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Electricity Use by New Furnaces

A Wisconsin Field Study

October 2003

Contractor: Energy Center of Wisconsin

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The power is within you.

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Technical Report

Electricity Use by New Furnaces

A Wisconsin Field Study

October 2003

Prepared by

Scott Pigg
Energy Center of Wisconsin
455 Science Drive, Suite 200
Madison, WI 53711
608.238.4601

Prepared for

focus on energy
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Project Manager

Scott Pigg
Energy Center of Wisconsin

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(800.762.7077, focusonenergy.com)

A number of individuals and organizations contributed to this effort. The project was commissioned by Wisconsin Energy Conservation Corporation, in its role as the administrator of residential programs under Focus on Energy. In particular, Ed Carroll was instrumental in making the study possible. Field work for the study was conducted by Greg Dalhoff (Dalhoff and Associates), George Penn (Global Energy Options) and Scott Pigg (Energy Center of Wisconsin). Brett Bergee (Energy Center of Wisconsin) recruited and scheduled participants in the study, and took the lead in managing the monitoring data—a task that required mailing out and subsequently downloading more than 750 data loggers over the course of the study. Steve Buss (Energy Center of Wisconsin) compiled the voluminous testing data for the 31 sites. Alex Weisheim (Auer Steel Corporation) and Dan Naidan (TSI, Inc.) provided useful technical sleuthing for two sites in the study. Scott Pigg (Energy Center of Wisconsin) managed the project, conducted the primary data analysis, and wrote the report.

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Needless to say, the final report does not necessarily reflect the views of these individuals or organizations.

Finally, this study would not have been possible without the cooperation of the 31 families that participated in the study. These families not only allowed multiple intrusions into their homes, but also actively assisted with the monitoring effort by swapping data loggers through the mail over a seven-month period.

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Abstract

Field tests and monitoring of 31 new Wisconsin furnaces showed that multi-stage furnaces with electronically commutated blower motors (ECMs) use significantly less electricity than conventional new condensing furnaces, especially when operated in year-round continuous-fan mode. The data suggest that a typical Wisconsin home will save about 465 kWh of electricity per year for heating and cooling operation, with the median ECM furnace using about half the electricity per therm for heating compared to the median non-ECM furnace. These savings increase significantly to more than 3,000 kWh when continuous-fan operation is included. Electricity use for heating operation was higher on average than standard rating data would indicate for ECM furnaces; this is most likely due to generally higher static pressures encountered in the field compared to rating test conditions. The study suggests that there are opportunities to further reduce electricity use by ECM furnaces through careful attention to filter static pressure drop. In addition, several ECM furnaces were found to be field configured for continuous-fan airflow well above the factory defaults; fan-only savings would be mitigated or non-existent in homes where this occurs. The ECM furnaces with two-stage heating capability typically operated more than 80 percent of the time at the low stage, with high-fire mainly invoked for setback recovery—but two sites operated mostly in high-fire. The study showed that most of the furnaces were oversized to the point that low-fire operation alone could meet design heating loads for the homes; setback recovery appears more to be the limiting factor in heating system sizing.

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Report Summary

This study examines electricity consumption by new Wisconsin furnaces, particularly with regard to differences between furnaces with multi-stage firing and electronically commuted blower motors (ECMs) versus single-stage furnaces with standard blower motors. The study also quantifies some basic furnace operational parameters such as annual operating hours and heating cycle length.

To conduct the study, 31 new furnaces were tested for electrical consumption, static pressure and airflow in various operating modes. The furnaces were also monitored over the latter part of the 2001/02 heating season and the entire 2002 cooling season. A model of furnace operation was developed for each site to standardize the results to typical weather conditions. Fourteen of the furnaces in the study used ECM blower motors, and most of these featured multi-stage firing operation.

From a technology perspective, the study provides basic confirmation that multi-stage ECM furnaces do provide substantial electricity savings over conventional condensing furnaces. Top findings from the study are as follows:

1. **The multi-stage ECM furnaces in the study used significantly less electricity than the standard single-stage furnaces with permanent-magnet split capacitor (PSC) blower motors.** Though the study could not control for differences from home to home in factors such as duct resistance, the results tend to confirm claims that ECM blower motors are inherently more efficient than standard blowers. The test results also demonstrate that furnaces equipped with ECM blowers are capable of operating over a much wider airflow range than standard PSC blowers. Since air handler power requirements increase with the cube of airflow, the ability to reduce airflow when appropriate—such as when providing background air circulation in continuous-fan mode—can mean dramatically lower air handler energy.

2. **The results suggest that an ECM furnace in a typical Wisconsin home will use about 465 kWh per year less electricity than a non-ECM furnace.** The majority of these estimated savings derive from heating mode electricity savings: the median ECM furnace in the study used about half the electricity for heating (0.5 kWh per therm of gas) compared to median non-ECM furnaces (1.0 kWh per therm). The data also showed lower blower power draw in cooling mode, which would also reduce the load on the air conditioning compressor. These savings far offset the finding that the ECM furnaces in the study averaged about 30 additional kWh per year in standby mode compared to the non-ECM furnaces.

3. **The study results indicate electricity savings in excess of 3,000 kWh when year-round continuous-fan operation is practiced.** Most of the ECM furnaces in the study used less than 200 Watts in this operating mode (and about half used less than 100 Watts), compared to 400 to 800 Watts for the non-ECM furnaces, which typically delivered air in continuous-fan mode at the heating speed. Over the 7,000-plus hours of operation in this mode that the data suggest would be typical of a furnace in Madison, Wisconsin, an ECM furnace using 100 Watts would use nearly 3,000 fewer kWh than a non-ECM furnace drawing 500 Watts in this mode. With the above heating- and cooling-mode savings, this would bring the total annual electricity savings to about 3,400 kWh for a typical Wisconsin home.

4. **Most of the two-stage ECM furnaces in the study operated in low stage for the majority of the time.** Eleven of the furnaces were two-stage ECM models, and the data suggest that nine of these would operate in low-fire mode for 80 percent or more of the time for typical Madison, Wisconsin weather. Although these furnaces run for more hours over the course of a heating season, their total electricity consumption is substantially less than a conventional single-stage furnace. Similarly, the two fully modulating furnaces in

the study appear to operate at or near their lowest firing rate for about half of the time. For all of these furnaces, high-fire is mainly invoked only to recover from periods of thermostat setback. Two furnaces operated mainly in high fire; these were both smaller furnaces with long heating cycles.

5. **On average, ECM furnaces in the study used more electricity per therm for heating than would be indicated by standard rating data.** The Gas Appliance Manufacturer's Association (GAMA) publishes standard ratings for annual gas and electricity consumption (in addition to gas efficiency) for furnaces based on standardized test procedures. The ECM furnaces in the study averaged nearly twice the electricity use per therm of gas than their GAMA ratings would indicate, and only three out of 14 furnaces used less than the rated kWh per therm. Static pressure appears to be a general factor: static pressure drop across the furnace and evaporator coil averaged about twice the value typically used in the standard rating test procedure, and ECM sites with higher static pressure drop tended to have higher deviation from the rated electricity use per therm. This is consistent with the fact that most ECM furnaces compensate for high static pressure by increasing the blower speed. (Note, however, that despite using more electricity than the rating data would indicate, the ECM furnaces still used considerably less electricity than the non-ECM furnaces in the study.) In addition, faulty field configuration was clearly a factor in one case, and substantial use of high-fire operation came into play for several other sites. The study suggests that heating electricity use of 0.6 kWh per therm of gas consumed could serve as a useful demarcation line between electrically efficient and less-efficient furnaces: this value neatly separates the ECM and non-ECM furnaces in the study both in terms of rating data and observed electricity use in the field.

6. **Additional electricity savings for ECM furnaces could be realized through careful attention to filter (and duct) pressure drop.** Static pressure drop across the filter varied widely among the sites, and no obvious correlations were found between type of filter or filter condition. Because ECM furnaces generally compensate for higher static pressure by boosting the blower speed to maintain a consistent airflow, additional savings could be realized by minimizing the static pressure that the system sees. This includes selecting filters with low pressure-drop characteristics, and (for new homes) minimizing duct friction. The data from the study suggest additional electricity savings may be obtained with ECM furnaces by using filters with low static pressure drop and by changing or cleaning filters regularly, since filters were found to represent about half of the total static pressure drop seen by the furnace on average. More research is needed to better understand the pressure drop characteristics of various types and brands of furnace filters, however.

7. **Field configuration of continuous-fan airflow was an issue at some sites.** Although ECM furnaces have an advantage of being capable of delivering continuous airflow at much lower electricity cost, this will occur only if the systems are configured properly. Fortunately, most of the furnaces in the study appear to be factory-set to operate at the lowest possible speed setting in continuous-fan mode—and are left that way by the installer. However, four of the 14 ECM furnaces were found to be set to a higher airflow for continuous-fan operation (including one furnace that was actually used in this mode). Non-ECM furnaces generally operated at the heating speed when called upon for continuous-fan operation, so the ability to modify the continuous-fan airflow is limited. However, at least one line of furnaces can be set to a separate lower fan speed for continuous-fan operation, though none of the four such furnaces in the study were configured in this way.

8. **Nearly all of the furnaces in the study were considerably oversized in terms of meeting design heating loads—but setback recovery may be more of a limiting factor.** The data suggest that at a 90F^{o} indoor/outdoor temperature difference, the majority of the furnaces will operate at only 40 to 60 percent of

their full output capacity on a daily basis. In fact, nearly all of the multi-stage furnaces could meet these design conditions using only the lowest firing rate. At the same time, analysis of setback recovery length indicates that about a third of the furnaces will have a setback recovery period that exceeds three hours at design conditions. Even under typical winter conditions, about a third of the homes had setback recovery periods of an hour or more. This raises interesting questions about whether the savings from thermostat setback outweigh the penalties of needing an oversized furnace for quick setback recovery.

9. **The ECM furnaces in the study had lower power factors on average than non-ECM furnaces.** Power factor can be an issue for utilities, because distribution equipment such as transformers must be sized to accommodate current flows, which are proportionally larger for loads with low power factors. The ECM furnaces generally had operating power factors in the range of 0.6 to 0.8, though individual tests sometimes showed far lower values at low operating speeds. Nearly all of the non-ECM furnaces in the study had power factors between 0.8 and 0.9. Since the ECM furnaces draw considerably less power than non-ECM furnaces, the displacement of a non-ECM furnace with an ECM model would still reduce the overall utility system capacity requirements.

It should be noted that the furnaces included in the study were deliberately chosen to include a variety of models, and may not be representative of the distribution of furnaces sold in the state each year. Energy savings figures above are couched in terms of what a typical Wisconsin homeowner might experience. In this sense, the study results do not necessarily reflect the savings attributable to program efforts to promote ECM furnaces: program participants may differ in their gas usage and furnace operational characteristics from the group of homeowners studied here, and this study does not deal with causal linkages between sales of ECM furnaces and program efforts to promote such sales.

Introduction

Background

Space heating and cooling are by far the largest energy expenditure in most Wisconsin homes; energy use for space conditioning is estimated to constitute more than half of the total energy use in the typical home (Pigg and Nevius, 2000). This gives the warm-air furnace—which is found in more than three fourths of Wisconsin single-family homes—a central role in consumer energy costs.

In the 1980s and 1990s, energy efficiency programs geared toward residential furnaces concentrated on the gas efficiency of these devices. These efforts have been successful; recent studies have shown that high efficiency condensing furnaces are currently present in about half of all single-family homes (Pigg and Nevius, 2000), and represent nearly eight out of every ten furnaces sold in the state each year.[1]

The Wisconsin success in creating a sustained market for high efficiency furnaces has led to a refocusing of program efforts to target electrical consumption by furnaces. While the benefits of high gas efficiency are generally understood, it is probably safe to say that many consumers do not realize that furnaces use a substantial amount of electricity, especially when the air handler is operated continuously (typically for air filtration or mitigation of temperature differences in the home). Moreover, standard ratings of furnace energy use, such as those published by the Gas Appliance Manufacturers Association (GAMA) show a tremendous variation in furnace electrical consumption, from less than 100 kWh per year to more than 1000.

To promote the installation of furnaces that are electrically efficient as well as efficient in terms of combustion, the Wisconsin statewide Focus on Energy program began offering a $150 reward for the installation of furnaces that use electronically commutated motors (ECM) in 2002. These ECMs (also sometimes referred to as brushless DC motors) have several advantages over the typical permanent-magnet split capacitor (PSC) blower motors found in most furnaces sold in the state each year. First, ECMs are claimed to be 20 to 30 percent more efficient than standard blower motors (Bryne, 2000; Sachs et al., 2002). Because the air handler represents a large proportion of the total electrical draw by the furnace, using an ECM in place of a standard PSC motor for this application offers an immediate boost in electrical efficiency. Some furnace models also use ECMs for the much smaller blower that moves combustion air through the venting system for power-vented and sealed combustion systems.

Second, the typical ECM blower can produce a much wider range of airflow than the PSC blower used in most furnaces, which typically have only three or four set speeds over a fairly narrow range. This can have a large impact on electrical draw, because power consumption by an air handler rises with the cube of airflow. Furnaces that can produce less airflow when appropriate (such as during continuous background circulation) will use substantially less electricity.

Furnace manufacturers have taken advantage of this fact by bundling ECM-based air handlers with multi-stage firing capability. The idea behind this approach is that the furnace can operate at a lower firing rate and less airflow for the majority of the heating season when heating loads are far below the design maximum. This results in quieter and less drafty operation in addition to reduced electrical consumption. Also—in contrast to most PSC-based furnaces—ECM furnaces also have a separately configurable continuous-fan settings and better ability to fine-tune

[1] Data on Wisconsin furnace sales comes from the Energy Center of Wisconsin's Furnace and A/C Sales Tracking Project.

airflow in cooling mode. In terms of the latter, ECM furnaces in theory provide better ability to maximize the efficiency of central air conditioning systems that use the furnace air handler.

Finally, the dominant ECM blower used in the market (manufactured by General Electric) uses a patented approach to monitor airflow and dynamically adjust the motor speed to deliver the target airflow over a wide range of static pressures. This eliminates most of the uncertainty surrounding whether a furnace is delivering the appropriate airflow for the task at hand. Standard blower motors simply run at a constant speed in any given operating mode. Differences in static pressure from home to home—or over time for a given home as the filter becomes loaded with dirt—means that airflow from these furnaces will vary, with potential adverse effects on performance.

Research Objectives

Despite the market presence of ECM furnaces since the late 1980s, little publicly available data exist to document the claimed performance advantages of these models. For example, do these furnaces indeed run most of the time at a reduced firing rate during the heating season? How much electricity do they draw compared to standard PSC furnaces in various operating modes?

Moreover, there is a general lack of field data on furnace operation in general. The number of hours that a furnace operates in a year—and the number of heating cycles it goes through—affects overall electricity use, but little field data exist on these parameters.

This study was therefore undertaken with the main objective of gathering field data on the operation of new ECM and non-ECM furnaces. The underlying premise is that the primary point of comparison should be between a new multi-stage ECM furnace and a single-stage non-ECM furnace, representing the choice faced by the consumer considering a furnace purchase.

A secondary objective of the research was to look at sizing and field configuration issues with these furnaces, with an eye towards efforts to improve installation practices.

Methods

Recruitment and Site Selection

To implement the study, a total of 31 sites were recruited, representing a mix of new ECM and non-ECM furnaces and a variety of models. The sites were recruited from three sources:

- Participants in a previous study of energy use in new Wisconsin homes who responded to a solicitation of interest in participating in a field study of furnaces. These homes were a mix of homes in the Wisconsin Energy Star® Homes program and comparable non-participants.
- A sample of participants from the Wisconsin Energy Star® Homes program for which program records showed the make and model of the furnace that was installed.
- A sample of participants in a previous state-funded rewards program for owners of older homes who purchased a new furnace.

Despite an effort to balance the study between new homes and older homes, all but five of the recruited sites ended up being new homes. All of the furnaces in the study were sealed combustion, condensing units with 90 percent or better combustion efficiency, and all were upflow "northern" models. The furnaces ranged from 50,000 to 120,000 Btu/hour input, and were all less than three years old at the start of the study. More detail about the furnaces and the sites can be found in Appendix A.

With a few exceptions, the furnaces in the study fall into two main categories: single-stage furnaces with PSC blower motors (14 sites) and two-stage furnaces with ECM blower motors (12 sites). The study also included:

- two sites with fully modulating (ECM) furnaces;
- one site with a two-stage, non-ECM furnace; and,
- one site with a (discontinued) single-stage, pulse-combustion furnace with an ECM blower.

Testing and Monitoring

The study involved a combination of short-term tests on each furnace and monitoring of operation over time. The rationale was that short-term measurements of electricity use could be combined with information about how long the furnaces operated to estimate total seasonal and annual electricity consumption. The timing of the study also precluded monitoring over an entire heating season, so the ability to extrapolate to a standard heating season was required.

Testing Approach

Two rounds of testing were conducted on each furnace. These corresponded with site visits to install and remove monitoring equipment. The first round was conducted in the latter part of February 2002; the second round was mostly conducted between September and November of 2002 (though two sites were tested in August).

Each round of testing involved putting the furnace through various operating modes while recording data on electricity use, static pressure, and temperature. Monitored parameters are summarized below:

Electrical Data

- Amperage, wattage, and power factor for the furnace, as well as the separate measurements for these parameters for the air handler blower and the combustion blower
- Voltage at the furnace electrical connection

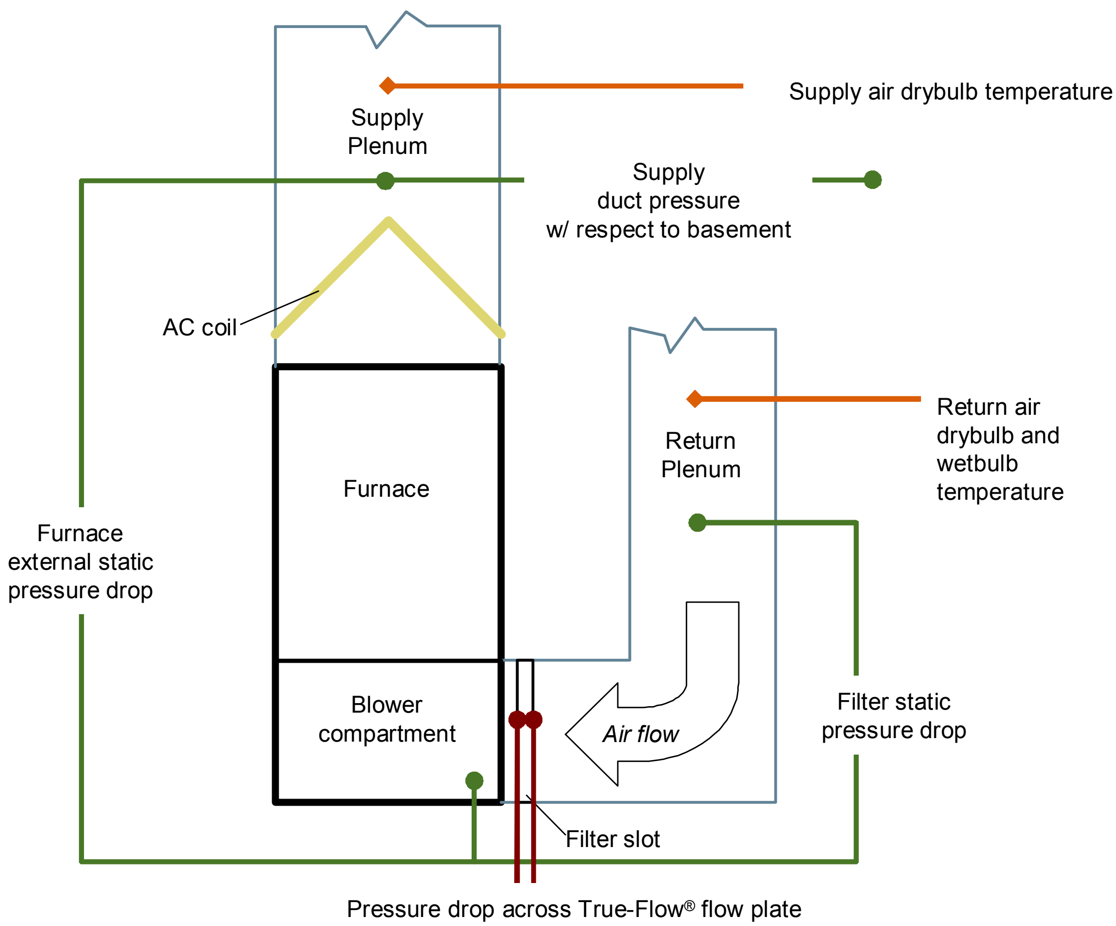
Static Pressure Drop (see figure 1)

- Between the supply ductwork (just after the AC coil) and furnace blower compartment
- Across the filter
- Between the furnace supply ductwork (at the location described above) and the basement (second round only)
- Across the Trueflow® airflow meter (used to determine airflow in the second round of testing only)

Temperature (see figure 1)

- Supply air dry-bulb temperature
- Return air dry-bulb temperature
- Return air wet-bulb temperature (second round of testing only)

Figure 1: Static pressure and temperature monitoring points.



Instrumentation

Power measurements were made using Dent instruments ElitePro® loggers with 15 Amp CTs connected to the overall electrical connection to the furnace, as well as the power leads to the air handler and combustion blowers (to allow disaggregation of these loads). A single voltage measurement was made at the service entrance to the furnace. The loggers were configured to record data as three-second averages of all values. The loggers have a stated typical accuracy of 0.5 percent for all values, including true wattage.

Static pressure measurements were made with Autotran Series 750 pressure transducers with a range of 0-1 inch of water column (IWC) (0.75% accuracy) using static pressure probe tips inserted into holes in the ductwork. The pressure transducers produced a 4-20mA signal that was sampled and recorded once a second by Onset Hobo® 4-channel data loggers (H08-006-04).

Temperature measurements were made with a single probe (TMC20-HA, 0.9F^{o} accuracy) at each location sampled and recorded at one-second intervals by the Hobo® 4-channel loggers. Soda straws were used to hold the probes away from the ductwork metal and 4 to 6 inches into the air stream. The wet-bulb temperature measurement was made by sewing a cotton wick over the temperature sensor and saturating it with water.

The on/off status of the gas valve and air handler was recorded during testing using relays and Hobo® state loggers (H06-001-02) as described in more detail below in the Monitoring Approach section.

In the first round of testing, no changes were made to the blower speed settings. Data were recorded over a heating cycle that typically lasted at least 5 minutes, under continuous-fan operation, and in standby mode. Two-stage furnaces were tested in low- and high-fire modes.

These tests were repeated in the second round of tests, which also involved operating the furnace at the cooling speed. When weather permitted, this was done by actually initiating a call for cooling at the thermostat, and monitoring for a minimum of 15 minutes. When the weather was too cold to operate the air conditioning, the blower was simply set to the cooling speed and the furnace operation was monitored for a few minutes.

For the second round of testing, airflow was also measured using a Trueflow® airflow meter. This device replaces the filter with a flow plate with known pressure drop characteristics. Pressure drop across the flow plate was logged in the same way as the other static pressure measurements. Because the flow plate does not necessarily have the same pressure drop characteristics as the filter it replaces, a correction factor was employed based on the square root of the ratio of the supply duct pressure with the filter and the flow plate in place. Used in this way, the Trueflow® has a stated accuracy of ±10 percent. Flow measurements were generally made at the end of cycle, so as not to disturb other measurements. Flow measurements during actual cooling cycles were made after 15 minutes of operation.

Data (including airflow) were also collected at alternate air handler speed settings in the second round of testing. For non-ECM furnaces, this generally meant measuring at each of four speed tap settings. The ECM furnaces in the study had many possible speed settings; four to six settings across a range of available speeds were selected for testing.

Finally, firing rates for the furnaces were also established during the second round of testing. This was done by timing how long it took for the furnace to consume two to three cubic feet of gas according to the home's gas meter.

Testing — Data Reduction Protocol

Raw data from the testing were in the form of one-second snapshots (pressure and temperature) and three-second averages (power, amperage, power factor, and volts) over the entire testing period. The three-second power data were first converted to one-second level data (by replicated observations between actual data points) and then merged with the pressure and temperature data to produce a single, one-second interval stream of data for the testing. Status change information from the state loggers was also merged into this dataset.

The beginning and ending points of individual tests, such as a heating cycle or a period of continuous-fan operation were marked in the data based on field notes, and average values over a core period of steady-state operation was identified for each. The core period was generally defined by removing the first and last 30 seconds of data, then taking the mean of the remaining data. For heating cycles, steady-state operation was defined as the period between blower startup at the beginning of the heating cycle and gas valve shutoff at the end. The identified core periods were visually inspected to ensure that transient effects (such as a spike in blower motor wattage at the time of startup) were not inadvertently included. For airflow measurements, the process involved also identifying a core period of operation with the flow plate and the filter in place.

The analysis also relied on measurements of total electricity use over relatively fixed operations, such as the startup phase of a heating cycle. These were calculated by simply summing the watt-seconds of electricity use between relevant events. For example, the electricity consumption during heating cycle shutdowns was calculated by summing the watt-seconds of electricity used from the point the gas valve closed (denoting the termination of a call for heat) to the point the blower motor shut down.

Time constraints typically prevented operating the furnaces to the point of steady-state conditions in terms of temperature rise. The field data were extrapolated to steady-state conditions using methods described in Appendix B.

Monitoring Approach

The goal of the monitoring was to track the amount of burner and blower on-time and cycling behavior of the furnaces as a function of outdoor temperature. This was generally done by monitoring the status of the gas valve and the air handler.

Gas valve status was recorded by wiring a relay (RIBUC1) in parallel with the gas valve such that whenever the gas valve was energized the relay contacts also closed. The relay contacts were connected to a Hobo® state logger (H06-001-02), which recorded the date and time (to the nearest 0.5 seconds) each time the gas valve opened and closed. For two-stage furnaces, two relays and data loggers were used; one recorded the status of the first stage, and the other tracked the status of the second stage. The gas valve used in some lines of furnaces in the study (Sites 12, 18, 24 and 27) was not amenable to connecting a relay; for these sites, the status of the combustion inducer blower was tracked, and the data were adjusted based on measured time delays between the inducer and gas valve operation.

Blower status was similarly monitored by attaching a relay with a state logger to the electronic air clear (EAC) terminals on the furnace control boards. The EAC terminals are typically energized whenever the blower operates.

In addition to tracking gas valve and blower status, a 20-amp current transformer (Hobo® CTV-A) was attached to the furnace to measure total amperage draw by the furnace. This was sampled every 90 seconds and recorded by a 4-channel Hobo® data logger. The amperage data was mainly used as a cross-check against the status data.

Finally a temperature logger (Hobo® H8 series) was placed at the thermostat to sample and record the temperature every 15 minutes. Some sites also received an outdoor temperature logger (Hobo® H8 Pro series) to record outdoor temperature as well (most of the subsequent analysis relied on weather station data, however).

Special consideration was needed for the two fully modulating furnaces in the study (Sites 28 and 32). Simply tracking gas-valve on/off status was not adequate for these because their output can be modulated between 40 and 100 percent of full output. The approach used was to leave these sites as the last for testing and monitoring installation, and then leave the Dent power monitoring equipment behind to record actual average wattage over one-minute intervals for these furnaces, in addition to tracking gas valve and air handler on/off status. One additional channel of the Dent loggers was also dedicated to recording the control voltage to the gas valve; this voltage varies from 6 to 18 VAC in proportion to the degree of modulation. The Dent loggers had sufficient on-board storage for about a month's worth of one-minute furnace wattage and gas valve control voltage data.

The data loggers and sensor wires were color coded so that the homeowners could replace the loggers as they filled up. Approximately once a month, each homeowner was mailed a new set of data loggers, along with a return envelope for the current loggers and a postcard to record the date and time of the swap (indoor temperature loggers were swapped only once over the course of monitoring). A few loggers were incorrectly configured, or not plugged in correctly, but these amounted to no more than 40 out of more than 750 data files received over the course of monitoring the 31 sites. In addition, some data loggers filled up before they could be swapped out, particularly the state loggers, which can hold a fixed number (about 1,000) of on/off cycles rather than data over a fixed amount of time. These data were accurate but incomplete. Considerable effort was spent identifying gaps in the data and removing the small amount of erroneous data from incorrectly configured loggers.

The monitoring equipment was installed at the sites over the latter part of February 2002, and monitoring officially continued through the end of August to capture the cooling season. Because some data loggers were not yet filled up and equipment was not completely removed until later in the fall, some data were obtained for the fall of 2002. No summer data was obtained from Site 5, because the homeowners left for the summer in early June. Fortunately, despite the late start of the study in the 2001/02 heating season, the coldest weather of the year occurred in early March just after the completion of monitoring installation. The furnaces were thus monitored over about a 100F^{o} temperature range, from about -5^{o}F to +95^{o}F.

Monitoring — Data Reduction Protocol

Raw data from the monitoring was in the form of a stream of date/time stamps of status changes for the gas valves and air handlers, 90-second interval data for furnace amperage, and 15-minute interval data for indoor temperature. The bulk of the analysis for this report was conducted using daily summaries of these data. Total daily burner and blower hours and cycles were calculated from the status data, as were minimum, maximum, and median daily cycle lengths. These were merged with daily average furnace amperage and indoor temperature data, as well as with daily average outdoor temperatures obtained from each of four nearby NOAA weather stations. Days with less than 90 percent data recovery were discarded. Appendix F provides basic scatterplots of some of these variables.

The resulting dataset of daily summary data formed the basis for the regression models of daily operating hours and cycles described in detail in Appendix C. Essentially, these models provided a means of estimating operating hours and cycles as a function of outdoor temperature. When combined with a distribution of outdoor temperature, the models provide estimates of total operating hours and cycles over the course of a year or season.

Results

Overview

Although furnaces involve a number of components, the air handler is by far the most important when it comes to electricity use.[2] As will be shown later, the air handler typically accounted for 75 percent or more of the electricity consumed by the furnace in the study. The test data collected on the furnaces in the study confirm two primary ways in which ECM furnaces save air handler energy: 1) an ECM is inherently more efficient than a typical PSC air handler motor; and, 2) ECM-based air handlers can be operated over a much wider usable range of speeds than can typical four-speed PSC air handlers.

Both of these advantages can be seen graphically in Figure 2, which shows the characteristic curve of blower power draw versus airflow for each site in the study. Though differences in variables such as duct and filter resistance make each curve unique—and strict comparison between sites difficult—the ECM-based air handlers generally draw less power at a given airflow than the PSC-based air handlers. This is consistent with the notion that ECM blowers are inherently more efficient (Byrne, 2000).

Moreover, Figure 2 dramatically illustrates the wider airflow range available from the ECM-based air handlers.[3] In practical terms, this means that these furnaces can operate at far lower wattage in situations where less airflow is needed, such as continuous fan-only operation and reduced-output heating for furnaces with multistage firing.

This report examines differences between ECM and non-ECM furnaces in four basic operating modes: heating, cooling, fan-only operation, and standby. These modes and key results are described below.

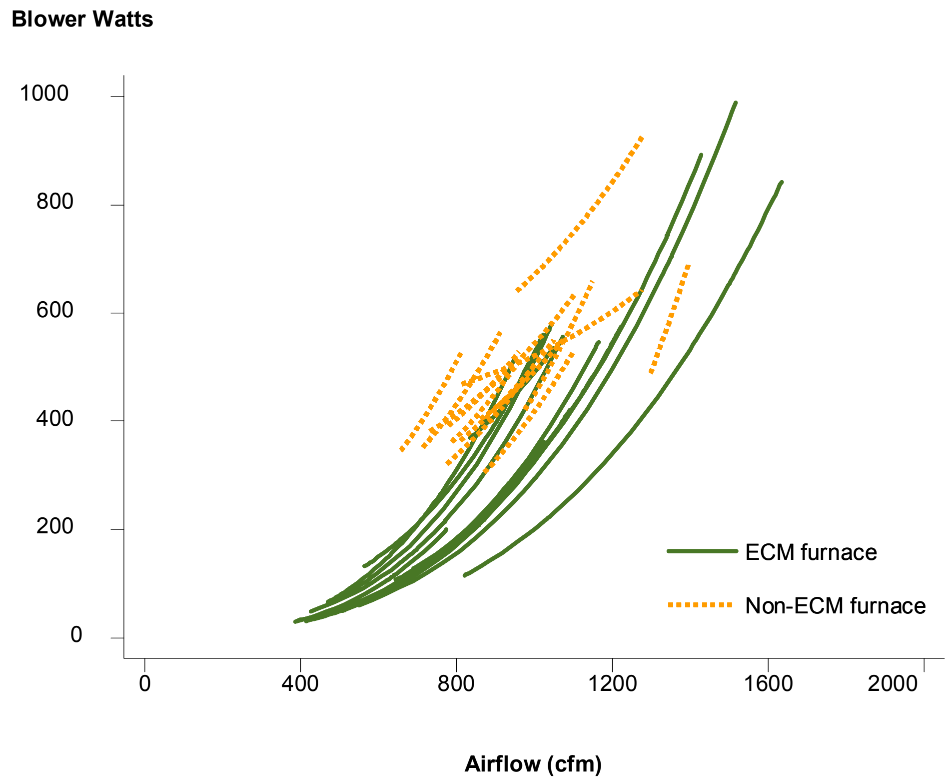
Heating Mode

The study suggests that a typical non-ECM condensing furnace in Wisconsin will fire for a total of about 1,000 hours over the course of an average heating season, and consume about 800 kWh of electricity—most of which will be used to power the air handler. A typical multi-stage ECM furnace will mainly operate in a reduced low-fire mode, with its full firing capability used primarily to recover from thermostat setback periods. Although the ECM furnace will operate more total hours in heating mode (since it is producing less heat per hour in low-fire mode), it will do so with far lower electrical power requirement for the air handler: the result is that the ECM furnace will use about half the electricity in heating mode (400 kWh) over the course of an average heating season.

[2] Throughout this report, the term "air handler" refers to the furnace blower motor and fan assembly used to circulate air through the furnace and deliver heated air to the house.

[3] Actually, many of the ECM furnaces are capable of higher airflows than shown. For the study, tests were conducted only up to the selected cooling speed based on the size of the central air conditioning system.

Figure 2: Blower power versus airflow curves for study furnaces.



Cooling Mode

In cooling operation, the furnace air handler provides airflow over the evaporator coil for the central air conditioning system to remove heat and circulate cooled air through the house. Airflow requirements in this mode are typically large, so the savings from ECM-based air handlers stem from their inherently higher operating efficiency. The study results suggest that a typical 2.5-ton air conditioner that is operated for 400 hours over an average Wisconsin cooling season will require 225 kWh of air handler energy from a non-ECM furnace and 155 kWh from an ECM furnace, for a difference of about 70 kWh. In addition, less air handler energy in the summer means less waste motor heat that must be removed by the air conditioner: this adds perhaps an additional 25 kWh to the cooling-mode savings for a typical ECM furnace.

Fan-Only Operation

Some homeowners choose to operate their furnace air handler continuously, regardless of the need for heating or cooling, to filter the air in the home or perhaps even out temperature variation around the home. Airflow requirements in these situations are low, but non-ECM furnaces are typically set up to deliver the heating-mode airflow when called upon for fan-only operation. The result is high air handler power requirement (typically about 500 Watts), and—over the more than 7,000 hours that would be typical for year-round continuous fan operation—more than 3,500 kWh of electricity consumption. As the study data show, however, a typical ECM furnace can operate at a very low airflow rate, and provide adequate air circulation for about 80 percent less air handler energy.

Standby Operation

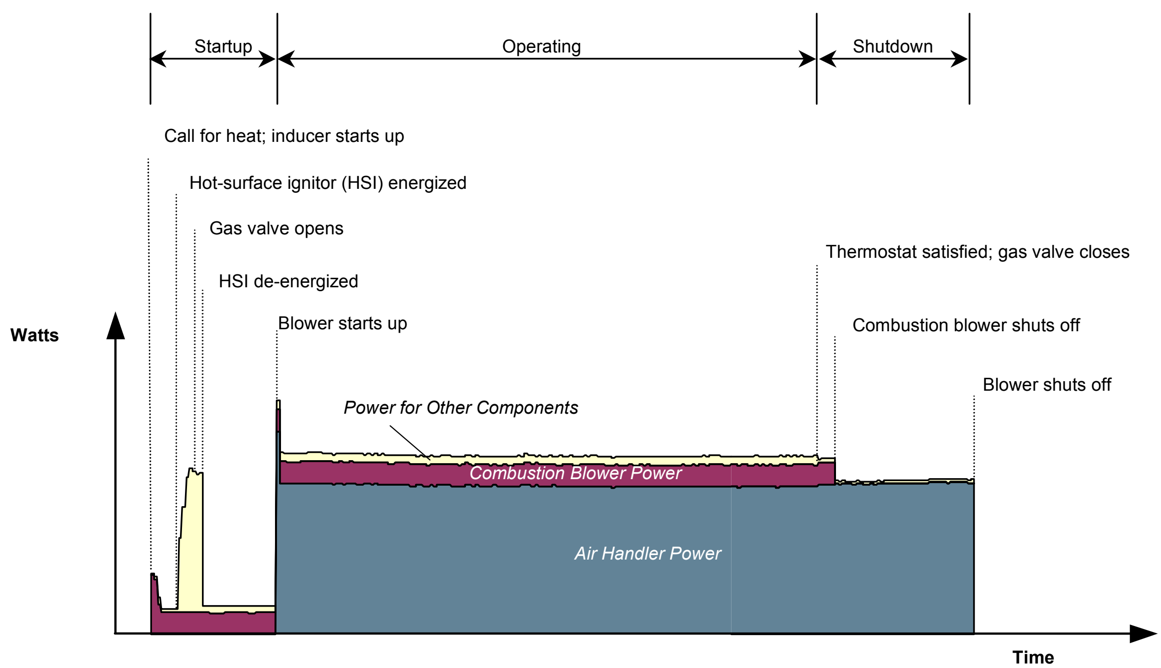
Standby is what furnaces do when they are not being called upon for heating, cooling airflow, or continuous fan-only circulation. Except for furnaces that are called upon to provide continuous air circulation, most furnaces spend the vast majority of their time (typically more than 7,000 hour per year) in this mode drawing a small amount of power that adds five to ten percent to the total annual electricity use for the furnace. The study results indicate that ECM furnaces use more electricity than non ECM furnaces in standby, which reduces the savings from these furnaces by about 30 kWh typically.

The sections that follow cover each of the above operating modes in more detail. Final sections examine the geographic variation in the results, the impact of filter pressure drop on power requirements, and power factor measurements.

Heating Mode

Heating is the most complicated mode of operation for furnaces, involving the most components of the furnace, as well as ignition and shutdown sequences. Figure 3 shows electrical consumption over a heating cycle for one of the furnaces in the study (similar plots for all of the furnaces can be found in Appendix B).

Figure 3: Electrical profile of a typical heating cycle.



Though they differ in timing and in some of the details, the furnaces in the study all follow same basic sequence of operation for heating:

1. Upon receiving a call for heat from the thermostat, the combustion blower starts up.

2. When the system is satisfied that combustion airflow is adequate, the hot-surface igniter (HSI) is energized and after a short warm-up period the gas valve is opened, igniting the burners.

3. After a warm-up interval, the air handler starts up. At this point the furnace begins to deliver warm air to the house.

4. When the thermostat terminates the call for heat, the gas valve immediately closes, extinguishing the burner; after a short purge period, the combustion blower also shuts down.

5. After a pre-programmed period of scavenging heat from the furnace, the air handler shuts off, completing the heating cycle.

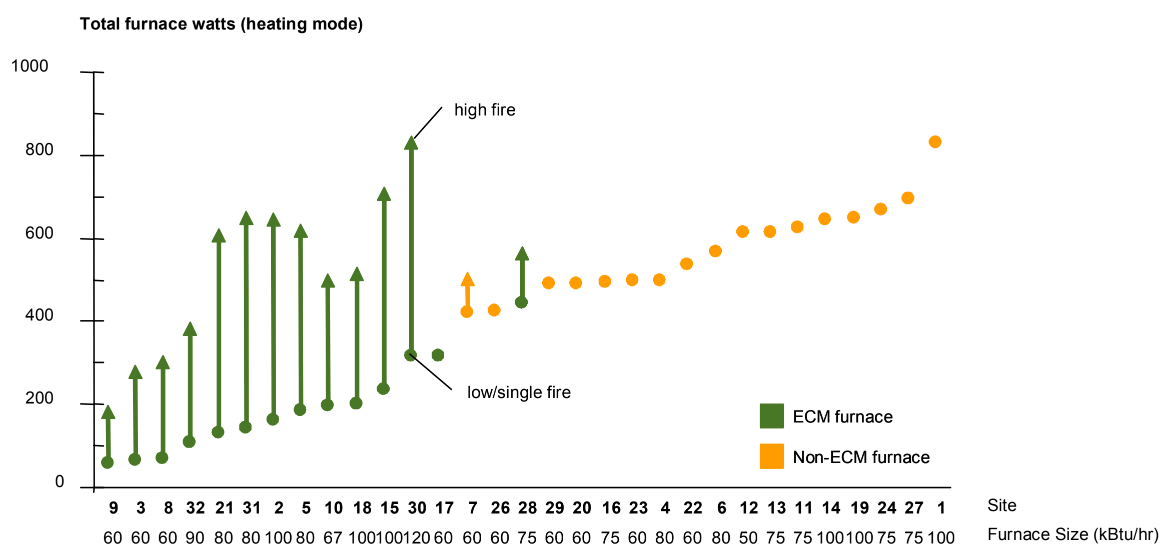
A heating cycle can be divided into three phases: startup, operating, and shutdown. The electricity consumed in the startup and shutdown phases is relatively constant from one heating cycle to the next, and hence is proportional to the number of heating cycles the furnace goes through. The total electricity consumed in the operating phase depends on how long the furnace is run. As the heating load on the home increases, both the number of cycles and the length of the heating cycle can be expected to increase. Analysis of the monitoring data collected on the furnaces in the study suggests that most of the increased run-time for furnaces comes from an increase in the number of cycles the furnace goes through rather than increases in the length of the cycle (see Appendices C and D).

Steady-State Power Draw

Figure 4 shows the overall power consumption of the furnaces in heating mode with both the burner and air handler in operation. It is readily apparent from this figure that the multi-stage ECM furnaces consume significantly less power in low-fire mode than do the single-stage non-ECM models. Some of this difference is no doubt due to the inherent efficiency advantage of the ECM blower, but much derives from the fact that the multi-stage ECM furnaces move considerably less air in low-fire mode. Since blower power is proportional to the cube of the airflow, even a modest reduction in airflow results in substantially lower blower power draw.

In high-fire mode, the multi-stage ECM furnaces in the study do not show as clear an advantage over the single-stage non-ECM furnaces in terms of power draw. The 60,000 Btu/hr models (Sites 3, 8 and 9) all show significantly lower power draw in high-fire mode compared to the non-ECM 60,000 Btu/hr sites (Sites 7, 26, 29, 20 and 23). When viewed in terms of blower wattage versus airflow, these furnaces are clearly set up to deliver less airflow at high-fire. But the 80- to 100-kBtu ECM furnaces draw about the same amount of power as the non-ECM furnaces in this size range.

Figure 4: Heating mode power draw.



Heating Speed Selection and Temperature Rise

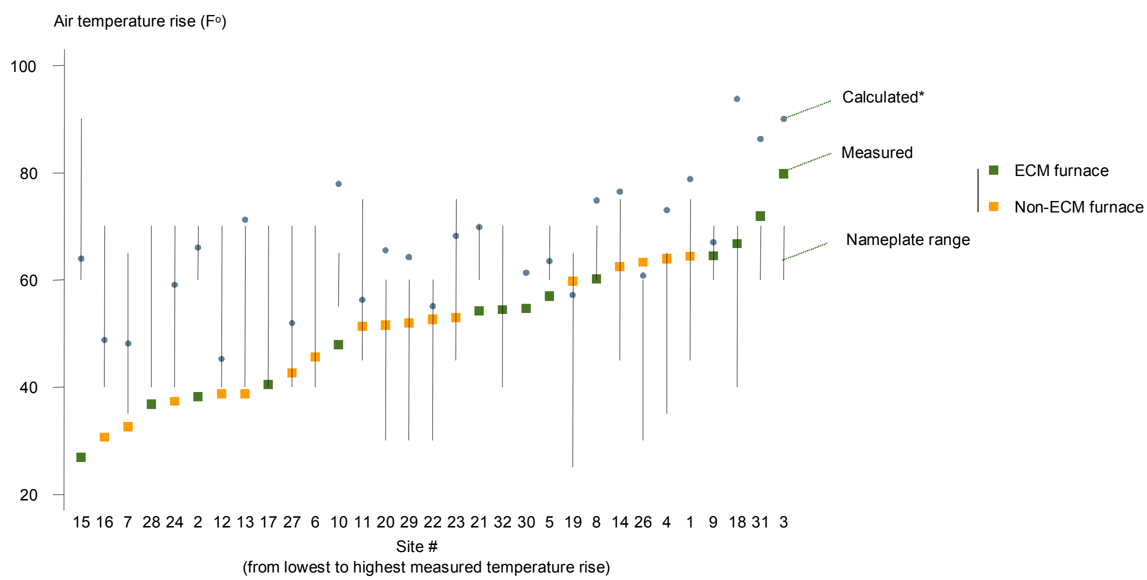
Because air handler energy is a large part of the total power draw, the field selection of the heating blower speed at the time of installation can affect the power consumption of the furnace. The non-ECM furnaces in the study generally have four speed taps to choose from: low, medium-low, medium-high, and high. These furnaces were all set to either medium-low or medium-high, and most appear to be set at the factory default value.

Among the ECM furnaces, it is noteworthy that some are not field adjustable in terms of the heating mode blower speed. These furnaces sense actual airflow and attempt to achieve a preset target airflow. The two fully modulating furnaces can be field set for either a 50 or 65 F° temperature rise. The lower figure would correspond to a higher airflow rate, and vice versa. Both of the furnaces in the study were set for the 50 F° rise; when we tested the higher setting (for Site 28), blower wattage was reduced by about 50 percent.

Each furnace has a nameplate range for temperature rise (i.e. the difference between the supply and return air temperatures in steady-state operation)—typically 40 to 70 F°. Furnaces operating below the nameplate temperature rise are probably moving excessive air—and using excessive electricity—while those operating above the range risk premature heat exchanger failure. Tests on the furnaces in the study showed that dropping one speed tap setting from the default reduced airflow and blower wattage by about 10 percent on average.

Steady-state temperature rise was calculated for each furnace based on test data (see Appendix B). The measurement data suggest that low temperature rises (indicating excessive airflow) are more common than the reverse—12 of the furnaces in the study were below the nameplate range, and only three were above the nameplate range (Figure 5).

Figure 5: Extrapolated temperature rise.



*Calculated based on measured airflow and rated heat output (adjusted for difference between rated and observed heat input)

However, the measurement data did not correspond well with the temperature rise calculated from the measured airflow and the estimated heat output of the furnaces. This second method generally predicted a higher temperature rise than was measured directly (Figure 5). It is possible that the single probes used to monitor air temperature on the supply side underestimated the average temperature of the overall air stream.

Heating Cycles and Hours of Operation

The monitoring data from the study allowed the development of models of daily hours of operation and number of heating cycles as a function of outdoor temperature. These models are needed to extrapolate the monitoring results to a full heating season and adjust the data to average weather conditions. (See Appendix C for more details on the modeling approach).

When modeled with Madison, Wisconsin weather data (which is close to the population-weighted average heating degree days for the state [WEB, 2002]), this exercise shows most furnaces in the study going through between 2,000 and 10,000 heating cycles per year with 500 to 1,500 burner-operating hours (Figure 6 and Figure 7).

The two furnaces with the lowest operating hours (Sites 30 and 14) are known to have substantial alternative heating sources in the home: the occupants at Site 30 rely mainly on a wood stove for space heat and use the furnace primarily as a means of distributing the wood heat throughout the house; the homeowner for Site 14 reported heavy use of a gas fireplace. Two other homes in the study had multiple heating systems, but showed operating hours that were not dissimilar to homes with a single heating system. Site 9 has in-floor hydronic heat in the basement. Site 8 has separate furnaces for each floor of the home (the monitored furnace served the first floor).

Hours of operation also depends on the relative sizing of the furnace in relation to the home's heating load, which in turn is a function of the size of the home, its thermal integrity, and the thermostat setpoint. Site 5 had by far the highest estimated operating hours; this site is also an older home with the highest measured average indoor temperature (see Appendix D). Indeed, three of the five older homes in the study occupy the top three slots in terms of estimated operating hours.

To get a better idea of the sizing of the furnaces in relation to the heating load of the homes, the modeled behavior of each furnace can be combined with knowledge of the gas consumption rate of the furnaces to estimate the percent of full furnace capacity at a given indoor/outdoor temperature difference. Figure 8 shows the results for an indoor/outdoor temperature difference of 90F^o, which is within the 80-95 F^o range specified (by region) by Wisconsin code (Comm 22.07). The results indicate that most of the furnaces in the study will run at only 40 to 60 percent of their full capacity under these conditions, and are thus about twice as big as needed to meet the daily heating load under these conditions. Since only one furnace in the study (Site 26) falls within the zone where 90 F^o is the required design temperature differential, and the remainder fall in the zones where 80 to 85 F^o design conditions are required, the results clearly demonstrate that furnaces are typically sized much larger than within 15% of design as required by Wisconsin code (Comm 22.12). Also, given that low-fire output for the two-stage furnaces in the study is typically about 65 percent of high-fire, it also means that these furnaces could meet the design heating load using just the low-fire mode of operation.

There is, however, another consideration in furnace sizing—setback recovery. Many of the homeowners in the study practiced temperature setbacks. As will be demonstrated later in this report, analysis of the time it takes to recover from the setback temperature (as a function of outdoor temperature) suggests that some furnaces would have quite long setback recovery periods under design conditions. From this standpoint, these furnaces are not over-sized.

Figure 6: Annual heating cycles.

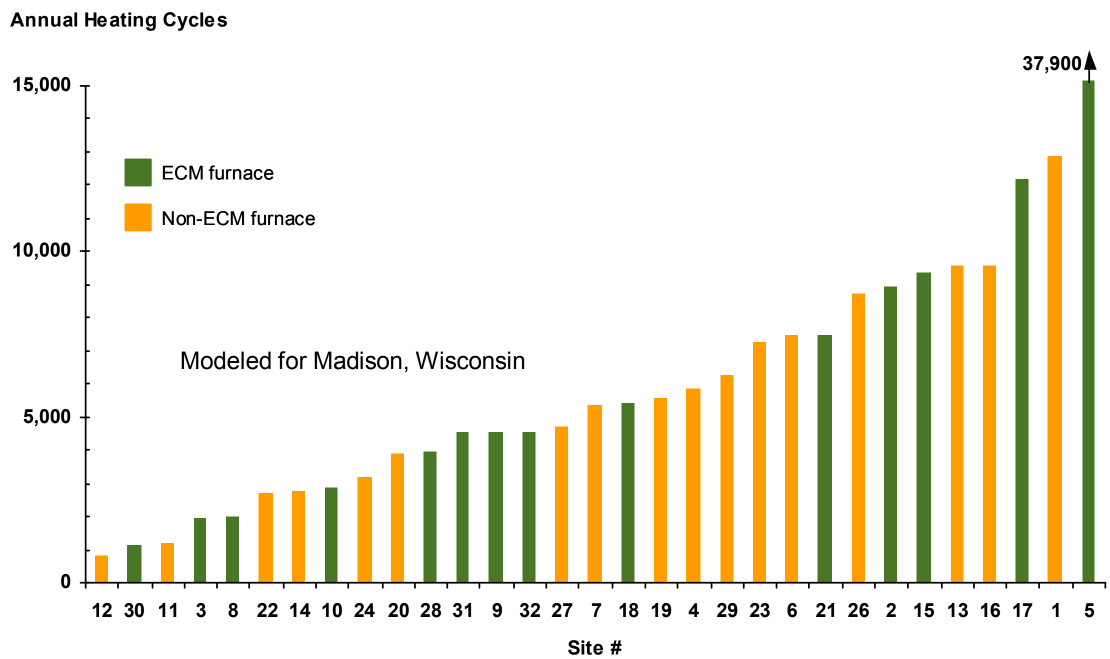


Figure 7: Annual operating hours.

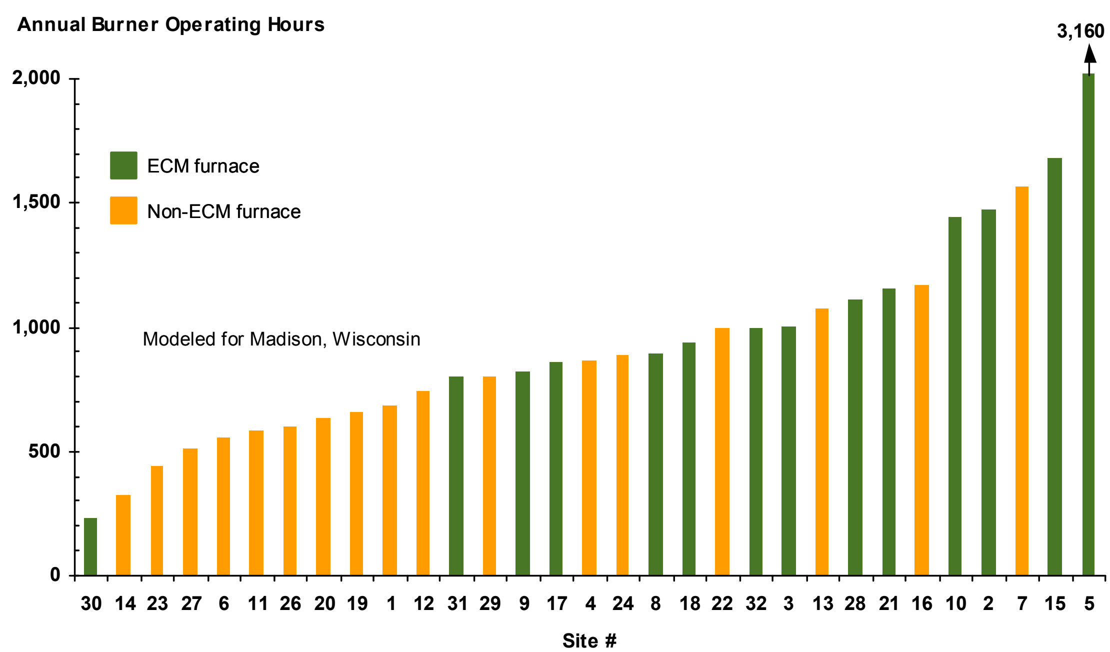
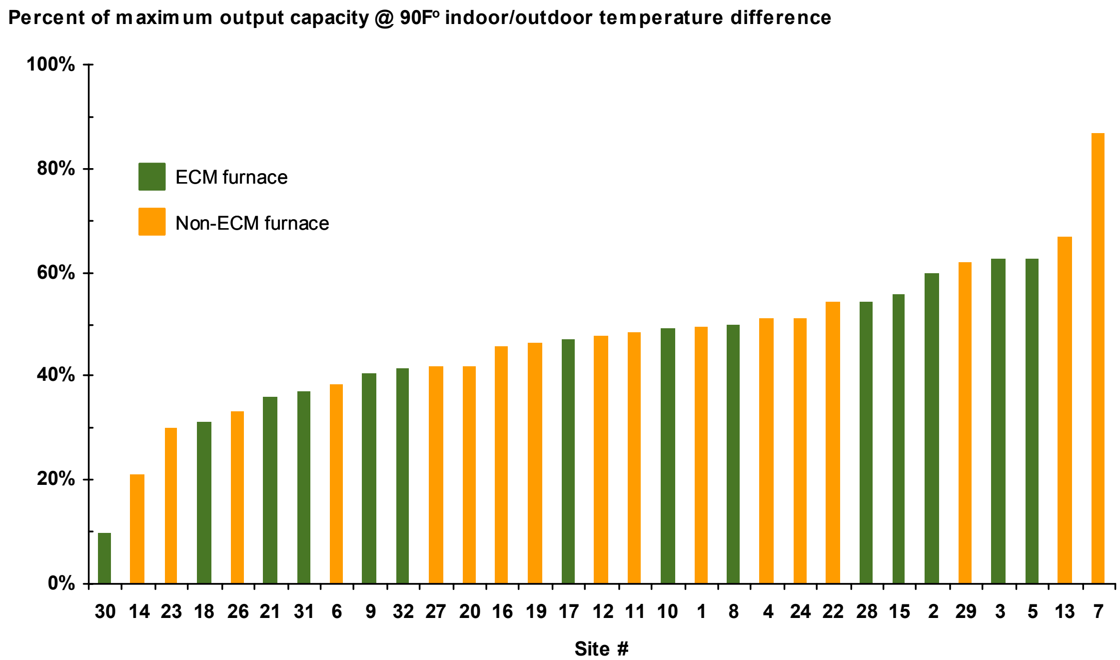


Figure 8: Percent of full capacity at design conditions.

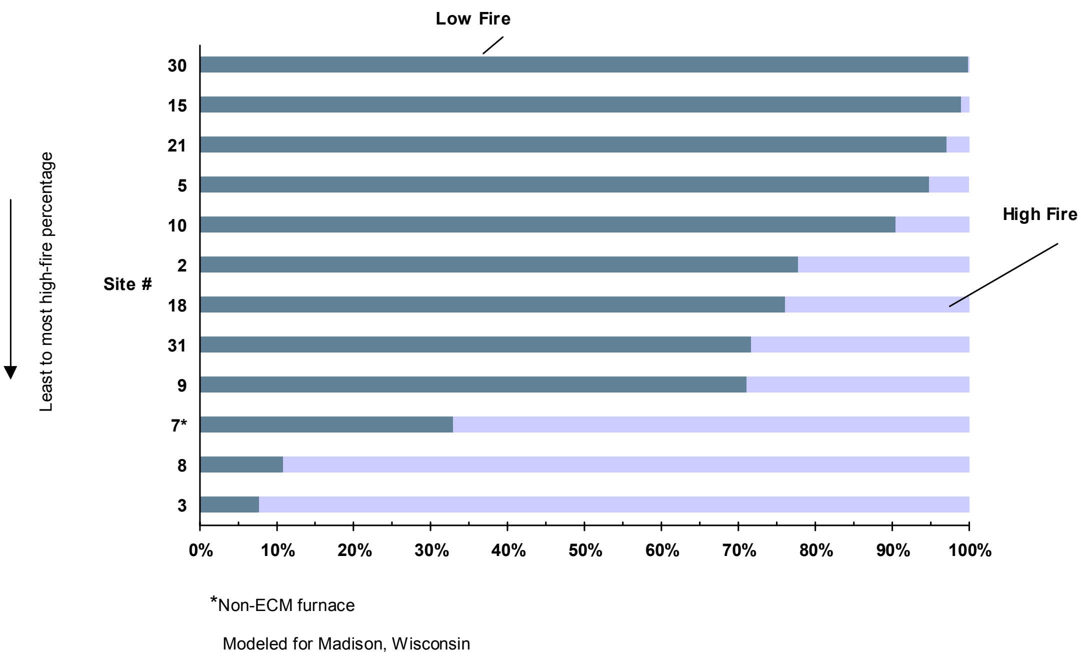


Low/High-Fire Ratio for Two-Stage Furnaces

The two-stage furnaces in the study can operate in one of two heating stages: high-fire (100 percent of rated output), or low-fire, which is generally about 65 percent of full output. The extrapolated low- and high-fire proportions for the two-stage furnaces in the study over the course of an average heating season are shown in Figure 9. Nine of the 11 ECM two-stage furnaces are estimated to operate in low-fire mode 70 percent or more of their firing time, a finding that is generally consistent with product literature claims.

Two ECM furnaces in the study (Sites 3 and 8), however, operated in high-fire mode nearly all the time during the monitoring period. Both of these sites exhibited very long heating cycles (for reasons that are only partially understood), and the high-fire operation appears to be the result of how the staging control was affected by this behavior (which was not seen for the six other sites with this type of staging control but more typical firing cycle lengths). Moreover, as will be shown shortly, the two sites in question still had lower electricity consumption than similar-sized non-ECM furnaces despite operating in high-fire mode the majority of the time.

Figure 9: Low/High-fire proportions for two-stage furnaces.



Operation of Fully Modulating Furnaces

The two fully modulating furnaces in the study (both of the same make, though different sizes) are capable of operating anywhere between 40 and 100 percent of full output. Modulation of these furnaces is controlled by a special thermostat designed for this furnace model. Figure 10 shows the operation of the furnace over a typical day for one of the sites. The furnace operated at low output (drawing about 150 Watts) except when the temperature was being boosted to a higher setpoint. During these periods, the furnace gradually ramped up to high output (about 550 Watts) over the course of about 15 minutes, then ramped back down to low fire when the room temperature began to approach the setpoint.

Analysis of about a month's worth of one-minute interval data on the control voltage to the gas valve (which is proportional to the firing rate) indicates that the furnaces at these sites operate at a fairly low firing rate half or more of the time (Figure 11).

Figure 10: Typical day of operation for a modulating furnace.

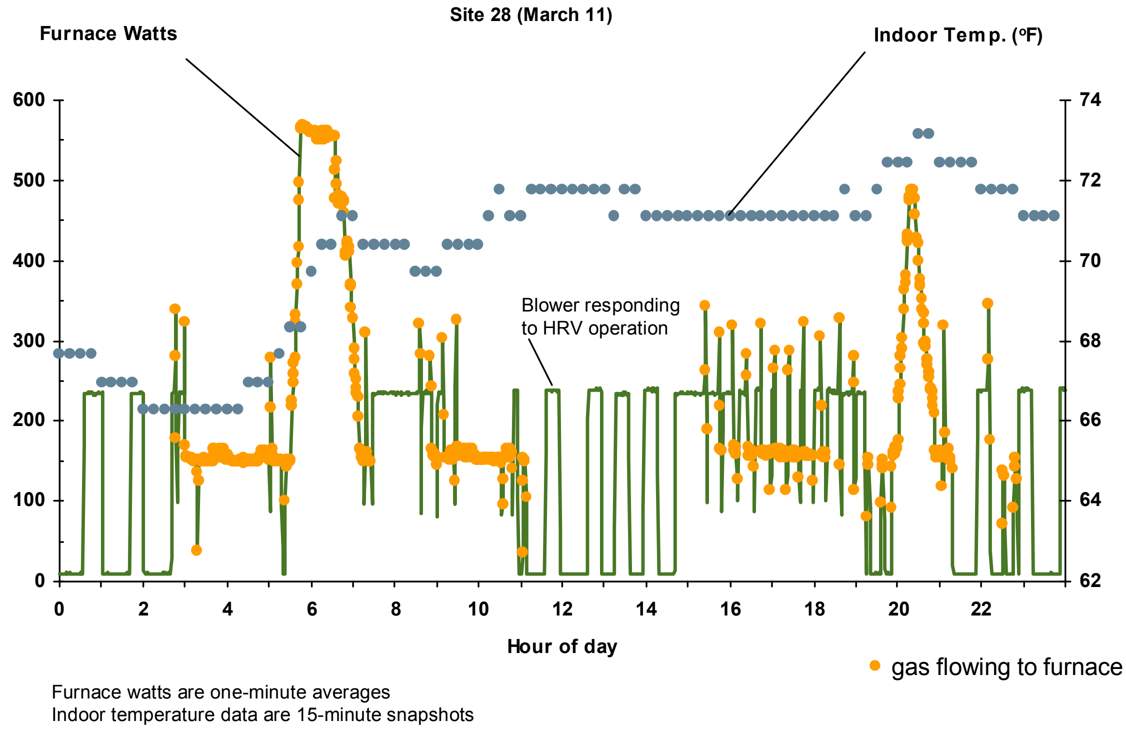
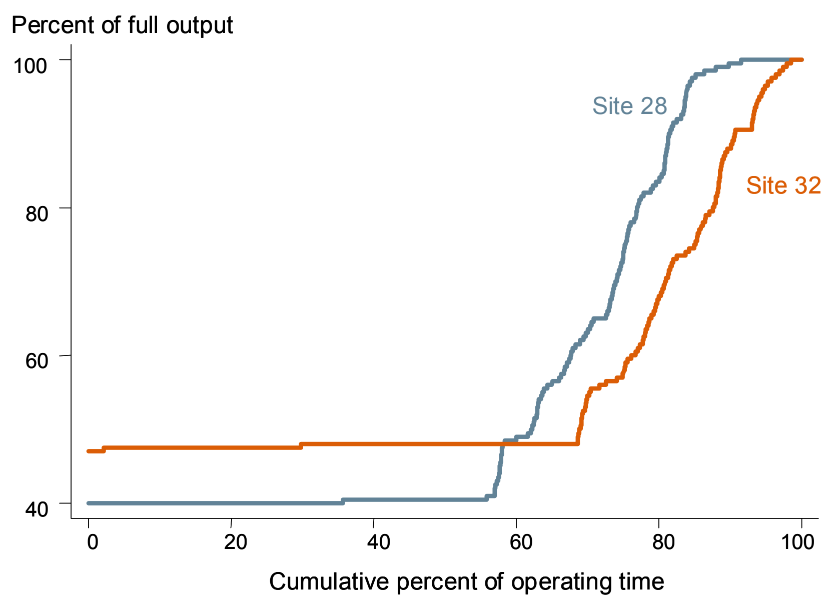


Figure 11: Distribution of output for modulating furnaces.



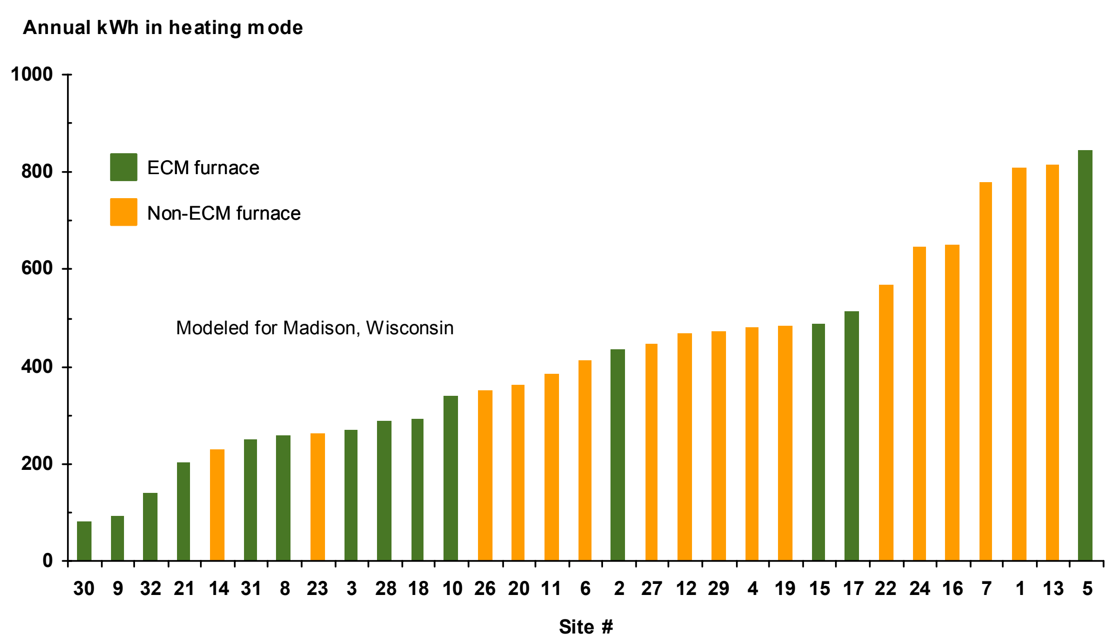
Annual Electricity Use in Heating Mode

As noted at the beginning of this section, furnaces use electricity during the startup, operating and shutdown phases of each heating cycle. When combined with the measurements of electricity consumption over the course of a heating cycle, the models of annual operating hours and cycles provide the basis for estimating annual electricity use by each furnace over a typical heating season. The data also allow this electricity use to be separated by furnace component and cycle phase.

Figure 12 shows estimates of the annual electricity consumption for each of the furnaces in the study. These estimates are obviously influenced by factors such as sizing, thermostat settings, and the use of auxiliary heat, all of which tend to cloud the comparison of ECM and non-ECM furnaces. For this reason, it is more instructive to look at the distribution of heating electricity use per therm of gas consumed (Figure 13). When viewed in this way, the two groups are clearly distinct, with the ECM furnaces mostly occupying the lower end of the distribution and the non-ECM furnaces at the upper end. The anomalous results for Site 17 appears to be due to misconfiguration of this three-zone system.[4]

The median ECM furnace in the study uses about 0.5 kWh per therm of gas in heating mode, which is about half that of the median non-ECM home. This suggests heating-mode savings of about 400 kWh per year for a typical older home with annual gas consumption of 800 therms.[5]

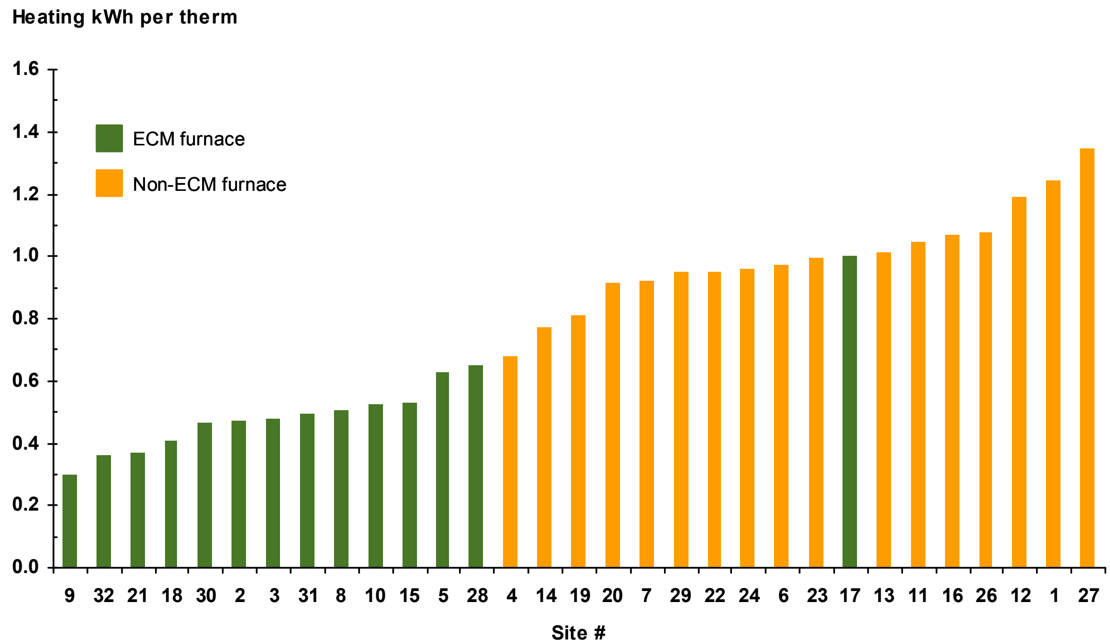
Figure 12: Annual electricity use in heating mode.



[4] Based on feedback from this study, the homeowner brought a heating contractor in to look at the system, which resulted in a number of changes to the setup of the system that should substantially reduce electricity use by the furnace.

[5] This level of gas usage is the average found from analysis of gas data for a sample of 97 Wisconsin homes built prior to 1994 with condensing furnaces in a recent characterization study of Wisconsin homes (Pigg and Nevius, 2000).

Figure 13: Annual electricity use per therm of gas consumed.



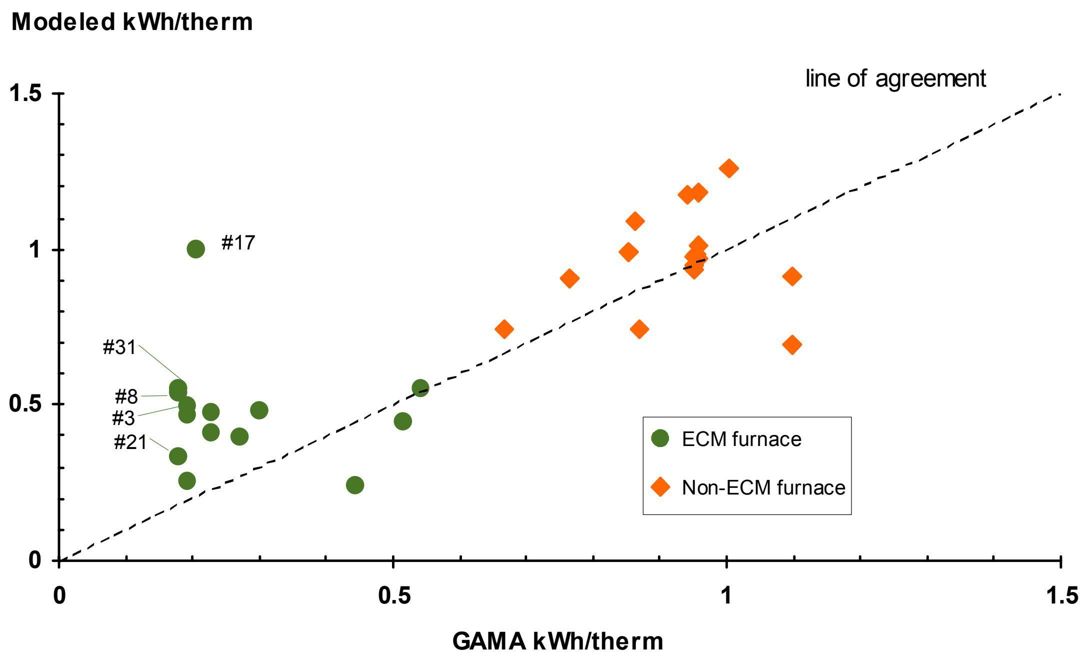
Heating Electricity Use — Field Results and GAMA Ratings

The estimates of annual electricity use per therm of gas consumption from the field results can be compared to rating data published by GAMA. The GAMA directory provides two published values for annual gas consumption and annual electricity consumption (Ef and Eae, respectively) under standard test conditions that can easily be combined to derive rating-based electricity use per therm.

Figure 14 compares the modeled estimates of annual heating electricity use per therm from the field data to the GAMA rating data.[6] A number of observations can be made from this comparison. First, at a gross level there is a general correspondence between the two values; sites with low rated electricity use per therm (generally ECM models) tend to have low values from the field, and those with higher ratings have higher observed values. In fact, the data suggest that a simple discriminant of Eae/Ef = 6 (corresponding to 0.6 kWh per therm) can be used to distinguish ECM from non-ECM furnaces. (This discriminant may not be applicable to "southern" style furnaces that have proportionately larger blower motors to accommodate larger air conditioning systems.)

[6] For this comparison, the field data were adjusted to remove differences between the measured and nominal gas input rates for the furnaces. The adjustments were generally less than 15 percent (see Appendix B).

Figure 14. Modeled versus rated heating kWh per therm.



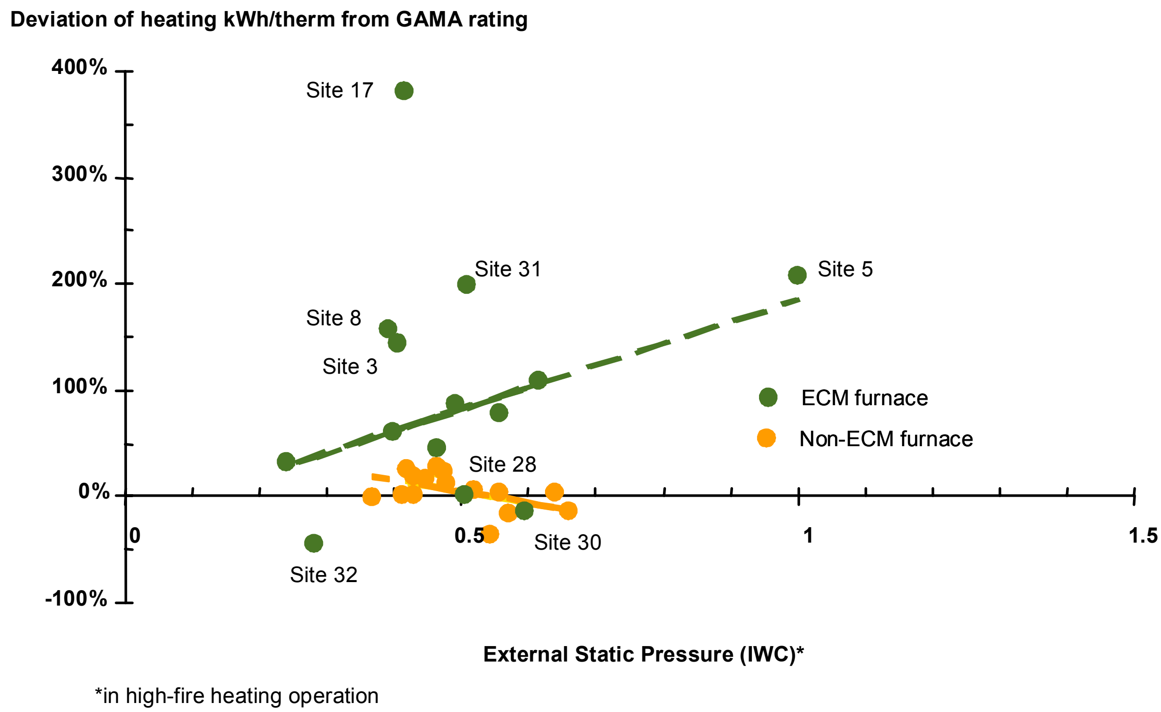
Second, the data suggest that the rating data tend to underestimate the actual electricity use of the furnaces on average—but more so for ECM furnaces on a percentage basis. In three-quarters of the cases, the field data show more electricity use per therm than the rating data would indicate, but this blends the fact that 86 percent of the ECM furnaces (12 of 14) exceeded the rating value compared to 65 percent of the non-ECM furnaces (6 of 17). Because the ECM furnaces generally occupy the low end of the kWh-per-therm scale, the difference between the two groups is fairly large in percentage terms: the median ECM furnace uses 82 percent more electricity per therm than the rating data would indicate, compared to just three percent for the median non-ECM site.

Clearly, there are site-specific configuration and behavioral factors that can strongly affect heating electricity use per therm. Site 17 uses much more electricity than its rating data would suggest; this furnace was found to be mis-configured for much higher airflow than needed. Similarly the two sites that operated in high-fire mode most of the time (Sites 3 and 8) are somewhat on the high side in kWh per therm compared to their ratings.

The data also reveal how behavioral factors can influence electricity use for the ECM furnaces. Sites 21 and 31 have identical furnaces that operate under comparable static pressures and have about the same total gas consumption. Yet Site 31 uses about 60 percent more electricity per therm than Site 21. The explanation for this difference is that the homeowners at Site 31 practice substantial day and night thermostat setbacks, while the homeowners at Site 21 keep their thermostat at a constant setting. The setback practice at Site 31 translates into about 30 percent high-fire operation compared to less than five percent high-fire at Site 21. Since high-fire operation has five to six times the overall power draw of low-fire for these sites but consumes only about 50 percent more gas, the upshot is higher electricity use per therm for Site 31.

The data also suggest that differences between static pressure levels in the field and those used in the ratings may underlie some of the observed differences. The ASHRAE standard on which the rating data are based stipulates a minimum external static pressure of 0.2 inches water column (IWC) at the highest firing rate for furnaces in the 55,000 to 80,000 Btu/hr size range, and 0.23 IWC for furnaces with firing rates of 80,000 to 100,000 Btu/hr. Both of these values are considerably lower than the observed external static pressure among the furnaces in the study, which ranged from 0.24 to 1.0 IWC and averaged about 0.5 IWC. (The field measurements were also made downstream of the central air conditioning evaporator coil, which means that true external static pressure across the furnace cabinet is even higher.) These high static pressures are consistent with other field data (e.g., Phillips, 1998 and Proctor and Parker, 2000)

Figure 15. Percent deviation of heating electricity use per therm from rating value.



As Figure 15 shows, the data show some tendency for the discrepancy between measured and rated electricity use per therm to go in opposite directions for the two groups as static pressure increases: ECM furnaces use more as static pressure increases (though there is considerable scatter in the data) and non-ECM furnaces use less. This is consistent with the way these furnaces operate. Non-ECM furnaces operate at a fixed speed: as static pressure increases for these furnaces, airflow (and electricity use) declines. In contrast, the ECM furnaces in the study use a blower motor manufactured by General Electric that can sense airflow and adjust its speed accordingly. As static pressure increases on an ECM furnace, the blower motor compensates by running at a higher speed (and using more electricity) to continue to deliver the desired airflow.

If external static pressure under actual conditions is higher on average than those used in the rating procedures (as this and other studies suggest), the result would be to narrow somewhat the differences between ECM and non-ECM furnaces in electricity use per therm—though the ECM furnaces still clearly use considerably less electricity than the non-ECM models.

Electricity Use by Component and Operating Phase

Figure 16 shows how heating-mode electricity use is distributed between the inducer fan, the air handler and other components of each furnace. As could be expected, the air handler accounts for the bulk of the electricity use for all of the furnaces, typically accounting for about 80 percent of the total electricity use in non-ECM furnaces, and about 70 percent in ECM models. The ECM furnaces show a somewhat higher proportion of electricity use for “other” components: this is less a consequence of these components drawing more power than non-ECM furnaces than it is the result of much lower fan power, resulting in “other” representing a proportionally larger slice of the pie.

Similarly, Figure 17 breaks electricity into the three phases of operation for heating: startup (from the call for heat until the air handler starts), operating, and shutdown (from the end of the call for heat to air handler shutdown). Again, it is no surprise that the operating phase dominates, accounting for about 80 percent of the total on average. But the data suggest that there are conditions under which startup and shutdown electricity can exceed the operating electricity use. Less than half of the electricity for Site 1, for example, is used during steady-date operation. This site has the second shortest average firing cycle length in the study (about three minutes of firing per cycle), and it has a fairly long blower-off delay (two minutes). Thus, this furnace spends about a minute warming up, two minutes operating, and then two minutes shutting down. Site 17 also has a large proportion of its electricity use devoted to shutdown due to an unusually long blower-off delay (more than 7 minutes). Cycle lengths are discussed in the next section.

Figure 16: Heating-mode electricity use by component.

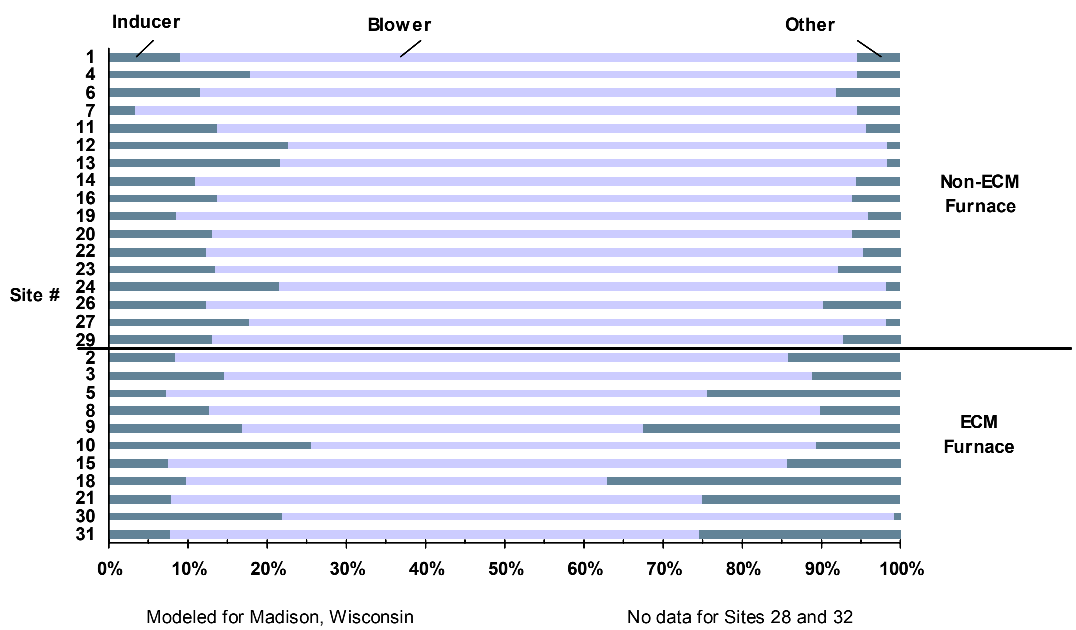
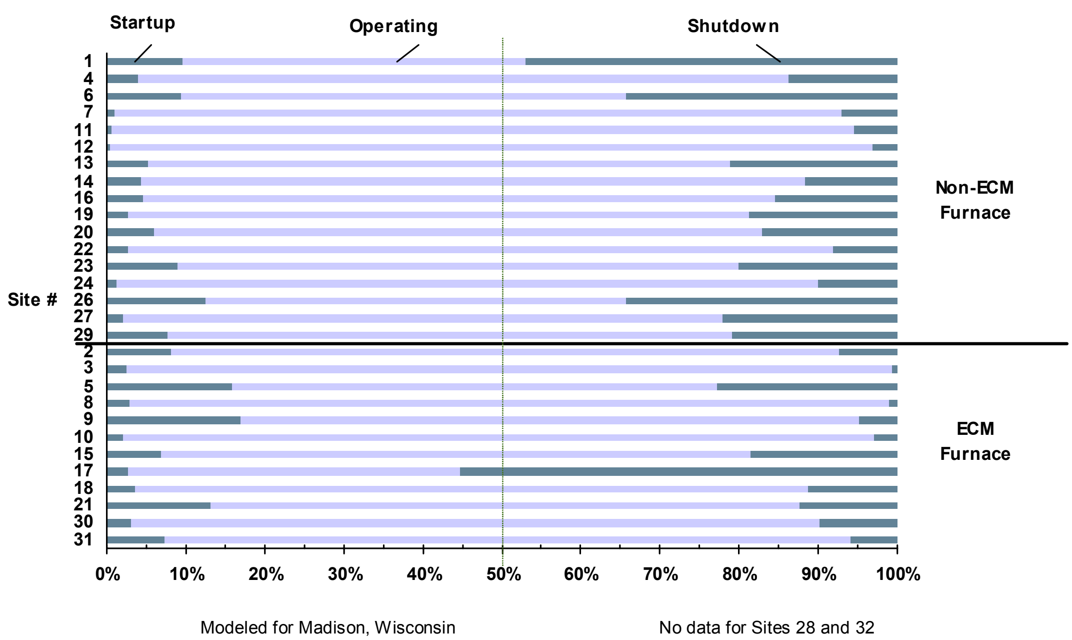


Figure 17: Heating-mode electricity use by cycle phase.



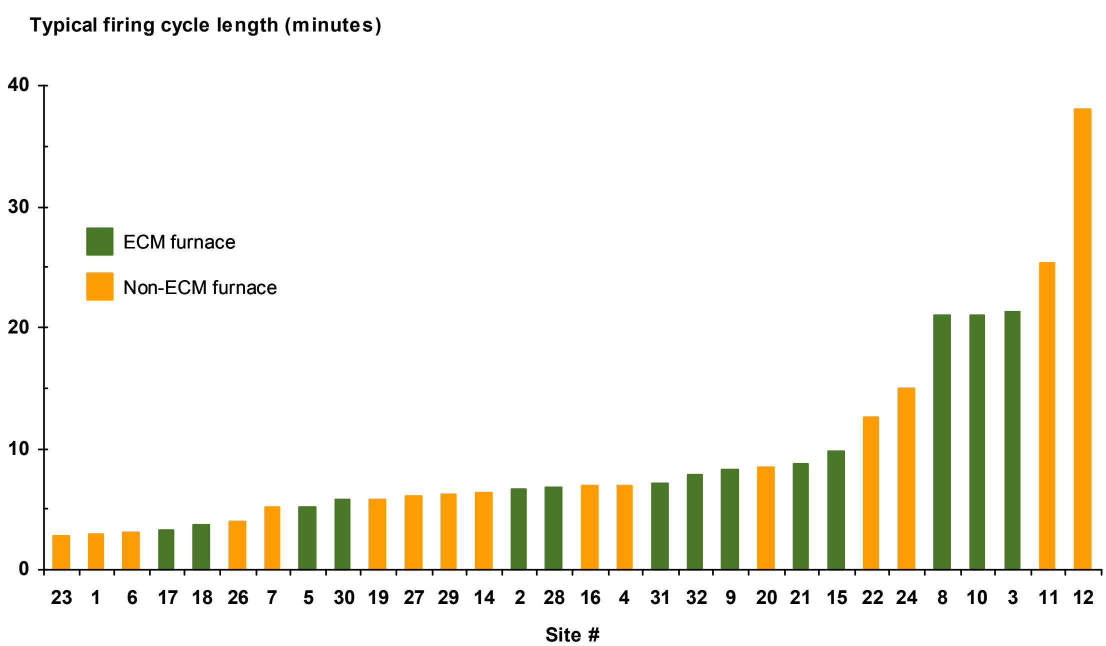
Cycling Behavior

As the preceding section shows, cycle length can affect electricity consumption. A certain amount of electricity is needed during the startup and shutdown phase of a heating cycle, so furnaces that cycle more frequently will use more electricity per therm of gas consumed.

Because of the way the data were collected, the study provides copious information on heating cycle length. We focus here on three summary statistics: the median and maximum daily firing time and the number of cycles per day. The median daily firing time is the middle value for firing length among all heating cycles in a given day and represents the length of a typical firing cycle for that day. The maximum daily firing time generally represents the setback recovery cycle for homes that practice thermostat setback. For many of the homes in the study, these values are a function of outdoor temperature; as outdoor temperature declines the median and maximum daily firing cycle length increases. For this reason, results shown below are normalized to a common outdoor temperature (see Appendix D).

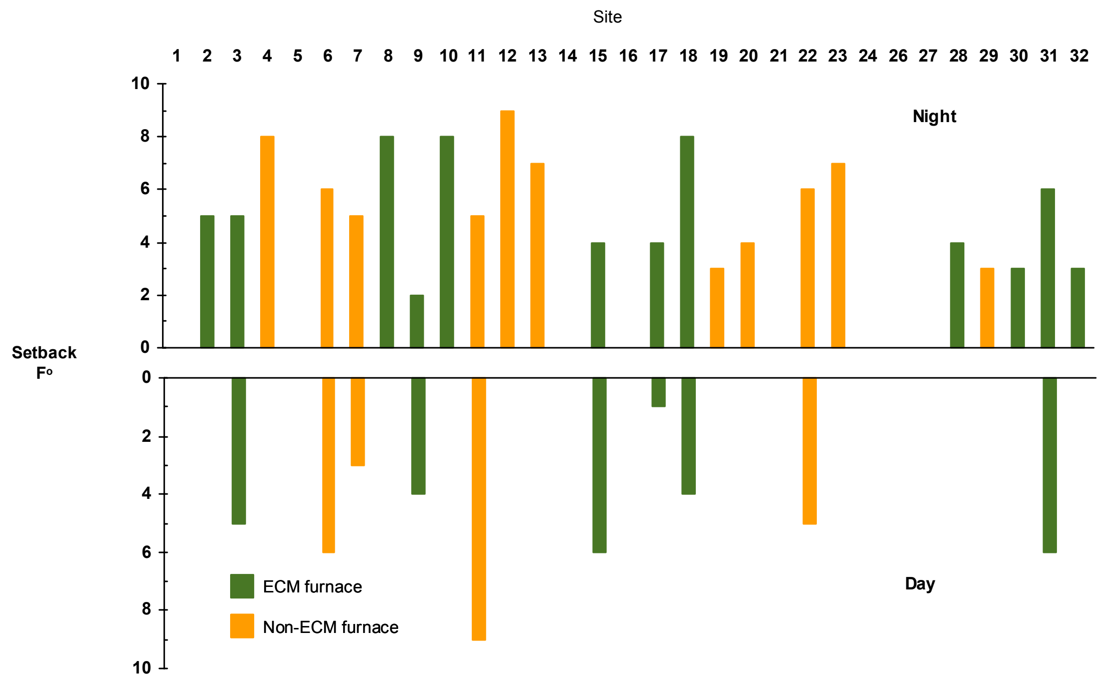
Figure 18 shows the median firing cycle length for the study sites. Most furnaces in the study had typical firing cycle lengths between 5 and 15 minutes, but a few had relatively short cycles, and five sites had typical firing times that exceeded 20 minutes. As noted previously, the two, two-stage furnace sites with staging control issues are in this group. Thermostat deadband and placement as well as furnace sizing undoubtedly all play into the cycle length.

Figure 18: Median firing cycle length.



Normalized to 32°F outdoor temperature (see Appendix D)
Not shown: Site 13

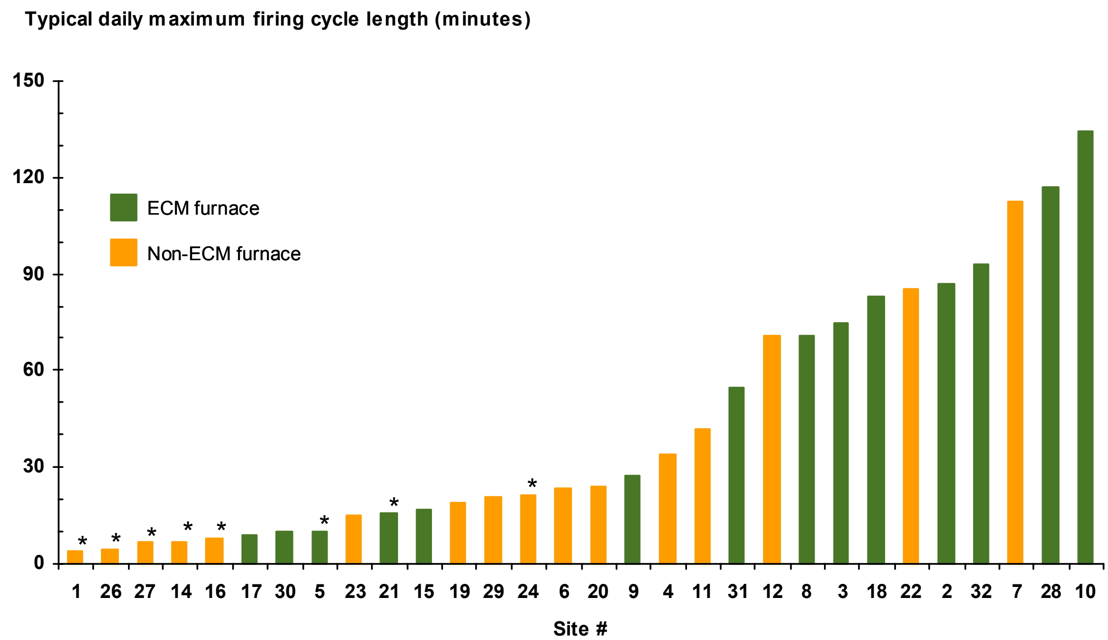
Figure 19: Typical daily thermostat setbacks.



Many of the homeowners in the study practiced thermostat setbacks, as Figure 19 shows (Appendix D contains more information about average indoor temperatures and time-of-day temperature profiles during the heating season). Analysis of the daily maximum heating cycle length—which normally represents the setback recovery period in homes where setback is practiced—shows a fairly wide range in setback recovery times under typical outdoor weather conditions (Figure 20). These recovery times are no doubt a function of both the depth of the setback and the sizing of the furnace in relation to the home's heating loads.

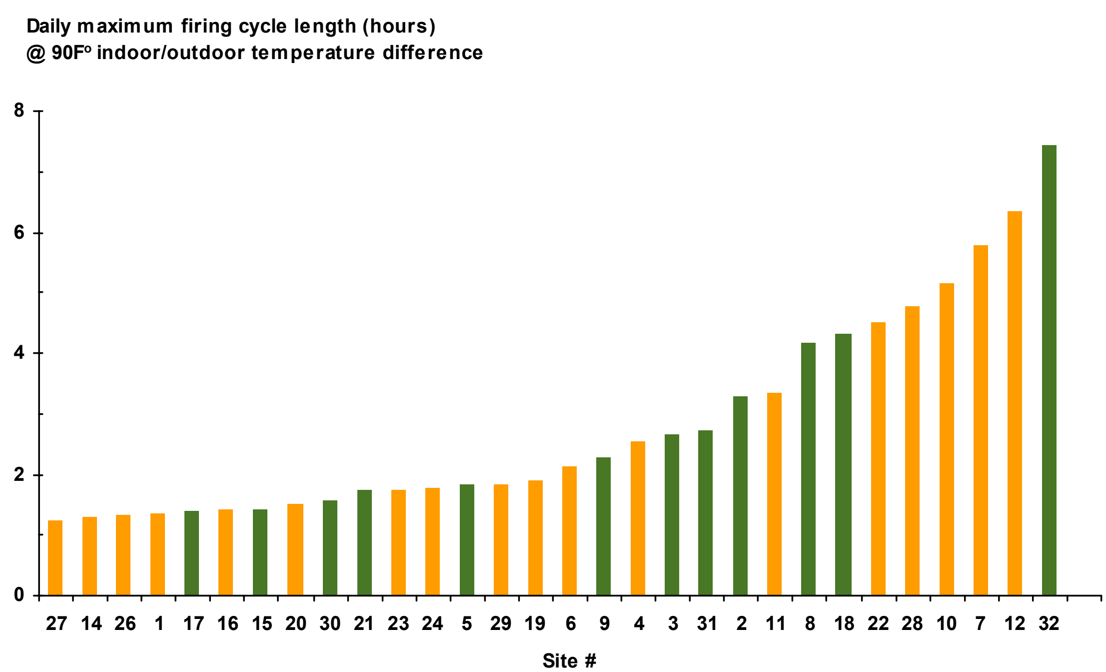
When the data on maximum daily firing cycle are extrapolated to design conditions (90 F° indoor/outdoor temperature difference), some sites appear to have very long setback recovery times (Figure 21). From this standpoint, these furnaces are not oversized. However, it can also be argued that if long setback recovery is an issue, homeowners should simply refrain from setting back the thermostat very much under extremely cold conditions.

Figure 20: Maximum daily firing cycle length under typical winter conditions.



*No setback practiced
Normalized to 32°F outdoor temperature (see Appendix D)
Not shown: Site 13

Figure 21: Maximum firing cycle length at design conditions.



The number of heating cycles that a furnace goes through in a day is strongly correlated with outdoor temperature for most of the sites (see Appendix C). Indeed it appears that, for the most part, it is more the increase in the number of heating cycles rather than the length of the heating cycle that contributes to the increase in total furnace run time as the outdoor temperature drops.

For most sites, the number of heating cycles in a day is fairly linear in outdoor temperature (scatter plots for all sites in the study are provided in Appendix C). However a few sites exhibit a relationship like the one shown in Figure 22, where there is an apparent limit in the number of heating cycles that the furnace can go through during a day. The exact cause of this behavior is unknown, but may be due to limits imposed by certain thermostats on the number of cycles per hour.

In any event, when normalized to typical winter conditions, there is a fairly wide variation in the number of daily heating cycles across the sites (Figure 23). As with heating cycle length, this variation probably reflects differences in thermostat deadbands, the relative sizing of the furnaces, and details about thermostat placement.

Figure 22: Daily heating cycles versus outdoor temperature for one site.

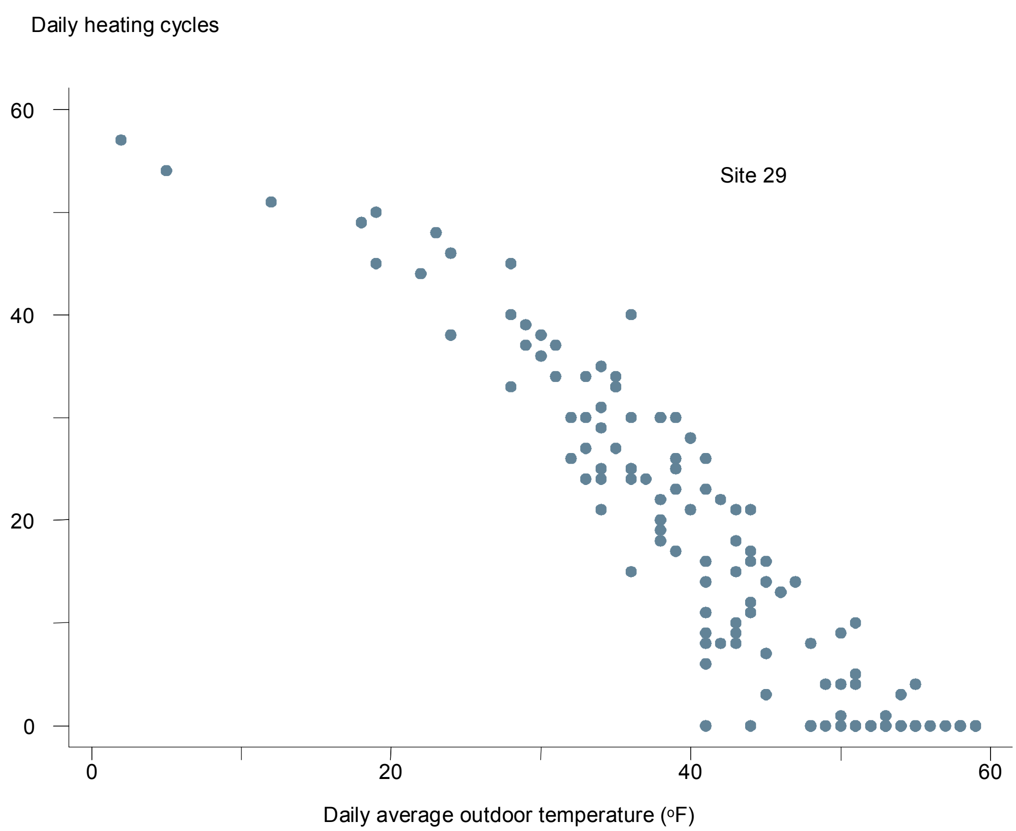
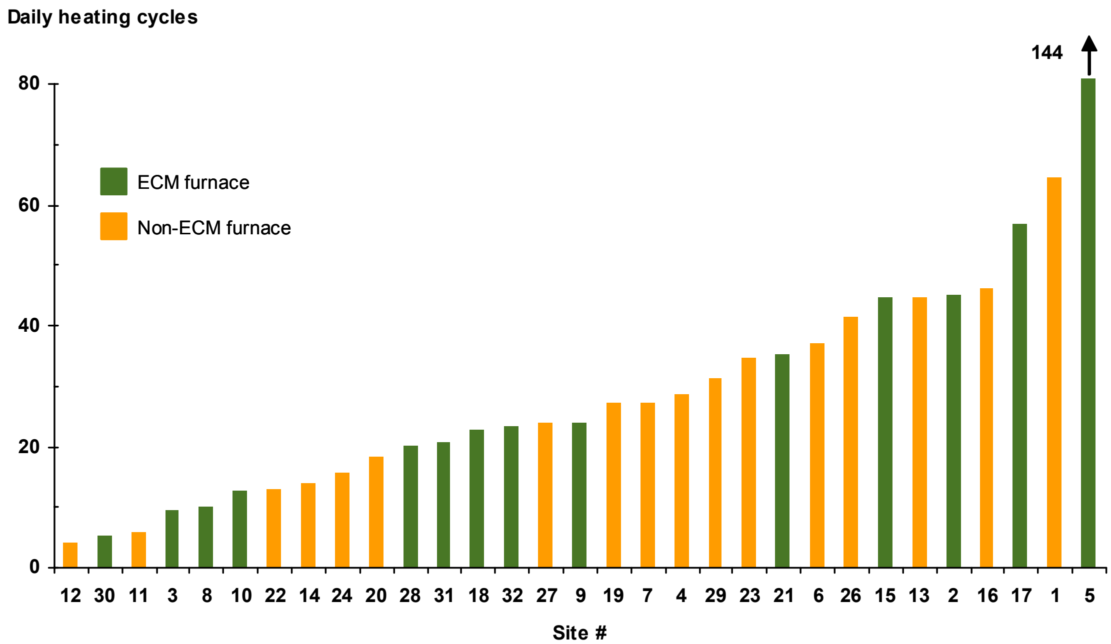


Figure 23: Typical daily number of heating cycles.



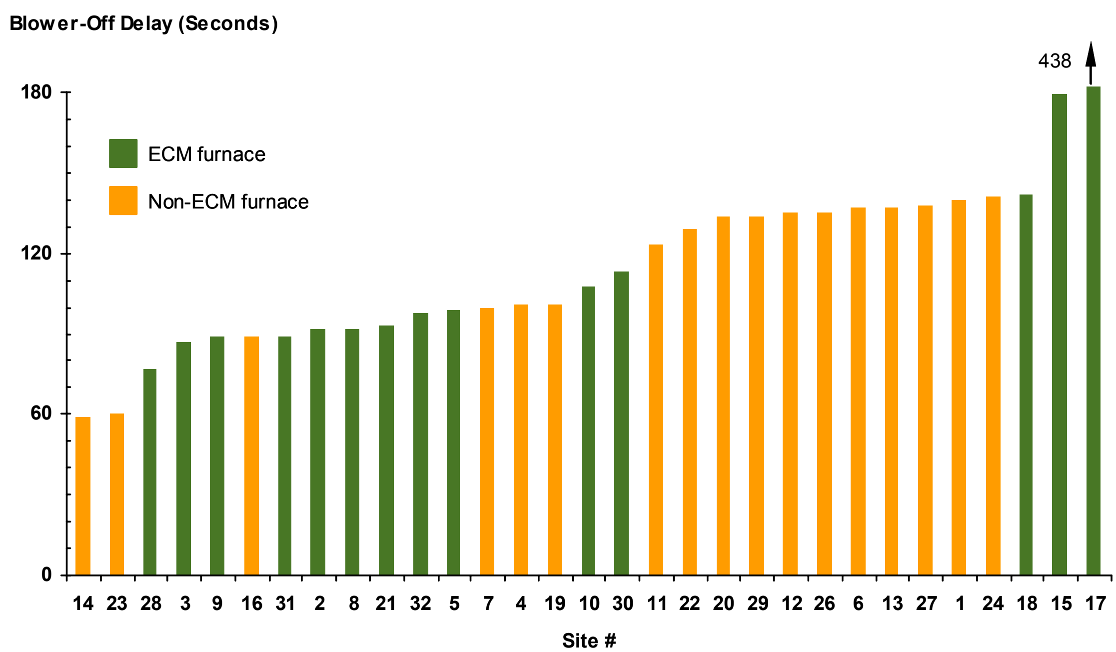
Normalized to 32°F outdoor temperature (see Appendix C)

Blower-Off Delay

The delay period between the time the call for heat ends and the air handler blower shuts down also affects electricity use. Longer blower-off delays translate into more electricity use per therm of gas consumed, though less so for the ECM models, as these furnaces typically drop to their lowest airflow during the blower-off delay. All of the furnaces in the study have blower-off delays that are field configurable via DIP switches on the control board.

Figure 24 shows the blower-off delays measured for the furnaces in the study during testing. Most are between 90 and 150 seconds. The very long blower-off delay for Site 17 is symptomatic of a number of configuration issues at this site.

Figure 24: Blower-off delay.

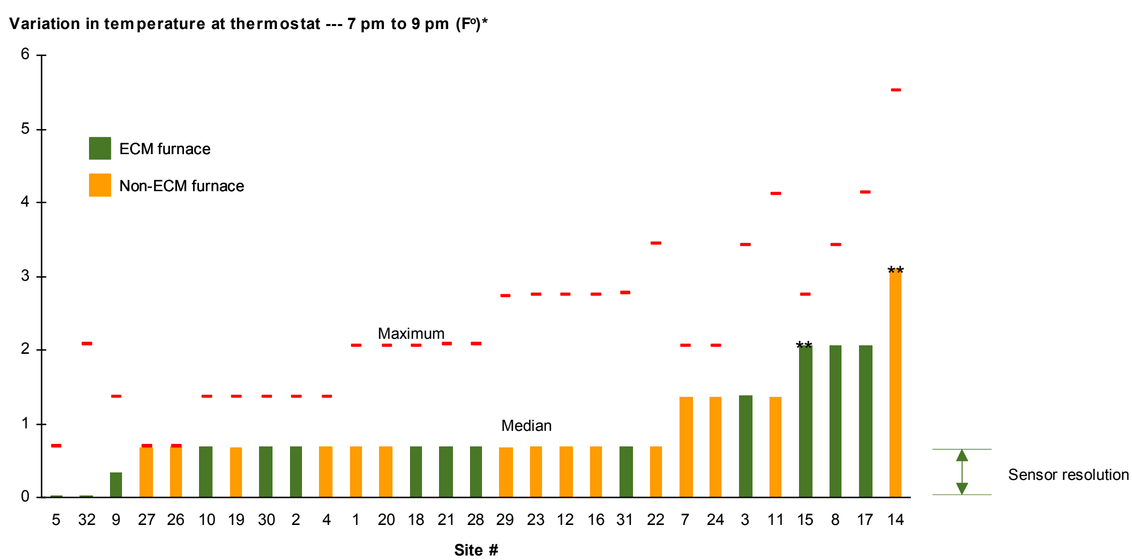


Heating Season Temperature Control

When it comes to maintaining tight control on indoor temperature, the data suggest that nearly all of the furnaces in the study do a good job. This observation comes from analysis of temperature data recorded by sensors placed at the thermostat as part of the study. The analysis focused on the daily period between 7 pm and 9 pm, which was the time the thermostat was most likely to be maintaining a constant setting (changes in indoor temperature at the beginning and end of setback periods could otherwise cloud the analysis). Analysis of the temperature range recorded during this time period shows that at most of the sites the indoor temperature typically varied by less than 1F^o (the resolution of the sensors used was about 0.7F^o), though a few sites showed a typical swing of 2 F^o (Figure 25). These statistics may underestimate the actual swing if the heating cycle period is such that the 15-minute interval at which the temperatures are recorded tends to be at the same point in the heating cycle. Nonetheless, even the maximum recorded temperature swing over the course of monitoring during these hours indicates less than a 3F^o variation for most of the sites.

It is notable that there is no clear difference in temperature swing between the ECM and non-ECM furnaces. It is also noteworthy that three of the five sites with heating cycles that typically exceed 20 minutes in length (Sites 3, 8 and 11) are also in the group with wider temperature swings, suggesting that the thermostats for these systems have a wider deadband (although subsequent field checks for Sites 3 and 8 revealed that they were set for a nominal 1F^o temperature swing).

Figure 25: Heating season indoor temperature swing.



*Calculated as difference between daily highest and lowest temperature between 7 pm and 9 pm (based on 8 measurements at 15-minute intervals). Days with average outdoor temperature above 40^{o}F excluded.

**Temperature not typically maintained at A constant setting during this time period

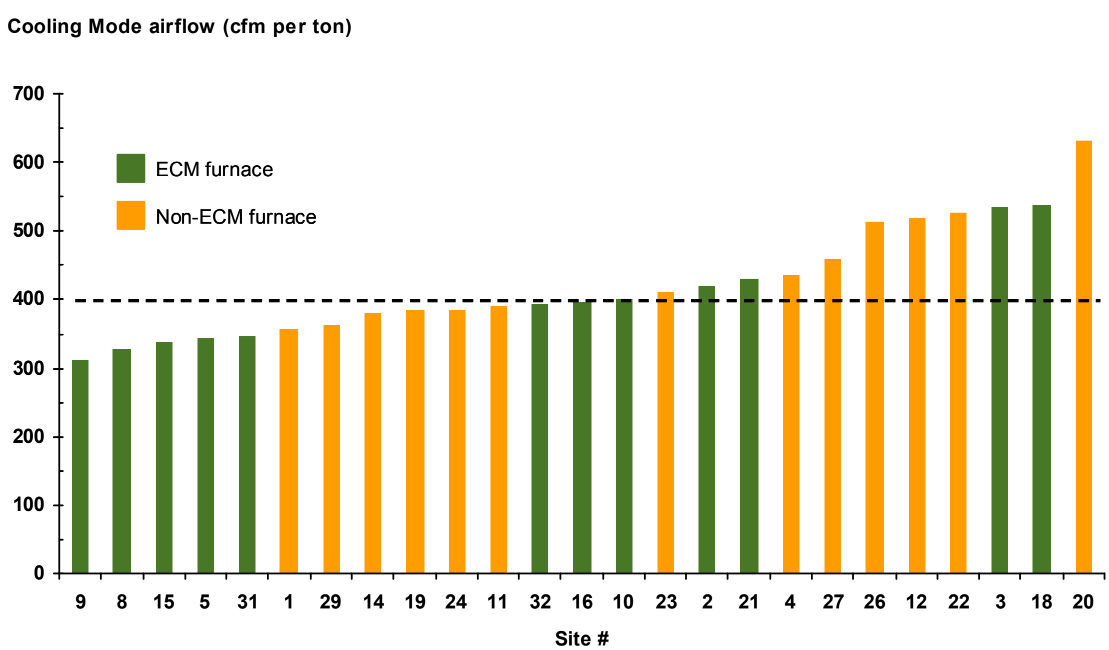
Cooling Mode

Airflow and Operating Watts

In cooling mode, the air handler operates at a pre-set cooling speed. The near-universal guideline is that the air handler should deliver 400 cfm per ton of air conditioning capacity. In practice, most non-ECM furnaces are simply set to the highest available airflow (only two of the 17 non-ECM furnaces in the study were set otherwise). ECM furnaces on the other hand typically have DIP switches that the installer sets to match the air conditioning tonnage, and provide 400 cfm per ton of airflow.

As Figure 26 shows, most of the furnaces actually delivered airflow somewhere in the range of 350 to 450 cfm per ton of air conditioning capacity when operating at the cooling speed. However, there is a group of mostly non-ECM furnaces with more than 500 cfm per ton of airflow. With the exception of Site 26—which was already set at the lowest possible cooling speed—these are sites with smaller central air conditioning systems for which the high speed setting on the air handler provides too much air flow. Air handler power requirements would be reduced by 20 to 25 percent (roughly 100 to 140 Watts) if the cooling speed setting was set to provide as close to 400 cfm per ton as possible.

Figure 26: Airflow per ton of air conditioning capacity at cooling speed.



Not shown: Sites 6, 7, 13, 17, 28 and 30

Figure 27: Cooling-mode wattage versus airflow.

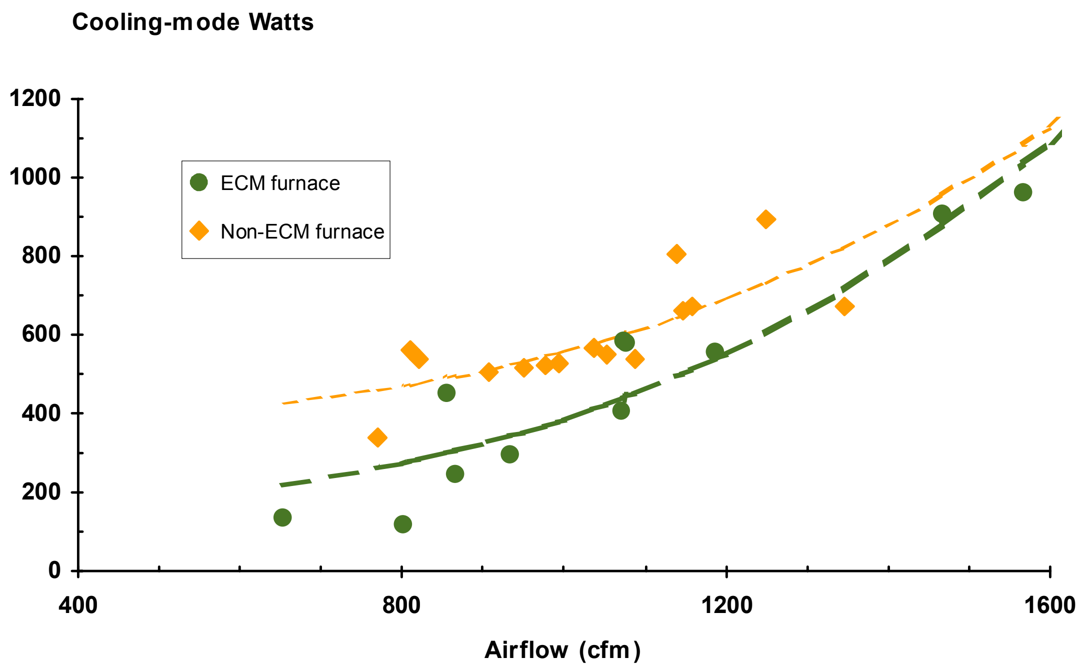


Figure 27 shows furnace wattage in cooling mode as a function of airflow. The data suggest that below about 4 tons of air conditioning (1600 cfm) ECM furnaces on average have lower power draw than non-ECM furnaces. Regression fits to the data suggest an average difference of about 175 Watts at 1000 cfm (2.5 tons) and 150 Watts at 1200 cfm (3 tons).

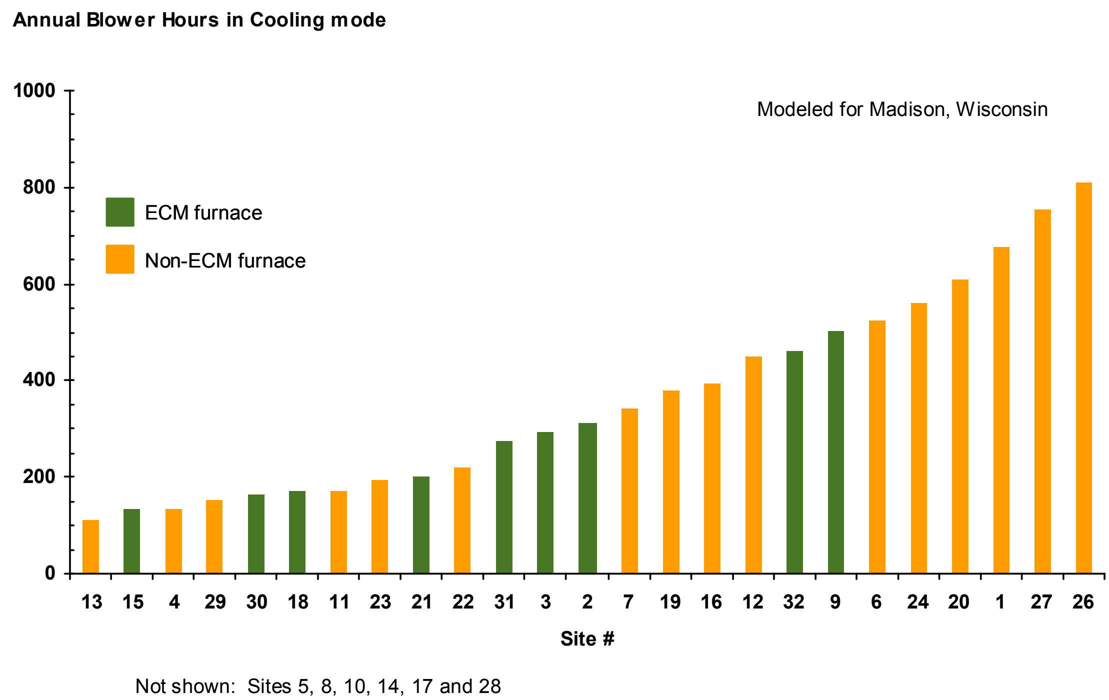
Operating Hours and Cooling-Mode Electricity Savings

Models of daily run-time as a function of outdoor temperature for each site (see Appendix C) show a wide range of predicted seasonal air-handler operating hours in cooling mode (Figure 28). This could be expected given the relatively discretionary nature of air conditioning use in Wisconsin.

However, if 400 hours is taken as a typical value for central air conditioning use, then ECM furnaces could be expected to yield 60 to 70 kWh of direct blower energy savings, based on the regression fits shown in Figure 27. Lower blower wattage also translates into less waste heat in the air stream to be removed by the air conditioning system. This additional electricity savings is estimated at about 20 to 25 kWh, bringing the overall estimate of ECM savings in cooling mode to 80 to 95 kWh per year for 2.5- and 3-ton air conditioning systems, respectively.[7]

[7] For example, for a 10 SEER system: 60 kWh of direct blower electricity savings * 3,413 Btu per kWh / (10 Btu per watt * 1000 watts per kW) = 20.5 kWh indirect cooling electricity savings.

Figure 28: Annual cooling-mode hours.



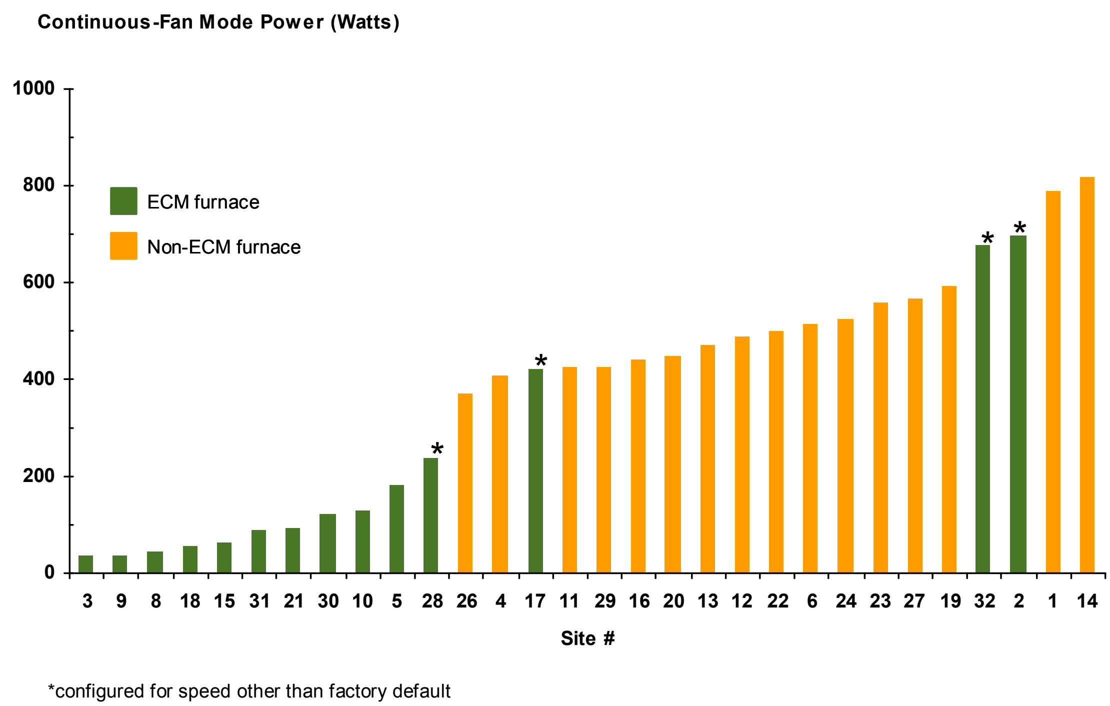
Continuous-Fan Mode

Continuous-fan mode corresponds to setting the fan switch on most thermostats to "on" (rather than "auto"). People choose to run the air handler continuously for a variety of reasons, but chief among these are filtering out house dust and reducing temperature differences in the home. A minority of participants in the study actually operate their furnace in continuous-fan mode part or all of the year (Table 1), but we tested all of the furnaces in this mode regardless of the actual practice of the homeowner, and were thus able to model continuous-fan electricity use.

Table 1: Continuous-fan use by study participants.

Continuous-fan use	Number of sites
Never	20 Sites
All year long	5 Sites (Sites 4, 10, 17, 18, 20)
Winter only	1 Sites (Sites 30)
Summer only	2 Sites (Sites 13, 21)
Ad hoc basis	3 Sites (Sites 8, 9, 14)

Figure 29: Continuous-fan mode power draw.

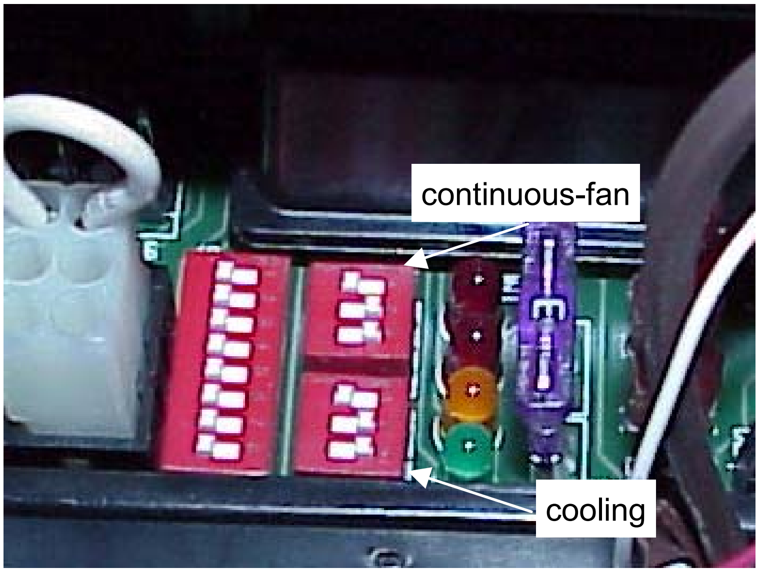


There is a clear difference in capability between the ECM and non-ECM furnaces in the study in power draw in continuous-fan mode. All of the ECM furnaces have a separate (and field adjustable) continuous-fan speed setting that is generally factory-set for a very low airflow delivery (typically 500-600 cfm). In contrast, all but two of the non-ECM furnaces in the study ran at the heating speed when called upon for continuous-fan operation.

As could be expected, this means that the ECM furnaces generally draw considerably less power in continuous-fan mode than the non-ECM sites (Figure 29). The ECM furnaces mostly draw less than 200 Watts of continuous-fan power, with 100 Watts as a reasonable average value. In contrast, the non-ECM furnaces drew between 400 and 800 Watts, with 500 being a typical value.

Four ECM furnaces were found to be configured to higher continuous-fan speeds than the factory default. Site 2 is the most interesting example of these. Continuous-fan airflow for the furnace at this site is determined by the settings of three DIP switches immediately to the right of an identical bank of DIP switches that set the cooling airflow. The settings at this site were found to be the same as the cooling airflow settings (Figure 30). This resulted in about twice the continuous-fan airflow than would have been the case at the factory default (1,400 measure cfm, versus 700 cfm) and nearly six times the blower power draw (750 Watts, versus 130 Watts).

Figure 30: Continuous-fan and cooling airflow DIP switches for Site 2.



Whether the contractor who installed the furnace was confused about how to set the DIP switches or simply felt that a furnace should deliver the cooling-mode airflow in continuous-fan mode is not known. However, it can be said that the homeowner was not consulted on this. When told about this, the homeowner—who did not normally use continuous-fan mode—said he had been under the impression that his new furnace was supposed to circulate air more quietly, but found it to be noisy when he tried running it in fan-on mode.

Both of the two modulating furnaces (Sites 28 and 32)—which were installed by the same heating contractor—were also found to be set to higher than default settings for continuous-fan mode. This furnace model has a DIP switch that allows one to choose between two airflow settings. When tested at the lower setting (500 cfm), the Site 28 furnace drew only 93 Watts, compared to 280 Watts at the higher setting (800 cfm).

Hours of Operation and Savings

Continuous-fan mode hours are essentially all hours that the furnace is not operating in heating or cooling modes. The furnace models described in Appendix C predict thousands of hours of continuous-fan operation in this mode (Figure 31). Median run-time hours for the furnaces in the study were 7,400 for year-round operation, 3,500 for winter-only operation, and 2,000 for summer-only operation.

Using rounded median values for operating hours and wattage draws for ECM and non-ECM furnace in this mode, Table 2 shows estimates of electricity savings in continuous-fan mode.

Figure 31: Hours of operation in continuous-fan mode.

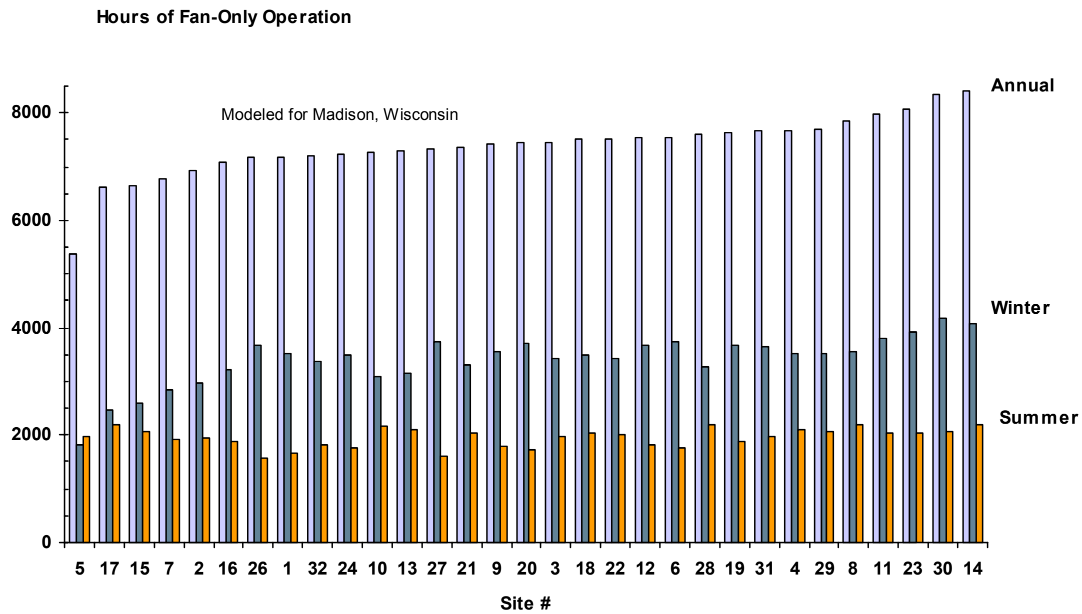


Table 2: Continuous-fan electricity use, by furnace type.

Season of Use	Continuous-Fan Mode Electricity Use (kWh) Non-ECM Furnace (median 500 Watts)	ECM Furnace (median 100 Watts)	Difference
Year-Round (median 7,400 hours)	3,700	740	2,960
Winter Only (median 3,500 hours)	1,750	350	1,400
Summer Only (median 2,000 hours)	1,000	200	800

Central Ventilation and Furnace Air Handler Operation

Central ventilation systems such as heat recovery ventilators (HRVs) are sometimes wired with an air handler interlock, meaning that whenever the HRV operates, the furnace air handler also operates at the continuous-fan speed. Ten sites in the study had central ventilation systems, but only four of these were interlocked with the furnace air handler. (Sites 16, 26, 28 and 32—interlocked HRV operation (on a 20-minute on, 40-minute off schedule) can be seen for Site 28 in Figure 10 on page 19.)

Homes with an interlocked central ventilation system will thus have higher furnace electricity use if they do not already practice continuous-fan operation. Estimating this additional electricity use is difficult though, because homeowner use of the systems can vary substantially (Pigg, 2002b).

Standby Power Consumption

All of the furnaces in the study consumed a small amount of power in standby mode. Standby power ranged from 4 to 13 Watts, with a median of 8 Watts (Figure 32). The ECM furnaces dominate the higher end of the distribution, presumably due to large and more complicated control circuitry. On average, the ECM furnaces consumed 4 Watts of standby power above that consumed by the non-ECM furnaces in the study.

Modeling of the furnaces in the study suggests that furnaces not running in continuous-fan mode have an average of about 7,500 hours per year of standby operation (Figure 33). This translates into additional electricity consumption of about 30 kWh per year in this mode for ECM furnaces in the study.

Figure 32: Standby mode power consumption.

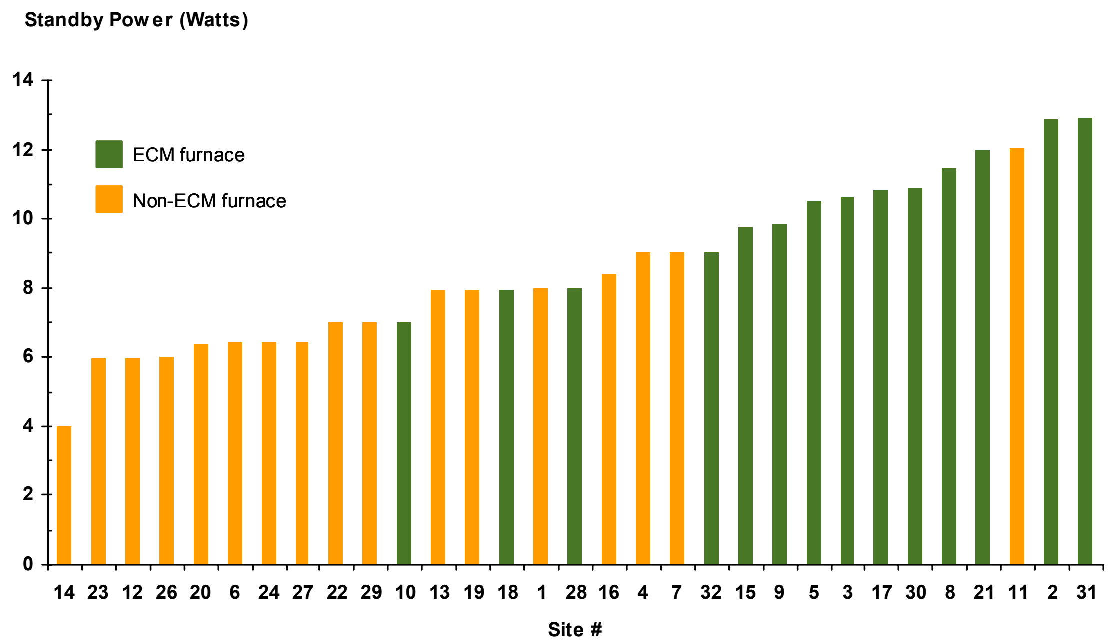
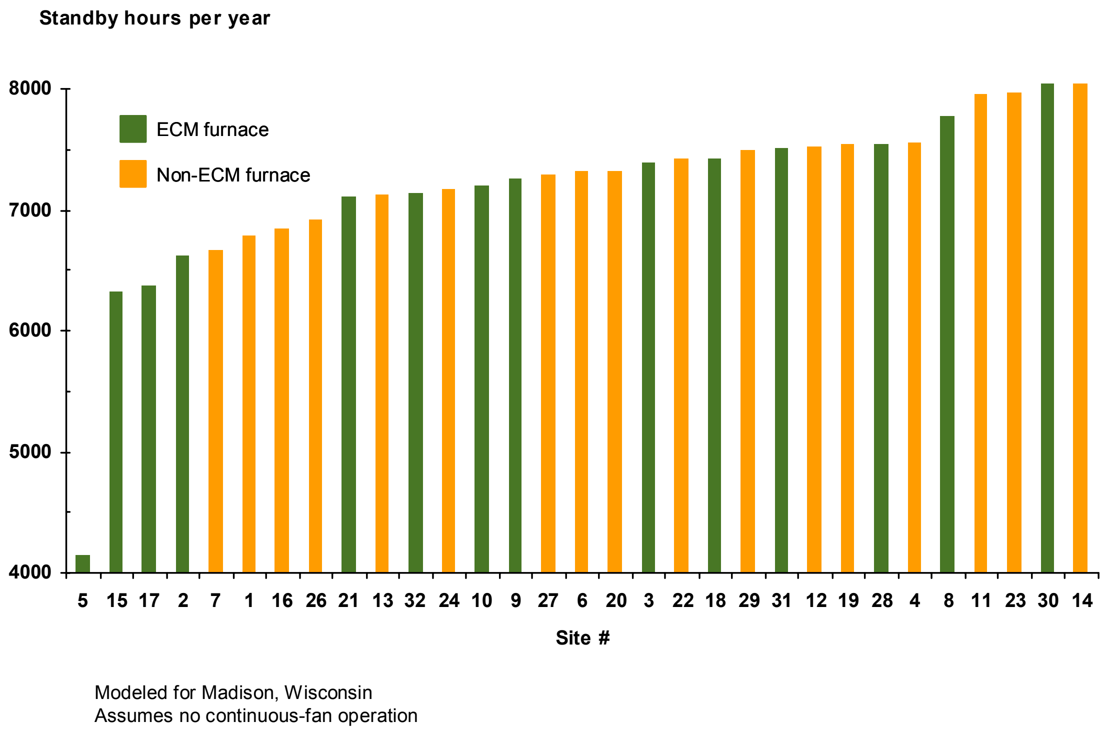


Figure 33: Annual hours of standby mode.



Summary of Electricity Use Results

Table 3 summarizes the preceding results based on typical values from the study. Two scenarios are shown: no continuous-fan use, and year-round continuous-fan operation. Both scenarios assume the presence of central air conditioning.

The results suggest that for the range of systems studied here, substituting an ECM furnace for a non-ECM furnace will save an average of about 465 kWh per year in homes that do not practice continuous-fan use, and about 3,455 kWh per year in homes that run the air handler continuously. At a current average electricity price of about 8 cents per kWh, this translates to $36 annual electricity savings in the former scenario, and about $270 annual savings in the latter.

Table 3: Summary of annual electricity use and ECM savings.

	No continuous-fan use			Year-round continuous-fan use		
Mode of Operation	**Non-ECM**	**ECM**	**Difference**	**Non-ECM**	**ECM**	**Difference**
Heating (kWh)[a]	800	400	400	800	400	400
Cooling (kWh)[b]	225	155	70	225	155	70
Continuous-Fan (kWh)	0	0	0	3,700	740	2,960
Standby (kWh)	60	90	-30	0	0	0
Total (kWh)	1,085	645	440	4,725	1,295	3,430
Indirect AC (kWh)[c]			25			25
Overall including indirect (kWh)			465			3,455

[a]For annual gas use of 800 therms.

[b] For a 2.5-ton air conditioner with airflow of 1000 cfm and 400 hours of operation per year.

[c]Represents additional air conditioning electricity difference from reduced need to remove air handler waste heat.

Geographic Variation

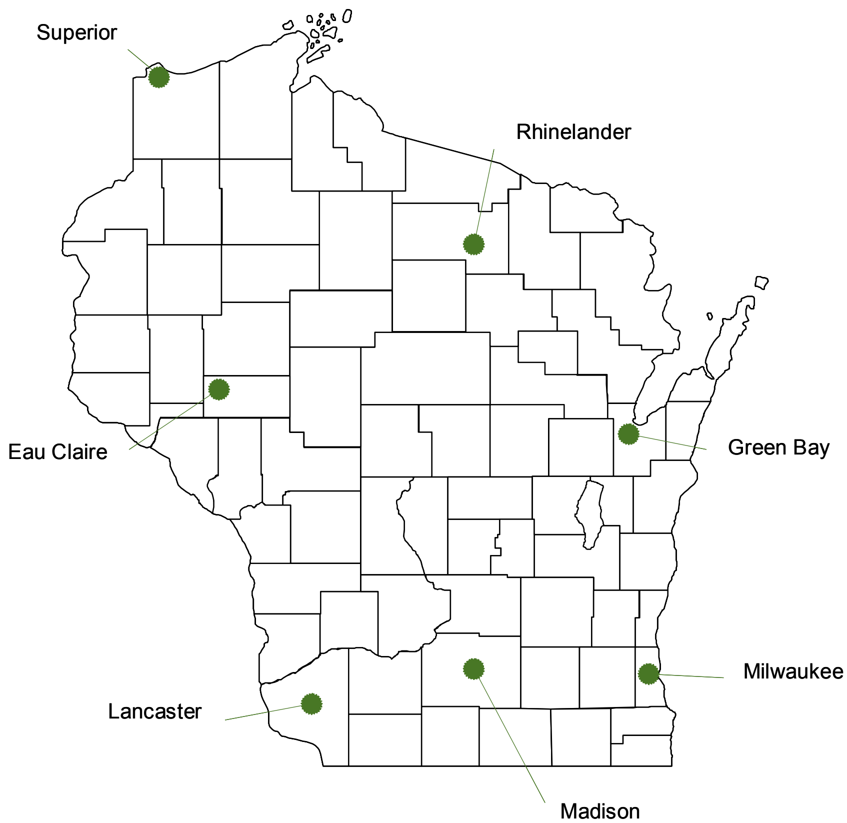
The results presented thus far are based on modeling the operation of the furnaces in the study with Madison, Wisconsin weather data. At about 7,600 heating degree days per year, Madison is close to the population-weighted average heating degree days for the state (7,800 heating degree days; WEB, 2002).

To provide a better sense of how the results vary over the state, Table 4 shows the median percentage difference in selected estimates when the furnaces are modeled with weather data in other parts of the state (Figure 34). While there are substantial differences in the modeled energy use for heating and cooling, heating electricity use per therm is relatively invariant to location. Similarly, modeled continuous-fan and standby hours are not strongly affected by location.

Table 4: Median change in selected modeled values for other locations, relative to Madison, Wisconsin.

		Green Bay	Milwaukee	Lancaster	Eau Claire	Superior	Rhinelander
Heating							
	Therms	+7.5%	-7.3%	+1.8%	+17.8%	+28.4%	+26.5%
	Cycles	+6.9%	-5.6%	+1.1%	+14.3%	+25.8%	+22.8%
	burner hours	+7.8%	-7.9%	+2.0%	+18.9%	+29.2%	+27.8%
	kWh	+7.7%	-7.6%	+1.9%	+18.4%	+28.8%	+27.3%
	kWh/therm	0.0%	+0.1%	0.0%	-0.2%	-0.1%	-0.2%
Cooling							
	Hours	-19.2%	+6.1%	+1.9%	-25.5%	-59.8%	-47.7%
	kWh	-18.8%	+5.7%	+2.0%	-24.9%	-59.6%	-47.2%
Cont.-fan hours		-0.4%	+0.7%	-0.3%	-1.3%	-1.7%	-1.9%
Standby hours		-0.4%	+0.8%	-0.3%	-1.5%	-2.0%	-2.1%

Figure 34: Location of weather stations used for modeling.



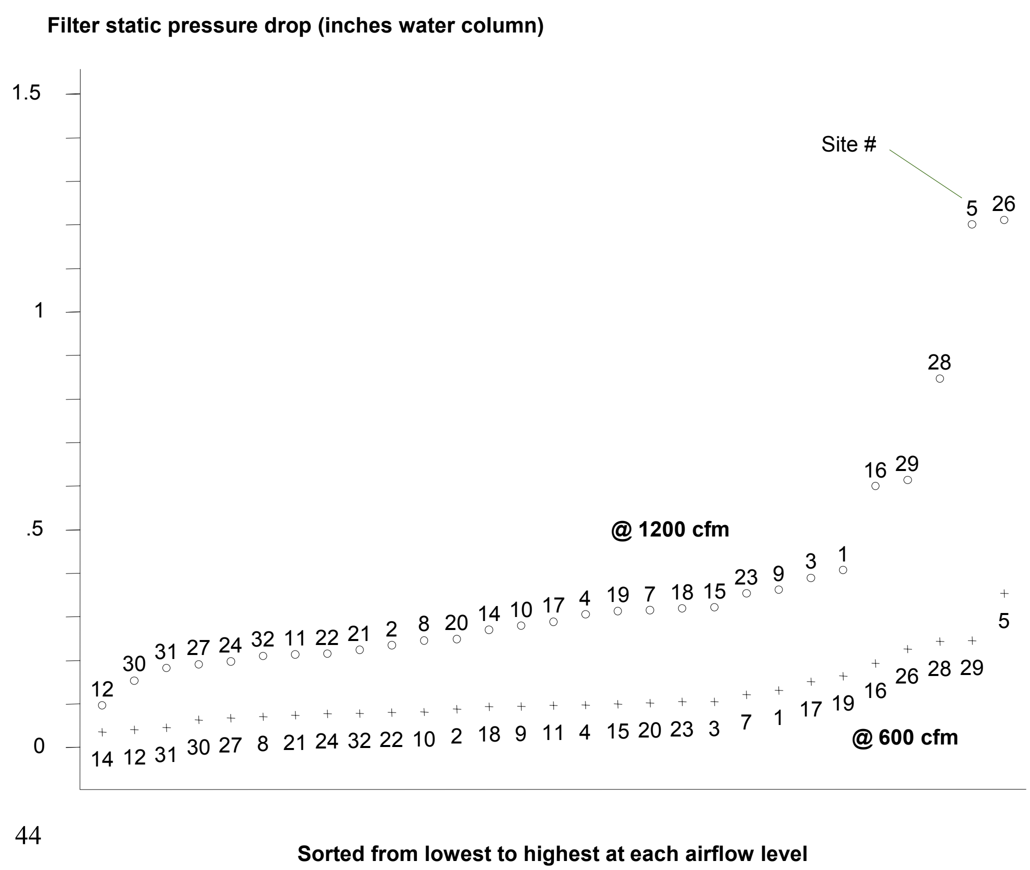
Filter Static Pressure Drop

As previously noted, the data from the study show higher electricity use with higher external static pressure for ECM furnaces. Moreover, the field measurements indicate that on average, about half of the total static pressure seen by the system is due to the pressure drop across the filter. This suggests that if filter static pressure can be reduced, the electricity use by ECM furnaces can be further reduced as well, since these furnaces compensate for high static pressure by increasing their speed and power.

Figure 35 shows the range of measured filter pressure drop normalized to two airflow levels that roughly correspond to low- and high-fire (and cooling) operation for a typical 80,000 Btu/hr furnace. There are five sites with noticeably higher pressure drops, but these do not appear to share common characteristics. Two of the sites use conventional ½ inch or 1 inch furnace filters, one (Site 28) uses a pleated media filter, one (Site 26) uses a washable filter, and one (Site 5) uses an electrostatic filter with a wire mesh pre-filter that was found to be extremely loaded.

If 0.05 IWC and 0.1 IWC are taken as the lowest easily achievable static pressure drop at these two airflows, then pressure drop across the median filter in the study could be reduced by about 0.05 IWC and 0.2 IWC, at 600 and 1200 cfm, respectively. Based on published performance data for one ECM furnace line, this could be expected to reduce air handler power requirements by about 10 Watts at the lower airflow rate, and by about 70 Watts at the higher rate for an ECM furnace, corresponding to perhaps a 10 percent reduction in total power requirements at both airflows.

Figure 35. Filter static pressure drop.



The above figures relate to the *median* furnace in the study. For a furnace with a high static pressure drop, such as Site 5, the savings from reducing the filter resistance (in this case by simply cleaning the mesh pre-filter) would be considerably higher. Based on the measurement data for Site 5 and the published performance data for the furnace, it appears that air handler power could be reduced by 40 to 60 percent by reducing the filter static pressure drop to a level comparable to the filters on the low end of the distribution.

Impact of ECM Furnaces on Gas Consumption

In theory, reducing blower electricity use will result in an increase in gas consumption during the heating season, because ECM furnaces have less waste blower heat, which would ordinarily somewhat offset the need for additional gas heat from the furnace. At least one field study (Gusdorf et al., 2003) has demonstrated as much when the furnace fan operates continuously throughout the heating season.

Gas consumption was not monitored for this study, so it is not possible to bring direct empirical data to bear on this question. The estimated typical 400 kWh electricity savings from ECMs in heating mode would translate into perhaps 15 therms of additional gas consumption at a typical gas efficiency for a condensing furnace. With continuous fan operation during the winter, this might rise to 65 therms.

However, the above figures assume that ECM and non-ECM furnaces have the same gas heating efficiency, which does not appear to be the case typically. The published heating efficiency (AFUE) for the 14 ECM furnaces in the study ranged from 92.5% to 95.0%, with a median of 94.1%. The 17 non-ECM furnaces had AFUE's that ranged from 92.0% to 92.5%, with a median of 92.2%. The difference between the median AFUE's for the two groups translates into about 16 therms less gas consumption for an ECM furnace with an annual heating load of 750 therms—enough to offset the calculated increase in gas consumption due to less waste electrical heat from an ECM furnace operating in heating mode. It is likely that a furnace operating in continuous-fan mode would still have a net increase in gas use, but the dollar savings to the consumer from reduced electricity use still overshadow any additional gas charges.

A Note on Power Factor

Although not a particular concern to consumers, power factor is of interest to utilities, which must size distribution systems to handle reactive as well as active power. Power factor measurements on the furnaces in the study showed that the ECM furnaces had somewhat lower power factors compared to non-ECM furnaces, except in standby mode. A more detailed compilation of power factor data can be found in Appendix B.

Table 5: Median measured power factor, by operating mode.

Operating Mode	ECM Furnaces	Non-ECM Furnaces
Heating	0.72 (low-fire) 0.68 (high-fire)	0.88
Cooling	0.63	0.81
Continuous Fan	0.69	0.87
Standby	0.62	0.40

Discussion

Results from this study are relevant from a variety of perspectives. The discussion that follows is organized around the following points of view:

- Wisconsin Focus on Energy program efforts
- National energy efficiency standards and program efforts
- Consumers
- Furnace contractors and distributors

Implications for Wisconsin Focus on Energy Program Efforts

First and foremost, the results from the study provide basic confirmation that multi-stage ECM furnaces do provide substantial electricity savings over conventional condensing furnaces. The savings are most dramatic in continuous-fan and heating modes, but are also apparent in cooling mode. Based on the small (and not necessarily representative) sample of homes covered by this study, the savings for a home in Madison, Wisconsin with typical gas consumption and air conditioning use appears to be about 450 kWh per year without continuous-fan operation, and more than 3,000 kWh per year with year-round continuous fan use. Peak demand savings are more difficult to discern from this study, but the results suggest that there are summer peak savings. Winter peak electricity demand is the most difficult to assess; many of the two-stage ECM furnaces will be operating in high-fire on a cold winter morning, and the data were most variable in this mode.

The above figures are meant to reflect the study results in a typical Wisconsin home. These may not be applicable to the population of participants in Focus programs that promote ECM furnaces if, for example, these participants use more or less gas, or have furnaces that are sized differently for their heating load.

Probably a larger source of uncertainty in estimates of savings due to program efforts to promote ECMs, however, lies on the behavioral side, which this study did not address. In particular, the average savings from a population of ECM furnaces is sensitive to the proportion of households that operate the furnace in continuous fan mode. Since the difference in savings between homes without continuous-fan use and those with year-round operation is so large, the average savings from blending these two is very sensitive to assumptions about the proportion of homes with continuous-fan use. If one assumes that 10 percent of homes practice year-round continuous-fan operation, then the overall average savings would be about 700 kWh per year (with half of the savings arising from homes with continuous-fan operation). Change this proportion to 20 percent, however, and the figure becomes 1,000 kWh per year, and continuous-fan homes represent two-thirds of the total.

In reality, the situation is more complicated than portrayed above. As the actual practices of the homeowners in this study demonstrate, some people practice year-round continuous-fan operation, but others do so only seasonally—or even on an ad hoc basis. Furthermore, some homeowners in new developments may practice continuous-fan operation temporarily to deal with ambient construction dust. Finally, other literature has alluded to a possible “take-back” effect; some people may purchase an ECM furnace precisely in order to operate their air handler continuously—in the absence of such a choice, they would not do so. All of these factors play into the average impacts from programs to promote ECM furnaces; unfortunately, these were mostly outside the scope of this technical look at these furnaces. Additional research is needed to quantify these practices in the Wisconsin population. Such research could be undertaken in conjunction with the biennial Appliance Sales Tracking telephone survey conducted by the Energy Center of Wisconsin.

The study also provides insights for efforts to affect how furnaces are installed and configured, such as the Wisconsin Efficient Heating and Cooling Initiative. Although these are discussed in more detail below under "Contractors and Distributors," it is worth noting here that the study offers evidence that high static pressure reduces the savings from ECMs, since these furnaces compensate by increasing the blower power input. This suggests that efforts to influence furnace filter selection and maintenance as well as duct design (for new construction) in order to minimize the static pressure experienced by an ECM furnace could bear fruit in additional electricity savings. This suggests a need to better understand the pressure drop characteristics of different types and brands of furnace filters, as well as how static pressure changes over time as the filters become loaded.

Further, the study suggests a need to promote the practice of always setting continuous-fan speed to the lowest possible option. Doing so requires no testing or equipment, and in most cases involves no action on the part of the installer, since most furnaces are already configured in this way. However, that four out of fourteen ECM furnaces in the study were configured for higher continuous-fan operation suggests that some contractors wrongly believe that more is better when it comes to continuous-fan airflow. Also, installers failed to take advantage of a separate low-speed tap for continuous-fan operation for some models of non-ECM furnaces.

Implications for National Energy Efficiency Standards and Program Efforts

This study provides some insights of national relevance. First, this study confirms previous research demonstrating that in actual practice static pressures are considerably higher than those stipulated in standard rating procedures. The furnaces in this study averaged 0.44 IWC of static pressure drop across the furnace and evaporator coil at high fire, which is more than twice the 0.2 inches generally used in the standard test procedure for rating furnace efficiency (which does not include pressure drop across the AC coil). In cooling mode, the study furnaces averaged an even higher 0.50 inches of static pressure drop. This difference is the most likely explanation for the finding that actual furnace electricity use in heating mode for ECM furnaces is on average higher than rating data would suggest.

Second, the study suggests that 0.6 kWh of heating electricity use per therm of gas consumption (or 6 kWh per million BTU of gas input) represents a useful demarcation line between electrically efficient furnaces (i.e., ECM model) and less electrically efficient models. This dividing point neatly separates the ECM and non-ECM furnaces in the study both in terms of their rating based electricity use per therm of gas consumption and in terms of the field results.

Third, the study indicates there would be some value in incorporating standby electricity use in national standards and program efforts. At a current 8 to 14 Watts, standby electricity use by furnaces exceeds that of many consumer electronic appliances, which typically have digital clocks and must sense inputs from infrared remotes. There is undoubtedly room for reduction in furnace standby electricity use with better control board design.

Finally, the study suggests that some fairly simple changes at the manufacturing level could have energy savings benefits even for non-ECM furnaces. For example, four non-ECM furnaces in the study had a separate speed tap lug for continuous-fan operation. This allows the air handler to run at the lowest speed setting in this mode independently of the speed selection for heating and cooling modes. Based on our test data, this could be expected to reduce continuous-fan electricity use by about 8 percent. However, none of the four study furnaces were field configured to make use of this feature, and the one heating contractor we spoke with who installs these furnaces stated he did not really understand its function. If the manufacturer were to simply plug the low speed tap wire into this lug at the factory, electricity use could be reduced by perhaps one percent on average across the units shipped by this manufacturer.

Implications for Consumers

This study clearly demonstrates that an ECM furnace is a "no brainer" for people who intend to operate their air handler continuously. With electricity savings on the order of $275 or more per year, the additional cost of these furnaces can be recovered within a few short years.[8] The extra cost of these furnaces is more difficult to justify solely on the basis of electricity savings for consumers who do not practice continuous-fan operation, but—with annual electricity savings of perhaps $30 to $40—the electricity savings are still worth considering.

Moreover, as a premium product, multi-stage ECM furnaces appear to offer comfort and noise advantages that may outweigh the electricity savings in the minds of many consumers. Though sound levels were not formally evaluated by this study, the ECM furnaces in the study were noticeably quieter in low-fire heating mode, which—as the study demonstrates—is the operating mode the majority of the time during the heating season.

Comfort was also not formally evaluated as a part of this study, but the data do document much lower airflow in low-fire heating mode for ECM furnaces, which could reasonably be expected to translate into fewer drafts from air handler operation. Though many ECM furnaces (indeed many new furnaces in general) are marketed as providing tighter control on temperature swings, the study did not reveal any clear difference in indoor temperature variation between ECM and non-ECM furnaces—though there are some limitations in our ability to measure such differences. The tightness with which indoor temperature is maintained is probably as much (or more) a function of the thermostat and its configuration as it is the type and model of furnace. Nonetheless, nearly all of the furnaces in the study showed a good ability to reduce temperature swings.

Implications for Heating Contractors and Furnace Distributors

Several field configuration lessons emerge from the data gathered for this study. First, the fact that some contractors are field configuring furnaces to operate at higher continuous-fan speeds than the factory default is troubling. Continuous-fan operation does not need high airflow; indeed higher airflow rates are more likely to create uncomfortable drafts in the home. And, from an energy efficiency perspective, higher airflow in continuous-fan mode wastes electricity. Even if the purchaser of a furnace does not intend to use continuous-fan operation, future occupants might do so, and it is unlikely that the initial configuration would be revisited. For all of these reasons, the

[8] Anecdotal reports put the cost increment for a typical two-stage ECM furnace over a conventional condensing furnace at $400 to $600.

general rule should be to use the lowest possible speed setting for continuous-fan mode, as most ECM furnaces are factory configured to do.

It is not possible to know from this study why the furnaces in the study were set up for higher airflow in this mode, nor is it possible to measure the prevalence of the practice. Two of the four such ECM furnaces were installed by the same heating contractor, one may have been a case of misunderstanding of DIP switch settings, and in one case, the high continuous-fan airflow setting was part of a larger array of configuration issues with a complicated zoning control system. Nonetheless the incidence is high enough to suggest the need for contractor training and education in this regard.

Second, installers should be cognizant of the relationships between furnace sizing, temperature swing, and staging control for two-stage furnaces. Long heating cycle lengths due to undersizing or other factors may interfere with staging control algorithms and result in excessive high-fire operation and undesirable variation in indoor temperature.

Third, when it comes to the perennial issue of furnace sizing, the study indicates that although most are considerably oversized in terms of meeting design heating loads—even under conservative assumptions for design conditions—the study does lend credence to the argument that some over-sizing is needed for setback recovery. The majority of homeowners in the study practiced thermostat setbacks during the heating season—as do the majority of Wisconsin homeowners in general—and recovery periods even under average winter conditions were fairly long for some of the homes. In this vein, the multi-stage ECM furnaces appear to offer the best of both worlds: reduced cycling, airflow and electricity use to meet the basic heating load of the home, combined with the ability to produce higher output to boost the indoor temperature after a setback.

Limitations

As with any effort, there are limitations to this study. The more important of these are enumerated below:

1. **Sample size.** As with any detailed field study, budget constraints prevented studying a larger sample of homes. With small samples the probability increases of obtaining a sample that—purely by chance—deviates substantially from the population from which it was drawn. This so-called sampling uncertainty can be quantified. For example, the 90 percent confidence interval for the average difference between ECM and non-ECM furnaces in heating mode electricity use per therm of gas for the study sample is ± 0.1 kWh/therm. With the study finding that ECM furnaces use about 0.5 kWh/therm less than non-ECM furnaces, one can be 90 percent confident from a sampling error standpoint that the average difference in the population is somewhere between 0.4 and 0.6 kWh/therm. However, non-random sampling errors probably dominate in this case (see next item); hence the report eschews reporting confidence intervals like the one above.

2. **Sample representativeness.** There are a number of ways in which the study sample might differ from the population at large in ways that would not be mitigated by a larger sample. Most notably, a variety of furnaces were deliberately selected for study; the market share for particular brands may therefore be under- over over-represented. Also, the study is dominated by new homes, many of which participated in the Wisconsin Energy Star Homes program—though about half the Wisconsin furnace market is thought to be made up of replacement furnaces for older homes. Finally, homeowners willing to participate in the study might be different than those who are not willing to participate—for example, they might be more inclined to operate in continuous-fan mode.

3. **Modeling uncertainty.** The study relies on models of heating and cooling energy use as a function of outdoor temperature to translate variable weather conditions over part of a season to long-term seasonal averages. There is uncertainty in this process, arising in the choice of the models used, in the fitting process for the model coefficients, and in the application of long-term averages in the context of climate change. In terms of the functional form of the models, the data suggest that, for most of the sites in the study, the majority of the variation in heating and cooling-mode hours and cycles is explained by outdoor temperature. However, other factors such as humidity during the cooling season that were not included in the models might change the estimates somewhat. Finally, there is also uncertainty in average values such as power draw measured during testing. These values can change over time, for example as filters load. Comparison of results across the two rounds of testing suggests that most values were stable to within about 10 percent.

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