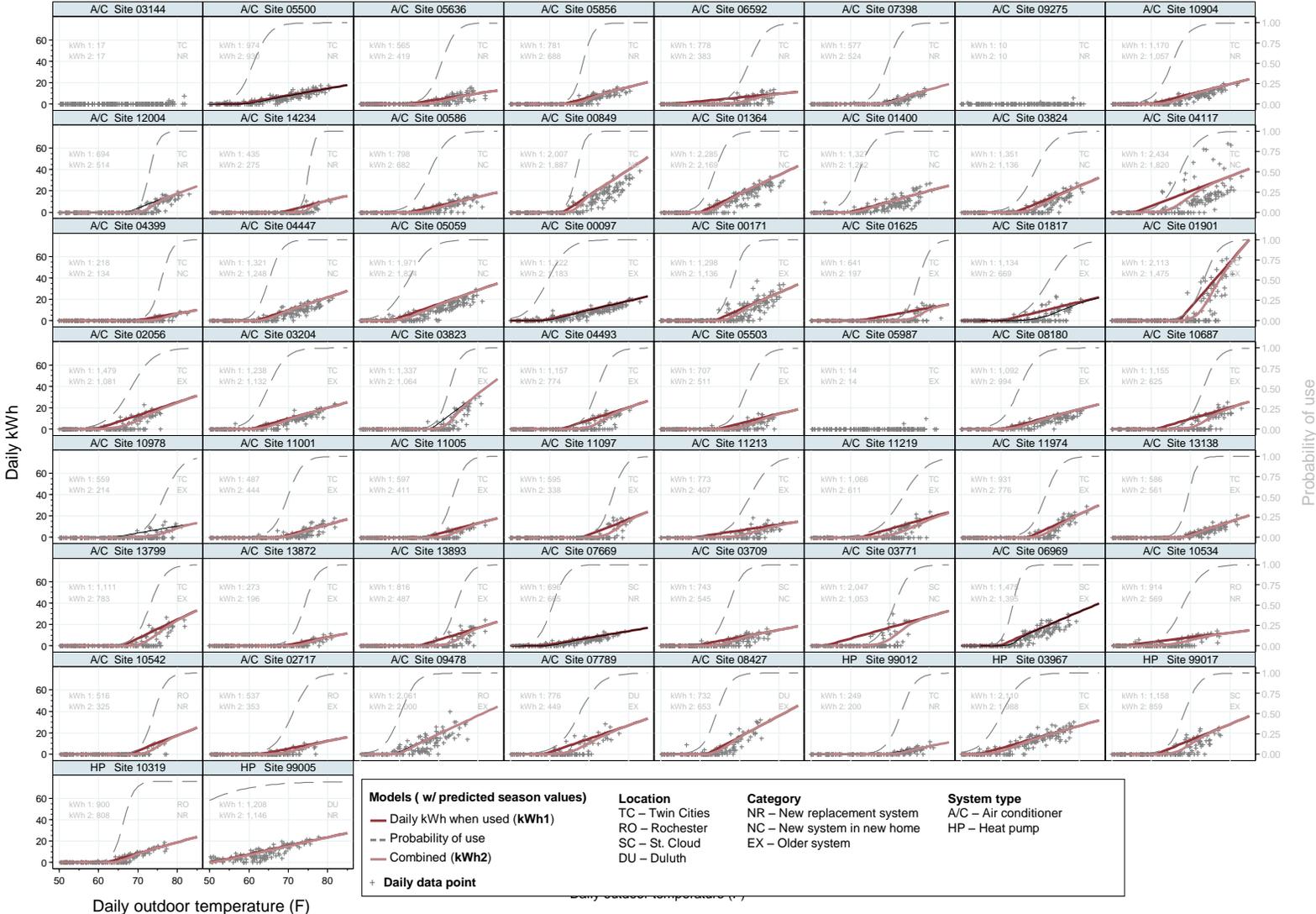


Figure 30. Modeled daily cooling-system electricity consumption.



Cooling-system use for three of the 58 sites could not be modeled in this manner, because the systems were used for fewer than seven days over the entire monitoring period. For these sites, we simply extrapolated the observed use to an average seasonal basis based on the ratio of normal cooling degree days to degree days during the monitoring period.

We also incorporated correction factors to account for the fact that most of the monitored systems had already received tune-up adjustments as part of the field study prior to the monitoring. To estimate what hours of operation and energy consumption would have been had these systems been monitored in an as-found condition, we corrected the estimated seasonal operating hours by the ratio of post-adjustment to pre-adjustment cooling output (as measured during testing). Similarly, we corrected the seasonal kWh estimates by the ratio of post-adjustment to pre-adjustment measured EER.

The fitted models for each site, allow for not only estimating seasonal operating hours and energy consumption at the actual location of the home, but also for estimating these values for other locations, simply by applying the model fits for the monitored sites to weather data for alternate locations. We applied the site-specific model results to each of 140 locations around the state where 30-year temperature averages were available. In doing so, we applied an additional correction to account for different design conditions in different locations. Specifically, we mapped each weather station to the nearest city for which a design temperature is specified in the Minnesota Residential Energy Code⁴⁶, and then developed a ratio correction to account for larger or smaller sizing in the simulated location (which we rounded to the nearest ½ ton). This analysis assumed a typical indoor temperature of 75F.

For example, in simulating the operating hours in Duluth (cooling design temperature of 81F) of a 3-ton system that was actually located in Rochester (design temperature of 85F), we estimate the adjusted system size as:

$$(81-75) / (85-75) * 3 \text{ tons} = 1.8 \text{ tons (rounded to 2 tons)}$$

We then apply a correction factor of 3/2 to the seasonal estimated hours of cooling operation for that system in Duluth.⁴⁷ This effectively assumes that in Duluth, a home like the Rochester site would likely have a 2-ton system instead of a three-ton system, and that smaller system would run about 50 percent more hours in that home than it would with the actual 3-ton system found at the Rochester site.

Note that this procedure does not make any assumptions about the degree to which systems are properly sized (or not): it simply translates whatever local over- or under-sizing exists for the site to other simulated areas, and then adjusts operating hours accordingly. Also note that the adjustment is only applied to hours of operation, and not seasonal energy consumption. We assume that the latter is relatively invariant to sizing; i.e. a 2-ton system will operate at 2/3rds

⁴⁶ See [Minnesota Rules 1322.0403 Subpart 2, R403.5.17](#) Climatic design conditions, Table 403.5.17.

⁴⁷ We capped the range of adjusted system sizes at between 2 and 5 tons, except that we allowed the small number of 1.5-ton systems to remain as such in locations where the design temperature was less than the site's actual location.

the wattage of an otherwise-equivalent 3-ton system, but run $3/2$ times the hours – with the same total energy consumption.⁴⁸

All of the above gives us an estimate of seasonal operating hours and electricity consumption for each of our 58 monitored sites at each of 140 locations in Minnesota. For the purposes of producing the contour plots shown in the report we followed the same procedure for stations in neighboring states so that the contours would be estimated appropriately near the borders of the state.

Heating Operation (gas furnaces)

Annual heating hours of operation and gas consumption for the monitored gas furnaces were estimated in a manner similar to that for cooling operation: we fit linear models of daily operating hours and gas consumption versus outdoor temperature, then used long-term averages to estimate seasonal values. However, since heating system use is much less discretionary in Minnesota's cold climate, we did not include a probability-of-use component to the analysis. We also did not include any tune-up correction factors, because these were quite minor for the tested furnaces. Finally, because the study sample included many multi-stage systems, hours of operation are expressed here in terms of high-stage-equivalents; in other words, modeled hours are the number of hours that a given furnace would run at its maximum output capacity.

For extrapolating modeled heating hours of operation to other locations, we followed the same procedure as for cooling, using statutory heating design temperatures, and assuming an indoor temperature of 70F. We also rounded adjusted heating-system sizes to the nearest 10 kBtuh. Figure 31 and Figure 32 show thumbnail plots of the model fits for each site.

⁴⁸ A sizing swap field test at two sites in Wisconsin in 2005 generally support this assumption: see Pigg (2008).

Figure 31. Modeled daily hours of operation for gas furnaces.

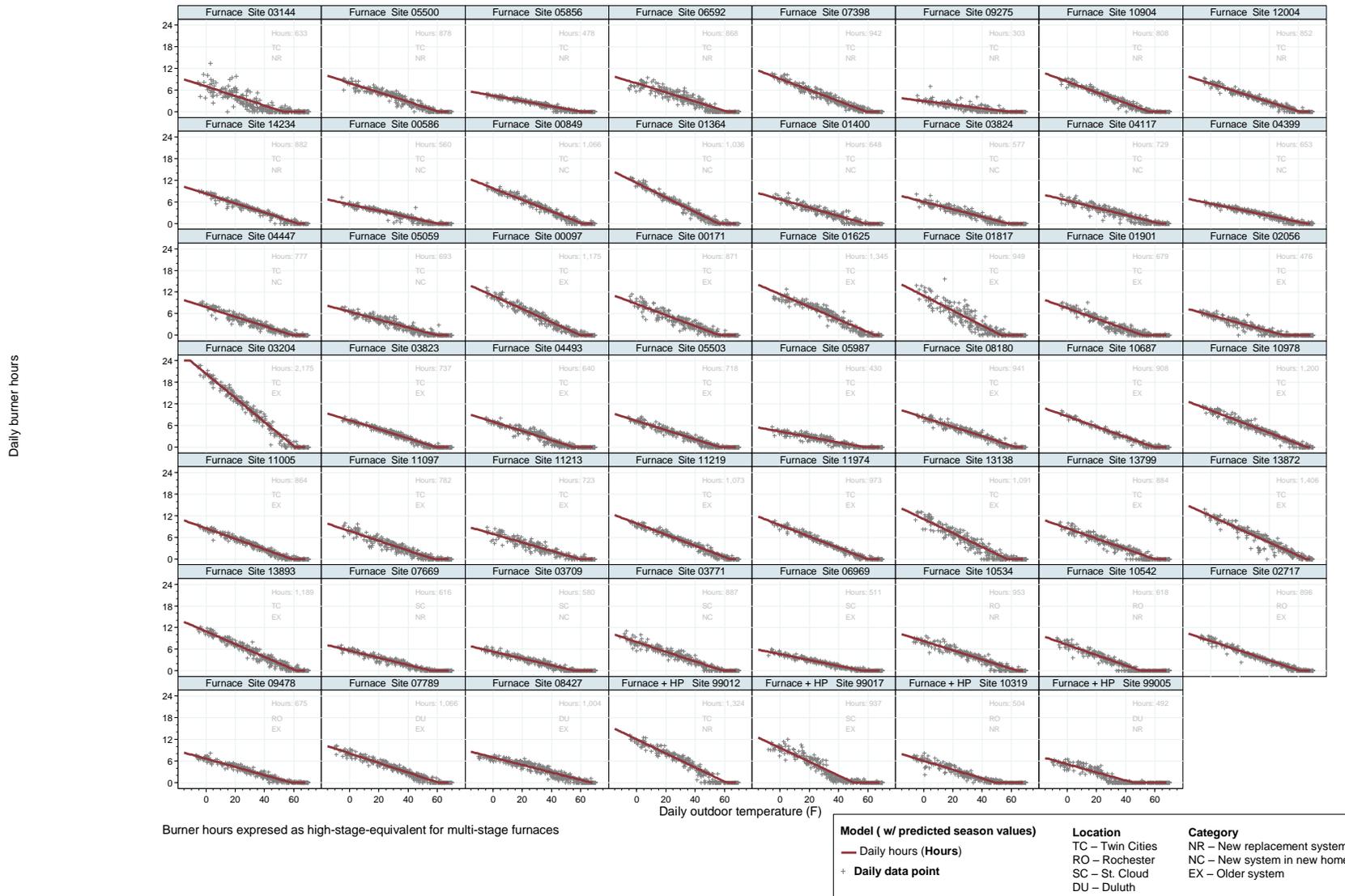
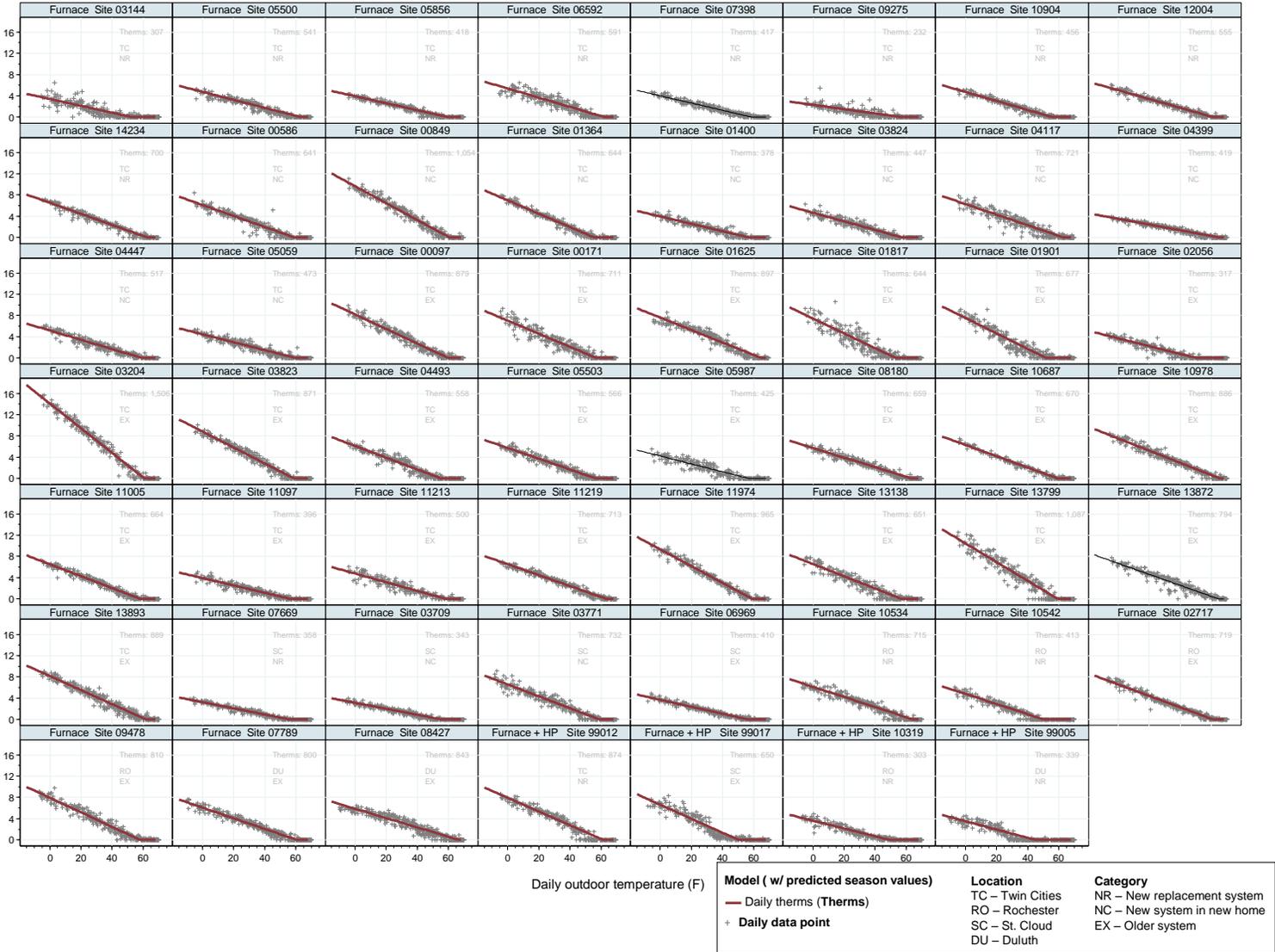


Figure 32. Modeled daily gas consumption for furnaces.



Appendix G – Airflow Measurement Comparison Details

This appendix provides additional detail on the comparison of airflow methods that contrasted hot-wire-anemometer, evaporator-coil-pressure-drop and temperature-split based methods against measurements made with a calibrated flow plate.

Hot-wire anemometer

We measured as-found cooling-mode airflow using an Extech SDL-350 hot-wire anemometer. Although we attempted these measurements for all sites, issues with data recovery eliminated analysis for some. To make the anemometer measurements for most sites, technicians drilled three holes in the return plenum, spaced at about $\frac{1}{4}$, $\frac{1}{2}$ and $\frac{3}{4}$ of the way across the duct, then inserting the hot-wire anemometer into each and slowly withdrawing it across the full depth of the duct while the instrument recorded velocity at one-second intervals.⁴⁹ For some sites, a five-hole protocol was implemented, which involved two additional holes at about 7 percent of the duct width in from each edge. We averaged the readings taken at each hole, averaged the readings across the traverse locations to get an overall average air velocity, and then converted this overall average velocity to volumetric airflow using the recorded duct dimensions.

Figure 33 shows the recorded velocity profiles for the 95 sites with usable data for the three (or five) probe locations. Some showed flat velocity profiles, while others show significant variation along the traverse. In some cases, the profiles for all three probe locations were very similar, but in other cases they were dramatically different, likely due to differences in the duct-system configurations and measurement locations.

To compare the hot-wire anemometer based airflow estimates to the flow plate results, we considered three scenarios that correspond to decreasing levels of measurement effort on the part of a technician:

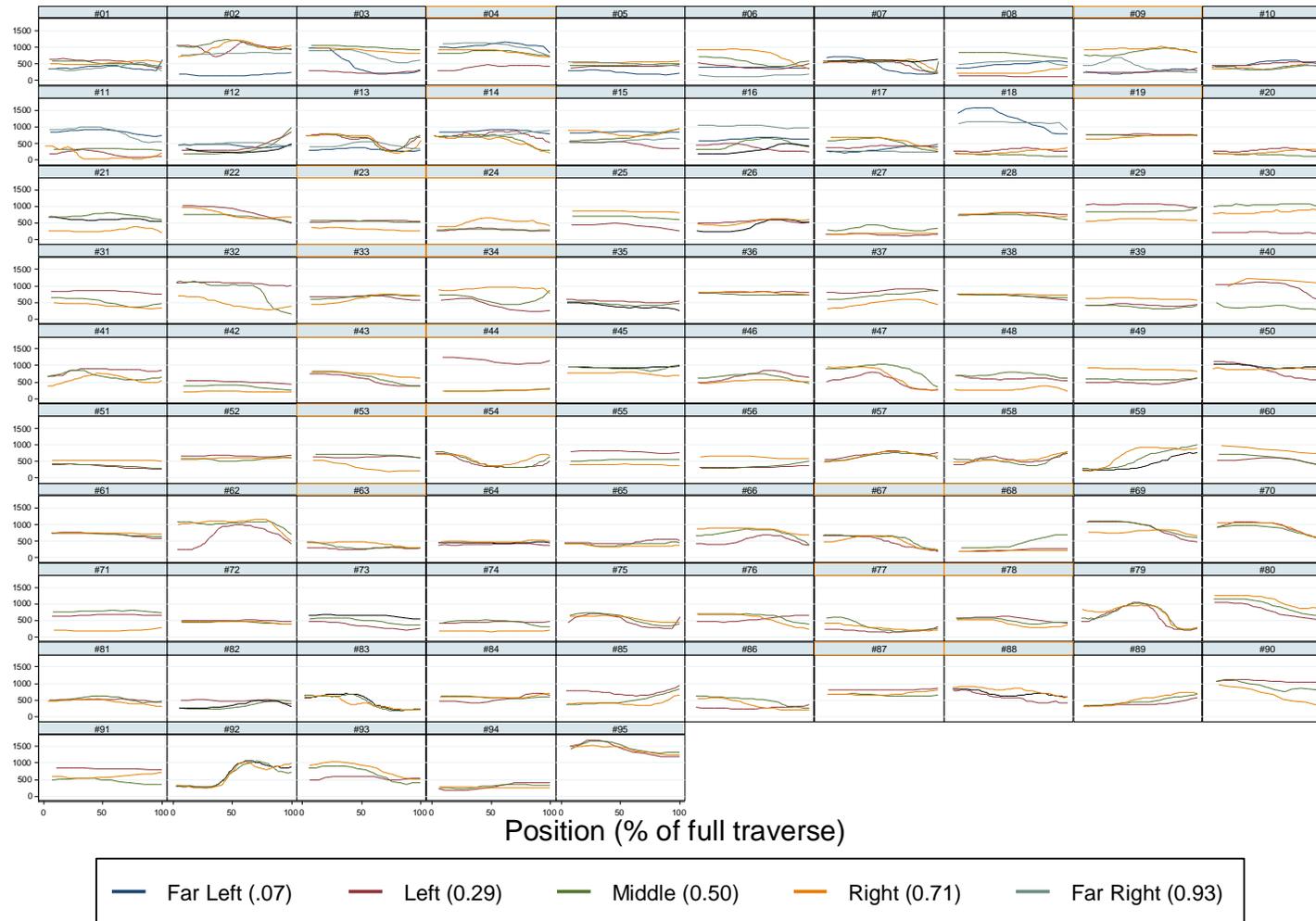
- Drilling five holes and conducting five separate traverses with the hot-wire anemometer;
- Drilling three holes and conducting three separate traverses with the hot-wire anemometer;
- Drilling one hole, and conducting a single traverse across the midpoint of the duct; and,
- Drilling one hole and taking a single velocity measurement at the center of the duct.

We simulate the latter scenarios by limiting the analysis to subsets of the data.

Figure 34 compares the three- or five-hole anemometer airflow measurements to the flow-plate based values, and Table 23 provides comparative statistics. As one might expect, the accuracy of the calculated airflow decreases as the number of measurements decreases on average. The median absolute error is lowest for the three-traverse scenario, and highest for the single, center-of-duct measurement.

⁴⁹ The median number of recorded data points per traverse was 16, and 90% of the traverses had between 11 and 33 recorded values.

Figure 33. Hot-wire anemometer velocity profiles across duct.



(Graphs are by site)

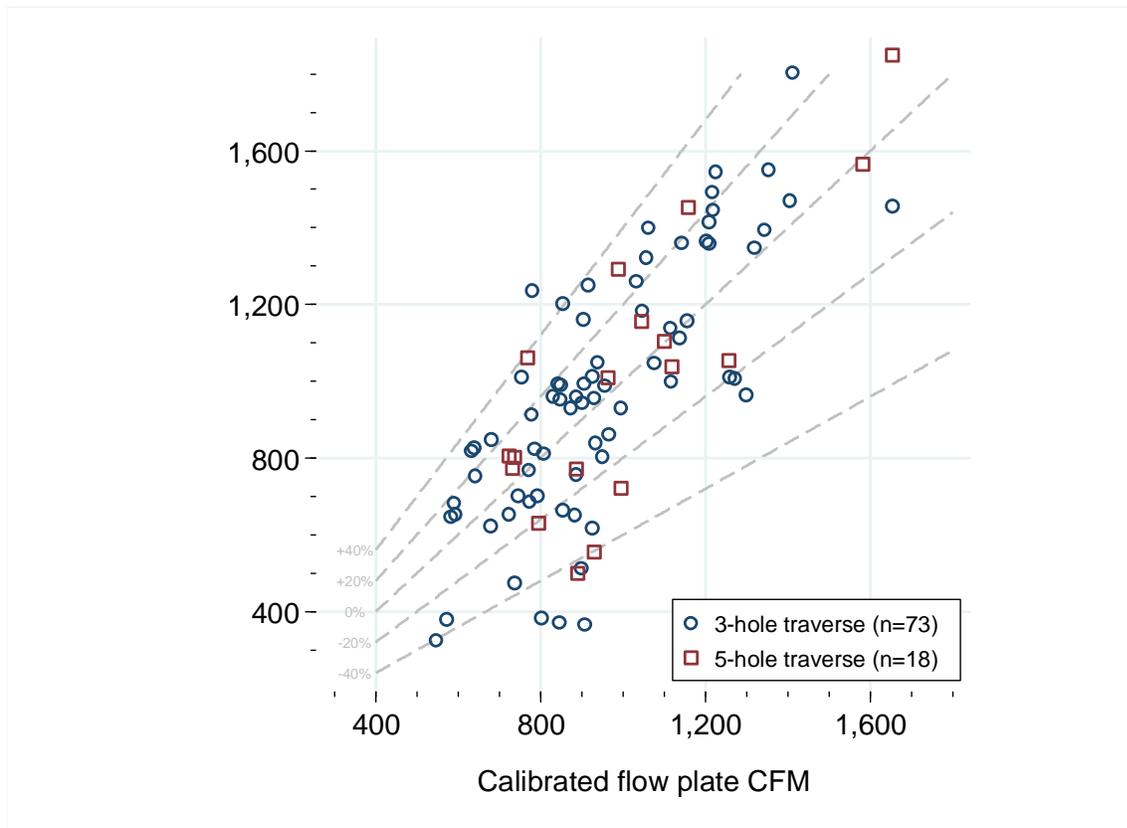
However, even for the three-traverse scenario, one can only be highly confident that the calculated airflow is within about 40 percent of the value recorded by the flow plate.⁵⁰ This suggests considerable uncertainty in the hot-wire anemometer based airflow measurements, especially given that cooling-mode airflow adjustments tend to be on the order of 25 to 30 percent.

Table 23. Error statistics for hot-wire anemometer tests.

	Traverses at five locations (n=18)	Traverses at three locations (n=91)	Midpoint traverse only (n=91)	Center-of-duct measurement only (n=91)
median absolute % error (relative to flow plate)	12%	15%	21%	28%
Percent of cases within...				
...±10%	33%	26%	26%	21%
...±20%	61%	47%	48%	36%
...±30%	78%	64%	67%	53%
...±40%	89%	90%	80%	68%
...±50%	100%	96%	91%	82%
mean % error	-1%	+2%	+6%	+10%
median % error	+2%	+5%	+6%	+10%

⁵⁰ Note also that all three scenarios show a small positive bias in estimated airflow on average. This is likely a consequence of excluding the typically lower-velocity flow close to the walls of the duct in the dimension that is perpendicular to the traverse. The magnitude of this bias is fairly small in relation to the overall uncertainty, however.

Figure 34. Hot-wire anemometer airflow versus airflow from calibrated flow plate.



Evaporator-coil pressure drop

We were able to identify the evaporator coil make/model and find published airflow characteristics for 29 sites, 26 of which were systems that were five years old or less. Coil pressure drop was captured automatically by the test rigs during testing (see [Appendix E](#)). To translate the measured pressure drops into airflow estimates, we first fit a power-law regression to the published data for each coil make and model, and then used the resulting regression models to convert observed pressure drop to coil-based airflow estimates.⁵¹

Figure 35 and Table 24 summarize the comparison of the evaporator-coil based measurement of airflow to the flow-plate based measurements. As with the hot-wire anemometer results, there is little bias, but considerable scatter, meaning that an individual coil-based estimate has non-

⁵¹ A power-law equation takes the form $Y = aX^b$. In this case, Y is airflow and X is pressure drop. This equation can be re-expressed as $\ln(y) = a + b \cdot \ln(x)$, which makes it amenable to standard linear regression analysis. Fluid flow theory predicts that the fitted value of b should be between 0.5 (turbulent flow) and 1.0 (laminar flow). The fitted values that we obtained ranged from 0.47 to 0.73, with a median of 0.61. Note also that manufacturers report both dry-coil and wet-coil values: we used the wet-coil values here, since the units were operating in cooling mode and generally producing condensate at the time of the test.

trivial uncertainty associated with it: in this case, about half of the sites show a value that is within ± 20 percent of the flow-plate value, and 95 percent of sites are within ± 40 percent.

Figure 35. Evaporator-coil based airflow versus flow-plate based airflow.

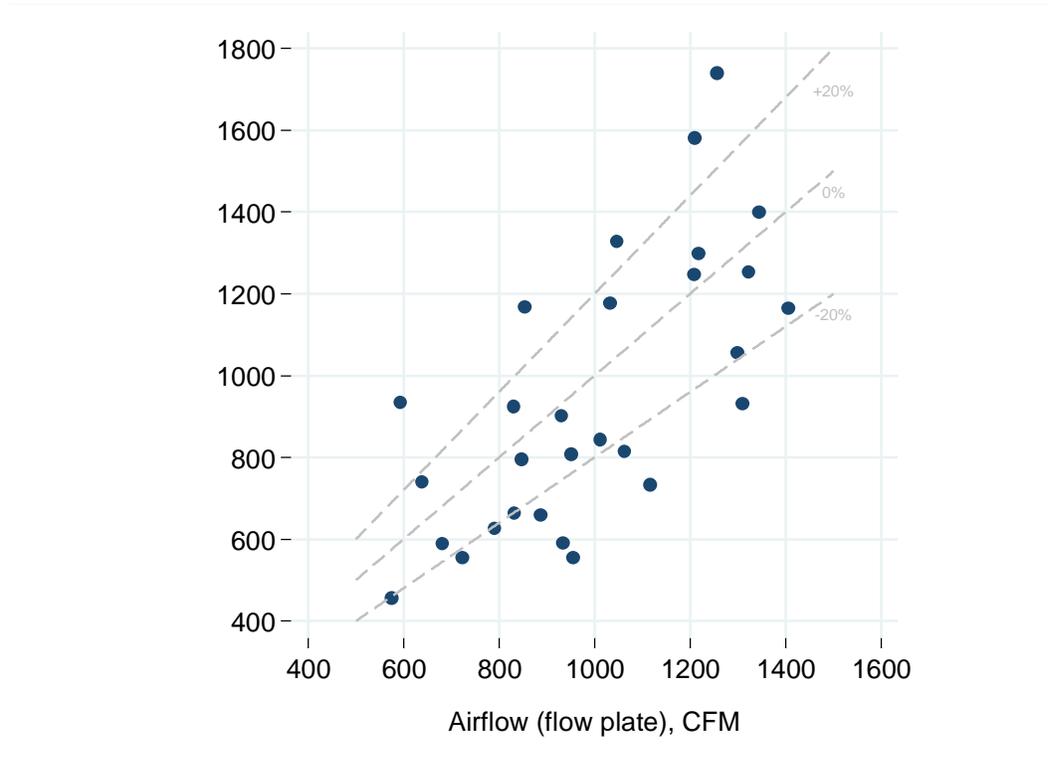


Table 24. Error statistics for evaporator-coil pressure drop based flow estimates.

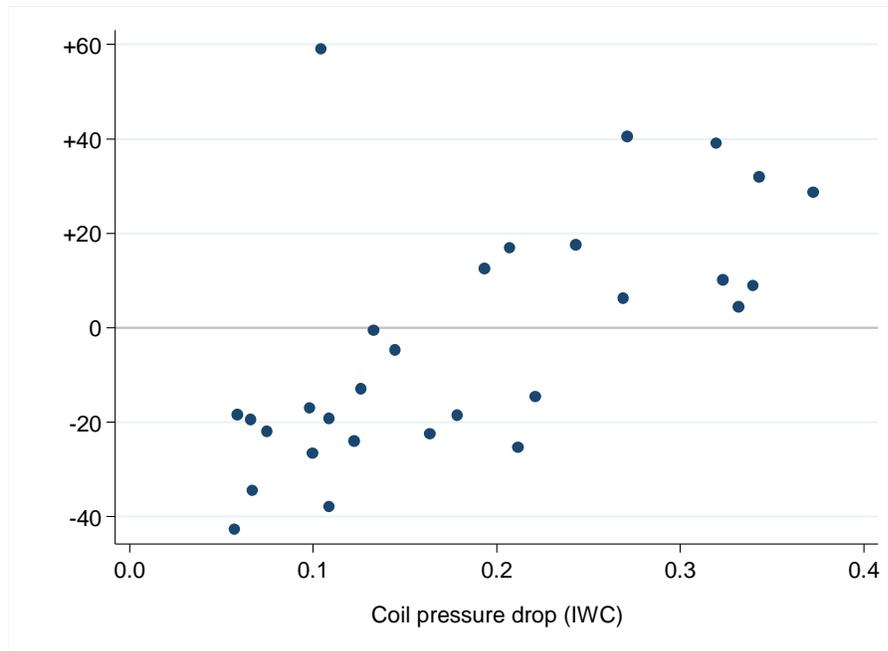
Statistic	Percent of cases
median absolute % error (relative to flow plate)	19%
Percent of cases within...	
... $\pm 10\%$	17%
... $\pm 20\%$	55%
... $\pm 30\%$	76%
... $\pm 40\%$	90%
... $\pm 50\%$	97%
mean % error	-3%
median % error	-13%

n=29

There is some evidence that the source of this uncertainty lies in where (and perhaps how) the static pressure measurements for coil pressure-drop are taken. Specifically, we observed that

the error between the two measurements tends to be positive when the measured pressure drop is high and negative when the pressure drop is low (Figure 36).

Figure 36. Airflow error versus coil pressure drop.



Our field protocol called for measuring static pressure above and below the evaporator coil, but did not specify precisely where these measurements were to be located in relation to the coil itself (which was typically hidden from view). Also, while the pressure tap downstream of the coil was a standard static-pressure probe, which does a good job of nullifying velocity effects on the measured pressure, the pressure upstream the coil was measured with a straight piece of metal tubing that may have been influenced by the velocity of the airstream.⁵²

Since the error appears to be a fairly linear function of the indicated coil pressure drop (with one notable outlier), it is possible to incorporate this relationship into the estimation process itself, and reduce the average absolute error by about half. This improves the accuracy of the coil-based flow estimates to the point where the calculated airflow is within ± 20 percent of the flow-plate value for about 85 percent of the cases. What we cannot determine without additional research however, is how well such a correction procedure would fare for a larger array of evaporator coils or other protocols for measuring the coil pressure drop.

Temperature Split Method

Cooling-mode temperature split is akin to furnace temperature rise in heating operation. If airflow is low, then the difference between the return and supply air (the temperature split) will be high. Similarly, if airflow is high, the temperature split will be low.

⁵² It is often difficult to put a standard static pressure probe just downstream of an evaporator coil without drilling into the furnace cabinet, which were reluctant to do.

However, two factors complicate the process of assessing airflow based on the temperature split. The first is that part of the cooling energy provided by air conditioners goes to dehumidification, so only part of it thus goes to reducing the temperature of the air. Moreover, this so-called sensible fraction varies with the humidity of the incoming airstream. For this reason, there is no single target temperature split for air conditioners, and a table of target values—based on the temperatures and humidity of the return air—is needed.

Second, while a temperature split that is significantly *higher* than the target value is nearly always indicative of *low* airflow, the converse is not necessarily true. A *low* measured temperature split could mean that airflow is too high, but it could also mean that airflow is fine and the output capacity of the unit is low because the unit is undercharged. And a temperature split that is in the acceptable range could mean that airflow is correct, but it could also be the combined result of low refrigerant charge and low airflow.

The practical implication of this is that tuning up an air conditioner (or heat pump) using the temperature split method is a more iterative process than is the case when airflow can be measured directly. This fact also makes it somewhat difficult to make a *post hoc* assessment of the temperature split method from the data that we collected, since we did not actually follow a temperature-split based protocol.

Nonetheless, since we have a measure of the cooling output of the system associated with each test we can take this into account when comparing the indicated temperature split—or more precisely, the deviation between the observed temperature split and the target value—to the measured airflow of the system. Figure 37 and Table 25 make this comparison for all sites and cooling-mode tests where a target temperature split could be determined using a published temperature-split table (Proctor Engineering, undated). The results show about 70 percent agreement between the two overall, which rises to about 80 percent when limited to tests where the observed cooling output was at least 80 percent of nominal.⁵³

⁵³ Note that here we use a range of 350 to 450 cfm/ton for acceptable airflow (versus the 300-400 cfm/ton used elsewhere), because target temperature-split tables are based on about 400 cfm/ton airflow.

Figure 37. Temperature split deviation from target versus measured airflow.

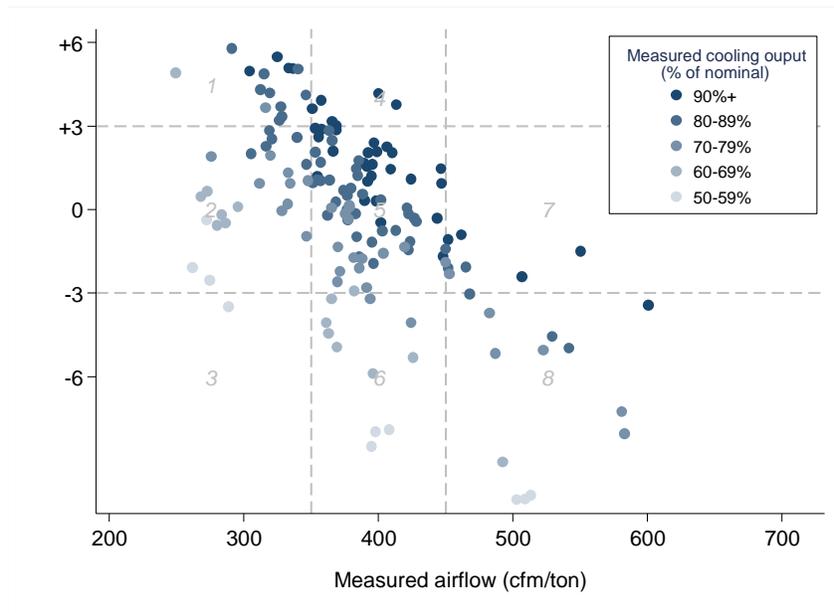


Table 25. Temperature-split versus flow-plate airflow assessment for all sites and cooling-mode tests.

Graph region	Temp-split indicated airflow	Flow-plate indicated airflow*	Agreement between methods?	All tests (n=153)	Measured cooling output at least 80% of nominal (n=95)
1	Low	Low	Yes	10%	14%
2	OK	Low	No	16%	6%
3	High	Low	No	1%	0%
4	Low	OK	No	4%	6%
5	OK	OK	Yes	49%	63%
6	High	OK	No	7%	0%
7	OK	High	No	5%	6%
8	High	High	Yes	9%	4%
Overall			Yes	68%	81%
			No	32%	19%

Note: temperature split assessment could not be made in 151 cases, because the return-air conditions were outside the range of the target temperature-split table.

*Low airflow is here defined as <350 cfm/ton; high airflow is defined as >450 cfm/ton.