Advanced Controls for Residential Heating Ventilation and Air Conditioning (HVAC) Fan

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Distributor participants
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Definition of Terms and Acronyms

AFUE – Annual Fuel Utilization Efficiency

Base – one of two fan control modes, corresponding to operation with the fan controller inactive

CFM – Cubic feet per minute

C_{house} – House thermal capacitance in units of Btu/°F

CIP – Conservation improvement program

Communicating Thermostat – uses a software-based communication protocol to control HVAC functions

ECM – Electrically Commutated Motor, a common type of fan motor

ECO – Minnesota Energy Conservation and Optimization Act

Fan type – type of electric motor used to power air handler fan

Greenfan – one of two fan control modes, corresponding to operation with the fan controller active

HES – Home Energy Squad

HVAC – Heating, ventilation, and air conditioning

Non-communicating thermostat – uses digital (on/off) signals to control HVAC functions

OAT – Outdoor air temperature

PSC – Permanent Split Capacitor, a common type of fan motor

$\dot{Q}_{net}$ – net heating capacity delivered

$\dot{Q}_{furnace}$ – heating capacity of the furnace

$\dot{Q}_{loss}$ – rate of heat loss from the building

$\dot{Q}_{i.g.}$ – rate of internal heat gains within the building

Stages – Levels of heating or cooling capacity that HVAC equipment can use

τ – tau, time constant for model of furnace temperature

Temperature dead band – the range of temperatures around the thermostat setpoint where the HVAC system provides no heating and no cooling

T_{amb} – Ambient, i.e., outdoor temperature model input in units of °F

T_{gain} – Air temperature rise for steady-state furnace operation

TMY – Typical meteorological year

UA_{house} – House heat loss coefficient in units of Btu/h-°F

$\dot{V}_{cfm}$– Volumetric Air flow rate of furnace in units of cubic feet per minute

Vent Type – Means of exhausting combustion products from gas-burning appliances. Primary types are natural draft and direct vent.

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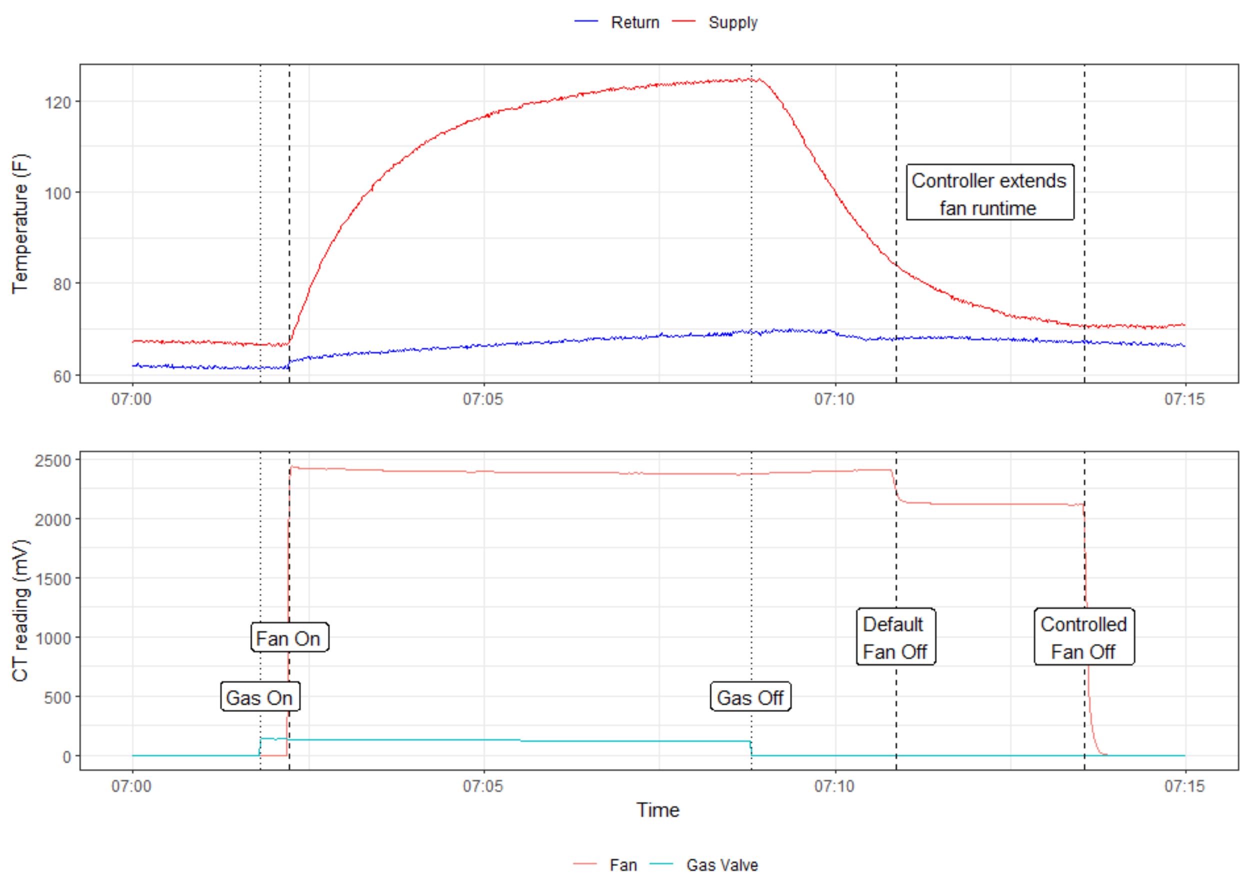
Executive Summary

Background

This study investigated the energy savings potential of a commercially available fan controller designed to be installed in residential HVAC systems. The device lengthens the fan-off delay, or the amount of time the air handler fan continues to operate following a cooling or heating cycle. The device is intended to reduce overall HVAC energy consumption by using the fan to deliver additional heating or cooling capacity relative to the system's baseline operation. Figure 1 shows the effect of the fan controller on a typical furnace cycle with a timeseries representation of temperatures and control signals. As Minnesota is in a heating-dominated climate, most of the market characterization, modeling, and field analysis focused on heating season performance, but the same analysis techniques were also applied to cooling season data.

Figure 1. Effect of fan controller on typical furnace cycle



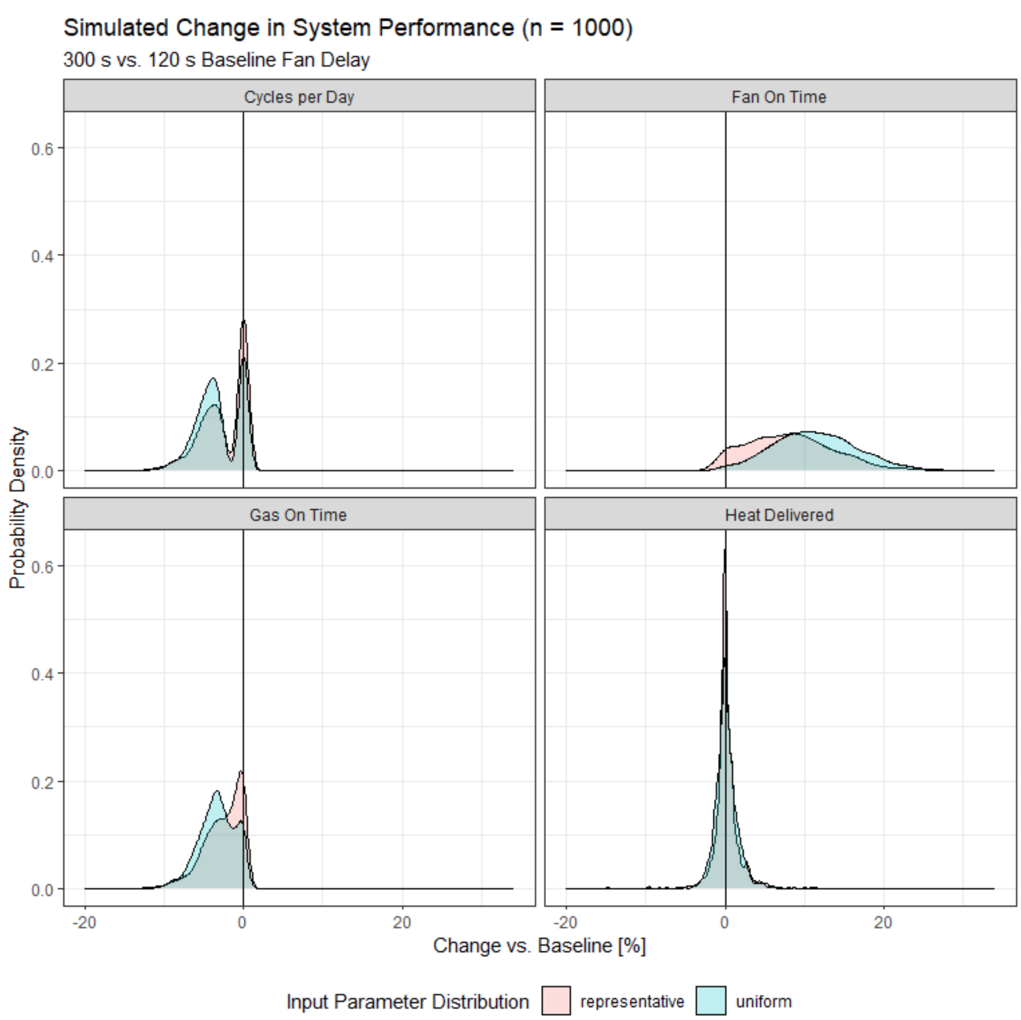
Market Characterization

A market characterization confirmed that the HVAC equipment included in this field study are generally representative of Minnesota systems. A large study of quality installation practices in Minnesota HVAC systems found that most natural gas furnaces are generally operating as designed, with little to adjust (Pigg, Cautley and Koski). The fan-off delays following a heating cycle for the 84 furnaces observed in that study were 180s or shorter. In a pilot project for this fan control device, all 20 observed fan-off delays were 150 seconds or shorter. In contrast, the median fan-off delay observed in the field study when the fan controller was active was 287 seconds. This discrepancy means that at least the opportunity to extend the fan-off delay during the heating season exists in Minnesota. Other furnace characteristics quantified in this study, such as size, efficiency, and temperature rise were consistent with past research.

Modeling

Simulations of the energy savings potential of this controller using realistic Minnesota building characteristics found that gas use was expected to be reduced by between 0% and 10%, with a median change of 2%, while the median impact on fan runtime was an 8% increase. These simulations assumed that no heat from the furnace heat exchanger moved to the conditioned space unless the fan was on.

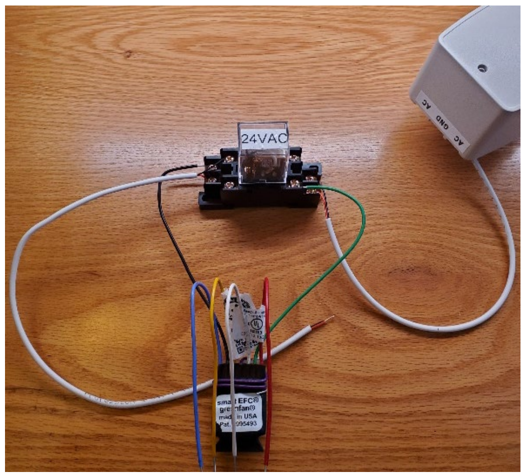
Figure 2. Percent change in outcomes by input parameter distribution



Field Evaluation

This project primarily focused on an extensive field study of the device in Minnesota homes. The controller was installed in 24 residential HVAC systems powered by a relay and Wi-Fi smart switch that allowed remote activation and deactivation. The controller was toggled between active and inactive states, labelled as greenfan and base control mode, respectively, every two weeks. This alternating mode test procedure allowed data to be collected across the full annual range of temperatures in both modes in a single year.

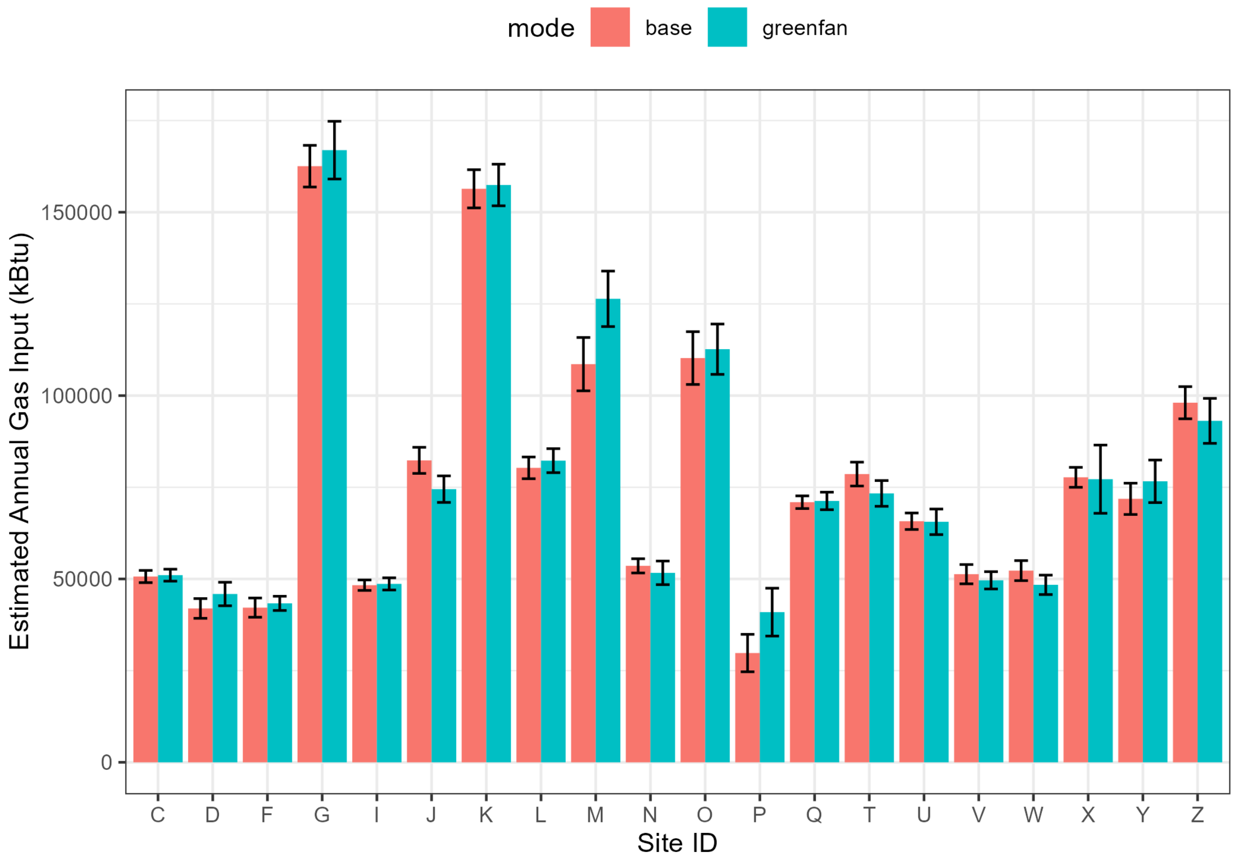
Figure 3. Fan controller, relay, and 24VAC transformer



Furnace and air conditioner operating data was collected at one-second intervals with a power meter and a datalogger at each site to facilitate accurate calculation of the fan-off delay duration. This data was aggregated into heating and cooling cycles to verify the controller function and labelling of the active control mode. For the statistical analysis, it was aggregated to the daily level and combined with weather data to develop relationships between gas use and heating degrees by control mode.

Multiple linear regression of energy use and heating or cooling degrees, with the interaction between control mode and heating or cooling degrees included as the additional predictor, was used to assess the impact of the fan controller on energy use at each site. The statistical significance of the coefficient for the interaction between control mode and heating or cooling degrees was used to assess whether the controller had a non-zero effect. This process was used for gas use, heating season fan electricity use, air conditioning electricity use, and cooling season fan electricity use. Energy consumption was estimated by applying the regression models to daily aggregated TMY 2020 data for Minneapolis-St. Paul International Airport, using the balance point measured at each site to calculate daily heating and cooling degrees, and summing the results to achieve an annual estimate.

Figure 4. Estimated annual gas use with 95% confidence intervals



The field evaluation showed that for 14 of 20 sites, there was no statically significant difference in annual gas use between a system operating with and without the fan controller. For the other six sites, three showed decreases in gas use, while the other three showed increases. A statistically significant increase in fan energy use was observed during the heating season at all four sites with sufficient data to estimate it. In cooling mode, none of the ten sites assessed showed a significant difference in air conditioner electricity consumption between modes. Two of the ten sites had significant increases in fan energy use in cooling mode, while the eight other sites had increases that were statistically insignificant.

Conclusions

While the modeling exercise showed the potential for up to 10% gas savings, it relied on the assumption that none of the heat from the heat exchanger moved into the conditioned space while the fan was off. The field analysis results seem to discredit this assumption.

For both heating and cooling operation, unmeasured factors such as solar gains and occupant behavior likely have a much larger effect on HVAC energy requirements than the fan-off delay. Overall, these results emphasize that any effect the fan controller has on gas use is small relative to other sources of uncertainty. It is not appropriate to attribute gas or electricity savings to this device.

Background

Fan Controller

The device is installed in the residential air handler cabinet by wiring it into the thermostat terminals on the air handler control board. The device detects signals from the thermostat and air handler controller, and uses the output connected to the fan request signal to keep the fan running beyond the time it would typically shut off.

The manufacturer of the device claims that the device saves 334 kWh/year of electricity and 21.7 therms/year of natural gas depending on the context, according to simulations as well as laboratory and field tests (Greenfan). This device is an approved energy conservation measure in the California technical reference manual for cooling only (California Technical Forum). The unit energy savings value for the measure was based on laboratory testing that evaluated impacts on cooling only, so there was a need to verify the claimed gas savings.

Previous studies found that the reduction in energy use was related to the part-load ratio of the heating or cooling system. The part-load ratio was defined as the ratio of the cooling or heating load to the cooling or heating capacity of the equipment, respectively. The part load ratio was assessed on an hourly or cycle basis. The savings achieved were inversely proportional to the part-load ratio, so as the part-load ratio increased toward unity, the energy savings decreased (Mowris).

Research Overview

This project was designed to verify the claimed energy savings of the fan control device. In the Minnesota context, most of the annual HVAC energy use for single-family residences is for heating, so verifying claimed gas savings was the focus.

Key project steps included market characterization, modeling savings potential, and field evaluation. The market characterization assessed past HVAC research in Minnesota to estimate the statewide savings potential, provide modeling inputs, and ensure the sample included in the field evaluation represented the HVAC systems in the state more broadly. The modeling work was intended to independently estimate the savings potential of the device and identify site characteristics that correlated with increased savings. Identifying such characteristics would support the development of a site selection tool, assuming that sites could be clearly identified as good candidates for this measure. Finally, the field evaluation phase consisted of a detailed evaluation of the heating and cooling performance of HVAC systems in 24 single-family homes and townhouses. High-resolution system operating data was collected for approximately one year at each site while the fan controller was remotely toggled between active and inactive modes every two weeks. Active and inactive fan controller modes are referred to as the greenfan and base control modes throughout.

Methodology

Market Characterization

The savings potential of the advanced residential fan control was believed to depend on the HVAC system into which it is installed. Some characteristics that were expected to significantly impact savings are not often collected as part of HVAC characterization work. Characterization of relevant system and fan operation of the existing HVAC stock in Minnesota was needed to evaluate the savings potential for this fan controller, collect modeling inputs, and verify that the field sample was representative.

Existing HVAC Equipment

Data from previous studies was used to characterize Minnesota's existing residential HVAC stock in a cost-effective manner. These studies include a 2016 CARD grant-funded project on residential HVAC installation and maintenance (Pigg, Cautley and Koski), which included information on operational performance for 84 furnaces. Additional furnace characteristics were collected from the pre-installation assessment portion of a 2014 Department of Energy Building America evaluation of combined space and water heating systems (Schoenbauer, Bohac and McAlpine). The team also referenced preliminary data on 20 sites from the 2018 Xcel Energy-funded pilot study that assessed the savings potential for this technology.

New HVAC Equipment

To support the field characterization, the team conducted distributor interviews to determine the state of the market for new HVAC equipment. Information from these interviews along with field characterization data were used to inform site selection criteria for field monitoring.

Distributor Interview Questions

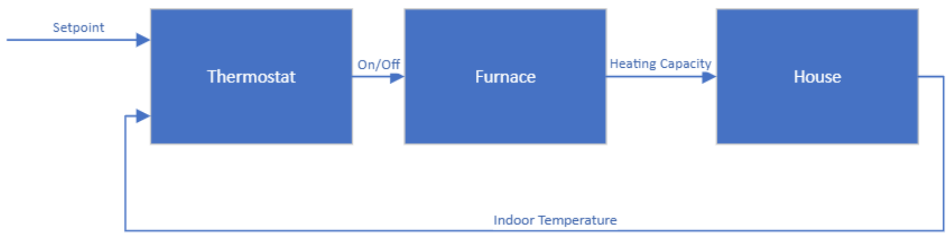
Five distributors were asked high-level questions about the kinds of products they sold, then more specific questions regarding furnace and AC features. A sample of the questions is listed below.

1. What models are the best-selling furnaces and ACs?
2. How often do furnace and AC fan specifications or features factor in stocking or sales decisions?
3. How important are the following properties for residential HVAC fans?
    a. Fan Type (e.g., ECM, PSC, etc.)
    b. Fan speed modulation (single speed, 2–5 speeds, fully modulating)
    c. Fan post-purge (delay) duration
4. How have fan properties changed in the last 10 years?
5. What kind of fan controls are included in products sold?
6. Do the products sold allow configuration of fan delay times?
7. Are fan settings changed during installation?
8. Any experiences with efficient fan controllers as a retrofit?
9. Any impressions of or concerns about retrofit fan controllers?
10. What factors might make contractors consider using efficient fan controllers?

Modeling

A time domain model of a home heating system was developed to understand the energy savings potential of the fan control device. The system model consisted of a state machine feedback controller representing the thermostat, a first order transfer function representing the furnace, and a lumped capacitance model representing the building. The model was designed to accept several configuration parameters, which enabled model tuning to simulate the performance of the heating systems of the various buildings in the sample.

Figure 5. Block diagram of furnace system model



Inputs to the thermostat model included a temperature setpoint schedule, a temperature dead band, and the indoor temperature as the feedback signal. The thermostat compared the feedback signal to the setpoint and used a simple hysteresis-based control to determine whether the furnace should turn on or turn off. Upon entry into a new state, the thermostat model logged the simulation time and initial supply air temperature for use in the furnace model. The thermostat was responsible for turning the fan on upon entry into the “on” state but turning the fan “off” was handled by the furnace model so that the fan-off delay could be provided as a configurable parameter.

After the thermostat, the system model executed the furnace model. This involved calculating the furnace capacity from the return and supply air temperature difference and fan state. The fan was assumed to be on if the furnace was on, or if the furnace was off and had been off for less time than specified in the fan-off delay configurable parameter. Crucially, the furnace heat capacity was assumed to be exactly zero unless the fan was on.

Energy balance calculations were carried out by determining the heat loss from the house as a function of indoor-outdoor temperature difference and looking up the estimated internal gains from the assumed internal gains schedule. Net heat transfer to the building was modeled as the sum of the furnace input, heat loss, and internal gains.

Equation 1. Energy balance formulation

$$\dot{Q}_{net} = \dot{Q}_{furnace} + \dot{Q}_{loss} + \dot{Q}_{i.g.}$$

Next, the model calculated the temperatures for use in the subsequent simulation timestep. The supply air temperature was calculated from the appropriate first-order response equation depending on the state of the furnace. When on, the supply air temperature increased toward its steady state offset from the return air temperature. When off, the supply air temperature decreased toward the return air temperature. The same configurable time constant was used for each mode.

Equation 2. Supply temperature prediction equation, burner on

$$T_{sat,on}(t+1) = T_{rat}(t) + K_{on}\left(1 - e^{-\frac{(t+1-t_{on})}{\tau}}\right)$$

Equation 3. Supply temperature prediction equation, burner off

$$T_{sat,off}(t+1) = T_{rat}(t) + K_{off}\left(e^{-\frac{(t+1-t_{off})}{\tau}}\right)$$

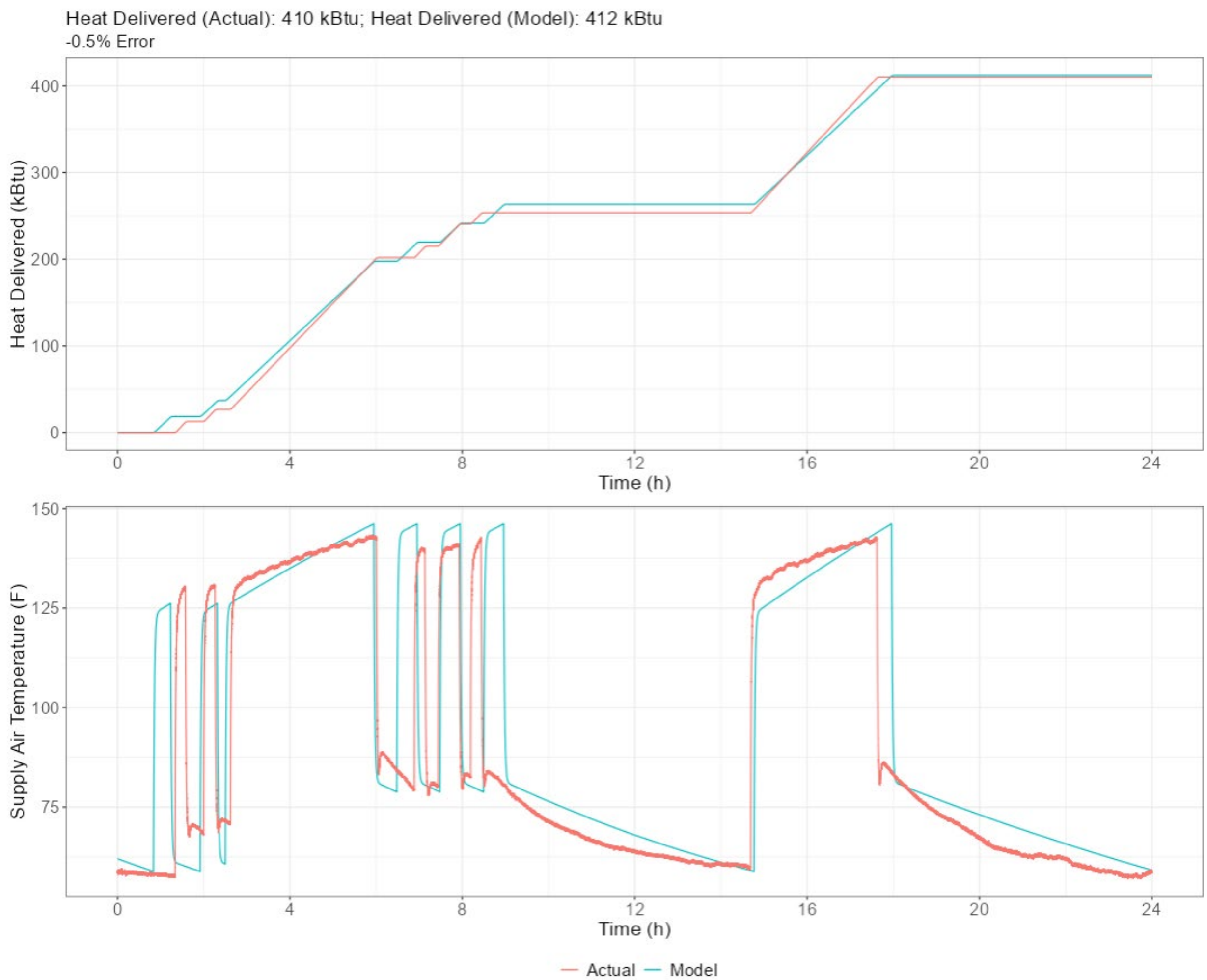
Finally, the model calculated the return air temperature to feed back to the thermostat in the next simulation time step. Because the air in the building was assumed to be a lumped capacitance subject to the net heat transfer calculated earlier in the current simulation time step, the change in temperature was proportional to the net heat transfer by a configurable capacitance term.

Equation 4. Return temperature prediction

$$T_{rat}(t+1) = T_{rat}(t) + \frac{\dot{Q}_{net}}{C_{house}}$$

The model was designed to accept time domain inputs such as the ambient temperature from field data to minimize the sources of error between the model and field data. However, the assumed thermostat schedule and internal gains schedule had a major effect on the modeled furnace cycling behavior. While it was possible to fine-tune these schedules such that the modeled energy delivered by the furnace matched the actual energy delivered by on a given day within 1%, the model was primarily used to isolate the effect of the fan delay parameter on the energy delivered per cycle and per day after tuning the model to plausible scenarios.

Figure 6. Actual and modeled heat delivered and supply air temperature vs. time



Field Evaluation

Site Requirements

This device required sites that were heated by a ducted forced air furnace and cooled by a ducted split air conditioner. In addition, the site HVAC equipment needed to be controlled by a non-communicating thermostat, i.e., a thermostat that uses digital signals to control HVAC functions. The fan controller is installed by wiring into the thermostat terminals and responds to the 24 VAC signals that come from a non-communicating thermostat. A communicating thermostat uses a software-based communication protocol to control HVAC functions and is therefore not compatible with the fan controller.

Participants not only needed a specific set of HVAC and control equipment, but also needed to be willing to use a specific control configuration. Participants were required to have their air handler fan set to run on-demand rather than continuously or be willing to change the setting to on-demand operation for the duration of the monitoring period. This corresponds to the “auto” fan setting on most thermostats. Since the fan controller is designed to save energy by extending the fan runtime via the thermostat fan signal, it has no impact on continuously operating fans.

Finally, site candidates with no planned changes to HVAC equipment, breaker panel, or the installation locations of these devices during the monitoring period were prioritized. Sites that increased the diversity of housing characteristics, such as age, size, and number of floors, in our participant pool were also included if possible.

Site Recruitment

Sites were recruited through field assessment visits, Home Energy Squad (HES) visits, and a database of contacts who had indicated to CEE that they would be interested in participating in future research projects.

A preliminary site assessment was conducted in parallel with the typical HES visit tasks to vet the home for potential participation. For sites that were good candidates, the team discussed participation with the homeowner. The potential research participant database had information including the contact’s HVAC system type, home location, and contact information. Preliminary visits were deemed unnecessary because the remaining preliminary home information could be gathered over the phone.

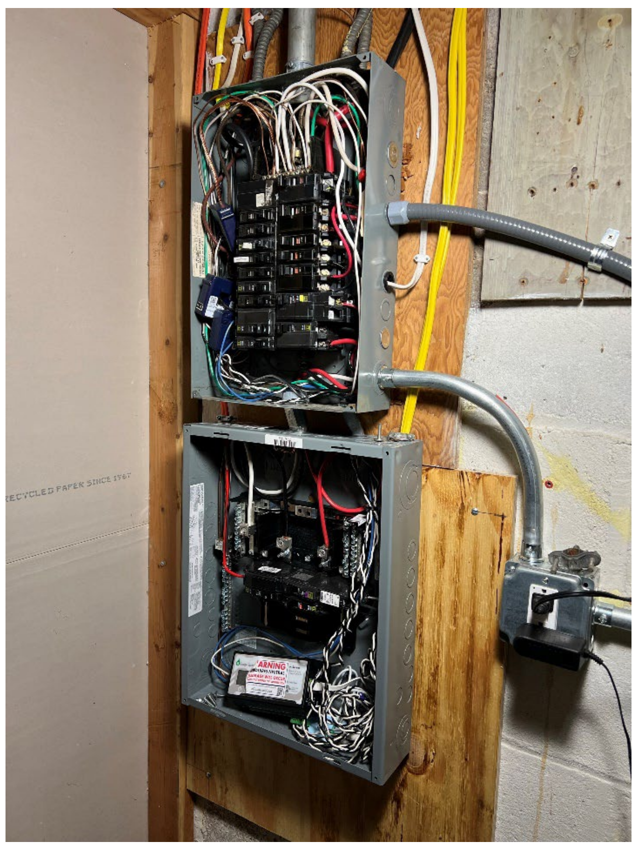
A standard set of screening criteria was applied to identify qualified candidates from the research participant database. When a potential candidate responded to initial outreach, researchers followed up with a short survey via email for additional information. This survey included home characteristics, equipment locations, Wi-Fi capabilities, thermostat settings, secondary heating and cooling sources, and photos of HVAC and electrical equipment. Once the survey was complete and the homeowner agreed to participate, the team scheduled a visit to install the fan controller and monitoring equipment.

Instrumentation

Each site was outfitted with two independent data loggers: one at the air handler to measure the furnace performance and one at the electrical panel to measure power consumption by the furnace and air conditioner. Both data loggers were configured to send raw data files to a central server daily. Each file included observations at one-second intervals.

Figure 7. Air handler data logger and representative installation on return duct

Figure 8. Power meter installed in panel



The furnace performance was characterized by measuring the return and supply air temperatures before and after the heat exchanger, supply fan current, and gas valve current. For furnaces with multi-stage gas valves, each stage was measured with an independent CT.

Figure 9. Representative instrumentation installation

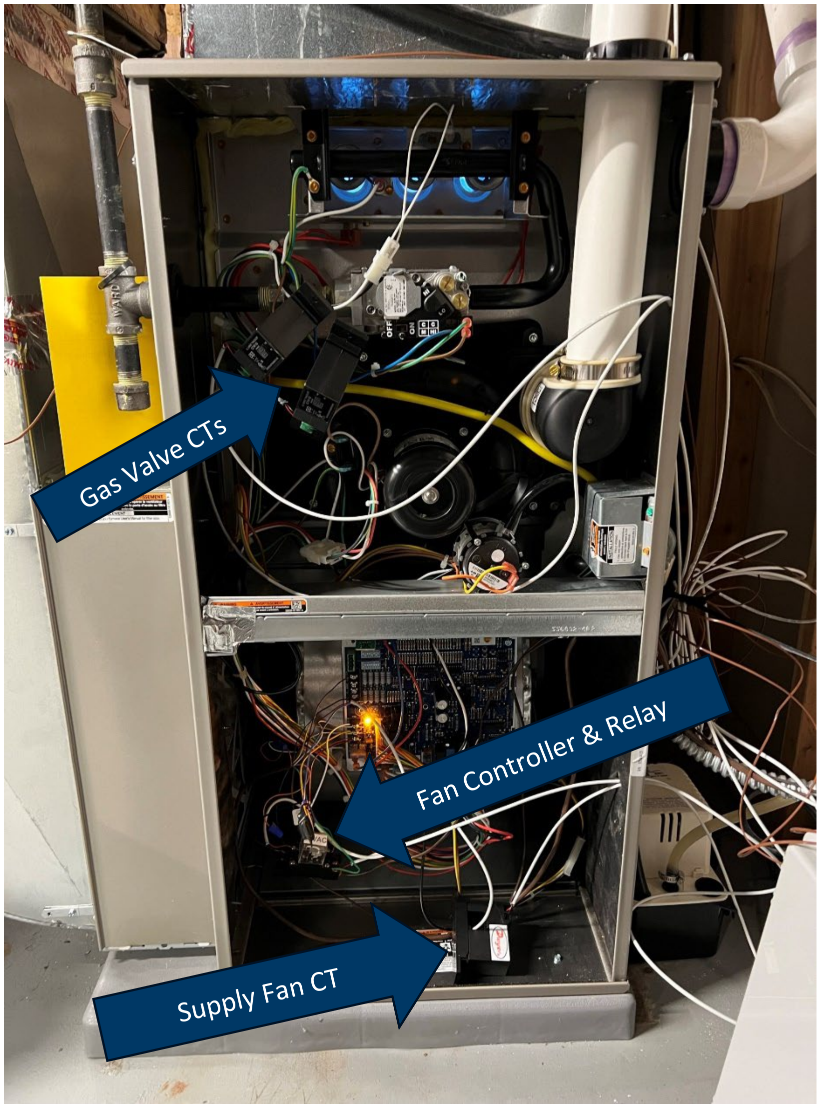
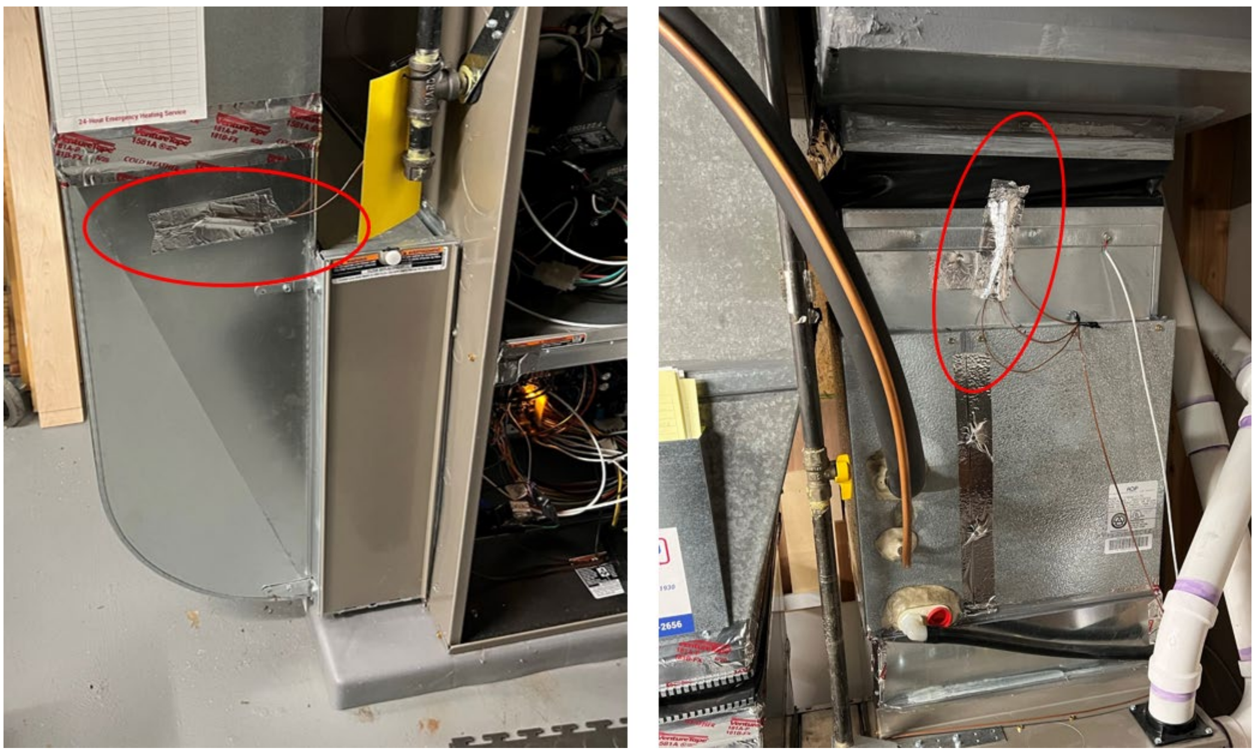


Table 1. Summary of instrumentation installation

Measurement	Sensor	Location
Supply Air Temperature	Thermocouple Array	Supply Air Duct
Return Air Temperature	Thermocouple	Return Air Duct
Supply Airflow	CT	Furnace Fan Cabinet
Gas Use	CT(s)	Furnace Burner Cabinet

Measurement	Sensor	Location
Furnace Power	Power Meter	Electrical Panel
Air Conditioner Outdoor Unit Power	Power Meter	Electrical Panel

Figure 10. Return air temperature (left) and supply air temperature (right) sensor locations



Alternating Mode Tests

An alternating mode testing methodology was used to accomplish the field evaluation of the fan controller in a single heating season. Base mode refers to the default operation of the system, while greenfan mode refers to operation with the fan controller active. At each site, a 24 VAC relay was wired between the thermostat and the fan controller. This allowed the fan controller to be bypassed when the relay was powered. The relay was powered by a 24 VAC plug-in transformer that was plugged into a Wi-Fi smart switch. This arrangement allowed remote activation of the relay to operate the system in base mode and remote deactivation to operate the system in greenfan mode. Each system was toggled between base and greenfan mode every two weeks.

Figure 11. Fan controller, relay, and transformer wiring

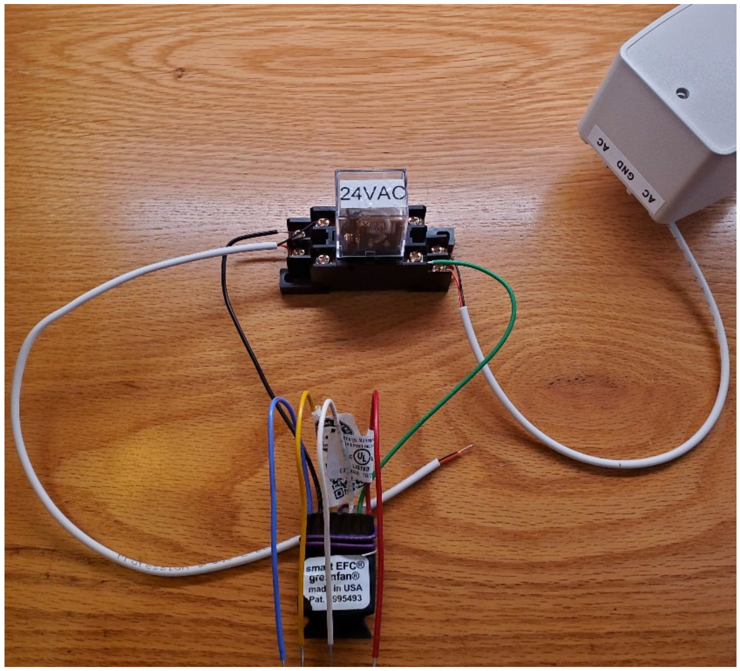
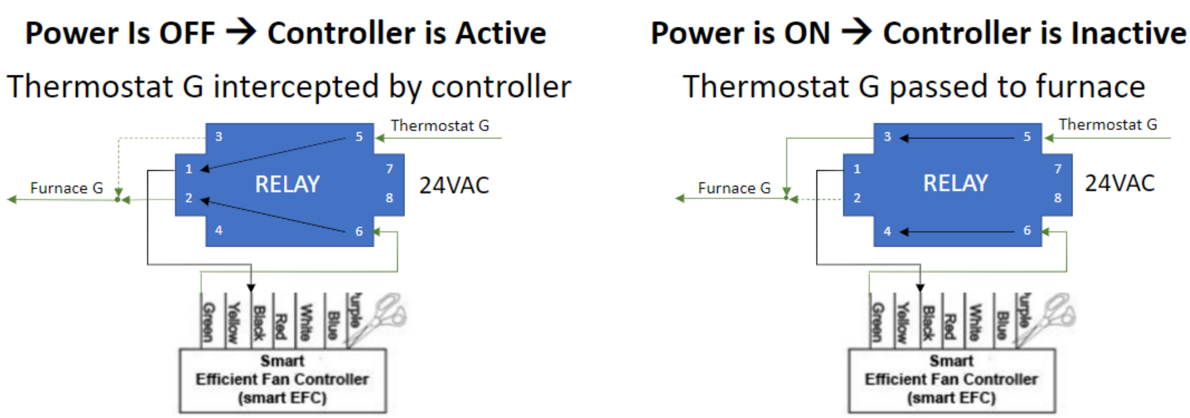


Figure 12. Relay and fan controller wiring diagram



Field Data Processing

Raw data was extracted and combined from each logger into a compressed file consisting of all observations for a given site for a given month. Then, weather data from the Minneapolis-St. Paul International Airport weather station was imported and the temperature and relative humidity was interpolated over one-second intervals before joining it to each file. The resulting files, each with about 2.5 million rows and 12 columns characterizing performance for a single month at a single site, were referred to as basic timeseries files.

The basic timeseries files were then cleaned by filtering out-of-range values and replacing them with interpolated values for all numeric fields. Any invalid data persisting for more than ten seconds in the dataset was left as NA rather than imputed with interpolated values. Out-of-range values for thermocouples were caused by the sensor contacting ductwork, while out-of-range values for the CTs were typically caused by loose sensor wires. For chronic sensor problems, returned visits were arranged to repair or replace sensors as needed. Sensor issues were relatively rare, with each of the field installed sensors reporting in-range values for more than 99% of observations.

Next, the dataset was augmented by joining fields from two additional data tables. The control mode table contained a record of the timestamp of every change in controller modes (i.e., base or greenfan) for each site. This table was joined by timestamp to the timeseries data, then the mode field was filled forward to assign a mode label to every observation. The site metadata table containing the thresholds and correlations used to characterize the HVAC system performance was joined by site ID. With these labels, thresholds, and correlations in place, statuses of all actuators such as the gas valve(s) and fan were calculated. Statuses were indicated with an integer value, with 1 representing ON and 0 representing OFF. Changes in the gas valve and fan statuses were used to label individual heating and cooling cycles. The beginning of a cycle was defined as the first observation for which the gas valve or AC was on and was previously off. Each cycle ended at the observation immediately preceding the beginning of the next cycle. All observations occurring after the AC or gas valve status changed from on to off and before the fan status changed from on to off were labeled as part of the fan-off delay period. These two labeling procedures allowed data to be aggregated by cycle, then find the total fan-off delay time by cycle. Controller function was visually verified with two different plots. First, distributions of fan-off delay time for each cycle by control mode were plotted and compared. As a final check, a point for each cycle was plotted on a scatter plot, with the y-axis indicating fan-off delay time, the x-axis indicating the first timestamp of the cycle, and the color representing the mode.

Gas use was estimated based on the furnace input rating conditions and the status of the gas valve(s). Gas was assumed to flow to the furnace at the rated flow rate whenever the gas valve was open. Any errors in estimating the actual gas use introduced by this assumption were consistent across control modes. For two-stage furnaces, the total gas flow rate G was computed as the sum of the product of the first stage gas valve status S_1 and first stage input rating R_1 and the product of the second stage gas valve status S_2 and the difference between the second stage input rating R_2 and first stage input rating, as shown in Equation 5.

Equation 5. Total gas flow rate

$$G = R_1 \times S_1 + (R_2 - R_1) \times S_2$$

Electricity use was estimated by summing the power measurements in kW at one second intervals over each day and appropriately converting the units to kWh.

All the high-resolution time series data was aggregated by day, averaging or summing numeric values as appropriate to summarize the daily performance. Total daily gas use and electricity use by average outdoor temperature and control mode (stratified by site) was plotted to check that the data followed the expected trends. For heating season analysis, any days without gas use were filtered out, and for cooling season analysis, any days with gas use were filtered out. As the final step to prepare for statistical analysis, the heating and cooling balance point temperatures for each site were identified. The heating balance point was assumed to be the maximum outdoor temperature with any gas use by site, while the cooling balance point was taken as the change point of a piecewise linear regression model fit to the electrical energy required by the air conditioner outdoor unit as a function of temperature. Site-specific heating degrees and cooling degrees fields were created by taking the difference between each balance point and the daily average temperature.

Data that did not represent system operation in either control mode was excluded. Specifically, sites that did not have data from each mode at a wide range of outdoor temperatures were excluded, and sites where the controller had no apparent impact on the fan-off delay were excluded. Some data from sites with failed sensors or communication issues were excluded. Finally, data with significantly different occupant behavior relative to the site data overall, e.g., deep indoor temperature setpoint setbacks, was excluded. Details of excluded sites and data are available in Appendix A: Data Processing and Sampling Details.

Field Data Analysis

To quantify the impact of the fan controller on gas use, linear regression models of energy use as a function of heating or cooling degrees and control mode were fit to the data. The intercepts of the linear models with respect to heating or cooling degrees were assumed to be consistent across control modes because the fan controller has no theoretical impact on the balance point temperatures. This belief informed two key modeling decisions. First, daily heating or cooling degrees were chosen to represent the heating or cooling load instead of the more typical outdoor air temperature because zero heating or cooling degrees is associated with no energy use. This relationship simplified the process of equating the intercepts across control modes. Second, the control mode was encoded as a dummy variable but only included as an interaction term with heating or cooling degrees in the model. The dummy variable itself was not included as a predictor because that would allow the intercepts of the linear models to differ across control modes.

The impact of the fan controller was tested by evaluating the p-value of the regression coefficient for the interaction term between the heating or cooling degrees and the control mode dummy variable. It was concluded that there was not enough evidence to claim that the coefficient of this parameter was different than zero for any p-values greater than 0.05. In cases where the coefficient was significantly different than zero, the energy impact was determined based on the sign of the coefficient, where a positive value corresponded to an increase in energy use and a negative value corresponded to a decrease in energy use associated with an active fan control mode.

A similar process was applied to quantify the impact of the fan controller on fan energy use. First, the total electrical energy consumed by the air handler was aggregated by day for the monitoring period from the power meter data. Then, this data was joined to the summarized daily furnace performance data. Finally, linear regression of electrical energy input as a function of heating or cooling degrees and control mode was performed.

Occupant Impacts Survey

A comfort survey including questions related to the quality of the air emitted by HVAC registers, noise, and fan behavior was administered five times from September through November 2023 to capture cooling and heating operation. This survey was sent to homeowners electronically during the middle of each two-week fan control period. Occupants were asked to answer questions considering their experience with their HVAC system over the past week. This design was intended to collect the data needed to assess whether the effects of the fan controller could be detected by occupants.

Results

Market Characterization

Assessment of Past MN HVAC Research

Findings from relevant previous studies of Minnesota furnaces were reviewed to support the market characterization. The fan-off delay, efficiency, size, and temperature rise characteristics of furnaces assessed through other projects are summarized below. The sites sampled in the quality installation project included single-family homes in the Twin Cities, St. Cloud, Rochester, and Duluth. The combined space and water heating research included sites that had participated in the Minnesota Low-Income Weatherization Assistance program but had not had a furnace replacement as part of weatherization work. For the pilot study, the team assessed 20 sites recruited through Home Energy Squad visits.

Fan-Off Delay

Data from past Minnesota HVAC research indicated a wide range of fan-off delays. Of the 84 furnaces tested in the quality installation project, all but two furnaces had fan-off delays of at least 90 seconds. The longest observed delays were up to 180 seconds. From the 20 sites assessed as part of the pilot study, the longest fan off delay observed was 150 seconds and the shortest was 0 seconds. However, the manual for the furnace with the 0 second fan-off delay indicated that the configurable range for this setting was 90 to 180 seconds, implying that the observed value of zero may have been due to a furnace controls malfunction. The advanced fan controller extends heating fan-off delays up to 300 seconds, indicating some savings potential on all the systems that were evaluated.

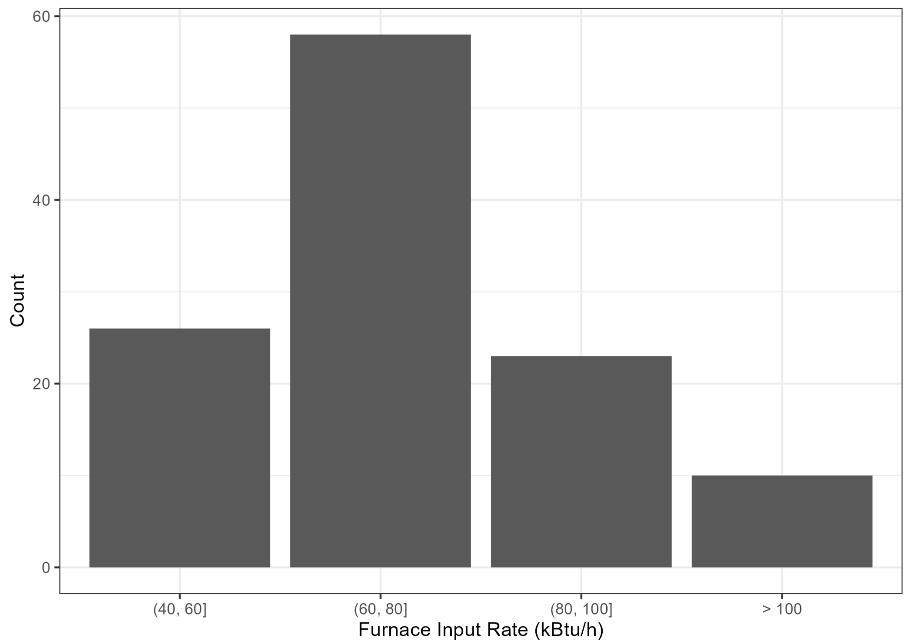
Efficiency

The CARD study on quality installations found that most new and existing furnaces in Minnesota are high-efficiency condensing furnaces that perform as intended. Roughly 75% of the furnaces included in the sample had efficiency ratings of at least 90%, while the rest had ratings of 80%. For the combined space and water heating research, most furnaces had efficiency ratings of about 80% — however, this was a byproduct of the sampling methods for this project, which intentionally excluded sites that had a newer condensing furnace installed as part of weatherization work. As such, the efficiency for the furnaces from this study was not considered representative. The pilot project found that 63% of the furnaces assessed had an AFUE of at least 90%.

Size

Across all studies assessed, nearly half the furnaces had maximum input rates between 60,000 Btu/h and 80,000 Btu/h. Furnaces with input rates more than 100,000 Btu/h made up less than 10% of the sample. Figure 13 shows the distribution.

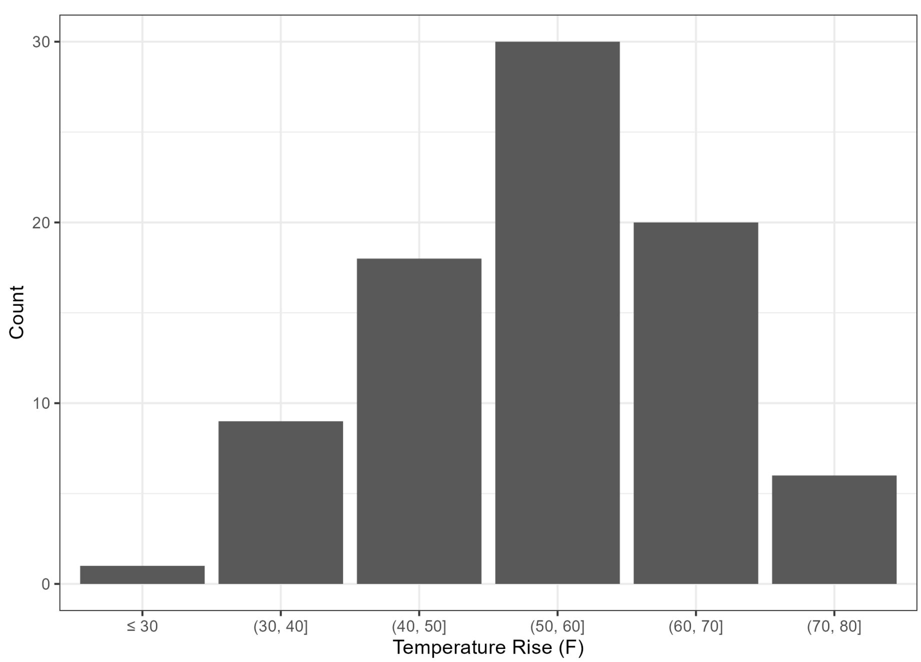
Figure 13. Minnesota furnace input rate distribution



Temperature Rise

The quality install project also assessed the steady-state temperature rise of the air passing through furnaces in the study. Temperature rise was between 40°F and 70°F in over 80% of the assessed furnaces.

Figure 14. Minnesota furnace temperature rise distribution



Distributor Interview Summary

All the distributors that were interviewed reported that they primarily sold furnaces with efficiency ratings above 90%. They stated they prefer to sell higher efficiency furnaces beyond the basic single-stage and single-speed furnaces but felt there was less motivation for contractors to push high-efficiency furnaces to consumers. The rationale for this trend was that comfort is the biggest driver for selling furnaces to customers and contractors, and rebates and efficiency are secondary considerations. While rebates were discussed as a potential driver for better equipment, the distributors believed that in most cases rebates did not make up the cost difference between high- and standard-efficiency equipment.

Even for contractors that prioritized efficiency, they are limited to selling what the market will buy. The distributors stated that efficiency is important to some consumers, but many do not understand the system operation or don't prioritize efficiency enough to use it as the basis of their purchasing decision.

Some interviewees touched on the progress the market has made toward higher efficiency units. They said that consumers are becoming more receptive of higher efficiency units beyond single-stage and single-speed equipment because the high-efficiency units can increase comfort in the home. Since comfort can be affected by the unit's fan type, the equipment choice will ultimately lean toward the fan types that provide the most comfort.

Roughly half of interviewees were familiar with fan controllers as a retrofit measure and most had positive opinions about the technology. Some concerns with aftermarket fan controllers included consumer comfort complaints due to drafts created by longer fan times after the burner cycle, compatibility with the variety of equipment in the field, and practicality with most new furnaces being variable speed.

Despite these reservations, most said that they saw the potential for savings from retrofit fan controllers to some degree. There was consensus that very old equipment should be replaced rather than retrofitted with a fan controller, and high-end furnaces would likely not benefit from a retrofit due to their variable speed fans. However, there would be an opportunity to achieve energy savings by retrofitting single-speed systems that cycle between on and off states. To maximize savings, they suggested that programs should aim to retrofit systems as soon as possible, since the window of opportunity for savings is only open until the existing equipment is replaced at the end of its useful life with the new and improved equipment on the market. Finally, they mentioned that the trend toward zoning in residential systems will continue to drive sales of more variable speed furnaces and heat pumps.

Modeling

The opportunity for heating energy savings was estimated by running pairs of daily heating system simulations with all input parameters fixed except for the fan delay parameter. For the fan delay parameter, 120 seconds was used to represent the baseline system behavior and 300 seconds was used to represent the alternative system behavior under the effect of the fan controller. This representation simplified the behavior of the fan controller, which controls the fan to run for a variable amount of time as a function of heating or cooling time. Finally, the cycle count, fan on time, gas on time, and total heat delivered were quantified for both the baseline and alternative simulations.

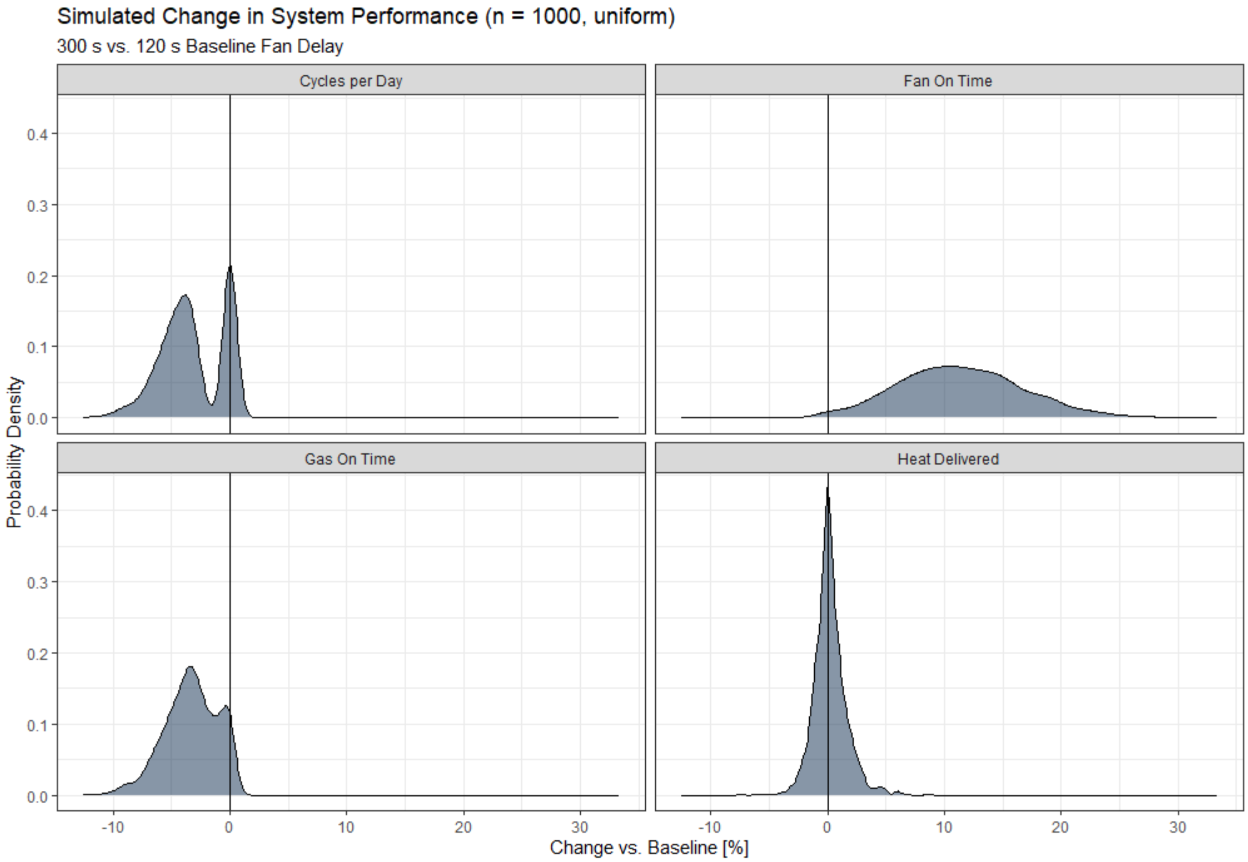
For the other simulation input parameters, many cases (e.g., 1000) were generated by randomly sampling values for the system time constant, house capacitance, house heat loss coefficient, and daily constant ambient temperature. Parameters for temperature gain and airflow were also randomly sampled, but combinations of these parameters were checked to ensure they resulted in a reasonable furnace heating capacity. Any combinations that fell outside of the 30 kBtu/h to 100 kBtu/h range were discarded. For all cases, a constant setpoint of 68°F, constant setpoint deadband of 1°F, and constant internal gains of 0 Btu/h were assumed. With the goal of opportunity analysis, each parameter was initially sampled from a uniform distribution as opposed to a more representative distribution. This allowed the team to estimate the range of savings outcomes assuming that each combination of system and house characteristics was equally likely. The input parameters used to generate the initial opportunity assessment are given in Table 2. Minimum and maximum values were selected based on rough estimates from the sites included in this study.

Table 2. Simulation parameters selected from uniform distributions

Parameters	Unit	Minimum Value	Maximum Value
T_{gain}	°F	40	90
$\dot{V}_{cfm}$	CFM	400	1400
τ	s	80	160
C_{house}	Btu/°F	3000	5000
UA_{house}	Btu/h-°F	200	500
T_{amb}	°F	-11	50

The results of this simulation show that, in general, the longer fan delay can reduce the number of furnace cycles per day by up to 12.5%, although sometimes it has no impact on the number of cycles. As a result, the gas on time can be reduced by up to 12.5%, with a median decrease of 3.3%. Unsurprisingly, increasing the fan delay causes the fan on time to increase between 0 and 33%, with a median increase of 11.1%. The capacity delivered is unaffected, as the furnace system meets the home heating load regardless of the control strategy.

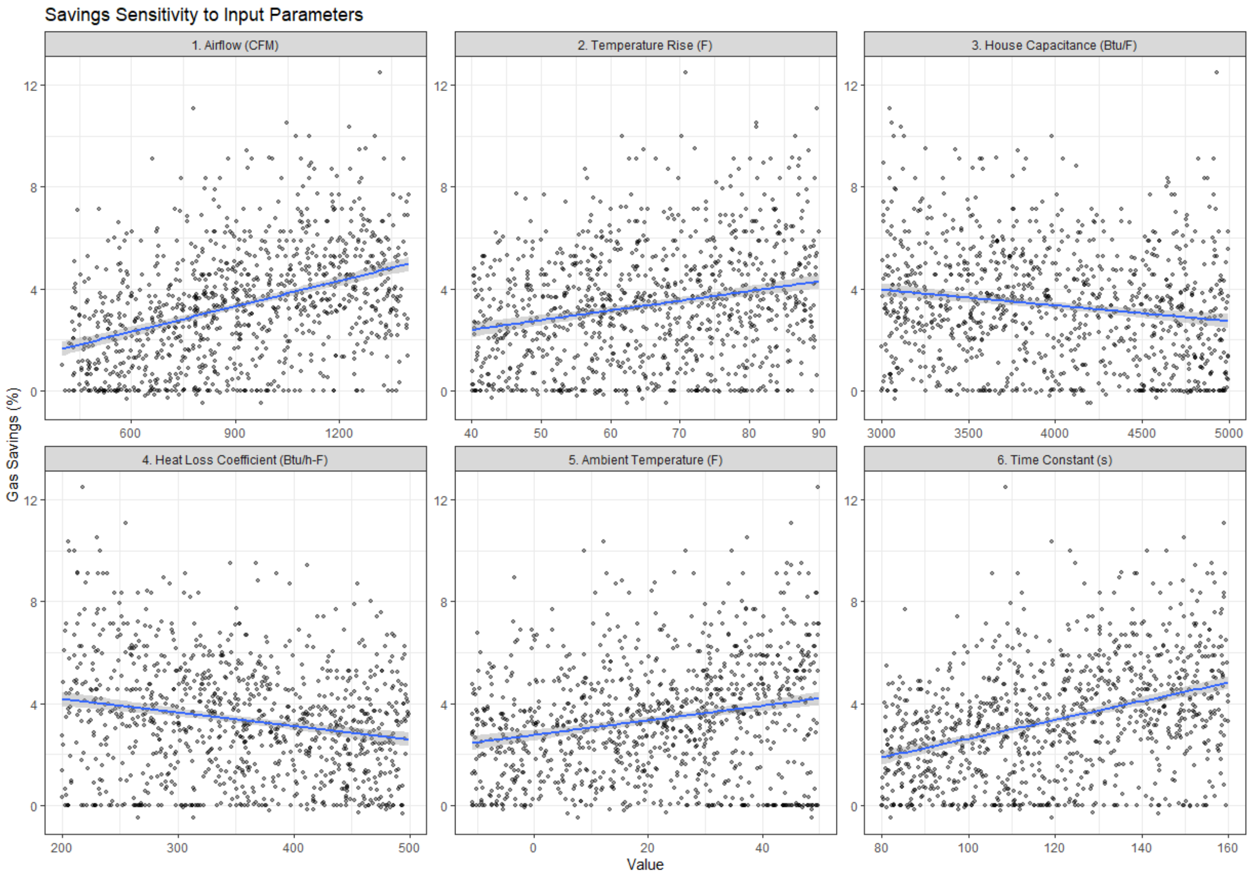
Figure 15. Changes in system performance due to increased fan-off delay



Correlating Savings and Simulation Input Parameters

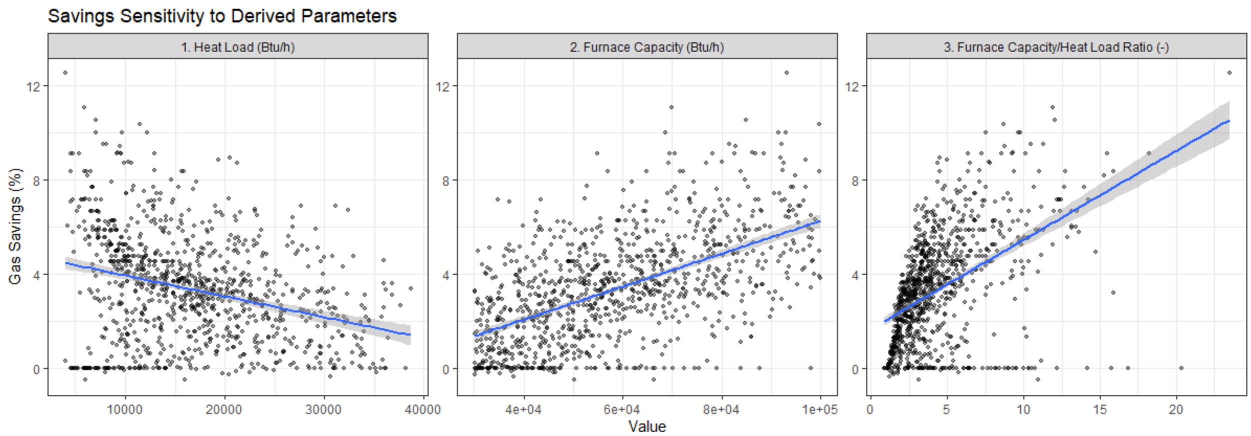
To understand the sensitivity of the gas savings to each input parameter, the relative savings against each input parameter, as well as some derived parameters, was plotted and overlaid with linear regression models. The slope of the regression line indicates positive or negative correlation between savings and the parameter. The spread of points about the regression line indicates the uncertainty in the impact of the parameter. This qualitative analysis showed that savings increased with increasing furnace airflow, temperature rise, ambient temperature, and furnace time constant. Savings decreased with increasing home heat loss coefficient and capacitance.

Figure 16. Sensitivity of savings to input parameters



Combining several input factors together shows the sensitivity of savings in more practical terms. Savings decrease with increasing heat load (combining effects of heat loss coefficient and ambient temperature), increase with furnace capacity (combining effects of airflow and temperature rise), and increase strongly with increasing furnace capacity to heat load ratio, which effectively summarizes the directional effect of all inputs except the house capacitance and time constant. This supports the theory that furnaces that are oversized for the typical house load benefit the most from extending the fan-off delay.

Figure 17. Sensitivity of savings to derived parameters



Sampling Input Parameters from Realistic Data

After the first pass analysis using uniform distributions of input parameters, the input parameters were resampled from distributions that represent their prevalence in the field. While the first pass analysis informed estimates of the maximum range of savings, this approach was used to estimate the most likely distribution of savings in Minnesota homes. Most parameters must be positive. The only parameter that can be positive or negative was the ambient temperature. Therefore, average daily ambient temperature was normally distributed, while all other parameters were lognormally distributed.

Furnace parameters were estimated from the high-resolution furnace operating data collected in this project. For each furnace cycle in the dataset, a supply air temperature rise from the beginning to end of the furnace cycle was calculated. These temperature rises were averaged for each site. The lognormal distribution was fit to the distribution of mean temperature rises across sites. For the airflow, the values were measured when installing the fan controller directly. For the time constant tau, an optimization routine to found the value of tau that minimized the error between a generic exponential cooling model and the actual supply temperature decrease for each furnace cycle from January through March 2023. The lognormal distribution was fit to the median tau for each site. The median tau value for each site was used instead of the mean in order to reduce the impact of outliers, which resulted from optimizations that did not converge.

House parameters came from analysis performed for the CARD project, “Exploring High-Performance Envelope Retrofits” (Quinnell and Genty). The population was approximately 1000 Minnesota single-family homes built before 1990. Overall heat transfer coefficients were calculated using the ASHRAE residential heat balance method (ASHRAE), while specific heat capacity values were estimated based on benchmark capacitance of 4000 Btu/F for a 2200 ft^2 house and scaled up or down according to building volume.

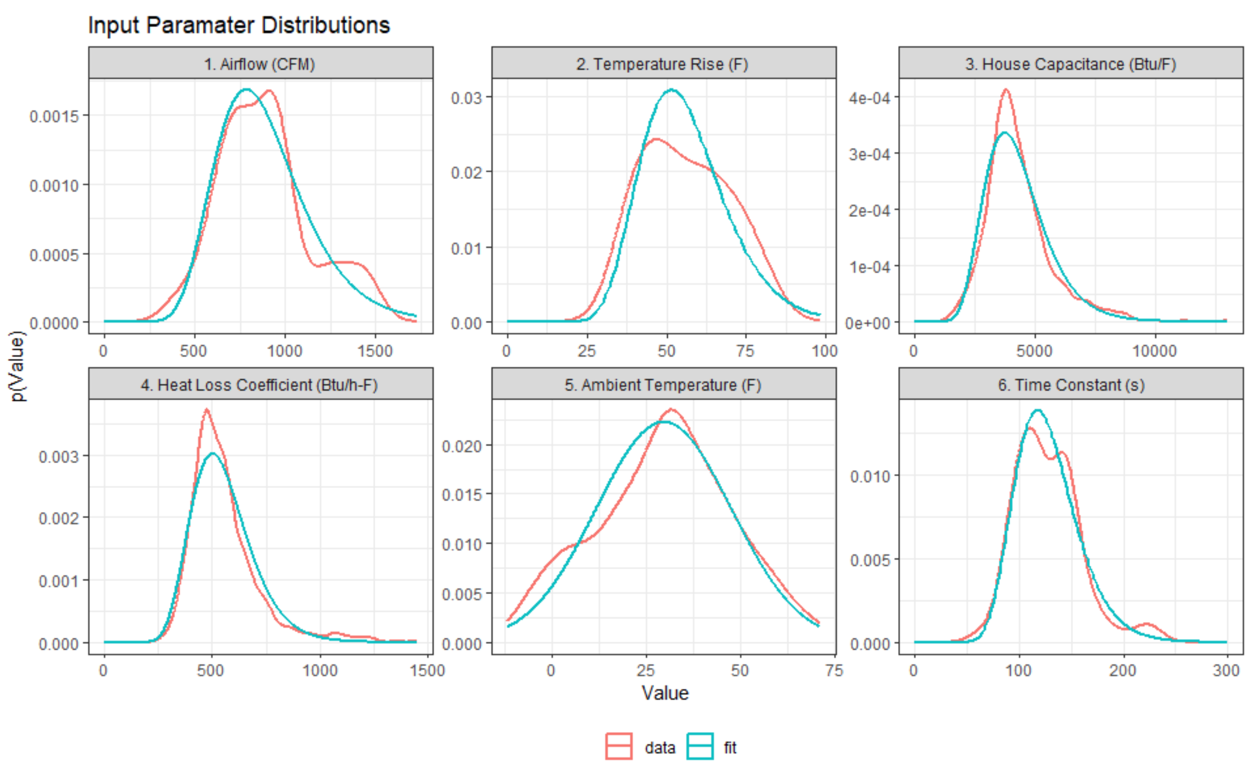
Finally, the ambient temperature distribution came from daily average temperatures for September 15 to April 15 from the TMY 2020 dataset for Minneapolis-St. Paul International Airport.

Distribution parameters are given in Table 3, while a graphical representation of the quality of the fits is shown in Figure 18.

Table 3. Simulation parameters selected from representative distributions

Parameters	Unit	Distribution	Sample	Location	Scale
T_{gain}	°F	Lognormal	24 RF Sites	3.998	0.2435
$\dot{V}_{cfm}$	CFM	Lognormal	24 RF Sites	6.750	0.2887
τ	s	Lognormal	24 RF Sites	4.806	0.2358
C_{house}	Btu/°F	Lognormal	968	8.3187	0.3033
UA_{house}	Btu/h-°F	Lognormal	968	6.2819	0.2554
T_{amb}	°F	Normal	TMY 2020	29.7	17.9

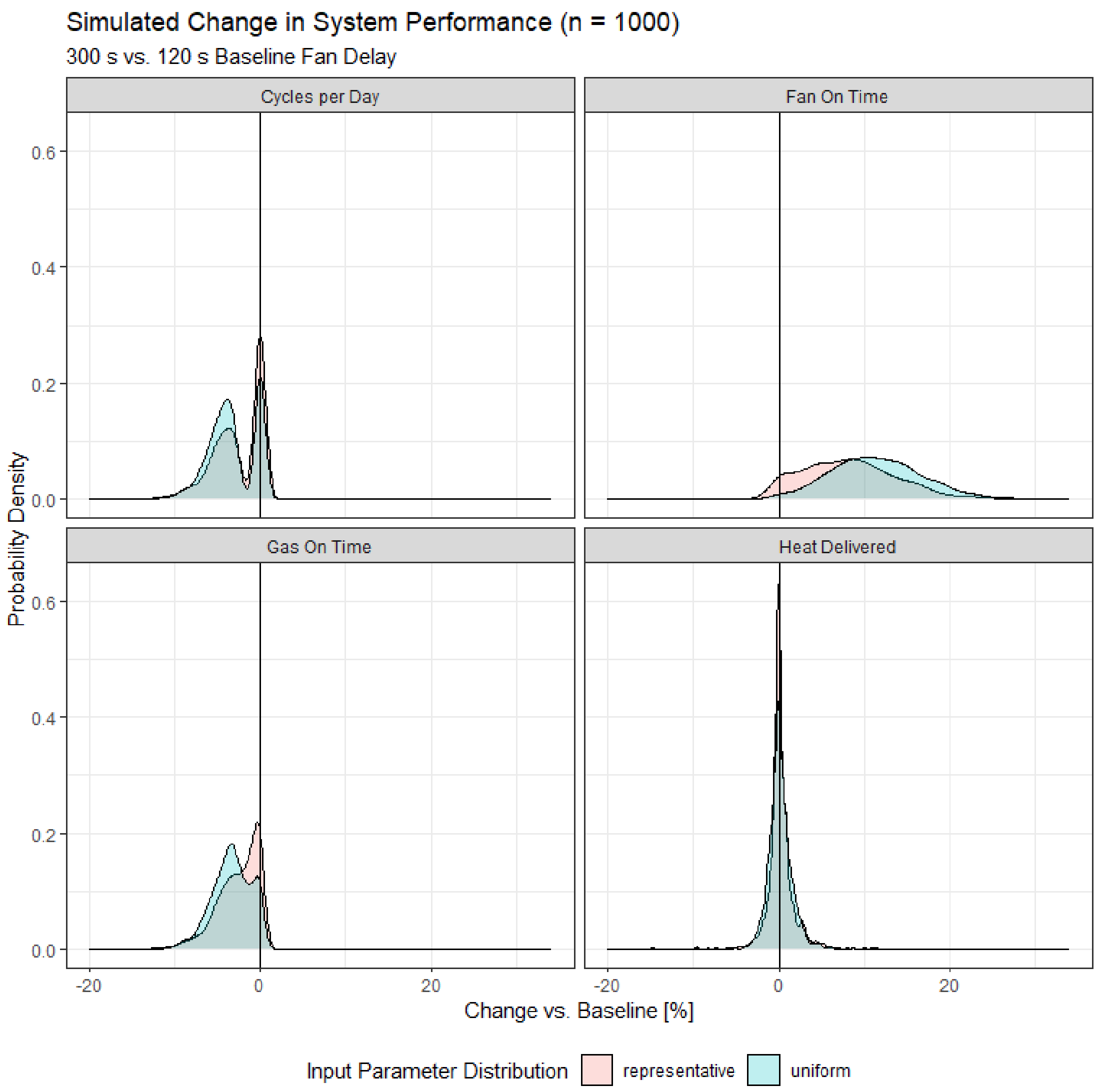
Figure 18. Input parameters distributions and fits



Using the representative distributions of input parameters, the overall results were similar to the results using uniformly distributed input parameters. The median decrease in gas use and cycles per day for the

1000 simulated cases was slightly smaller at about 2%, the median increase in fan runtime was 8%, and the median change in capacity delivered was 0%. Because there was no restriction on ambient temperature in this simulation, 24/1000 cases did not require any heating, resulting in undefined percent changes for these cases. Overall, this analysis suggests that there is potential for the use of this fan control device to result in between 0 and 10% gas use reduction in Minnesota residences, assuming none of the heat remaining in the heat exchanger at the time the fan turns off eventually moves into the conditioned space. In physical terms, for a home with an annual gas consumption rate of 500 therms/year, 5% savings corresponds to 25 therms, which is close to the manufacturer claimed 21 therms/year.

Figure 19. Percent change in outcomes by input parameter distribution



Site Selection Implications

The key finding from the modeling in terms of site selection was that sites with large furnace size to heating load ratios (i.e., oversized furnaces) appeared to have the highest savings potential. While this result was not found early enough to directly influence site selection, it led to the inclusion of size to load ratio as a key site characteristic.

Field Evaluation

Site Selection

Fifteen homes went through preliminary testing on HES visits, and five participated in the project. While the conversion rate of candidates to participants was relatively high for the HES visits, the time required to accompany HES staff on visits made it more efficient to recruit participants through CEE's research database. From the database, approximately 180 potential participants were contacted with a response rate of roughly 15%. From these responses, another nineteen participants were enrolled. Table 4 summarizes the key characteristics of the sites included in this project.

Table 4. Key characteristics of sites

Site	Floor Area (ft^2)	Stories	Furnace Stages	Base fan-off delay (s)	Median SAT at gas off (F)	Furnace Efficiency (%)	Stage 1 Rating (Btu/h)	Design Load (Btu/h)	Size/Load Ratio (-)
B[d]	2168	2	1	N/A	N/A	96	60,000	N/A	N/A
C	1160	2	1	120	120	80	75,000	17,699	3.39
D[a]	1086	3	1	120	141	80	66,000	14,069	3.75
F	1340	3	1	135	124	80	66,000	14,201	3.72
G[c]	2560	2	1	150	134	95	115,000	53,177	2.05
I	2000	1.5	2	120	113	80	58,000	16,633	2.79
J[b]	1300	3	1	30	127	80	110,000	22,679	3.88
K	4156	3	1	100	123	80	120,000	41,190	2.33
L[c]	3000	2	2	120	149	96	65,000	33,357	1.87
M[a]	4500	3	2	90	124	80	72,000	37,692	1.53

Site	Floor Area (ft^2)	Stories	Furnace Stages	Base fan-off delay (s)	Median SAT at gas off (F)	Furnace Efficiency (%)	Stage 1 Rating (Btu/h)	Design Load (Btu/h)	Size/Load Ratio (-)
N	1128	4	2	80	110	80	52,500	17,022	2.47
O	3656	2	1	135	129	95	80,000	38,976	1.95
P[a]	1303	1.5	1	100	123	80	45,000	15,715	2.29
Q[c]	1700	1.5	2	120	142	95	31,500	27,586	1.08
T[b]	1400	2	2	120	109	96	39,000	29,500	1.27
U	1500	1.5	2	120	109	96	39,000	23,492	1.59
V	1700	2	1	120	138	80	66,000	15,513	3.40
W[b]	1696	2	3	120	117	97	32,000	19,217	1.62
X[c]	2640	2	1	120	140	80	88,000	21,540	3.27
Y	3278	3	1	120	118	92	90,000	27,297	3.03
Z	1500	1.5	1	90	151	92	75,000	36,010	1.92

a) Sites with significant increase in gas use in greenfan mode

b) Sites with significant decrease in gas use in greenfan mode

c) Airside and gas valve-based load calculations differed by more than 20%

d) Site B only operated in greenfan mode (no base fan-off delay), and measured temperatures were invalid

Summary of Sites in Sample

Operating data was processed from all 24 sites in this study. Gas use was analyzed for the 20 sites with sufficient heating season data and differences in fan operation between modes in heating season. Heating season fan electricity use was evaluated for three of these sites that had sufficient power meter data. Air conditioning outdoor unit and cooling season supply fan electricity use were quantified for the

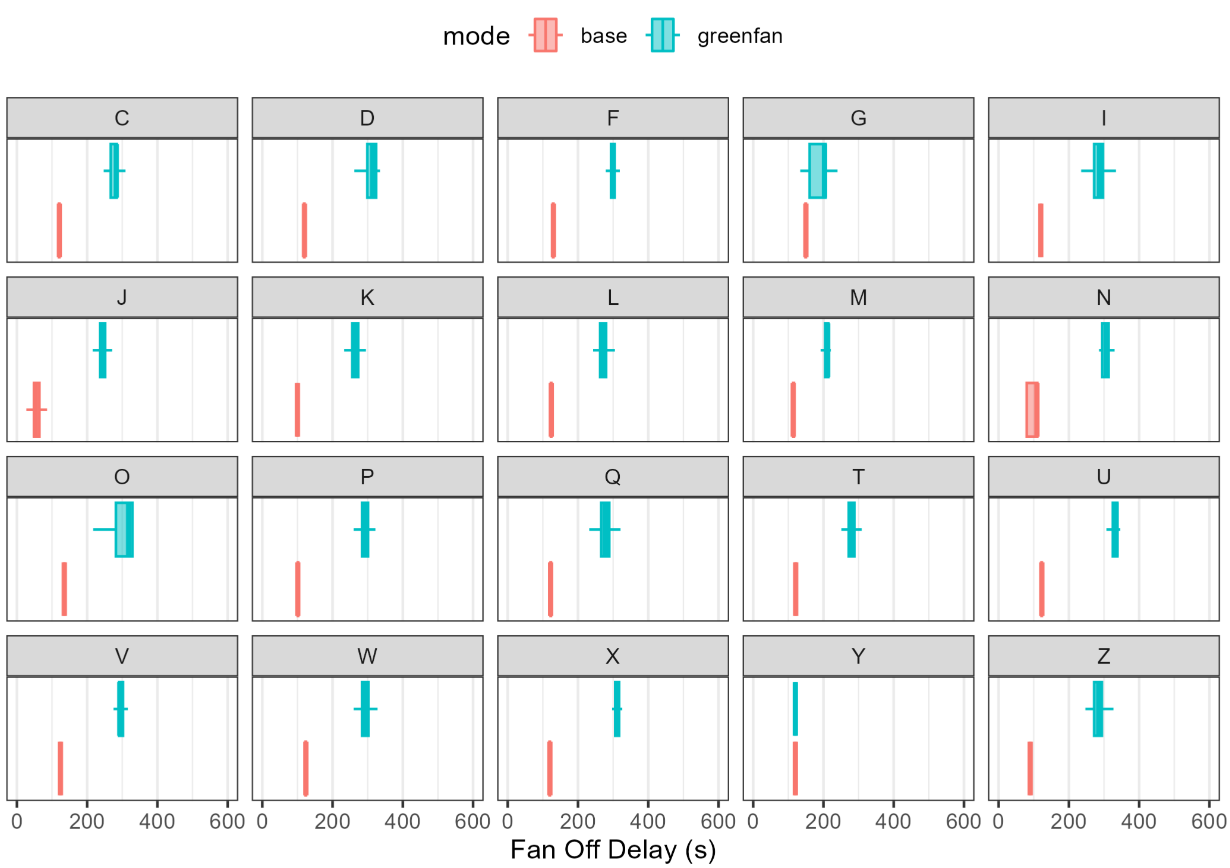
10 sites with differences in fan operation between modes in the cooling season. Details of the sites excluded from each step are included in Appendix A: Data Processing and Sampling Details.

Verification of Controller Function

Heating Season

Figure 20 shows boxplots (with outliers hidden) describing the distributions of fan-off delay time observed at each site by mode in heating season. For all sites except Y, the greenfan mode fan-off delay appears longer and more variable than the base mode. This is the expected behavior of the controller. The median of all the median fan-off delays across sites is 120.5 seconds in base mode and 287 seconds in greenfan mode. For base mode, 18 of 20 sites had a median fan-off delay between 100 seconds and 150 seconds (inclusive), while the median values for fan-off delay in greenfan mode ranged from 203 seconds to 334 seconds, except for site Y. While site Y appears to have a non-functioning greenfan mode, expected operation was confirmed by plotting timeseries fan current signals. These plots showed that the fan-off delay was extended relative to base mode, although the fan current dropped to near zero before ramping back up for the extended fan-off delay. Based on the rules implemented for calculating fan-off delay times, this behavior did not register as a fan-off delay, but because it had the same physical impact, site Y was included in the subsequent analysis.

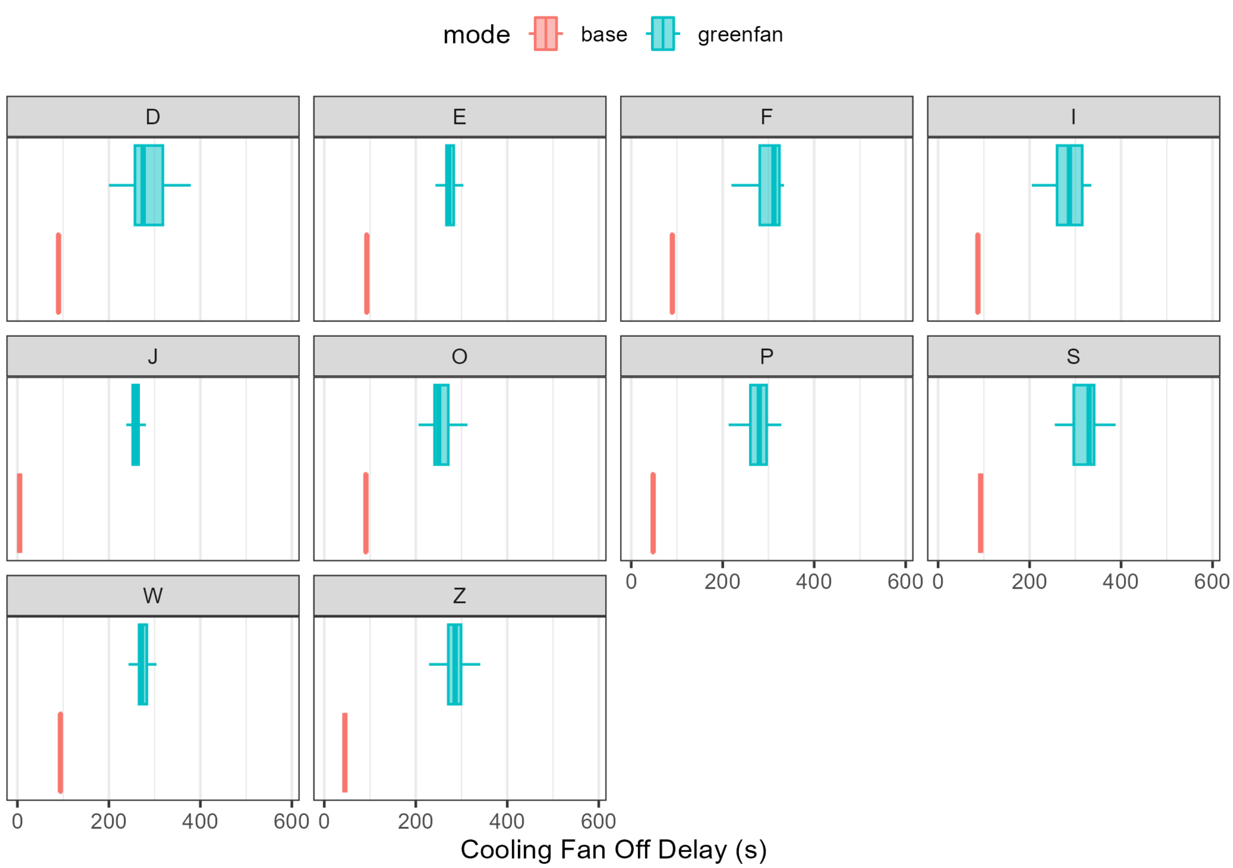
Figure 20. Distributions of fan-off delay time by mode in heating season



Cooling Season

Distributions of fan-off delay times by site and mode for cooling season are shown in Figure 21. The median of the base fan-off delay across sites in this sample was 120 seconds, while the median of the greenfan mode fan-off delay across sites in this sample was 292.5 seconds.

Figure 21. Distributions of fan-off delay time by mode in cooling season

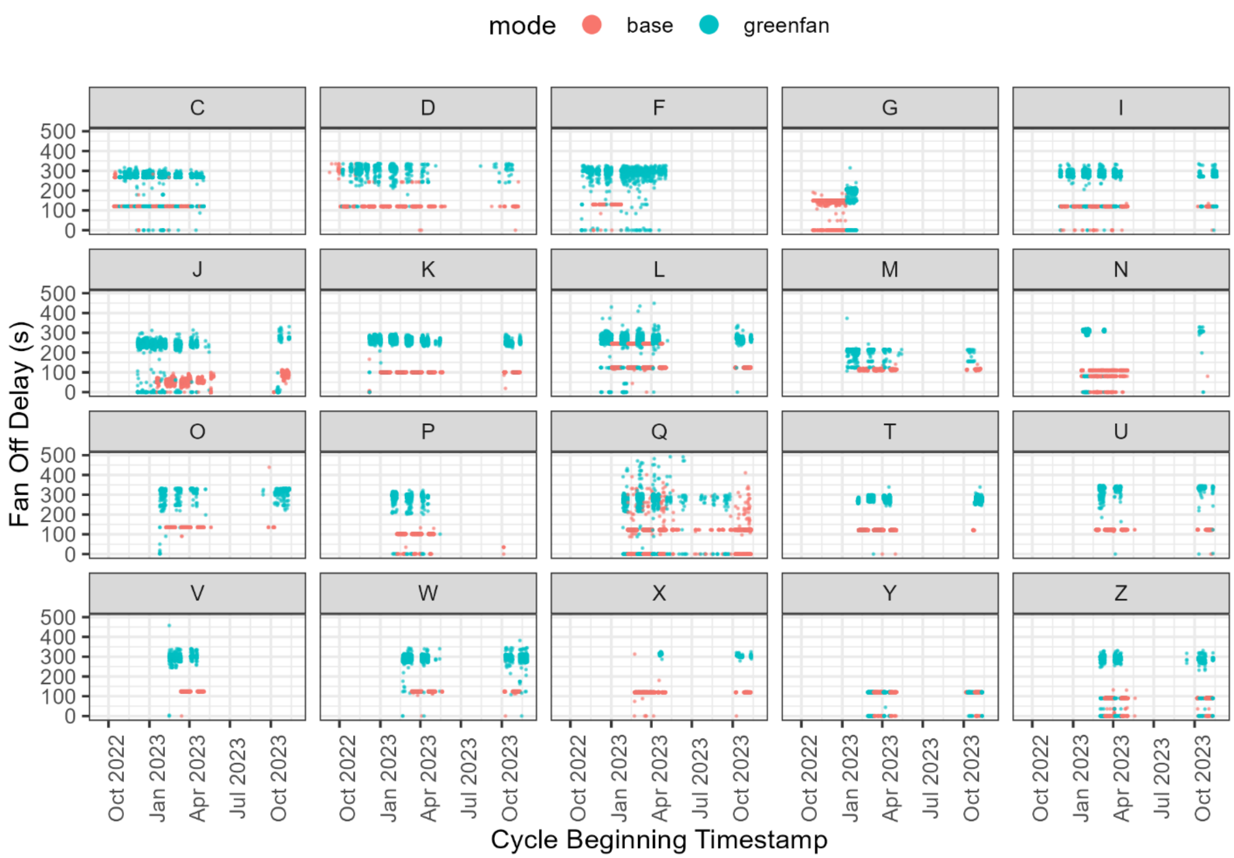


Verification of Control Mode Labels

Heating Season

To confirm controller labels, each cycle was plotted as a point on a timeseries plot, with the y-value corresponding to the fan-off delay in seconds. Accurate labels were critical to reduce error in the subsequent regression analysis. In general, the expected characteristics of the plot are clouds of points in alternating colors corresponding to the alternating mode tests. The point clouds in greenfan mode were expected to have longer fan-off delay times and therefore higher but more scattered y-values. This visualization helped identify labeling issues, as well as other factors affecting fan-off delay times. For example, this plot revealed that the fan CT failed at site G after February 2, 2023. It also uncovered furnace control algorithms that perform functions related to the fan-off delay at site L and site N. Notice that these two sites have multiple levels for typical base mode fan-off delays. Further investigation revealed that at site L, the fan-off delay was extended to 240 seconds when the second gas valve stage was active for more than 200 seconds during the cycle. At site N, the fan-off delay was increased from approximately 80 seconds to 120 seconds if the cycle gas-on time was below 740 seconds. Notably, the fan-off delay is manipulated by the furnace embedded controls in these cases for two different purposes. At site L, it is used for the same purpose as the fan controller, i.e., to distribute remaining heat from the heat exchanger to the home, while at site N, the function is possibly included to reduce short cycling of the furnace by improving the air distribution.

Figure 22. Cycle fan-off delay vs. time by site and mode in heating season

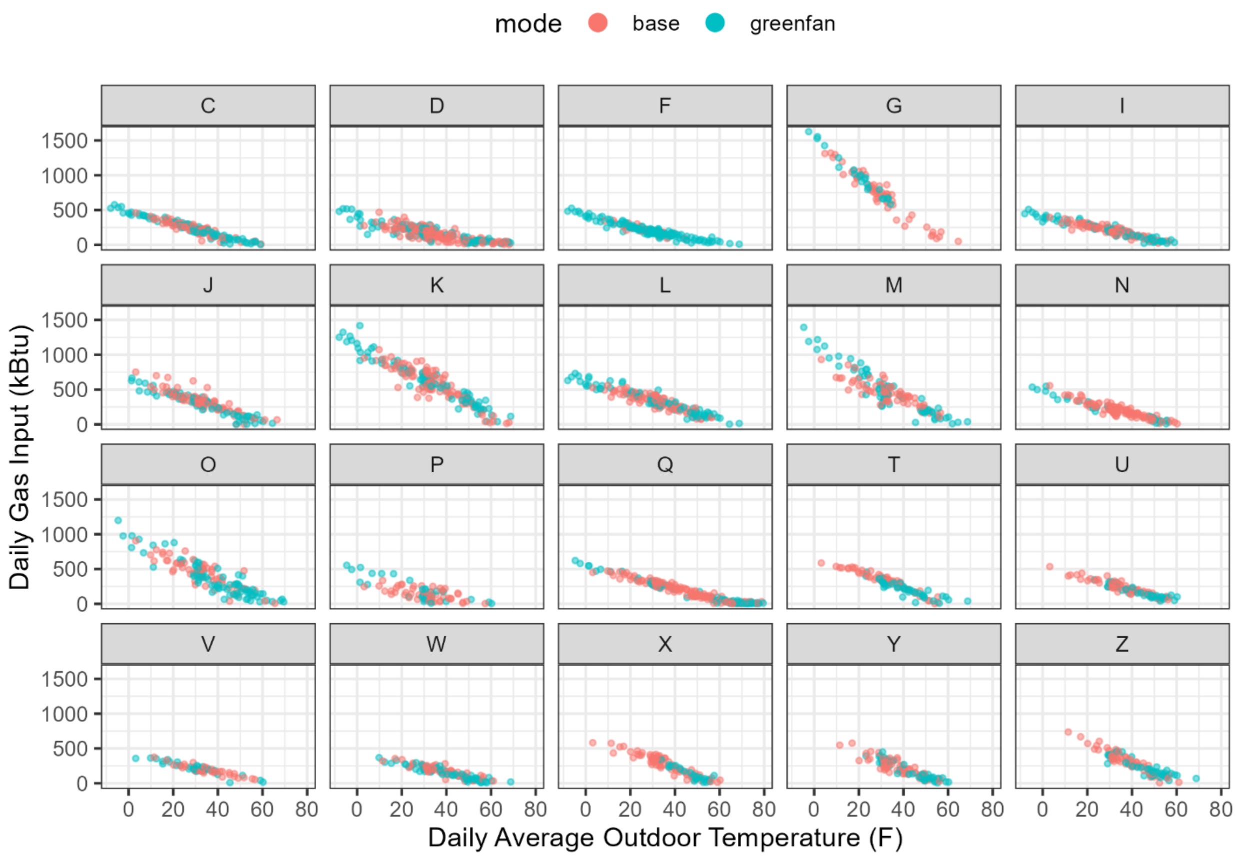


Controller Impact on Energy Input

Furnace Gas Use

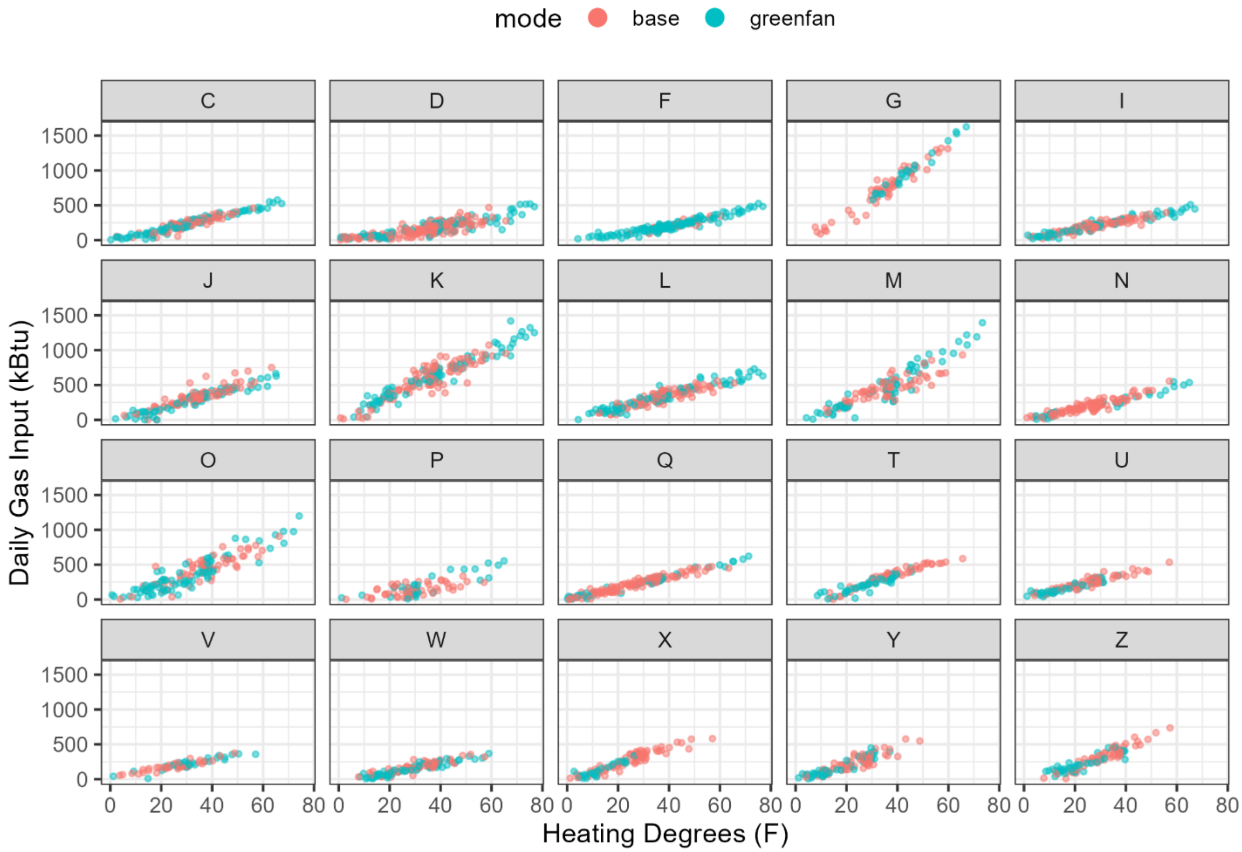
Figure 23 shows the calculated daily total gas use for the furnace vs. average outdoor air temperature by site and mode for all days with non-zero gas use. As expected, each site shows a negative correlation between gas use and temperature overall, as gas use increases in colder weather. The impact of the control mode on gas use is not obvious from this initial plot.

Figure 23. Daily gas input vs. daily average outdoor temperature



The balance point temperatures calculated for each site are the maximum daily average outdoor temperatures for which gas was used for heating. Balance point temperatures ranged from 59°F to 69°F across sites. Subtracting the daily average outdoor temperature from the balance point transformed the x-axis and resulted in a visualization of gas use where the y-intercept of the correlation between gas use and heating load is near zero, as shown in Figure 24.

Figure 24. Daily gas input vs. heating degrees



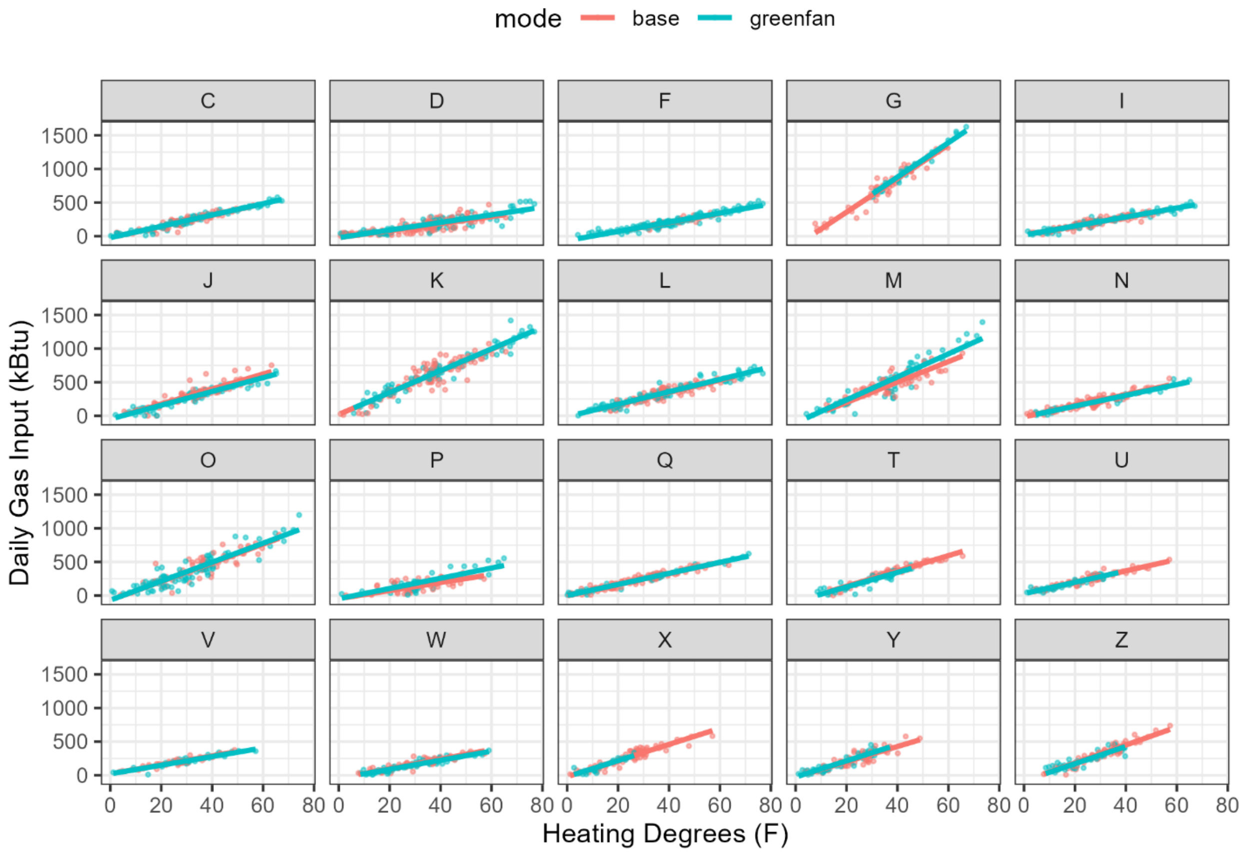
Coefficients ($\hat{\beta}_i$) were estimated from the data to describe energy use (E) as a function of heating or cooling load (L) and control mode (M) through linear regression, as shown in Equation 6. Mode was encoded as a dummy variable, with the reference level of base mode encoded as 0 and the alternative level of greenfan mode encoded as 1. This model formulation allowed the team to automatically quantify the significance of the impact control mode has on energy use by assessing the p-value of the coefficient for the interaction term, $\hat{\beta}_2$. In cases where the effect of the control mode on energy use was significant, the sign of $\hat{\beta}_2$ indicated the direction of the impact (increased or decreased energy use relative to base mode).

Figure 25 shows the predictions of the linear model overlaid on the observed data. In many cases, the slope of the regression line for each mode appears virtually identical.

Equation 6. Regression formulation

$$E = \hat{\beta}_0 + \hat{\beta}_1 L + \hat{\beta}_2 LM$$

Figure 25. Regression fit to observed gas use data



Balance points, coefficient estimates and significance levels for the regression model fit to each site are shown in Table 5. A statistically significant difference (at the $p < 0.05$ level) in the slope of the regression line associated with greenfan mode is only present for 6 of 20 sites: M, J, P, T, D, and W. For these 6 sites, $\hat{\beta}_2$ is positive for sites M, P, and D, indicating that greenfan mode is associated with an increase in daily gas use, while a negative $\hat{\beta}_2$ for sites J, T, and W indicates greenfan mode is associated with a decrease in daily gas use.

Table 5. Regression results, furnace gas use, sorted by significance p of $\widehat{B}_2$

Site	Balance Point [F]	Intercept ($\widehat{\beta}_0$)	Load ($\widehat{\beta}_1$)	Load × Mode ($\widehat{\beta}_2$)	Significance *p* of $\widehat{\beta}_2$
M	68.7	-105.5	15.2	1.925	<0.001
J	66.5	-47.5	11.2	-0.912	<0.001
P	60.2	-47.2	6.0	1.609	0.003

Site	Balance Point [F]	Intercept ($\widehat{\beta}_0$)	Load ($\widehat{\beta}_1$)	Load × Mode ($\widehat{\beta}_2$)	Significance *p* of $\widehat{\beta}_2$
T	68.8	-88.3	11.4	-0.568	0.023
D	68.8	-21.9	5.2	0.424	0.035
W	68.8	-46.1	7.1	-0.417	0.041
Y	60.2	-27.4	11.4	0.689	0.189
Z	68.8	-85.2	13.4	-0.533	0.203
G	64.6	-142.8	25.0	0.542	0.232
L	68.8	-12.0	9.0	0.212	0.278
N	60.2	-15.5	8.3	-0.275	0.298
V	60.2	20.2	6.7	-0.242	0.341
F	68.8	-65.9	6.7	0.125	0.371
O	69.5	-69.1	13.9	0.255	0.594
C	59.3	-21.9	8.4	0.056	0.727
I	59.0	17.2	6.6	0.053	0.729
K	68.8	21.6	16.1	0.111	0.753
Q	66.6	1.0	8.2	0.040	0.813
X	60.2	-22.0	12.0	-0.074	0.918
U	60.2	27.9	8.5	-0.022	0.942

To quantify the magnitude of the impact in meaningful units, typical annual gas use in each mode was calculated using the models and the TMY 2020 data for the Minneapolis-St. Paul Airport weather station. Note that the confidence interval limits for percent savings have opposite signs for the 14 of 20 sites that showed no significant difference between gas use in base and greenfan modes. This reinforces the point that the data provides insufficient evidence to say that the effect of the fan controller is different from zero.

Figure 26. Estimated annual gas use with 95% confidence intervals

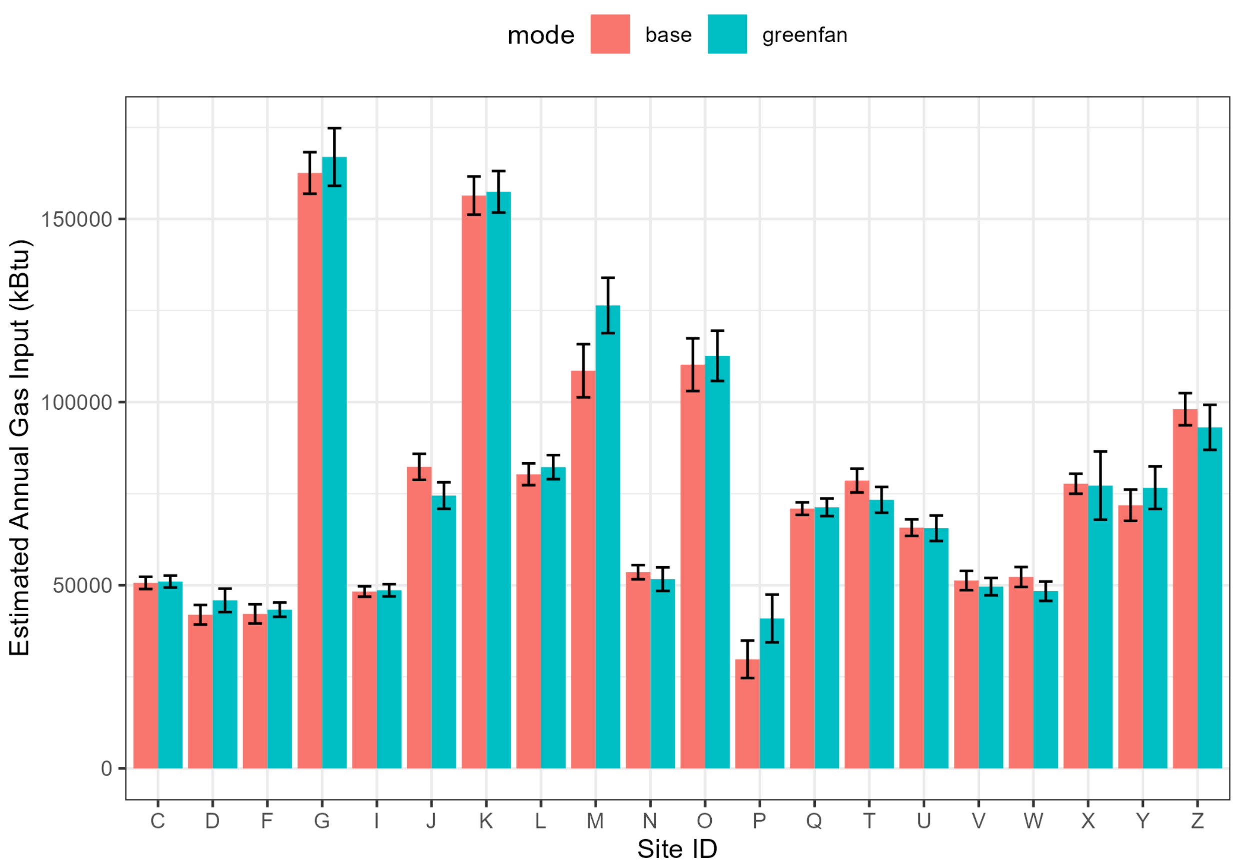


Table 6. Annual estimated gas use and savings

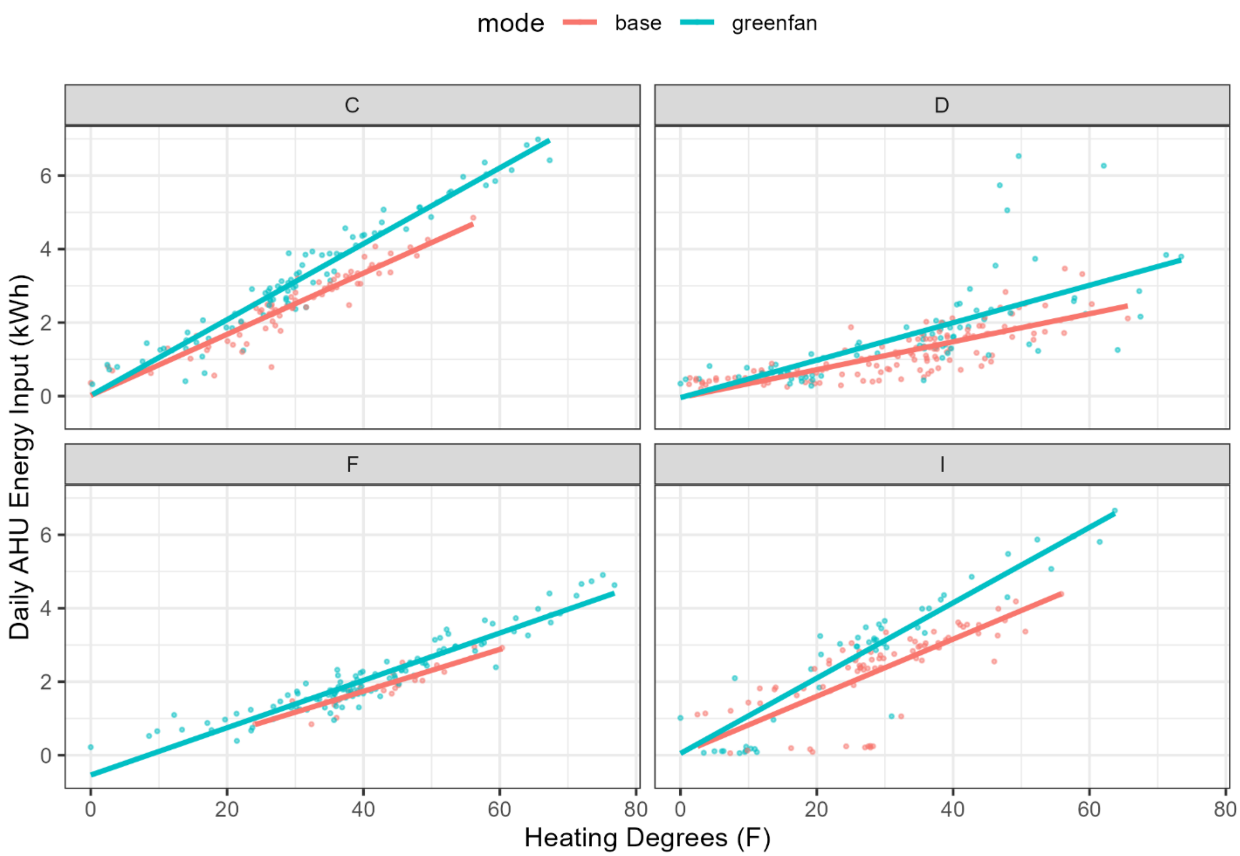
Site	Estimate, base (kBtu)	Standard Error, base (kBtu)	Estimate, greenfan (kBtu)	Standard Error, greenfan (kBtu)	95% Confidence Interval for savings associated with Greenfan mode (%)
C	50,658	843	51,030	825	-5%, 4%
D	41,956	1,363	45,894	1,625	-19%, 1%

Site	Estimate, base (kBtu)	Standard Error, base (kBtu)	Estimate, greenfan (kBtu)	Standard Error, greenfan (kBtu)	95% Confidence Interval for savings associated with Greenfan mode (%)
F	42,180	1,328	43,343	983	-10%, 5%
G	162,552	2,852	166,926	3,949	-9%, 3%
I	48,299	720	48,650	842	-5%, 4%
J	82,336	1,801	74,488	1,829	3%, 16%
K	156,388	2,640	157,422	2,875	-6%, 4%
L	80,291	1,500	82,258	1,659	-8%, 3%
M	108,567	3,674	126,388	3,821	-26%, -7%
N	53,572	981	51,666	1,624	-3%, 11%
O	110,228	3,639	112,649	3,470	-11%, 7%
P	29,795	2,565	40,949	3,279	-65%, -10%
Q	70,931	873	71,273	1,210	-5%, 4%
T	78,597	1,642	73,324	1,771	1%, 13%
U	65,734	1,133	65,581	1,756	-6%, 7%
V	51,302	1,316	49,629	1,184	-4%, 10%
W	52,271	1,377	48,396	1,337	0%, 15%
X	77,716	1,371	77,205	4,688	-12%, 13%
Y	71,849	2,149	76,626	2,919	-17%, 3%
Z	98,059	2,209	93,111	3,088	-3%, 13%

Air Handler Heating Season Energy Use

Regression equations were fit to the daily total air handler electrical input as a function of the average daily ambient temperature and mode for three sites using the same approach as for the gas use data.

Figure 27. Regression fit to observed AHU electricity use data in heating season



Using the TMY weather data to predict annual furnace electricity consumption for heating by mode produced the results shown in Table 7. The p-value of the estimate for the mode coefficient was much less than 0.05 in each case, indicating that the mode is associated with a statistically significant difference in electricity use. In each case, this difference was an increase in greenfan mode relative to base mode. For the confidence intervals for savings, note that a negative percent savings is associated with increased use associated with greenfan mode. On average, the sites used 122 additional kWh for fan operation in heating season, a 27% increase.

Figure 28. Estimated heating season fan electricity with 95% confidence intervals

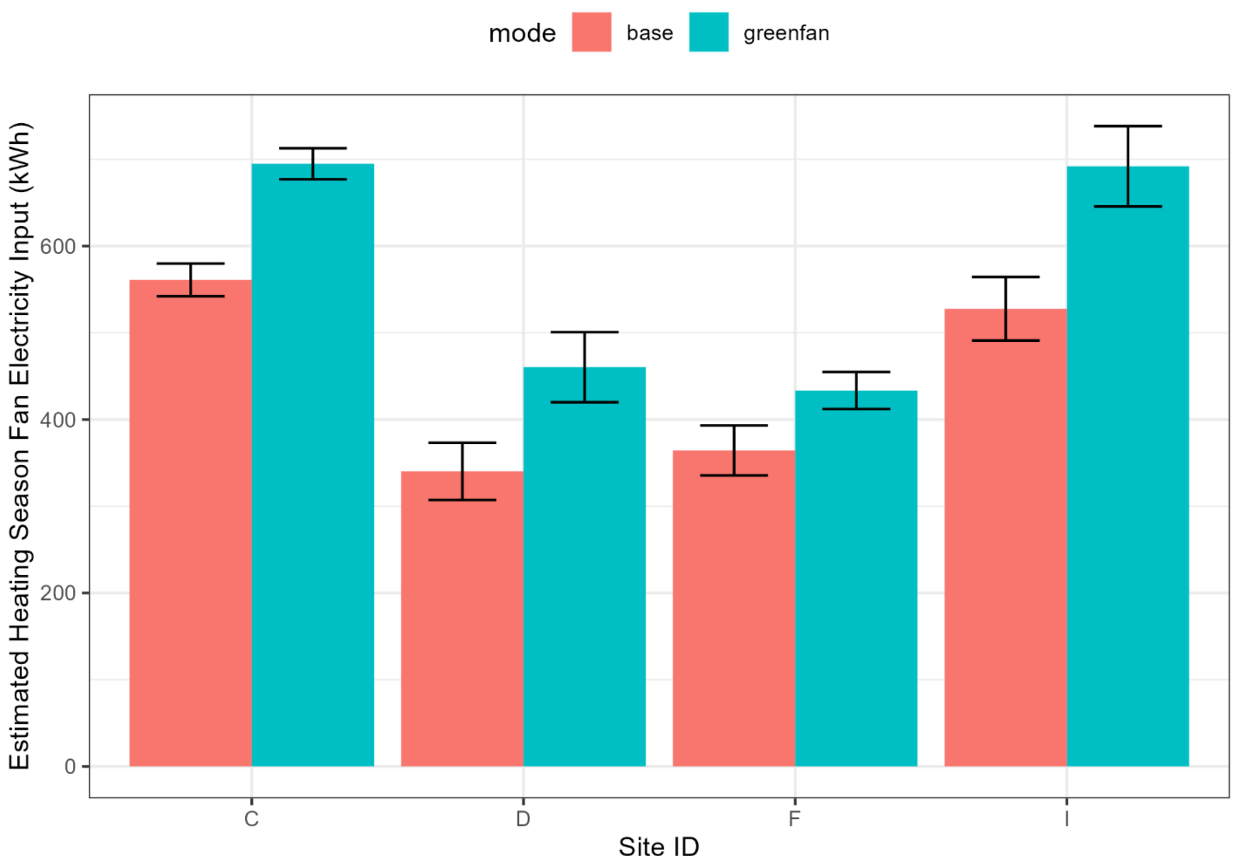


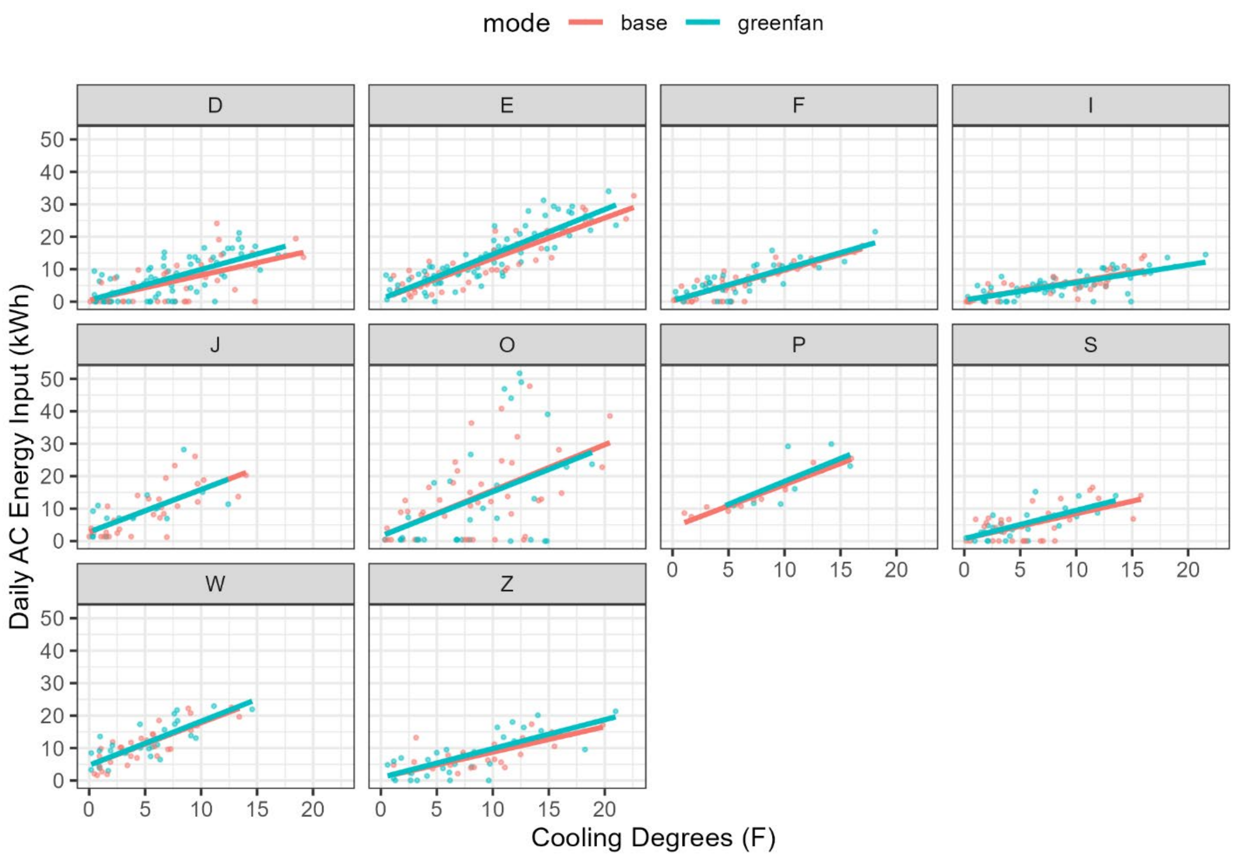
Table 7. Annual estimated electricity use and savings, heating

Site	Estimate, base (kWh)	Standard Error, base (kWh)	Estimate, greenfan (kWh)	Standard Error, greenfan (kWh)	95% Confidence Interval for savings associated with Greenfan mode (%)
C	561	10	695	9	-28%, -19%
D	340	17	460	21	-51%, -20%
F	364	15	433	11	-29%, -9%
I	527	19	692	23	-42%, -20%

Air Conditioner Energy Use

The same analysis approach was repeated again for the daily air conditioning outdoor unit energy use as a function of cooling degrees and mode. The cooling season energy consumption data was much less consistent than the heating season data due to the impact of latent cooling loads.

Figure 29. Regression fit to observed air conditioning energy use



The additional uncertainty surrounding cooling energy use tends to dominate the regression, and the mode coefficient was not found to be significantly different from zero in any case. That is, there is no evidence to suggest that operating in greenfan mode would result in reduced air conditioner outdoor unit energy consumption.

Table 8. Regression results, air conditioning

Site	Balance Point [F]	Intercept ($\widehat{\beta}_0$)	Load ($\widehat{\beta}_1$)	Load × Mode ($\widehat{\beta}_2$)	Significance p of $\widehat{\beta}_2$
D	67.4	0.45	0.77	0.18	0.104
E	64.0	0.80	1.25	0.13	0.059

Site	Balance Point [F]	Intercept ($\widehat{\beta}_0$)	Load ($\widehat{\beta}_1$)	Load × Mode ($\widehat{\beta}_2$)	Significance *p* of $\widehat{\beta}_2$
F	69.6	0.28	0.95	0.04	0.636
I	66.2	0.48	0.57	-0.03	0.618
J	72.6	2.80	1.31	0.00	0.999
O	66.1	1.53	1.41	-0.04	0.889
P	66.8	4.31	1.31	0.10	0.532
S	70.8	0.74	0.77	0.10	0.424
W	73.2	4.70	1.31	0.04	0.768
Z	66.7	0.92	0.78	0.11	0.291

Air Handler Cooling Season Energy Use

Finally, the impact of the fan controller on cooling season energy use by the air handler was assessed. As in heating season, a small energy penalty due to increased fan runtimes associated with greenfan mode was expected.

Figure 30. Regression fit to observed AHU electricity use data in cooling season

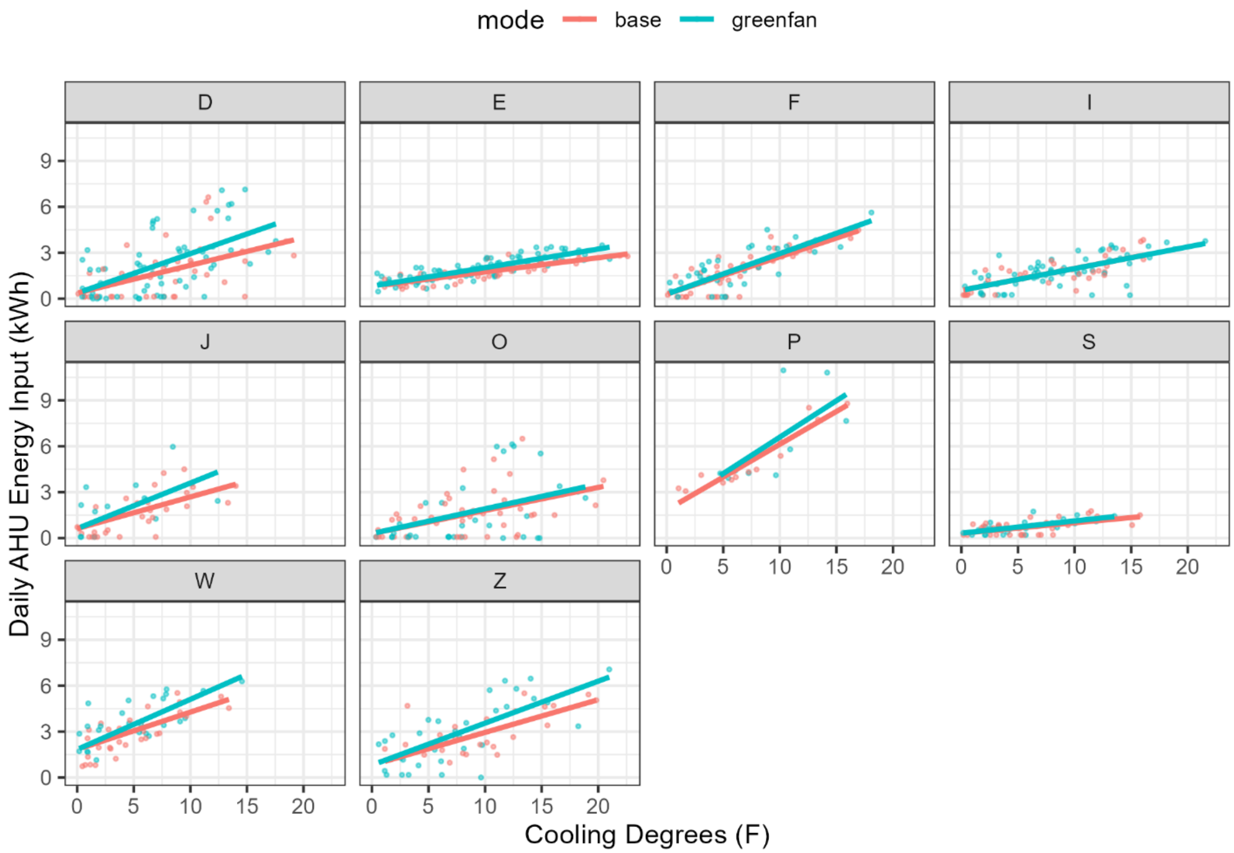


Table 9. Regression results, AHU in cooling season

Site	Intercept ($\hat{\beta}_0$)	Load ($\hat{\beta}_1$)	Load × Mode ($\hat{\beta}_2$)	Significance *p* of $\hat{\beta}_2$
D	0.37	0.18	0.08	**0.034**
E	0.82	0.09	0.03	**<0.001**
F	0.29	0.24	0.02	0.378
I	0.55	0.14	0.00	0.981

Site	Intercept ($\widehat{\beta}_0$)	Load ($\widehat{\beta}_1$)	Load × Mode ($\widehat{\beta}_2$)	Significance *p* of $\widehat{\beta}_2$
J	0.62	0.21	0.09	0.123
O	0.30	0.15	0.01	0.760
P	1.84	0.43	0.05	0.475
S	0.32	0.07	0.01	0.319
W	4.70	1.31	0.04	0.768
Z	0.92	0.78	0.11	0.291

In practice, the effect of the fan control mode on the fan energy as a function of sensible cooling load was statistically significant for only two of ten sites. While the effect is not significant, the sign of the coefficient for the interaction term between the load and fan control mode is always greater than or equal to zero, which is consistent with the expected result of additional fan energy use associated with greenfan mode.

Occupant Impacts Survey

Survey responses were cross-referenced with the control mode table, which indicated the current fan control mode at each site. The goal was to identify any correlation between occupant perceptions of the fan behavior and the actual fan behavior. No participants consistently responded with a perception of fan cycle run times that matched the expected cycle time given the active fan control mode. In each round of surveys, regardless of fan control mode, participants indicated that they felt the fan was running longer, shorter, or the same duration as was typical. Occupants generally felt that their HVAC system was keeping them comfortable.

Discussion of Results

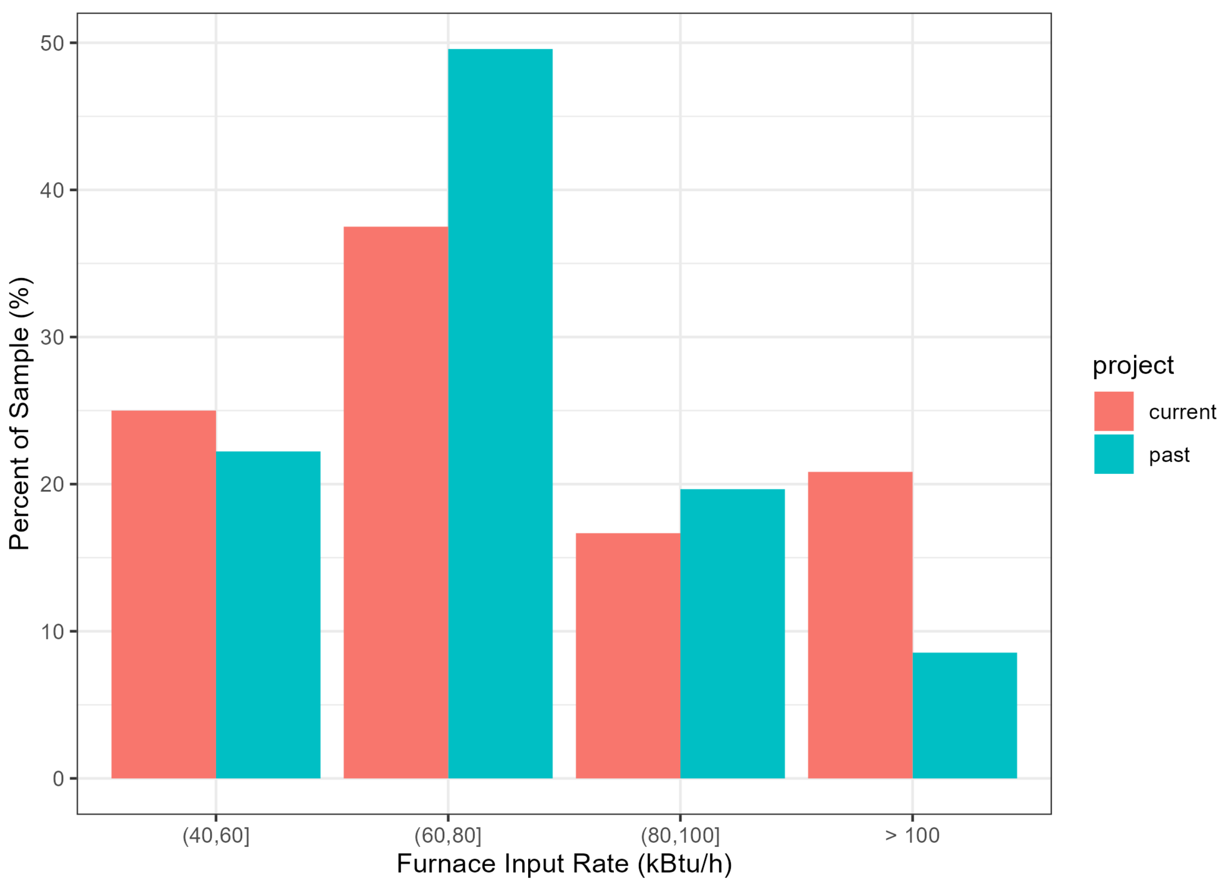
Market Characterization

Given the limited savings potential indicated by the field evaluation results, the key outcome of the market characterization was confirmation that the furnaces included in this study were representative of existing furnaces installed in Minnesota. The initial goal of identifying furnace characteristics correlated with savings potential became less important.

Furnace Size

The furnace sizes, based on the high stage input rating, are similar between this study and past research. The majority are rated at or below 80 kBtu/h. This study slightly oversampled large furnaces (> 100 kBtu/h) relative to past research. However, larger furnaces were expected to have a higher savings potential, so this discrepancy was acceptable.

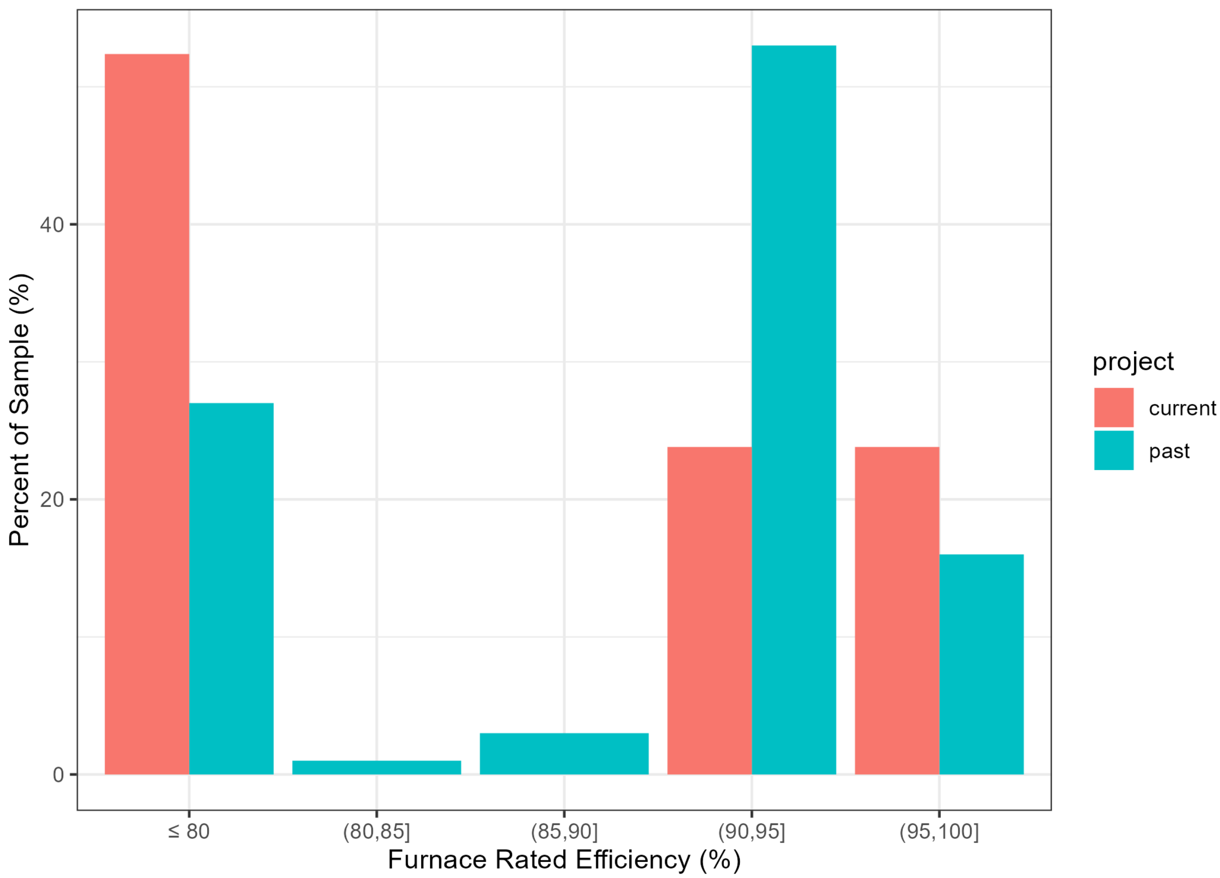
Figure 31. Comparison of furnace max input rate in current sample and past research



Efficiency

More of the furnaces in this sample were 80% efficient furnaces relative to past research. Considering distributor comments that high-efficiency furnaces dominate the market for furnace replacements, this could mean that the sample for this project skewed toward older furnaces. Overall, the sample in this project included roughly half 80% furnaces and half furnaces with efficiency > 90%, so there is no concern that it excluded a key portion of the market.

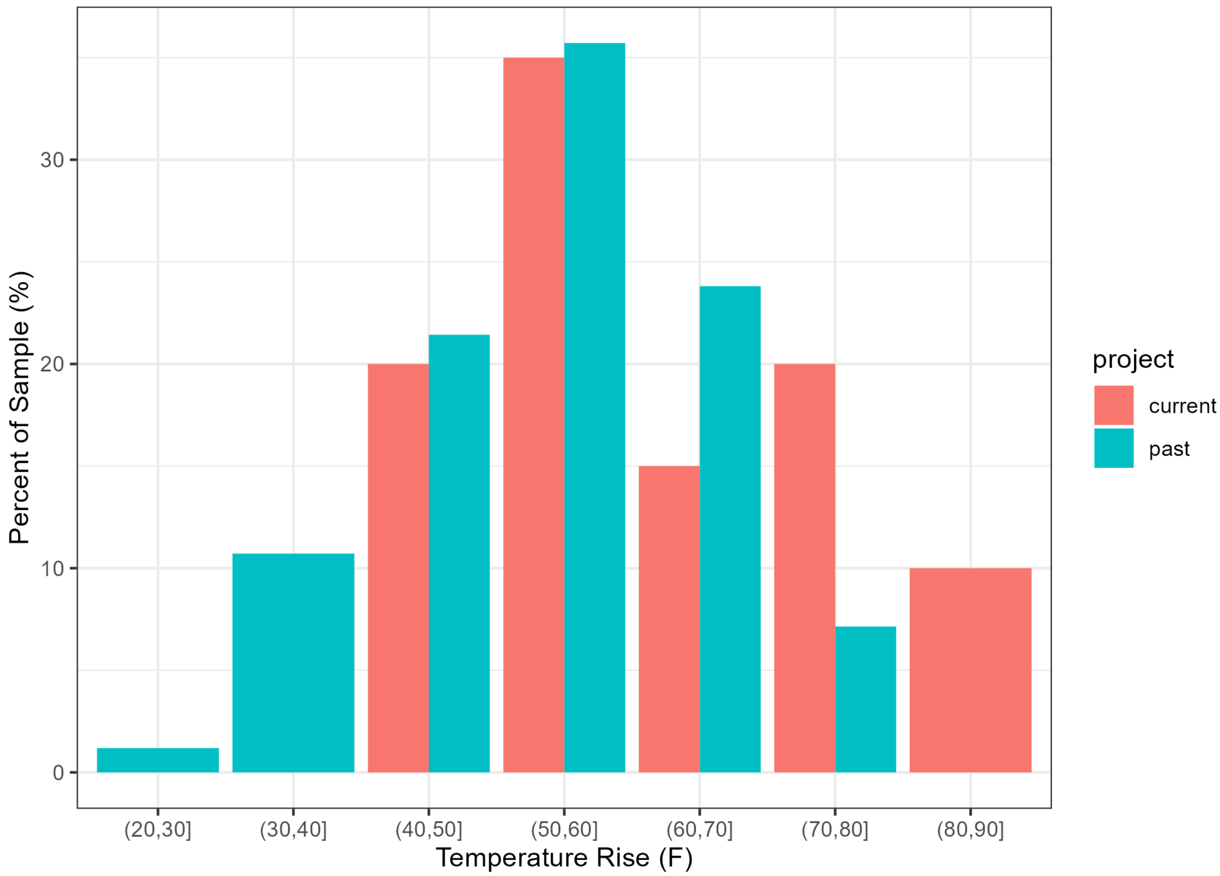
Figure 32. Comparison of furnace efficiency in current sample and past research



Temperature Rise

The temperature rise distributions are similar between past and current research, although this sample skews toward slightly higher temperature rises. Again, this discrepancy is acceptable, as higher temperature rises were expected to increase the savings potential of the fan controller.

Figure 33. Comparison of temperature rise in current sample and past research



Modeling

The key assumption from the modeling work was that when the fan was off, the capacity delivered by the furnace was exactly zero. In physical terms, this means that any remaining stored energy in the furnace heat exchanger after the fan turns off was not transferred to the conditioned space. Given that the field testing results do not support the savings estimate of 0 to 10% gas savings from the modeling, this assumption was identified as the most likely source of the discrepancy.

In practice, a significant portion of the remaining heat from the heat exchanger likely dissipates through the ductwork through natural convection. Since the ductwork is located within the building envelope in Minnesota homes, typically within the semi-conditioned basement space, this heat eventually makes its way into the conditioned space.

Field Evaluation

Site Selection

The original plan for this study was to include 33 to 40 sites total, with 8 to 10 detailed monitoring packages collecting electrical power and temperature data at one-second intervals, and 25 to 30 basic monitoring packages collecting total daily energy consumption. The initial monitoring package chosen for this project did not provide the level of accuracy needed in practice, with errors in temperature and current readings in excess of 10% relative to independent measurements. A higher level of accuracy was needed because the device under test may have delivered gas savings of less than 10%. Another instrumentation package that met the accuracy requirements was identified, but long procurement lead times created delays of two to three months, which limited the ability to recruit sites before the 2022–2023 heating season. As a result, the total number of sites in the project was reduced from 33 to 24. The team compensated for this smaller sample by installing the detailed monitoring package at all sites instead of only 8 to 10 sites.

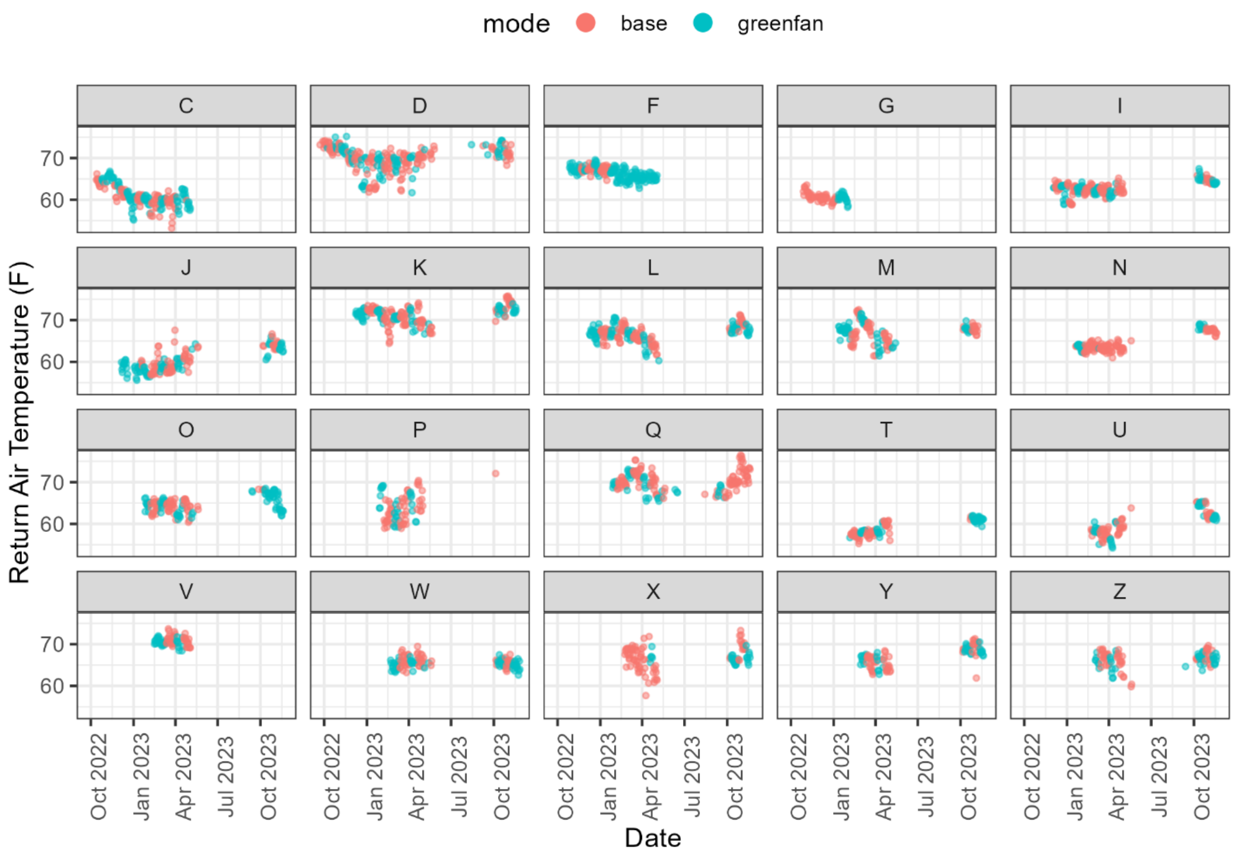
To overcome the delays introduced by the late monitoring package change and enroll 24 sites before the end of the 2022–2023 heating season, recruiting and equipment installation occurred in parallel. The site selection criteria was modified to only consider HVAC system characteristics, only excluding interested sites if their HVAC equipment was not compatible with the fan controller. While this increased the risk that the sample would not represent the housing characteristics found in Minnesota, the team proceeded under the assumption that this risk would be better mitigated by enrolling sites as quickly as possible and achieving a larger sample as opposed to being more selective and taking more time to build the participant pool.

Sites with Significant Changes in Gas Use

For the six sites where greenfan mode was associated with a significant change in daily gas use, factors that could possibly be correlated to increased or decreased gas use, such as furnace size to load ratio, number of building stories, and furnace efficiency were assessed. Two sites that showed significant savings (T and W) had 96% and 97% efficient furnaces, while the three sites that showed significant use increases had 80% efficient furnaces. However, there were other sites with these same efficiencies that showed no significant difference between modes, and site J had an 80% efficient furnace that did show savings associated with greenfan mode. Size to load ratio also does not appear to correlate with savings, as the significant savings and significant increases groups both had members with relatively low and relatively high size to load ratios. Of the six sites with base fan-off delay durations of less than 120 s, two (M and P) showed significant increases in use, while one (J) showed significant savings. This implied that short fan-off delay durations do not necessarily benefit from lengthening.

Because heating load technically depends on the difference between the indoor and outdoor temperatures, and we assumed that return air temperatures were consistent across modes, daily average return air temperature by mode was plotted over time for all sites to confirm any indoor temperature setpoints applying to a single mode had been excluded as intended.

Figure 34. Return air temperature vs. time by site and control mode



Days seemed to have corresponding return air temperatures across modes. Differences were likely not due to setbacks during vacancies. Based on this evidence, there is likely a significant difference in gas use associated with greenfan mode for these five sites, although the differences appeared uncorrelated with any site characteristic that were observed. Unfortunately, this means that it would be difficult to target specific applications where this device may result in energy savings.

For the sites where the device saved energy, it is possible that the heat exchangers of the efficient furnaces provided highly effective heat transfer to the air stream, and characteristics of the air distribution system caused the temperature at the thermostat to remain elevated between cycles, extending the time between cycles. It is possible that for the sites that showed increases in gas use, return duct leakage allowed cool air from unconditioned basements to be drawn into the duct system and distributed to the area around the thermostat, reducing the time between furnace cycles.

Sites with No Significant Changes in Gas Use

Most sites (14 of 20) exhibited no significant difference in gas use associated with greenfan mode. For these sites, the uncertainty associated with the estimate of the interaction term coefficient $\hat{\beta}_2$ was large relative to the value of the estimate. As a result, at most sites there is insufficient evidence to say that the actual value of the interaction term coefficient β_2 is different than zero.

In physical terms, this means there are other factors that affect daily gas use that have a far greater impact than the fan-off delay. These factors show up in this analysis as sources of uncertainty. These other factors that affect heating loads either positively or negatively include solar heat gains, occupancy, and occupant behaviors such as cooking, modifying the thermostat setpoint, and opening doors or windows.

All three sites assessed showed significant increases in heating season electricity use related to greenfan mode operation. While the ranges of expected increases in electricity use varied from site to site, the average for these four sites was a 27% increase in electricity use by the furnace. Site-to-site variation depended on base and greenfan fan-off delays. For example, site D had relatively long greenfan mode fan-off delays, while site F had a relatively long base mode fan-off delay of 135 seconds. As such, the relative fan energy impact was largest at site D (-35%) and smallest at site F (-19%).

While increases in electricity use were expected based on the operating principle of the controller, the incremental electricity use was designed to be offset by gas savings. This analysis shows that the controller uses additional electricity to circulate air, but the expected benefit of reduced gas use is unrealized.

One possible reason why the results show limited gas savings potential in Minnesota is that the ratio of furnace sizing to heating load is much lower in Minnesota’s climate relative than warmer climates. The modeling results in this study and previous lab testing results are consistent in showing that the degree of furnace oversizing directly correlates with savings potential (Mowris). In Minnesota, far more of the total heat delivered comes during the portion of the furnace cycle when the burner is active, meaning the heat delivered during the fan-off delay is less important in this context.

Cooling Season Impacts

Extending the fan runtime in cooling mode had no statistically significant impact on air conditioning energy use in this study. The impact of extending the fan-off delay was much smaller than the impact of the sensible cooling load, and apparently much smaller than other unmeasured factors. The same unmeasured factors from heating season apply to cooling season, but cooling season loads are also heavily impacted by the latent load associated with the humidity of the air. Some sites showed statistically insignificant savings, while others showed statistically insignificant increases in energy use. There is no evidence to support that the effect of the fan controller on air conditioning energy use is different from zero.

Conclusions and Recommendations

The field evaluation showed that for 14 of 20 sites there was no statically significant difference in annual gas use between a system operating with and without the fan controller. In addition, for the other six sites, three showed decreases in gas use, while the three others showed increases. For the sites that experienced increased gas use, it is possible that return duct leakage in the unconditioned space causes cooler air to be distributed near the thermostat when the fan runs longer, resulting in shorter times between furnace cycles. For the sites that experienced savings, there are likely unmeasured characteristics of the house or air distribution system that caused the temperature near the thermostat to remain elevated longer because of the fan controller.

While the modeling exercise showed the potential for up to 10% gas savings, correlated with furnace size to load ratio, it relied on the assumption that none of the heat from the heat exchanger moved into the conditioned space while the fan was off. The field analysis results seem to discredit this assumption.

Overall, these results emphasize that any effect the fan controller has on gas use is small relative to other sources of uncertainty in estimating annual gas use, and it is not appropriate to attribute gas savings to this device.

For the four sites with sufficient power meter data to assess the impact of the fan controller on fan electricity consumption in heating mode, each site experienced a significant increase in fan energy consumption (27%, or 122 kWh).

In cooling mode, none of the ten sites assessed showed a significant difference in air conditioner electricity consumption between modes. Two of the ten sites showed significant increases in fan energy use in cooling mode, with the increases at the eight other sites statistically insignificant. For cooling mode, the primary conclusion is that unmeasured factors such as solar gains and latent loads likely have a much larger effect on the cooling energy requirements than the fan-off delay.

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Appendix A: Data Processing and Sampling Details

Heating Season Gas Use

Of the 24 total sites included in this project, insufficient heating season data was collected for two sites due to communication issues during the coldest months of 2023 (sites E and S). From December 2022 through March 2023, Site E had only 2% of the expected number of observations, while Site S had only 0.05% of the expected number. For comparison, the five sites with install dates prior to December 2022 averaged over 99.9% data coverage.

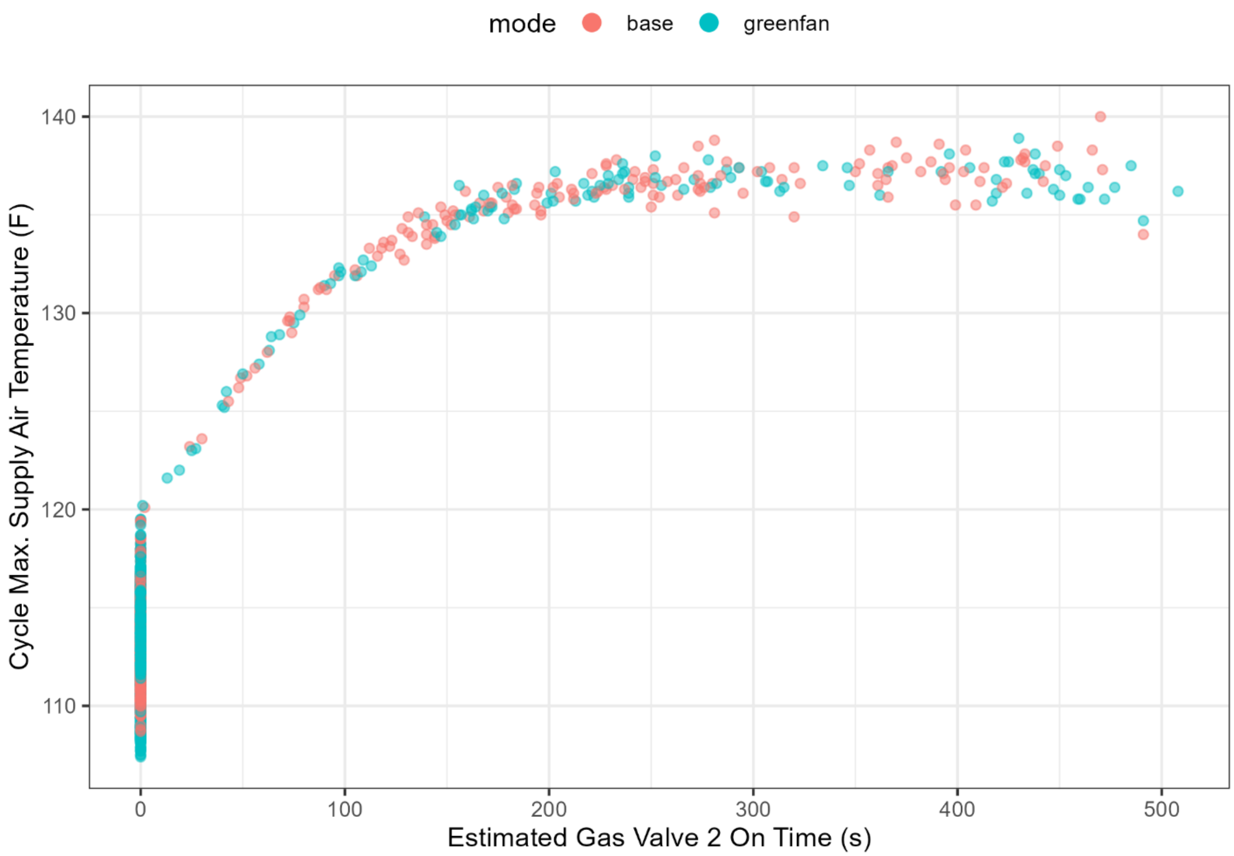
Site H showed no apparent performance difference between control modes in heating mode. In cooling and fan-only mode with the fan controller active, whether the controller was wired through the relay or directly, the fan would cycle on for about 10 seconds and off for about 10 seconds. When the controller was inactive, or the controller and relay were removed, the system operated as expected in cooling and fan-only modes. Multiple controllers and relays were tested with the same results. It is possible that an old transformer that was left in place and connected to a new transformer had been interfering with signals that the fan controller measures.

Site B stopped responding to outreach before the relay to toggle between greenfan and base modes could be installed, and so only included data in greenfan mode. As the analysis was based on comparisons across modes for each site, the data collected from Site B was not useful in determining the impact of the controller.

Sites E, S, H, and B, were excluded from the analysis of fan-off delay time as a function of control mode, leaving 20 sites in the pool. Of the 20 sites with verified heating season controller function, unique data processing issues persisted at two sites.

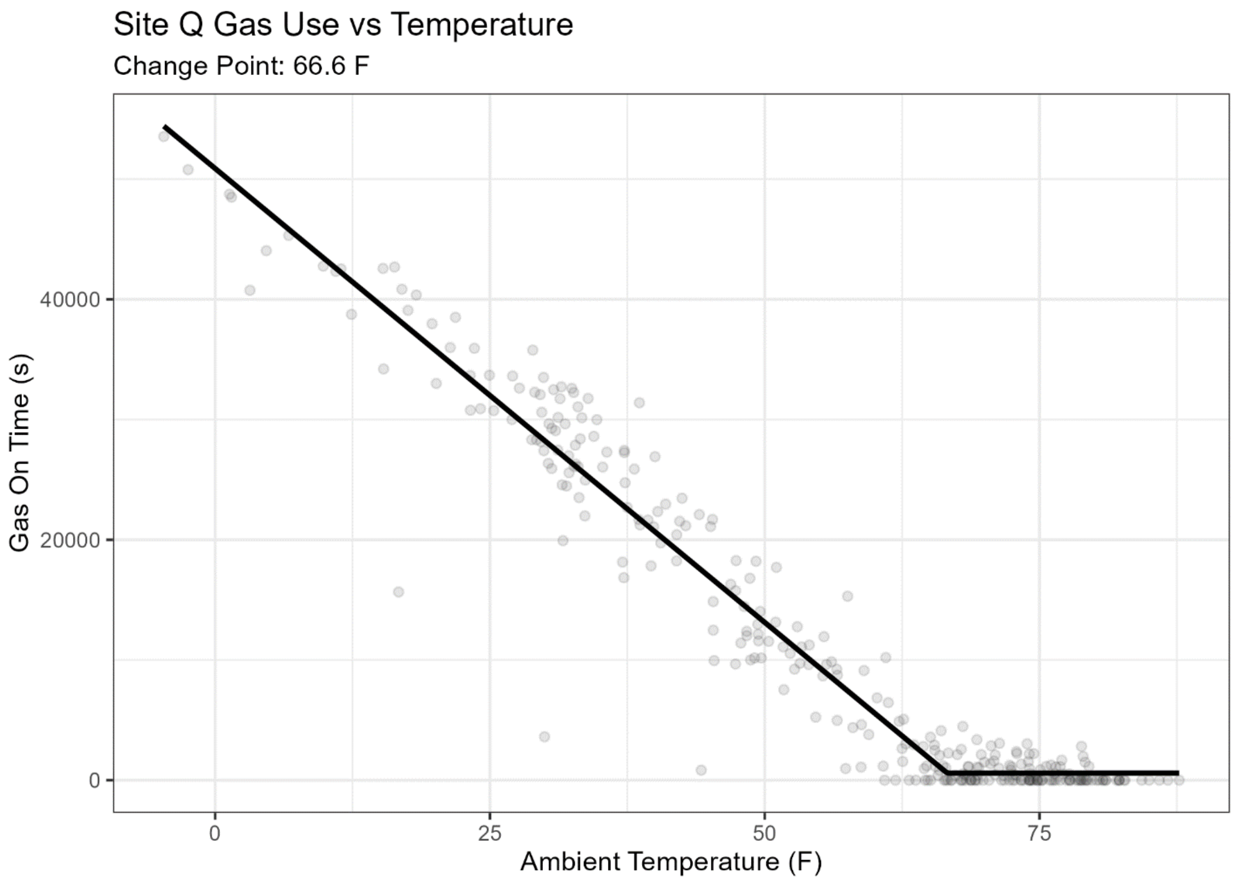
At Site I, the sensor for the second gas valve stage was mistakenly omitted from the instrumentation package. As a workaround, the second gas valve stage was assumed to be active whenever the supply air temperature exceeded 120°F based on characteristics of the timeseries data. Errors introduced through this assumption were expected to affect base and greenfan modes equally, with the main impact being inaccuracies in the delivered heating capacity estimates that were based on gas use. Figure 35 shows the correlation between the assumed second gas valve status and the cycle maximum supply air temperature, with the expected relationship of the maximum temperature increasing toward a limit as second gas valve on time increases.

Figure 35. Site I correlation between maximum cycle SAT and assumed gas valve 2 on time



At Site Q, the maximum daily average temperature with non-zero gas use was 79°F, whereas all other sites had balance point temperatures below 69.5°F. This behavior was not due to an incorrect detection threshold for gas valve activation, but actual heating cycles in the summer. Since the heuristic approach to estimating the balance point temperature (i.e., maximum daily average temperature for days with non-zero gas use) gave unrealistic results for this site, an alternative approach was used. A piecewise linear model of daily gas on time as a function of daily average temperature was fit to the data. The change point that minimized the sum of squared residuals for the piecewise fit, 66.6°F, was identified as the balance point.

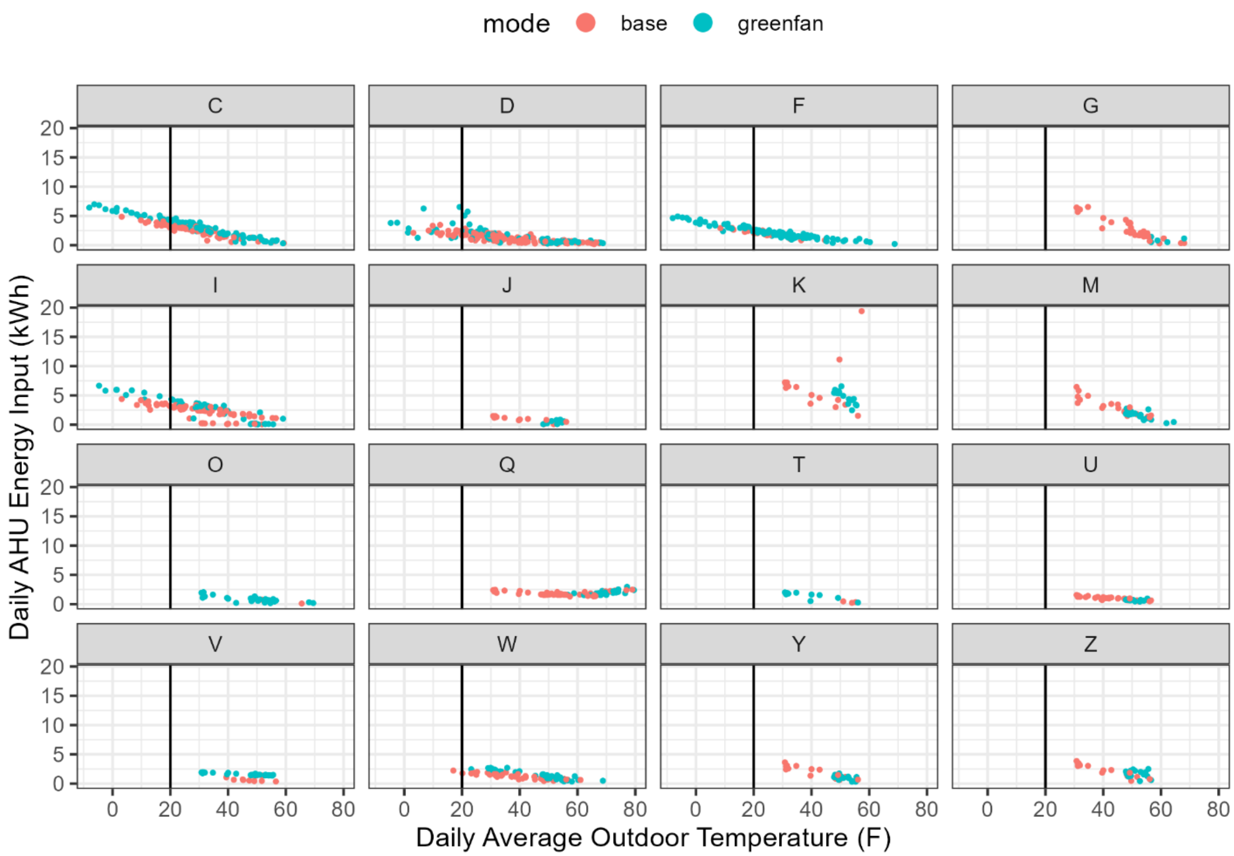
Figure 36. Site Q balance point calculation results



Heating Season Fan Energy

The daily heating season electrical consumption of the air handler (AHU) was plotted against temperature at the same 20 sites included in the gas use analysis. Of these, only four sites (C, D, F, and I) had sufficient data at temperatures below 20°F (indicated by the vertical black line) due to the timing of the power meter installations. The installation of the power meters and furnace data loggers was separated to ensure sufficient furnace heating season data was captured, since the power meters required coordination with an electrician to install, and the primary application of the power meters was to analyze cooling season data.

Figure 37. Daily electrical input vs. average outdoor temperature in heating season



Cooling Season Air Conditioning Outdoor Unit Energy

Of the 20 sites with cooling season performance data, 10 showed the expected relationship between control mode and fan-off delay with minimal data processing. Calculating the fan-off delay depends on identifying the time when the gas valve or AC compressor turns off and the time when the air handler fan turns off. With this instrumentation approach, the AC compressor power and air handler fan current are in different datasets, which means that any small discrepancies in aligning the tables based on timestamps can cause calculation errors. As the expected cooling season benefits were smaller than the heating side, only the 10 sites with easily verifiable performance in the subsequent regression analysis were used.

Figure 38. Cooling fan-off delay distributions by mode, all sites