

# Evaluation of Retrofit Variable-Speed Furnace Fan Motors

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*Consortium for Advanced Residential Buildings*

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**Evaluation of Retrofit Variable-Speed Furnace Fan Motors**

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## Definitions

AHU	Air handling unit
BPM	Brushless, permanent magnet (motor)
CARB	Consortium for Advanced Residential Buildings
CFM	Cubic feet per minute
ECM	Electronically commutated motor
HVAC	Heating, ventilation, and air conditioning
NREL	National Renewable Energy Laboratory
NYSERDA	New York State Energy Research and Development Authority
PEG	Proctor Engineering Group
PSC	Permanent split capacitor (motor)
SIR	Savings-to-investment ratio
TrueFlow	Device used to measure AHU's airflow rate

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## Executive Summary

In conjunction with NYSERDA and PEG, CARB has evaluated the Concept 3 replacement motors for residential furnaces. These brushless, permanent magnet (BPM) motors can use much less electricity than their PSC (permanent split capacitor) predecessors. These motors have been primarily developed for and used in cooling-dominated climates. This evaluation focuses on the heating-dominated climate of upstate New York. Previous studies have been based largely on modeling, laboratory testing, and/or benefits of BPM motors in new furnaces. This study specifically focuses on replacement BPM motors in cold-climate homes to characterize field performance and cost effectiveness. The results of this study are intended to be useful to home performance contractors, heating, ventilation, and air conditioning (HVAC) contractors, and home efficiency program stakeholders.

The project includes eight homes in and near Syracuse, New York. During initial site visits, baseline tests were performed (pressures, flows, and power consumption) and monitoring equipment was installed. The monitoring equipment ran for approximately 6 months, recording portions of both heating and cooling seasons. After this stage, CARB returned to the home with a technician from Tag Mechanical (the HVAC contractor), replaced the motor, repeated the tests, and reset the monitoring equipment for another 6 months.

Not surprisingly, results indicate that BPM replacement motors will be most cost effective in homes with right-sized HVAC equipment (with longer run times) and proper ductwork (i.e., low static pressures). Additionally, more dramatic savings can be realized if the occupants use fan-only operation to circulate air when there is no thermal load. There are millions of cold-climate, U.S. homes that meet these criteria, but the savings in most homes tested in this study were modest.

There were certainly substantial electric power reductions with the new motors. Average fan power reductions were approximately 126 Watts during heating and 220 Watts during cooling operation. Over the course of entire heating and cooling seasons, these translate into modest average electric energy savings of 163 kWh. Average cost savings were \$20/year. Homes where the fan was used outside of heating and cooling modes saved an additional \$42/year on average.

In the homes tested, heating and cooling savings alone would not usually justify the installed cost of approximately \$475. Installed costs would need to be less than \$300 to achieve a savings-to-investment ratio of at least 1.0. However, in the homes where the air handler fan was used in “fan-only” mode (in addition to heating and cooling), average savings-to-investment ratio was 1.3 with an internal rate of return of 7.5% at an installed cost of \$475. This replacement motor measure, therefore, should be used selectively in homes where several of the following conditions apply:

- The furnace likely has at least 10 years of useful life remaining.
- Heating and cooling equipment is right-sized (thus operates longer and more frequently).
- Operating pressures are relatively low (no constrictive ducts).
- The furnace fan is frequently used outside of heating and cooling operation.

# 1 Introduction and Background

Most existing residential furnaces use permanent split capacitor (PSC) motors. A few of these motors have multiple speeds (sometimes accomplished by using multiple sets of coils), but most PSC motors vary speed by changing the slip which has a small effect on the power draw. Higher efficiency motors have been available for a number of years and have been used as replacements for refrigeration evaporator fan motors. Since 1985, furnace manufacturers have used higher efficiency, variable-speed BPM fan motors (also known as electronically commutated motors or ECMs) in some high-end residential furnaces. In recent years, new furnaces with BPM motors have gained market share. Instead of single- or multi-speed PSC motors, most new two-stage furnaces employ BPM motors to achieve a wider performance range with lower power consumption. The vast majority of existing residential furnaces, however, employ relatively inefficient PSC motors.

The benefits of BPM blower motors have been well documented in studies such as the Energy Center of Wisconsin 2003 study of field performance of new residential furnaces, which found 50% electric energy savings in heating, 31% savings in cooling, and 80% savings for continuous fan operation (Pigg 2003). Other studies have shown the savings depend dramatically on heating, ventilation, and air conditioning (HVAC) system characteristics, especially static pressure differentials (Lutz et al. 2006; Walker 2007).

Until recently, BPM motors were quite expensive. Incremental costs for BPM motors in a new furnace were typically \$800–\$1,200. While this incremental cost has come down for new furnaces, BPM motors have been impractical to retrofit into existing furnaces due to incompatible control requirements. In 2008, the Concept 3 BPM motor became commercially available (the motor is now sold as the Fieldpiece LER motor). The Concept 3 is designed specifically for retrofit into existing furnaces as a replacement for the standard PSC motors. Cost to the installing HVAC contractor is less than \$200, which is competitive with PSC replacement motors. This reduced cost could make installation of these motors more practical and cost effective. The goal of this project was to evaluate exactly this: the practicality and cost effectiveness of the Concept 3 drop-in replacement ECM motors in cold climates.

## 1.1 Concept 3 Motor Controls and Airflow

The Concept 3 motor is designed to interface with a typical 24-Volt thermostat that allows for heating, cooling, and fan-only operation. The configuration and controls of the Concept 3 are simple. This streamlines installation, but it may also limit the savings functionality of the system. For cooling operation, there are two possible configurations:

- **Dry climate.** The fan motor runs at 100% speed during a call for cooling. After the thermostat is satisfied, the motor runs for an additional 4–10 minutes at 25% speed to take advantage of the cold coil.
- **Humid climate.** The fan motor runs at 85% of full speed during a call for cooling. The fan shuts off immediately at the end of the call to prevent drying the coil. If fan-only operation is called for, the fan will not operate for 20 minutes after a cooling cycle. If another cooling call occurs within this period, the system will turn on.

The cooling mode is determined by the connection of a single wire on the Concept 3 motor (see Figure 1). Regardless of the cooling setting, during a call for heating the fan motor runs at 85% of full speed beginning 30 seconds after the call begins. After the call ends, the fan runs for an additional 3 minutes. During a call for fan-only, the motor will run at approximately 50% of full speed.

In New York State, the humid setting was obviously chosen for cooling operation. There are two potential limitations associated with this:

- Motor speed is limited to 85%. Matching existing flow rates can be challenging.
- Motor speed is the same for both heating and cooling operation; airflow rates are therefore nearly identical.

### 1.2 Installation

While the control configuration (discussed above) can be limiting, wiring and configuring the motor are very straightforward. Figure 1 shows the wiring diagram from the Concept 3 installation manual. The connection that can differ is the orange wire—used to determine humid or dry cooling modes.

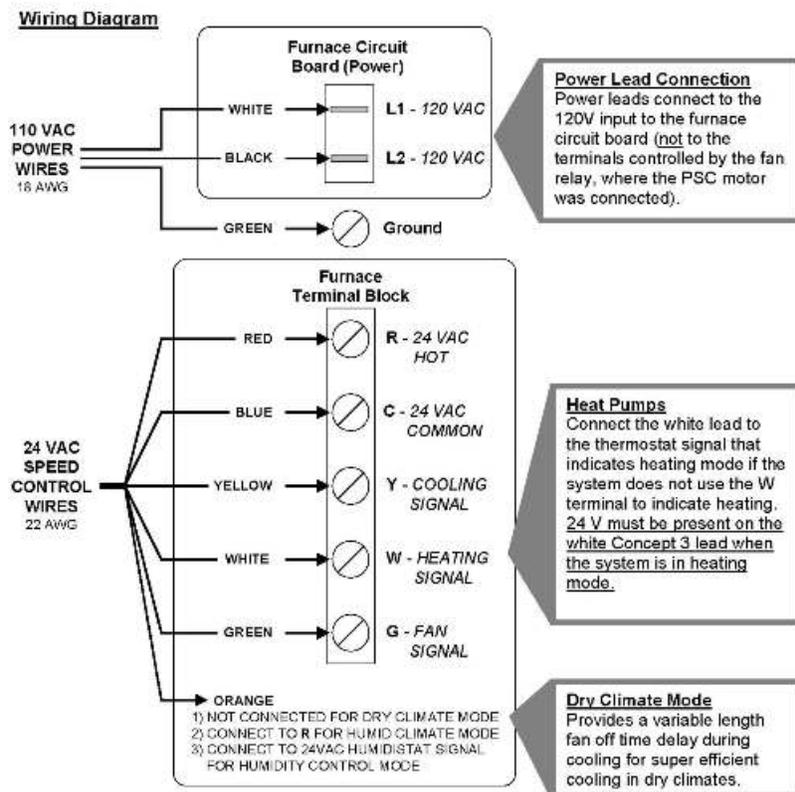


Figure 1. Wiring diagram from the Concept 3 Installation Manual (PEG 2010)

The physical installation of the motor is straightforward as well—provided that the motor being replaced also uses a belly band. Rheem and Ruud furnaces typically use bracket mounts to secure

the motors in the fans. At the two sites where original motors used bracket mounts, the motor replacement required twice as much time. At other sites, switching the motor took an average of 2 hours.

## 2 Research/Experimental Methods

### 2.1 Research Questions

The key questions that this research and evaluation project set out to answer are:

- What are the electric power and energy implications (during both cooling and heating) of the new BPM motor in these test homes when compared to the original PSC motor?
- How do the savings vary with different system characteristics, including flow rate, static pressure difference, and duct leakage?
- How difficult is it to install the replacement motor? What are typical installed costs?
- In what systems are these motors most practical and cost effective?
- What simple tests can be performed on systems to accurately assess potential benefits of the replacement motors and identify cost-effective candidates for the retrofit?

As the project progressed, it was clear that one additional question is very important:

- How many furnaces are compatible with the Concept 3 motor? Can furnaces be upgraded on a wide scale?

### 2.2 Technical Approach

CARB worked with Tag Mechanical, an HVAC contractor in Syracuse, New York, to identify 10 residential forced-air systems that meet these general requirements:

- Homes must be in New York State—a requirement associated with the NYSERDA cofunding.
- In order to evaluate savings under all operating conditions, homes must have central, forced-air heating and cooling systems.
- To streamline monitoring systems, each AHU must not serve multiple zones (i.e., no zone dampers—homes that achieve zoning with multiple AHUs may still be good candidates).
- To be compatible with the Concept 3 motor, AHUs must use ½-hp (or smaller) PSC motors.
- Some furnaces have brackets mounted to their motors and are poor candidates. Any furnace with a motor mount other than a belly band poses some challenges.
- Units must use 24-Volt thermostats.
- The existing motor should rotate clockwise (viewed from the shaft end).
- The furnace cabinet width must be 17 in. or greater.
- Owners must agree to participate in the study and sign the participation agreement. Owners receive an efficient fan motor installed at no cost to them.

After a customer signed the agreement and after verifying that the furnace appears to be compatible with the Concept 3 motor, CARB and Tag scheduled a preliminary visit to the home. After verifying that the system was compatible with the Concept 3 motor, the following tests were performed:

- Combustion safety tests to ensure systems are operating safely
- Recording of make, model, and configuration of all system components
- Duct leakage tests
- Under steady-state conditions, measurement of power, voltage, current, power factor, supply plenum static pressure, and return plenum static pressure at each operating condition (heating, cooling, and fan-only)
- Replacing the furnace filter with a TrueFlow pitot array plate and repeating the above measurements along with velocity pressure and airflow rate at each operating condition
- Installation of monitoring equipment (described below)
- Verification that the system was operating properly before leaving.

Long-term monitoring covered part of a cooling season and part of a heating season. After approximately 6 months, each site was revisited and the motor was replaced. Each of the measurements listed above was repeated with the new motor in place.

CARB worked closely with installers of each new motor to determine how much time the replacement process took, how much this installation would cost, if there were any unforeseen challenges with this particular system, etc.

### **2.3 Measurements**

The first step in evaluations was safety testing. CARB checked for gas leaks and performed combustion safety tests at all homes. Duct leakage measurement was generally the next step in the process. The overall procedure for duct blaster tests was as follows:

1. Turn HVAC systems off.
2. Using tape or other material, block or mask all supply and return registers.
3. Remove filter.
4. Attach the blower to the duct system—typically at the AHU.
5. Insert a static pressure reference tap, typically in the supply plenum.
6. Turn on the duct blaster fan and pressurize the duct system to 25 Pa.
7. Measure the flow rate through the fan; this is the total duct leakage.

Power measurements were taken with a Fluke 43B power quality analyzer with an i30s current probe. During short-term tests, CARB recorded one-time measurements of voltage, current, power, and power factor of the furnace under each operating condition (heating, cooling, and fan only). During heating, these measurements were taken after the burner had ignited and the igniter

had turned off. During cooling, similar electrical measurements were taken on the condensing unit.

Long-term monitoring was accomplished using Onset Computer Hobo data loggers. Loggers recorded data at 2-minute intervals for 30 days during the cooling season and 60 days during the heating season. Monitored parameters were:

- Outdoor temperature and relative humidity
- Supply plenum air temperature
- Return plenum air temperature and relative humidity
- Current draw of the AHU
- Current draw of the condensing unit (during cooling).

## 2.4 Monitoring Equipment

The key equipment used in the project is outlined in Table 1.

**Table 1. Summary of Equipment Used for Testing and Monitoring**

Measurement	Equipment Needed
Carbon Monoxide Concentrations and Draft Pressure	Bacharach Fyrite Pro
Duct Leakage	Energy Conservatory Series B Duct Blaster
Pressure Measurements (Other Than Combustion Draft Pressures)	Energy Conservatory DG 700 manometer
Airflow Rate	Energy Conservatory TrueFlow Pitot array plate
Electrical Power, Current, and Voltage	Fluke 43B power quality analyzer with i30s current sensor
Return Plenum Air Temperature and Relative Humidity	Onset Hobo U12-011
Supply Plenum Air Temperature	Onset Hobo U12-006 with TMC20-HD
Outdoor Air Temperature	Onset Hobo U23-001
AHU and Condensing Unit Current	Onset Hobo U12-006 with CTV-A current transducer

## 2.5 Analysis

As the short-term test methodology describes, CARB measured the power consumption and flow characteristics of each motor under steady state at each operating condition. The somewhat simplified long-term monitoring protocol (utilizing current sensors) was primarily meant to document runtime of the system during each operating mode.

When analyzing heating performance, it was determined that the furnace was in heating mode when the furnace current was above a threshold (approximately 3 Amps) and when there was a large temperature rise (usually 10°–20°F) across the furnace. These thresholds varied a small amount from system to system. This runtime, in conjunction with the steady-state power

measurements, provided estimates for electrical energy consumed for space heating. A very similar approach was used for cooling (with current and temperature drop thresholds).

Ideally, real electrical energy consumed by each system over each monitoring period would have been measured. The primary reason that such a strategy was not pursued was the added time, equipment, and intrusiveness to set up such monitoring equipment. Initial site visits typically required 4–5 hours. Installing more rigorous electrical monitoring equipment would have required more time—possibly the installation of an additional electrical box and requiring services of an electrician. While project budgets would have been stretched too thinly with this approach, the added time required—from the homeowners’ perspective—was the key limitation. Finding participants to the study was by far the largest hurdle encountered, and longer, more intrusive, and more frequent site visits would not have been acceptable to many participants.

Approximate thermal energy delivered to the home was calculated based on flow rates measured during short-term tests and measured temperature differentials. As with electrical energy consumption, less uncertainty would be achieved with more rigorous monitoring. For example, heat calculations assume flow is constant as measured during short-term tests. Flow rates will vary based on filter status, wet coils, etc. In addition, supply temperature values are from single-point measurements. As with more rigorous electrical monitoring, installing flow arrays and averaging temperature sensors would have increased the installation time and would not have been acceptable to many participants. These uncertainties are relatively modest, and conclusions would not be different with more rigorous measurement protocols.

Knowing system runtime in each mode, indoor air conditions, outdoor air conditions, and supply air temperatures allow for apples-to-apples comparisons of system performance with the two types of motors. Using local climate data (NREL 2005) in conjunction with the outdoor temperature and humidity conditions recorded at the sites, results from the relatively short monitoring period (1–2 months for each season for each motor) were extrapolated to annual energy consumption.

## **2.6 Identifying Sites**

One unexpected finding was the limited number of systems that were compatible with the Concept 3 motor. Syracuse, New York is obviously in a heating-dominated climate. As such, there are many homes that do not have central air conditioning (this was a requirement of NYSERDA for the evaluation—that both heating and cooling performance be monitored). It is estimated that 60%–80% of people contacted or considered for this study were not considered further because they did not have forced-air systems that provide both heating and air conditioning.

Among sites that did have central furnaces and air conditioning, many people were simply not interested in participating in the study. Researchers reached out to hundreds of contacts in the Syracuse area, but interested responses were rare. It is very hard to quantify this aspect of sample selection, as non-responses can mean many different things.

Finally, among homeowners contacted who both had air conditioning and were interested in participating in the study, a majority of systems were not compatible with the Concept 3 motor. The key reasons for this:

- **Many furnaces encountered had ¾-hp motors.** The Concept 3 can replace only ½-hp and smaller motors. At least 50% of interested candidates with air conditioning were ruled out because of large furnace motors.
- **Rheem and Ruud furnaces.** The vast majority of furnace motors have belly bands. Rheem and Ruud furnaces, on the other hand, have motors that use bracket mounts. While retrofitting a Rheem/Ruud furnace with a belly band is possible, PEG recommends against it (as does a Tag Mechanical technician after replacing one such motor in the study).
- **Small cabinets.** In order for the new motors to be installed with proper clearance, furnace cabinets must be at least 17 in. wide. Approximately five systems that did have smaller motors (1/5 to 1/2 hp) were encountered, but with narrow cabinets (~14 in.).

Because of these challenges, project participation goals (10 sites) were not fully met. CARB ultimately found 12 sites, but two were disqualified because of combustion safety concerns and two occupants moved before the study was finished, resulting in a total of eight sites.

## 3 Results

### 3.1 Motor Replacement

In total, eight PSC motors were replaced with BPM motors. Six of the replacements were very straightforward, requiring approximately 2 hours of the technician's time. The other two sites had motors with bracket mounts and replacement was much more involved.

Site 3 had a Rheem furnace. At the initial site visit, the technician inspected the motor and determined that replacement would be possible but certainly more involved than a belly band installation. When the motor was replaced 6 months later, the project was indeed more involved. The technician left to visit a supply house and purchased three different belly band retrofit kits. Back at the home, he needed to use parts of several kits to get the Concept 3 motor installed securely into the fan. Total replacement time was 3.5 hours.



**Figure 2. BPM motor with retrofit belly band being replaced in a Rheem furnace at site 3**

Site 7 had a Lennox furnace. It was only when the fan was removed from this furnace that the bracket mounting was discovered. Without mirrors, flashlight, and/or a borescope, it was not easy to determine the motor mounting type without removing the fan assembly. The technician called the Tag office and another technician came out with belly band kits he had on-hand. None of these proved adequate, and the technicians went to a supply house to purchase another kit.

This kit ended up working extremely well (Mars model 08049, Johnstone Supply S58-612). If this had been on-hand, installation would likely not have taken any longer than 2 hours. Total

installation time ended up being 3.5 hours—5.5 person-hours including the time of the second technician. CARB recommended keeping one of these products on-hand for future installations, but it is not certain that this model would work well for all fans.



**Figure 3. (Left): Original PSC motor at site 7 with mounting brackets; (Right): Concept 3 motor installed with retrofit belly band kit**

At each site (except the first), the technician left the original motor at the home in case problems were encountered and the motor needed to be replaced. At the first site, the Tag technician wasn't aware of this protocol and removed the old motor.

After installation of each Concept 3 Motor, the installing technician was asked several short questions about the replacement procedure (see Appendix). The responses were straightforward. It was only the two sites that had bracket motor mounts that presented problems. A summary of the comments is in Table 2.

### **3.2 Initial Test Results**

Initial tests did indeed show power savings with the Concept 3 motor. Among the eight systems where motors were replaced, average AHU power draw was reduced by 126 Watts during heating, 220 Watts during cooling, and 442 Watts during fan-only operation. These savings come with some caveats, however, mostly related to flow rates. Table 3 through Table 5 show the results in each system. These tables also show measured airflow values. Figure 4 through Figure 6 show CFM/Watt ratios for each site.

**Table 2. Summary of Installer Feedback**

Site	Installation Comments
Site 1	<p>Replacement time: 3 hours</p> <p>Uncertainty mounting belly bands and/or brackets—technician was not sure what would work. It would be nice to have an exact belly band model to keep on hand.</p> <p>Would like more information on adjusting the torque screw, e.g. what is the range? Which direction is higher/slower?</p> <p>Installation will definitely become easier/quicker with repetition and experience.</p>
Site 2	<p>Replacement time: 2 hours</p> <p>No issues—straightforward replacement.</p> <p>Torque screw is tricky—hard to access/see/feel.</p>
Site 3	<p>Replacement time: 3.5 hours (including trip to Grainger)</p> <p>Technician had to get appropriate bracket/belly band kit. This ultimately required combining pieces of two different kits.</p> <p>Mounting the belly band is difficult with the plastic spacers around the Concept 3 motor.</p> <p>Technician recommended against any more Rheem retrofits</p> <p>Torque screw impossible to access when fan is installed—had to drill hole in side of cabinet to access from outside.</p>
Site 4	<p>Replacement time: 2 hours</p> <p>Condensing furnace—condensate drain was hard-piped (PVC) in motor. This had to be removed and replaced to remove fan.</p> <p>Everything else very straightforward.</p>
Site 5	<p>Replacement time: 1–1.5 hours</p> <p>No issues, no comments, no problem</p>
Site 7	<p>Replacement time: 3.5 hours (5.5 person-hours)</p> <p>Surprise bracket mount—could not tell until fan was removed.</p> <p>Trip to shop and then to HVAC supply show was needed.</p> <p>Technician may keep this model belly band kit on-hand for future installations.</p>
Site 10	<p>Replacement time: 1.25 hours</p> <p>Needed dual spade connector for installation</p> <p>Torque screw took several tries to set at correct speed</p> <p>Condensate line was busted</p>
Site 12	<p>Replacement time 1.5–2 hours</p> <p>Extra wiring for humidifier added slight complication</p>

**Table 3. Flow and Power Measurements of Furnaces During Heating Operation**

Site	Airflow (CFM)		Power (Watts)	
	Original	Concept 3	Original	Concept 3
1	732	909	480	450
2	1,441	1,345	710	480
3	895	1,005	600	490
4	970	917	750	440
5	952	922	580	420
7	1,028	1,095	500	480
10	663	697	371	330
12	742	829	460	350

**Table 4. Flow and Power Measurements of AHUs During Cooling Operation**

Site	Airflow (CFM)		Power (Watts)	
	Original	Concept 3	Original	Concept 3
1	810	929	620	410
2	1,515	1,374	680	400
3	1,011	1,062	560	380
4	1,130	908	870	360
5	925	943	430	290
7	1,142	1,098	600	460
10	768	711	421	260
12	847	868	387	250

**Table 5. Flow and Power Measurements of AHUs During Fan-Only Operation**

Site	Airflow (CFM)		Power (Watts)	
	Original	Concept 3	Original	Concept 3
1	732	455	420	86
2	1,470	655	680	60
3	737	485	388	63
4	1,121	443	870	56
5	989	555	470	80
7	1,112	521	600	99
10	593	330	256	44
12	797	396	382	45

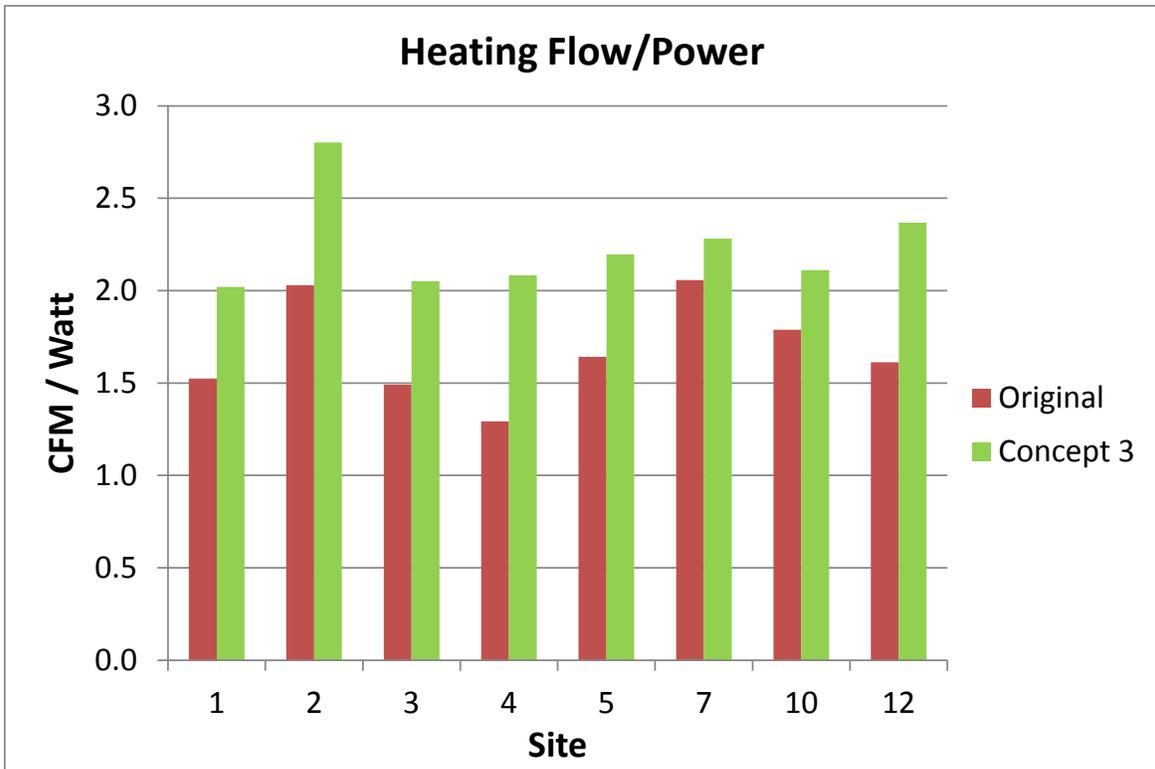


Figure 4. Flow/power during heating operation

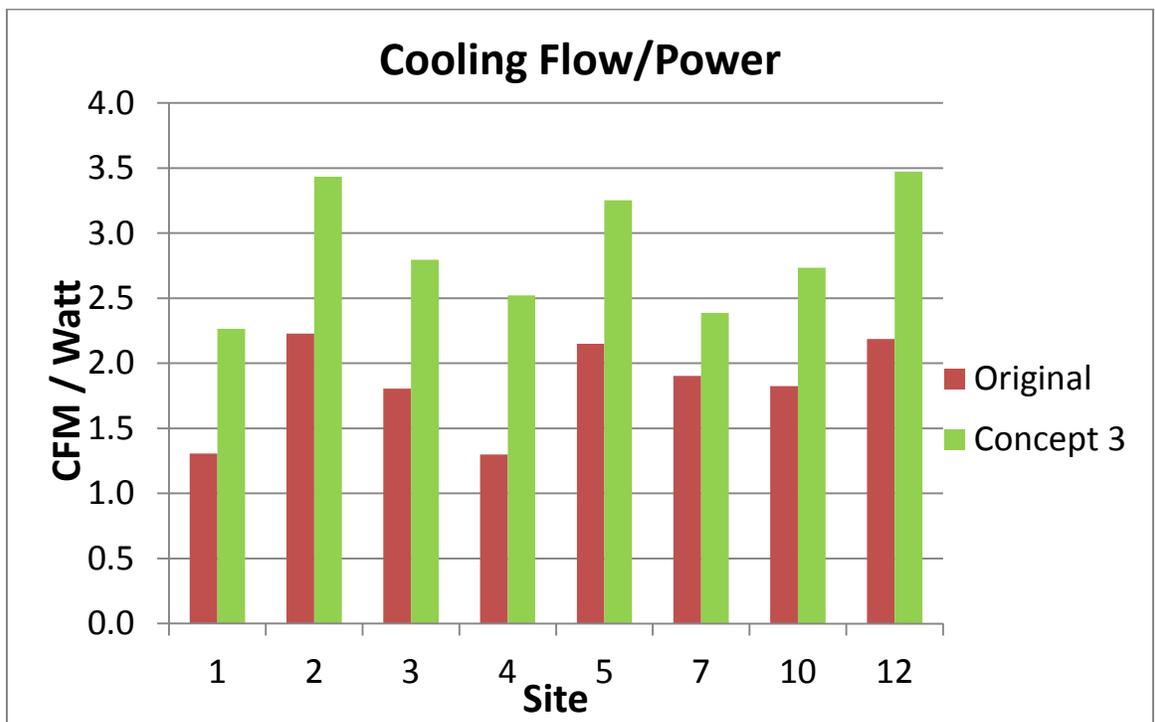


Figure 5. Flow/power during cooling operation

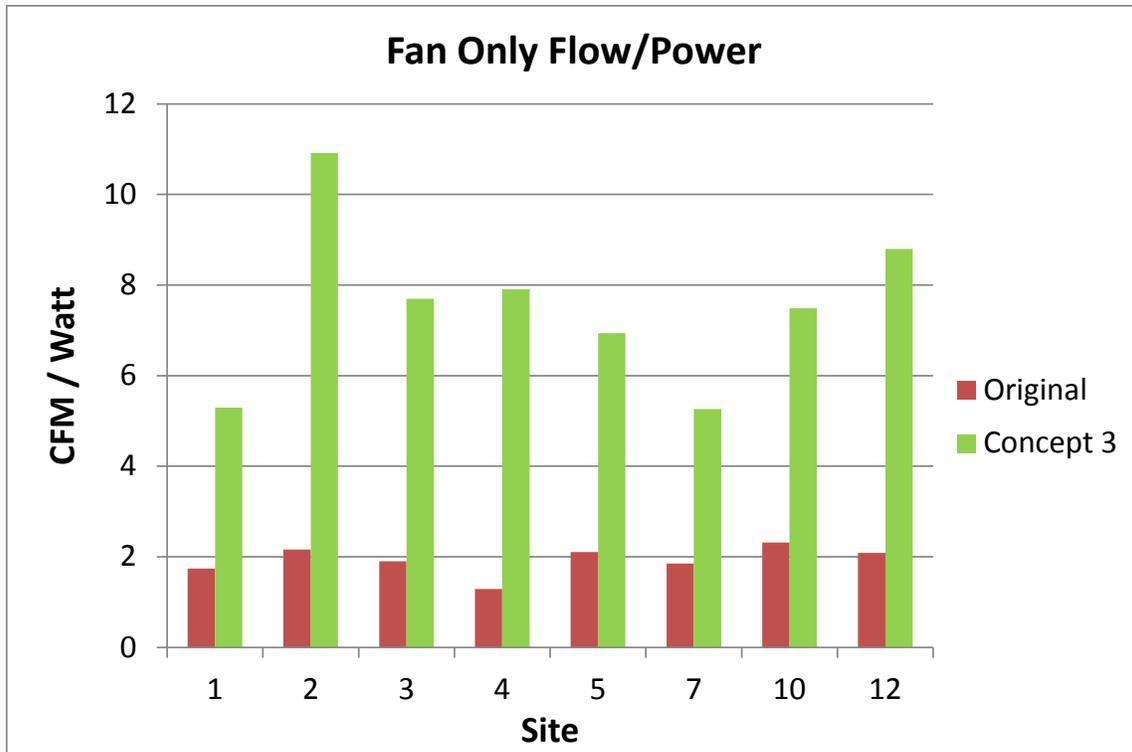
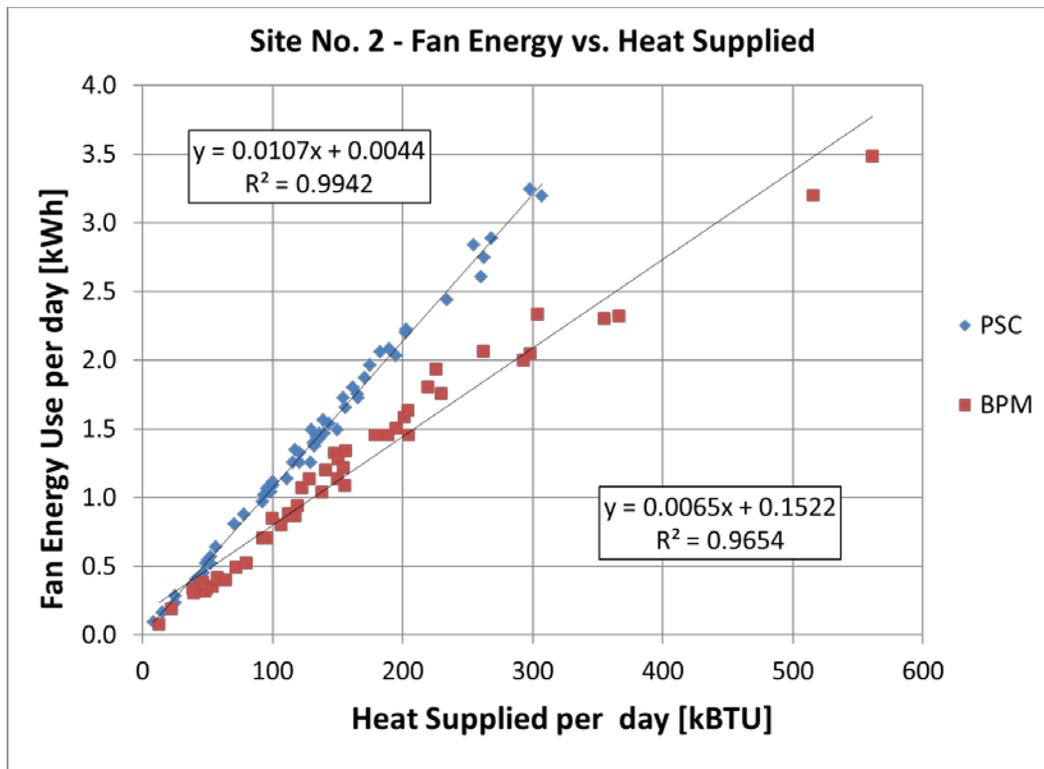


Figure 6. Flow/power during fan-only operation

### 3.3 Long-Term Monitoring Results

#### 3.3.1 Heating

Long-term monitoring was performed at eight sites. From this monitoring researchers obtained the runtime in each operating mode, the approximate amount of heating energy or sensible cooling delivered to the air stream, and the corresponding indoor and outdoor temperature and humidity conditions. With these data, researchers plotted AHU electricity used during each day versus heating energy delivered to the air stream. An example of this is shown in Figure 7. Charts from other sites are in the Appendix.



**Figure 7. Relationship of furnace electricity (with different motors) to heat delivered at site 2**

Looking at the ratio of the two slopes in Figure 7, it appears the Concept 3 motor (BPM) uses 39% less electricity to deliver the same amount of heat as the original PSC motor. This is fairly consistent with short-term test results (Table 3 above). One limitation in this analysis is that it assumes constant airflow; this is not necessarily valid as filters become soiled over time.

As full heating seasons were not monitored, measured performance comparisons over complete heating seasons are not possible. In addition, the first winter evaluated was very mild for Syracuse. In order to make estimates of typical annual operating costs for each motor, daily runtime of each furnace as was examined a function of average outdoor air temperature (see example in Figure 8). For every measured 2-minute interval, the furnace fan was determined to be running to supply heating when air temperature rise and AHU current were above set thresholds (thresholds varied by system, but 3 Amps and 20°F temperature rise were typical).

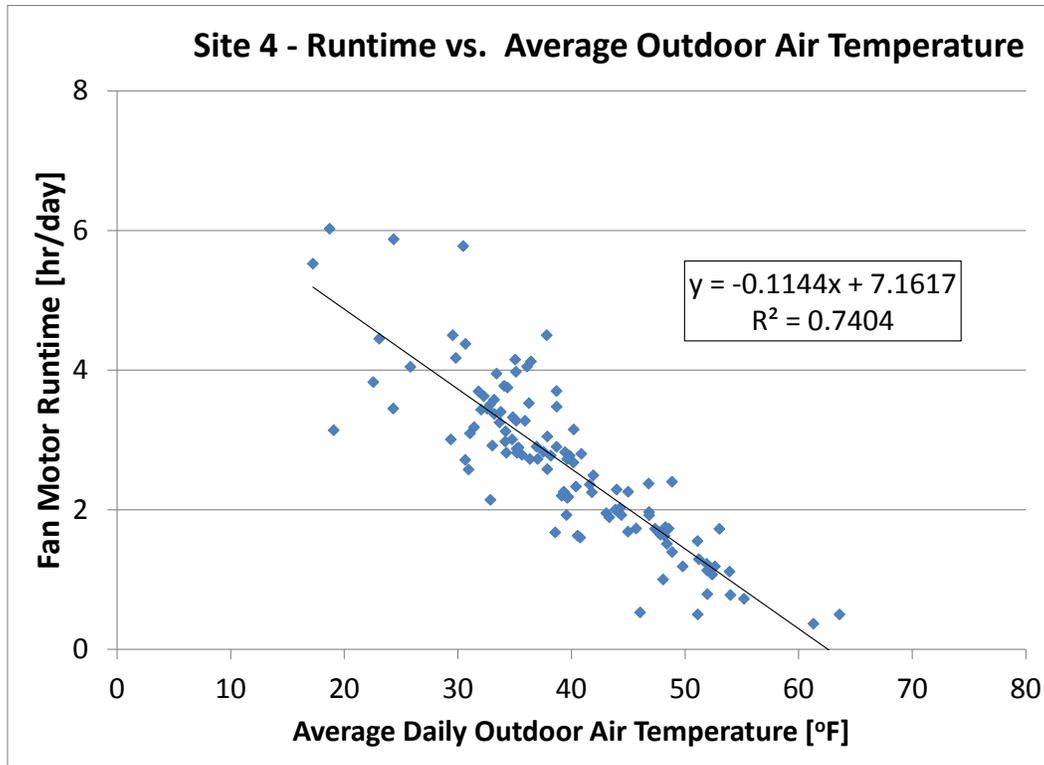


Figure 8. Heating runtime regression for site 4

Using Syracuse Typical Meteorological Year version 3 data, average daily temperatures throughout the year were calculated. Using the regression equations like that in Figure 8, expected daily run time for all days with average temperatures below the balance point (64.3°F in this example) was also determined. Annual electricity savings expected from the BPM motor is simply the product of the difference in measured power (from Table 3) and the runtime. These values are shown in Table 6.

Table 6. Estimated Annual Furnace Runtime and BPM Motor Savings During Heating Operation

Site	Annual Heating Run Time	BPM Power Savings	BPM Motor Savings	
	[hrs]	[Watts]	[kWh]	Cost*
1	1376	30	41	\$6
2	488	230	112	\$17
3	698	110	77	\$12
4	674	310	209	\$31
5	629	160	101	\$15
7	1041	20	21	\$3
10	926	41	38	\$6
12	693	110	76	\$11
Avg.	816	126	84	\$13

\*Electricity rates of \$0.15 per kWh

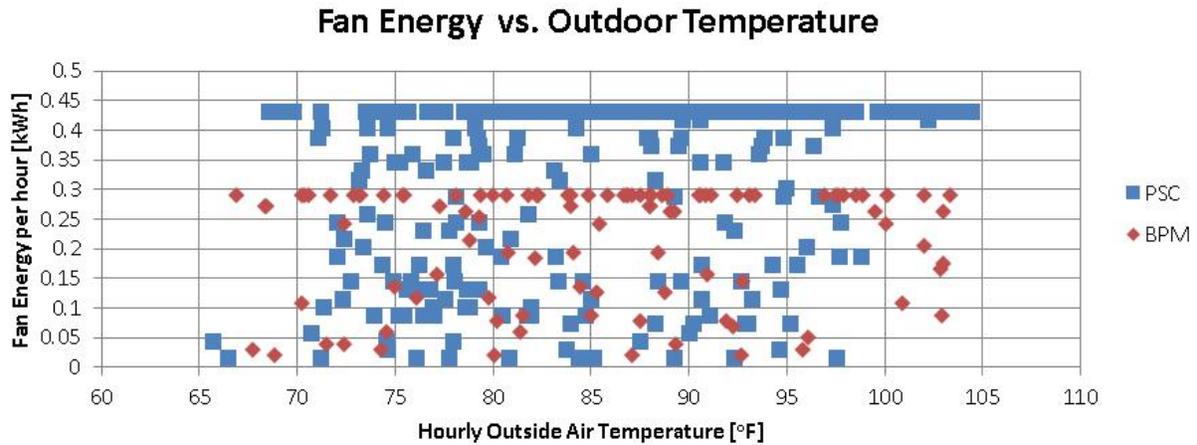
One item that Table 6 does not capture is possible increased gas consumption with the BPM motors. Electrical fan energy is transferred to the air stream, and lower electricity consumption translates into less heat delivered to the home. While this drop in heating capacity is very small (on the order 1% for the systems here), over the course of the year it's likely more gas would be consumed to make up for this electrical energy. This increased gas was calculated using rated furnace efficiencies and is outlined in Table 7.

**Table 7. Estimated Additional Gas Costs**

Site	Furnace Efficiency	Additional Gas Required	
	[AFUE]	[therms]	Cost*
1	81%	1.7	\$2
2	80%	4.8	\$6
3	92%	2.8	\$3
4	93%	7.7	\$9
5	91%	3.8	\$5
7	78%	0.9	\$1
10	94%	1.4	\$2
12	79%	3.3	\$4
Avg.	-	3.3	\$4

**3.3.2 Cooling**

Plots of AHU electricity versus sensible cooling show similar savings (see example in Figure 10), but determining savings over entire cooling seasons was difficult with the data collected. The period evaluated with the original PSC motor (August–September 2011) was very mild. The season evaluated with the BPM motor (July 2012) was extremely hot. CARB was not able to find valid relationships between outdoor conditions and air conditioner runtime during these periods. A typical example of this is shown in Figure 9. There is no practical correlation between fan energy and outdoor air temperature.



**Figure 9. Poor correlation between fan energy and outdoor air temperature at site 5**

However, to obtain at least an approximation of annual savings, the average daily run time for each air conditioner during cooling season was multiplied by 90 days—the typical length of the cooling season. Estimated air conditioner runtime varies widely from site to site—between 135 and 623 operating hours. While during heating operation the lower fan energy may require more gas, during cooling operation there should be additional savings from the reduction in fan waste heat. The effective energy efficiency ratio (EER) of the cooling system based on equipment specifications was also estimated. While this procedure can provide only rough estimates of annual savings, Table 8 shows that these savings are quite modest. Estimates of total annual savings at each site are summarized in Table 9.

**Table 8. Estimates of Annual Cooling Runtime and Fan Energy Savings**

Site	Estimated Annual AC Operation	BPM Power Savings	Approx. EER	Annual Savings	
	[hrs]	[Watts]	[Btu/Wh]	[kWh]	Cost*
1	144	210	8	43	\$6
2	139	280	10	52	\$8
3	366	180	11	86	\$13
4	210	510	11	140	\$21
5	488	140	10	92	\$14
7	379	140	10	71	\$11
10	135	161	11.5	28	\$4
12	623	137	10	114	\$17
<b>Avg.</b>	310	220	-	78	\$12

\*Electricity rates of \$0.15 per kWh

**Table 9. Estimated Savings (Both Heating and Cooling) at Each Site From BPM Motor**

Site	Estimated Annual Savings
1	\$11
2	\$19
3	\$21
4	\$43
5	\$24
7	\$13
10	\$8
12	\$25
<b>Avg.</b>	\$20

While site 4 shows the highest savings, this comes with a significant caveat. The reason for these savings is that the Concept 3 motor could not reproduce the original cooling flow rates. The technician replaced the Concept 3 with a larger BPM motor; this is discussed further below.

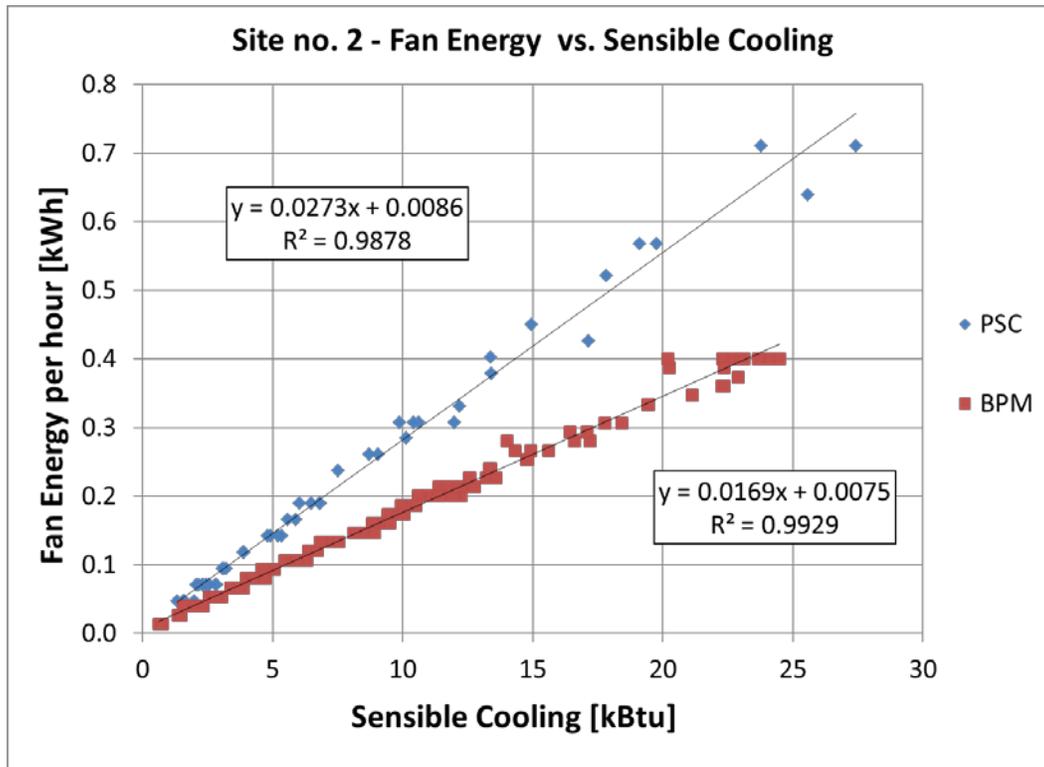


Figure 10. Relationship of AHU electricity (with different motors) to sensible cooling at site 2

### 3.4 Fan-Only Operation

Fan-only operation was observed at four of the eight sites. Estimated annual savings are displayed in Table 10. Annual fan-only operation was estimated by extrapolating fan-only hours recorded in the total monitoring period over an entire year (e.g. annual fan-only hours are twice the fan-only hours measured over 6 months). These savings (Table 10) are significantly larger than the heating and cooling savings shown in Table 9.

Table 10. Estimated Savings (Fan-Only) at Each Site From BPM Motor

Site	Annual Fan-Only	BPM Power	BPM Motor	
	Run Time [hrs]	Savings [Watts]	Savings [kwh]	Cost*
1	528	334	176	\$26
2	356	620	221	\$33
5	1206	390	470	\$71
7	524	501	263	\$39

\*Electricity rates of \$0.15 per kWh

While fan-only operation with the Concept 3 uses dramatically less power, it also provides much lower airflow. This is an intentional design feature: when not needed for heating or cooling, the lower AHU flow rate is acceptable to most residents. Using approximately 25% of the power, the Concept 3 will deliver approximately 50% of the flow rate (compared to full speed).

Fan-only operation varies dramatically from home to home. Those who do use fan-only have various motives for using the setting. Many of the homeowners interviewed said that the primary reason for utilizing this setting was simply “to move air around the house” or similar. Even though the fan flow is significantly reduced with the ECM motor, it still may adequately satisfy the homeowner (this was not true for site 1 as discussed below). If the AHU fan is operated outside of heating and cooling periods—for ventilation, filtration, “to move air”, etc.—the potential energy savings of the BPM motor are dramatically higher.

### **3.5 Homeowner Feedback**

Before monitoring began and at the completion of long-term monitoring, home residents were interviewed to assess their satisfaction with the HVAC system. In general, the responses have been mildly positive. There were a few comments about different sounds, and people noticed little if any changes in comfort. One customer, however, had several complaints about the altered system. These are discussed in Section 3.6 below.

### **3.6 Site 1: Customer Satisfaction Challenges**

At site 1, the owner complained about two noises after the motor was replaced. One noise was popping or “oil canning” of the return trunk when the furnace started and stopped. This return trunk is undersized, and the changes in pressure caused the sheet metal to pop in and out—accompanied by a significant noise. CARB and Tag noticed this noise before the motor was replaced; the owner, however, did not. While the pressures and flow rates with the new motor were similar, the owner became bothered by the popping noise after the motor had been replaced. Technicians returned to the site and installed a piece of angle bracing on the return trunk to prevent this popping (Figure 11).



**Figure 11. Angle bracket installed on the return trunk to prevent the duct from “popping” in and out on fan startup and shutdown**

The other noise that the customer complained about was a slight vibration or rattling within the furnace. The exact source of this noise could not be isolated, but it was occurring behind or above the burner, possibly within the heat exchanger. The noise occurred only when the furnace was in heating mode, and it happened only when the heat exchanger was warm (i.e., from a cold start it took approximately 10 minutes of burner firing before the rattling occurred). The noise is not loud, but it is noticeable. Tag and CARB could not find a way to address this without dismantling—and perhaps replacing—the heat exchanger.

It is unclear if or how the motor replacement could have caused this vibration. The motor speed was lowered to see if that fixed the problem; it did not. While this noise is not ideal, it is not terribly loud. The owner was not extremely happy with this situation, but he was satisfied with the elimination of the popping noise of the return trunk.

Finally, the owner at site 1 was not pleased with the lower airflow rate during fan-only operation. CARB explained that this was an energy-saving strategy if fan-only operation is utilized (see Table 5), but the customer was not happy with the lower flow rates. After monitoring was complete, the settings were changed so the fan ran at cooling speed when only the fan is called for. This disables the coil drying feature of the Concept 3, but this is what the customer chose.

### **3.7 Site 4: Flow Rate Challenges and Evergreen IM Motor**

All of the participating sites, including site 4, had ½-hp or smaller motors. However, upon installing the Concept 3 motor, the maximum flow rate attained during cooling was only 908 CFM (compared to 1,130 CFM with the original ½-hp, PSC motor). As this home had a 4-ton air conditioner, it already had low flow (282 CFM/ton) with the original motor. With the Concept 3 motor, flow rate was reduced to 227 CFM/ton. At this rate, coil freezing became a concern.

A technician checked refrigerant pressures when cooling season began. While pressures seemed acceptable, there were still concerns. To address them, the motor was replaced with a larger BPM Motor: a 1-hp Evergreen IM motor made by Genteq. CARB was not on site when the motor was replaced. When CARB visited the site later, the motor was operating at 1,440 CFM and consuming 880 Watts during cooling operation. In heating mode, the furnace was not operational. CARB coordinated with Tag to correct these issues (reduce cooling flow rate to near the original 1,130 CFM and get the furnace to operate in heating mode). After the technician returned to fix the system, CARB measured performance as shown in Table 11. A discussion comparing these two motor options is included in the Section 4 and Section 5.

**Table 11. Power and Flow Measurements at Site 4**

Mode	Original PSC		Concept 3		Evergreen	
	Power [W]	Flow [CFM]	Power [W]	Flow [CFM]	Power [W]	Flow [CFM]
Heating	750	970	440	917	500	1036
Cooling	870	1130	360	908	760	1257
Fan Only	870	1121	56	443	150	738

## 4 Discussion

Table 5 shows that the Concept 3 motors certainly do result in lower power consumption. The average power reduction was 38% (220 Watts) during cooling 23% (126 Watts) during heating. The fan-only power consumption is 87% lower (442 Watts) on average, though this comes with a nearly 50% drop in flow rate. Energy cost savings estimates from the Concept 3, however, are often modest. Estimated savings at the eight sites range from \$8 to \$95 per year. There are three main reasons these numbers are low.

1. **Heating-dominated climate.** Fan motor savings clearly can have more impact in cooling-dominated climates. As discussed above, any reduction in waste heat from furnace fan motors must be made up by burning more fuel. While natural gas (the fuel used in all homes evaluated here) is much less costly than electricity, this increased gas use does eat into fan motor savings.
2. **Oversized equipment.** In most of the homes, the furnace heating capacities seemed quite high. Whereas single-stage heating equipment sized to meet the design heating load may typically operate 1,500–2,000 hours/year in Syracuse, only at sites 2 and 7 did CARB calculate typical heating runtimes above 1,000 hours/year. At the other six sites, average furnace runtime was 684 hours/year. With much fewer hours of operation, the associated fan energy savings is proportionately less.
3. **Single fan speed.** In most of the homes, the original heating flow rates (with PSC motor) were somewhat lower than the cooling flow rates. In a climate with a humid cooling season (like New York), the Concept 3 runs at the same speed during both heating and cooling. BPM fan motor speeds were adjusted to match original cooling flows as closely as possible, meaning heating flow rates with the BPM motor were higher than original rates. These higher flow rates do not increase heat output (from a given burner capacity) and result in less savings than would be possible with different controls.

For sites that do use a fair amount of fan-only operation and can tolerate lower airflow rates, there are much greater opportunities for energy savings from these replacement motors.

### 4.1 Duct Leakage and Static Pressure

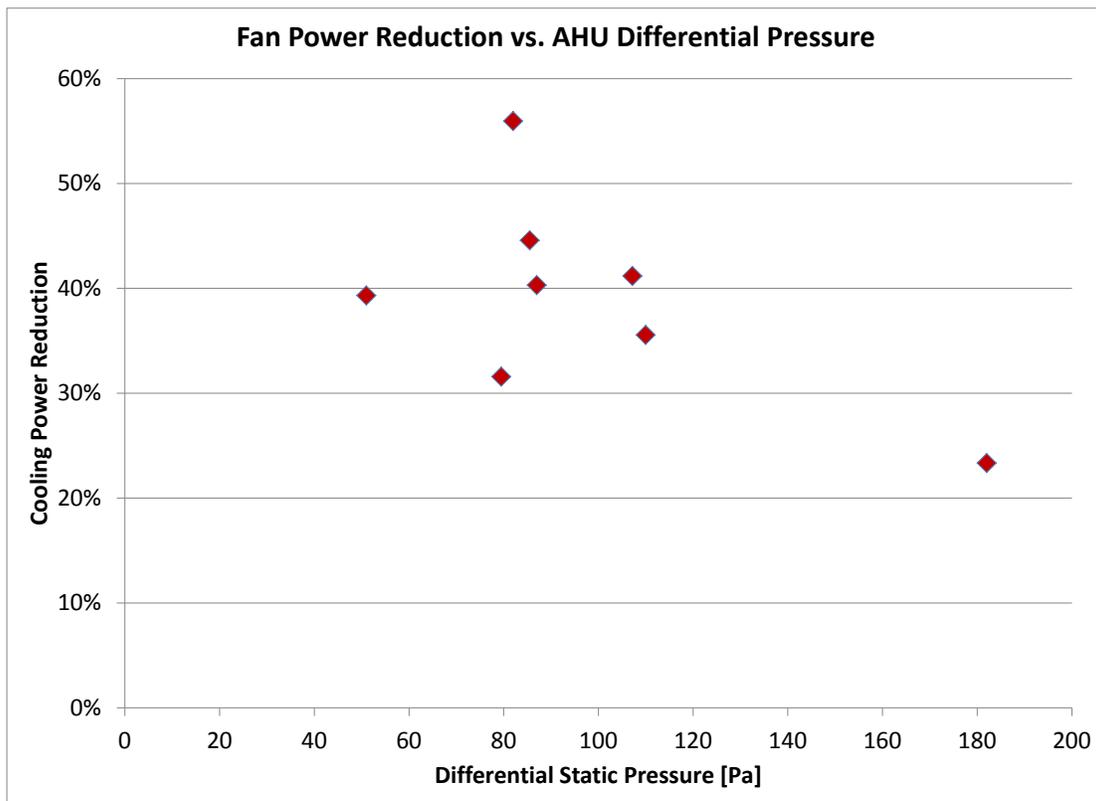
At higher static pressures, there is less difference in power consumption between PSC and BPM motors. It's been proposed (Walker 2007; Lutz et al. 2006) that most existing residential duct systems are too constrictive—i.e., ducts are undersized and therefore savings from BPM motors are very small. While a great number of duct systems are undersized, they are also very leaky. It may be that this leakage results in lower pressures—and therefore higher BPM savings. Certainly duct leakage is not desirable. If duct leakage is reduced as part of energy improvement measures, savings from BPM motors may also be reduced.

In order to examine the effects of constrictive and/or leaky ducts, researchers measured pressure differentials in the systems. Static pressure measurements were taken upstream of the filters and downstream of the cooling coils. The exact location of these pressure taps, however, varied with system geometries and duct access. Duct leakage testing was not possible at all sites, but duct systems were similar. There was little attention paid to duct sealing at any of these sites.

Table 12 summarizes differential static pressures, duct leakage, and AHU power reduction during cooling mode. Power reduction at site 4 is not listed because flow rate with the Concept 3 motor was so much lower. Figure 12 shows the relationship between power savings and differential pressure graphically. While there is not an overwhelming trend in this limited dataset, the system with the highest static pressure has the lowest fan power savings.

**Table 12. Pressure, Leakage, and Power Savings During Cooling Operation**

Site	Differential Pressure [Pa]	Total Duct Leakage [CFM @ 25 Pa]	AHU Power Reduction
1	107	NA	41%
2	87	NA	40%
3	80	1215	32%
4	82	1325	NA
5	110	869	36%
7	182	830	23%
10	86	740	45%
12	58	795	39%



**Figure 12. Power reduction in cooling mode versus differential static pressure**

During heating operation, one study (Franco et al. 2008) estimated savings from ECM furnace fans in cold-climates at 10%–47%, with higher savings from “ideal” ducts. The ducts in this study were far from ideal, but average reduction in heating electricity was 23%. If the duct systems here had been well sealed, differential static pressures would have been higher, and savings from ECMs may have been much lower.

#### 4.2 Concept 3 Versus Evergreen IM

The other main product available in the retrofit BPM motors market for residential AHUs is the Evergreen IM motor from Genteq. One of these motors was installed at site 4 where airflows with the Concept 3 were not acceptable. While CARB has experience just at this one site, there seem to be some important differences in the models.

- **Capacity.** The Evergreen IM motor has two models: ½-hp and 1-hp. CARB encountered many furnaces with ¾-hp motors, and the larger Evergreen IM model could be appropriate for many of these where the ½-hp Concept 3 is not.
- **Variable flow rates.** The Evergreen IM can easily be set for different flow rates during heating and cooling. In all of the furnaces evaluated here (with the Concept 3), this could have resulted in some additional savings.
- **Simplicity.** While the Evergreen IM is more versatile, the Concept 3 seems to be designed for more straightforward installation. The Evergreen IM manual is 40 pages long. While reading the entire manual may not be necessary for a good installation, it certainly has potential to be a barrier to quality installation. The Concept 3 manual is six pages long and dominated by large, clear graphics (such as Figure 1). After the Evergreen IM was installed at site 4, CARB found the fan speed at the highest settings possible (well above the original flow rates and static pressures) and the furnace did not operate in heating mode. It is impossible to judge from a sample of one site, but the additional wiring, much longer manual, and more involved installation procedure may lead to improper operation.
- **Humid climate.** With the Concept 3, wiring is the same for all installations with the exception of one wire. In humid climates, this orange wire should be connected to enable the humid climate operation mode. This mode results in slightly lower fan speed (which can be a problem as discussed above), but it also “locks out” the AHU fan after a call for cooling. If a user has set the fan to always be on, the fan will not turn on for 20 minutes, giving the coil a chance to dry and improve dehumidification of the system.
- **Cost.** Prices of these motors are similar, though the Concept 3 may cost slightly less. An evaluation of list prices from a few vendors shows prices for the Fieldpiece LER (aka Concept 3) ranging from \$200–\$225. A similar search for Genteq’s Evergreen IM shows costs \$60–\$70 higher.

#### 4.3 Achieving Proper Flow Rates

In order to match the flow rates of the PSC motors, installation instructions (for both the Evergreen IM and Concept 3) call for measuring the static supply pressure of the PSC motor and matching that pressure with the BPM motor. Measuring and matching static pressures may not be standard for many HVAC contractors. Researchers were on site for all but two of motor installations (one of which was the Evergreen IM motor). When researchers visited the sites to

take measurements, both motors were installed at their highest speed delivering much higher flow rates than the original motors. The speeds had to be lowered before tests continued. This is a potential concern if implementing these motors on a wider scale; higher fan speeds could dramatically reduce or eliminate savings.

#### **4.4 Noise**

The Concept 3 motor makes a slight “whirring” noise for 1-2 seconds when it shuts down. This is usually only noticeable by a person standing near the furnace (e.g., in the mechanical room). This noise did lead to a complaint at site 12, however. The homeowner here was initially very happy with the noise levels. He said during normal operation the fan was much quieter than with the PSC motor. However, when the motor shut down the “whirring” seemed to carry to the first floor. The motor was replaced with another Concept 3, but the noise remained. CARB offered to replace his original PSC motor, but he chose not to do this. By the end of the 6-month monitoring period, occupants said they were quite used to the noise and did not find it objectionable.

See Section 3.6 for a description of vibration noise complaints at site 1. It’s unclear what exactly is causing this noise, but CARB cannot rule out different vibrations or harmonics caused by the new motor.

#### **4.5 Older Equipment**

Implementing this energy saving mechanism requires utilizing older furnaces. This leads to several questions, including: Is the furnace in good working order? Will it need to be replaced soon? If so, should furnace replacement be considered rather than motor replacement? If the furnace is not old and still under warranty, what effect does motor replacement have on the furnace warranty?

These questions are important, but they usually need to be addressed on a case-by-case basis. Replacing an induced-draft, 80%-efficient furnace with a sealed-combustion, 95%-efficient furnace with an ECM is certainly desirable for reasons beyond motor efficiency. The cost of furnace replacement is several thousand dollars, but this should be considered if a furnace is nearing the end of its useful life. During combustion safety tests at site 6, CARB found dangerous levels of carbon monoxide in the exhaust stream. The owner addressed this by replacing the furnace with a condensing, sealed-combustion model with a BPM motor.

At site 8, initial combustion safety tests were quite good; carbon monoxide concentrations were low, draft was very good, etc. However, when Tag Mechanical came to replace the motor, they noticed a backdraft safety switch had been removed. The furnace was old enough that a replacement part could not be found, and the fan motor was not replaced because of safety concerns.

With respect to warranties, the replacement motor itself comes with a 2-year warranty from the manufacturer. CARB consulted with Proctor Engineering Group about the larger furnace warranty question, and PEG knows of no cases where a furnace manufacturer did not honor a warranty because of installation of a Concept 3 motor. In their opinion, the risk of this happening is “extremely low.”

#### **4.6 System Compatibility**

One of the biggest challenges in this project was finding appropriate equipment and willing participants. In addition to slowing the study, this also raised questions about the potential for widespread adoption of this technology. The study required tests on systems with both heating and cooling. In upstate New York, many homes do not have central air conditioning. Savings from heating alone are certainly possible, but in the systems monitored, savings during cooling season were very similar to heating season savings. Heating savings alone would not usually justify the cost of motor replacement.

The large number of furnaces that contain  $\frac{3}{4}$ -hp fan motors may be a barrier to implementing the Concept 3 technology on a wider scale. Among willing and interested participants in the study, CARB found that approximately 50% or more had to be eliminated because of larger ( $\frac{3}{4}$ -hp) fan motors. The Evergreen IM motor seems a viable alternative for many of these systems.

#### **4.7 Cost Effectiveness**

The list price of the Concept 3 motor itself is approximately \$250. After several installations, a Tag technician could replace new motor in 2.5 hours—usually less. At \$90/hour, total installed cost may be approximately \$475. It is very likely, however, that many contractors would charge more for this service, especially if it was the only work being performed at a site. Using average expected savings—during heating and cooling operation only—of \$20, it's clear that the technology is not cost effective in most of these homes. Assuming a 15-year useful life, an energy inflation rate of 3%, and a discount rate of 3%, the \$475 investment would have a savings-to-investment ratio (SIR) of 0.63. Installed costs would need to be below \$300 to achieve a SIR of 1.0 or higher.

It's also clear, however, that the motors do consume much less power—an average of 38% less when delivering comparable airflow rates. It's also noteworthy that even in a cold climate such as Syracuse, New York, the estimated savings during cooling operation are on par with savings during heating season. Clearly the potential for savings in climates with longer and more intense cooling seasons, such as New York City, is greater.

There are also instances, even in a Syracuse climate, where the motors are clearly cost effective. At sites 1, 2, 5, and 7, fan-only operation (averaging 450 hours/year) resulted in higher savings—\$42/year for heating, cooling, and fan-only operation. It is important to note again that fan-only savings are largely attributed to the lower airflow rate; this may not always be acceptable. With installed costs of \$475, the average SIR on these sites is 1.3 with an internal rate of return of 7.5%.

In homes with right-sized heating systems, hours of operation could be double those found in most of the homes evaluated here. This could double heating savings. Overall, however, CARB expects this technology will be cost effective only in certain cold-climate applications. The limited savings, system compatibility issues, and risk of investing in older equipment may not be practical on a wide scale.

## 5 Conclusions

Below are answers to the project's initial research questions:

- What are the electric power and energy implications (during both cooling and heating) of the new BPM motor in these test homes when compared to the original PSC motor?

*During heating operation, the average Concept 3 motor consumed 126 Watts less than the average PSC motor it replaced. During cooling, the average savings were 220 Watts. This represents a 23% and 38% reduction in AHU power, respectively. Average annual energy savings—for heating and cooling—were 163 kWh.*

- How do the savings differ with different system characteristics, including flow rate, static pressure difference, and duct leakage?

*Though there was not an overwhelming correlation, systems with lower duct leakage and higher static pressures tended to have lower power savings. In CARB's experience, older duct systems are quite leaky. If ducts are meticulously sealed as part of energy improvements, energy savings from BPM motors may be more modest than reported here.*

- How difficult is it to install the replacement motor? What are typical installed costs?

*Installation is not difficult. For an installer familiar with the motor, replacement typically requires 2.5 hours or less. Motors with bracket mounts, however, may require twice the time and additional parts.*

- In what systems are these motors most practical and cost effective?

*The motors do not appear to be terribly cost effective in many cold-climate homes. As cooling loads increase, the savings may increase dramatically. Homes that use the AHU fan for other reasons (ventilation, filtration, etc.) can achieve significant savings even in a cold climate (though with lower fan-only flow rates).*

- What simple tests can be performed on systems to accurately assess potential benefits of the replacement motors and identify cost-effective candidates for the retrofit?

*As mentioned above, cost-effective applications in a cold climate may be the exception rather than the rule. Homes with higher cooling loads, right-sized furnaces with longer runtimes, and duct systems with relatively low static pressure drops can result in higher savings. Homes that use fan-only operation frequently (e.g., for filtration or ventilation) may make installing BPM motors very cost effective.*

- How many furnaces are compatible with the Concept 3 motor? Can furnaces be upgraded on a large scale?

*The Concept 3 motor may not be viable in many homes with larger capacity furnaces (80 kBtu/h or larger). Many such furnaces have ¾-hp fan motors. Even in one furnace with a ½-hp motor CARB could not get adequate flows from the Concept 3, and in five of the eight installations Concept 3 speed was set as high as possible.*

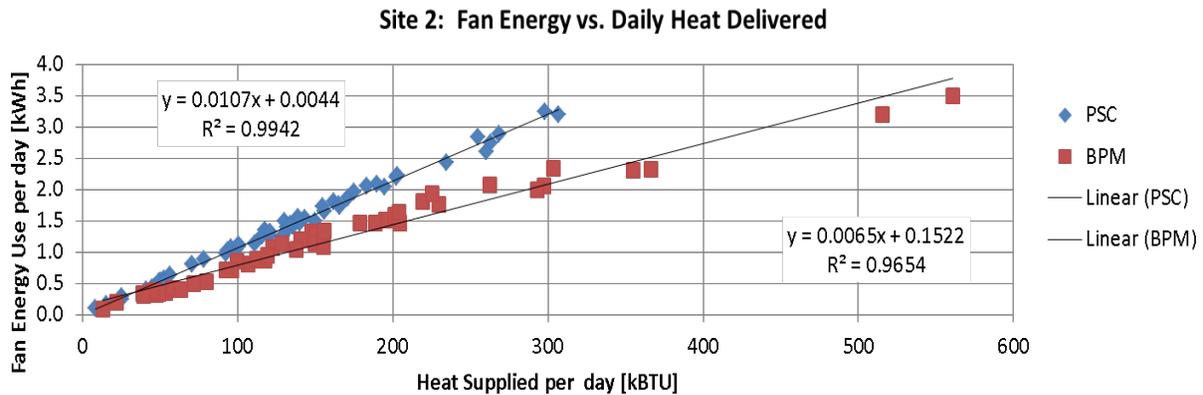
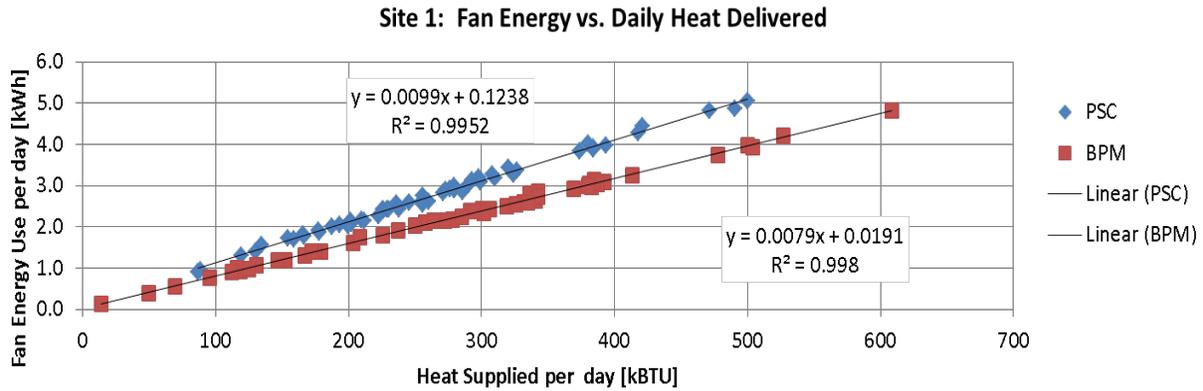
*The Genteq Evergreen IM, however, is available in a 1-hp version. Tests on one site showed good results. This may be a viable option for many furnaces with larger motors.*

In summary, the Concept 3 replacement fan motor uses significantly less power than PSC motors found in many existing furnaces. In cold climates, however, it may be the exception that these replacements will be cost effective unless the HVAC systems are operated in fan-only mode for filtration, ventilation, or other reasons.

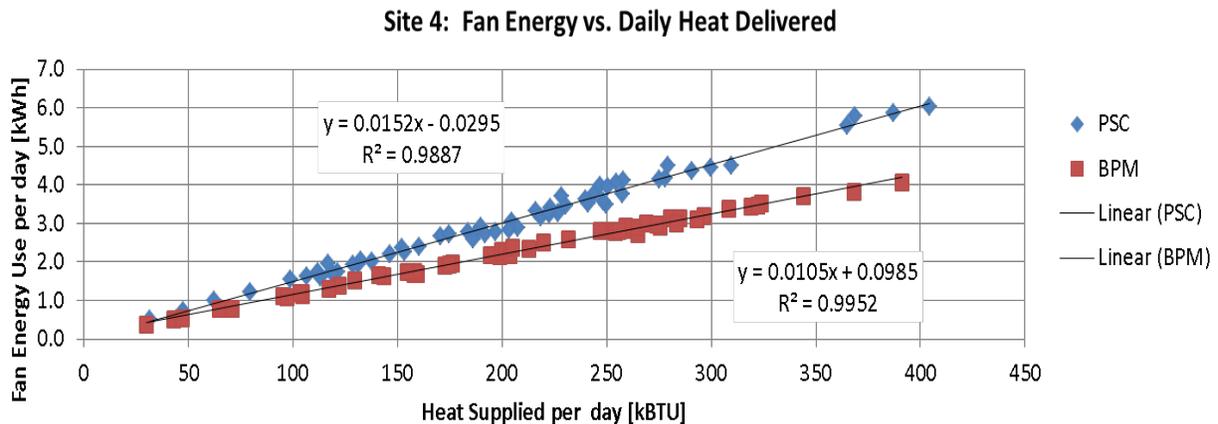
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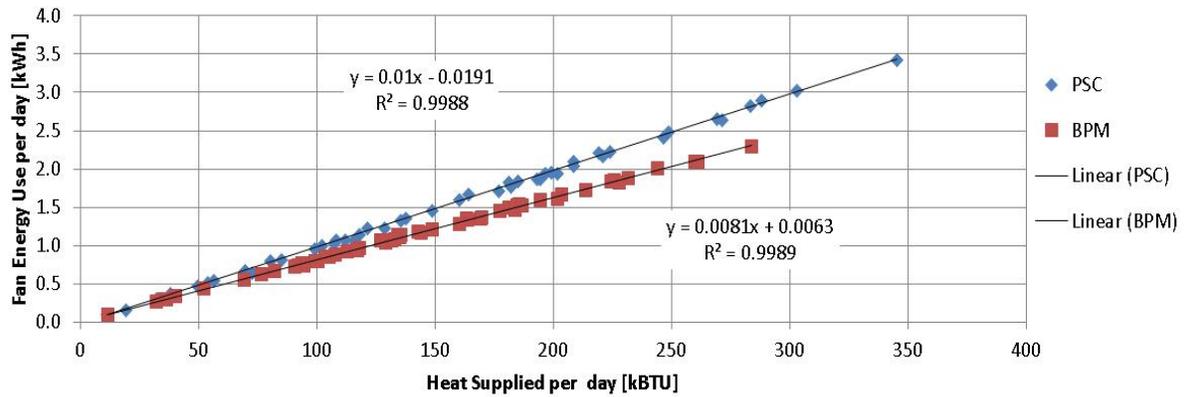
## Appendix A: Air Handling Unit Electricity Versus Heat Delivered



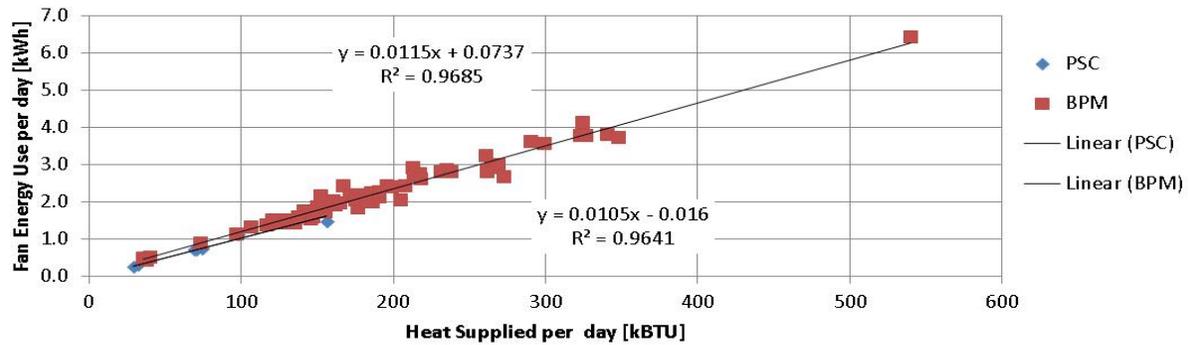
Note on site 3: Because of equipment failure, thermal energy measurements are not available during monitoring of BPM heating season performance.



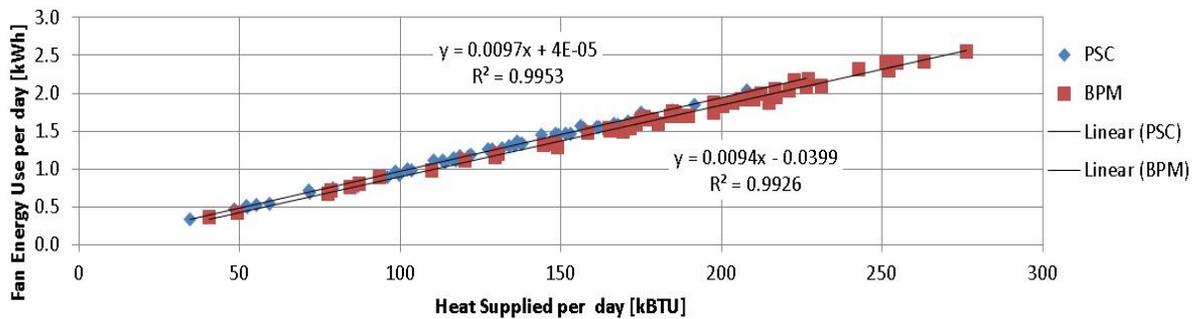
Site 5: Fan Energy vs. Daily Heat Delivered



Site 7: Fan Energy vs. Daily Heat Delivered



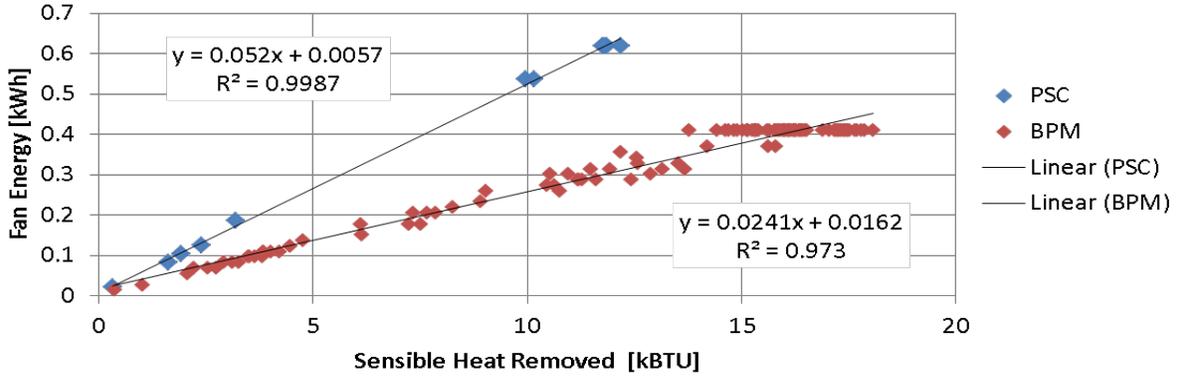
Site 10: Fan Energy vs. Daily Heat Delivered



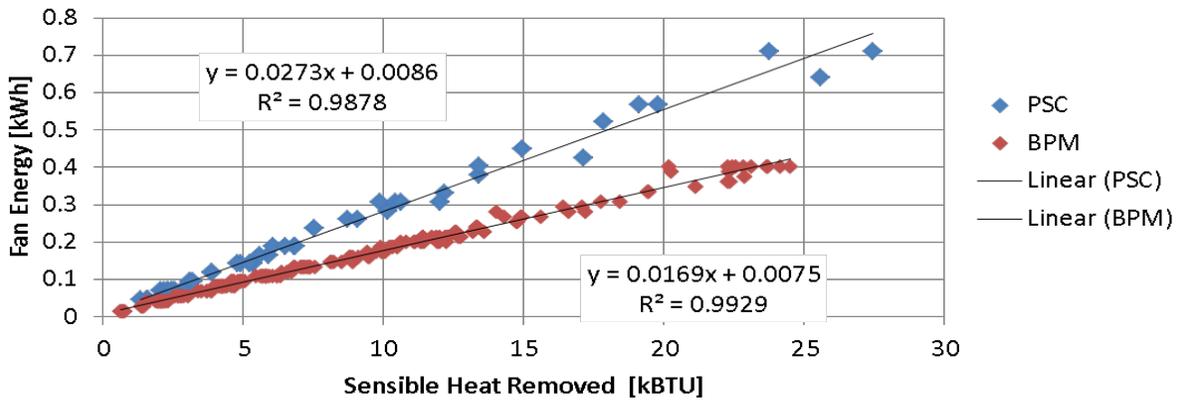
Note on site 12: Because of equipment failure, thermal energy measurements are not available during monitoring of BPM heating season performance.

## Appendix B: Air Handling Unit Electricity Versus Sensible Cooling

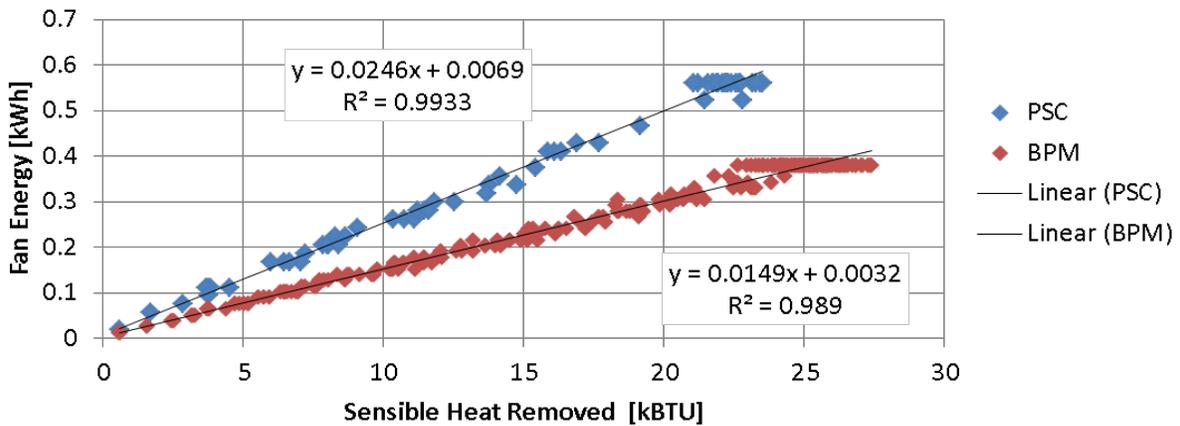
Site 1: Hourly Fan Energy vs. Sensible Heat Removed



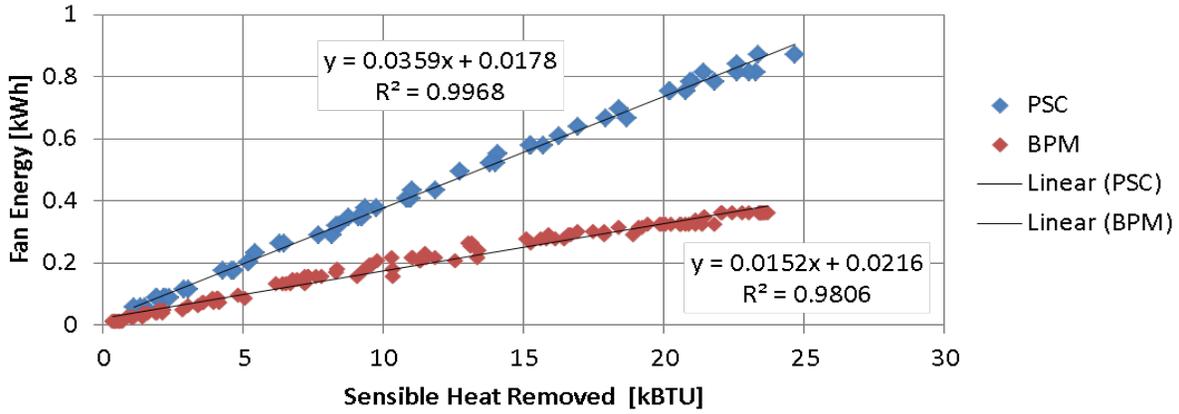
Site 2: Hourly Fan Energy vs. Sensible Heat Removed



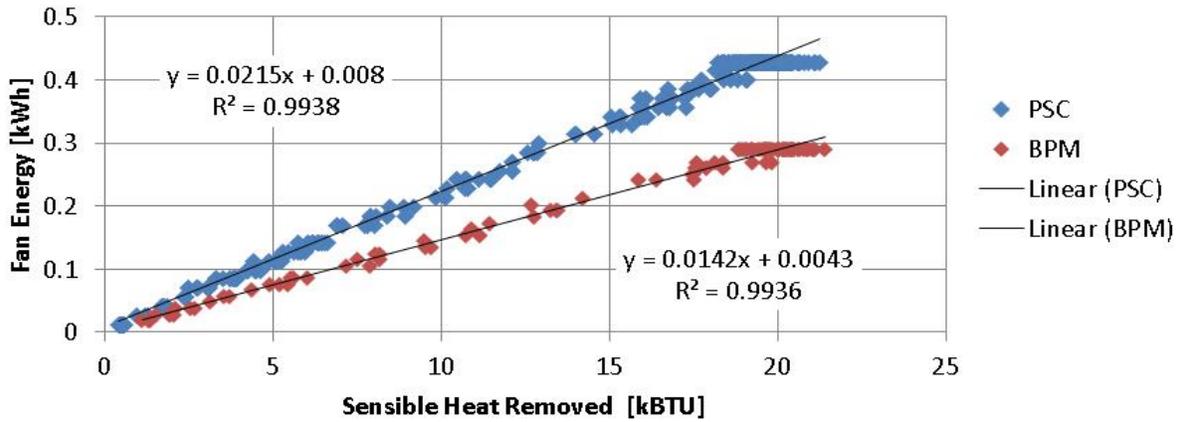
Site 3: Hourly Fan Energy vs. Sensible Heat Removed



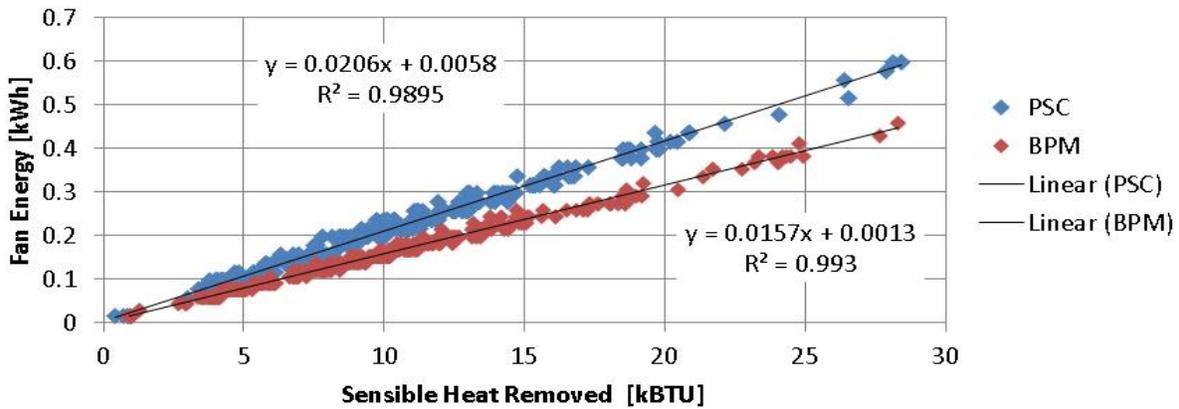
**Site 4: Fan Energy vs. Sensible Heat Removed**



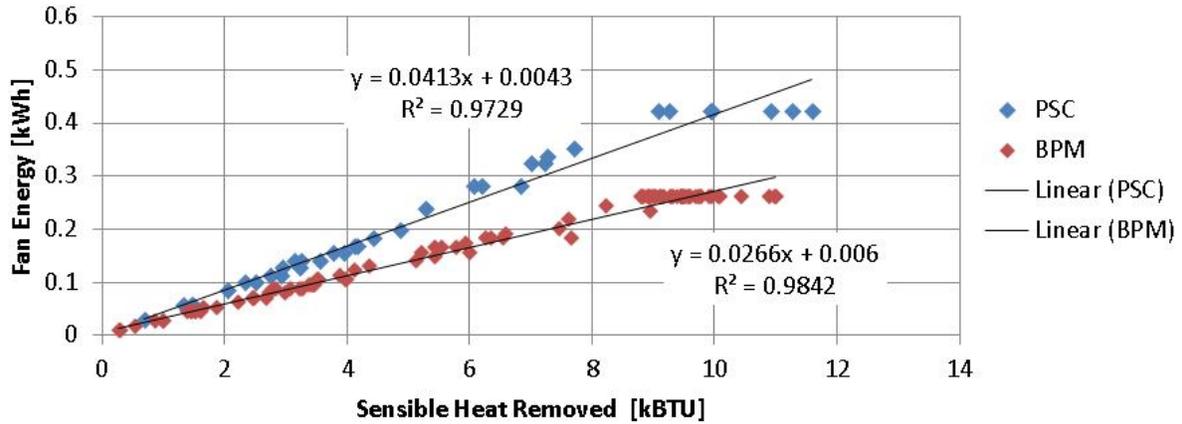
**Site 5: Fan Energy vs. Sensible Heat Removed**



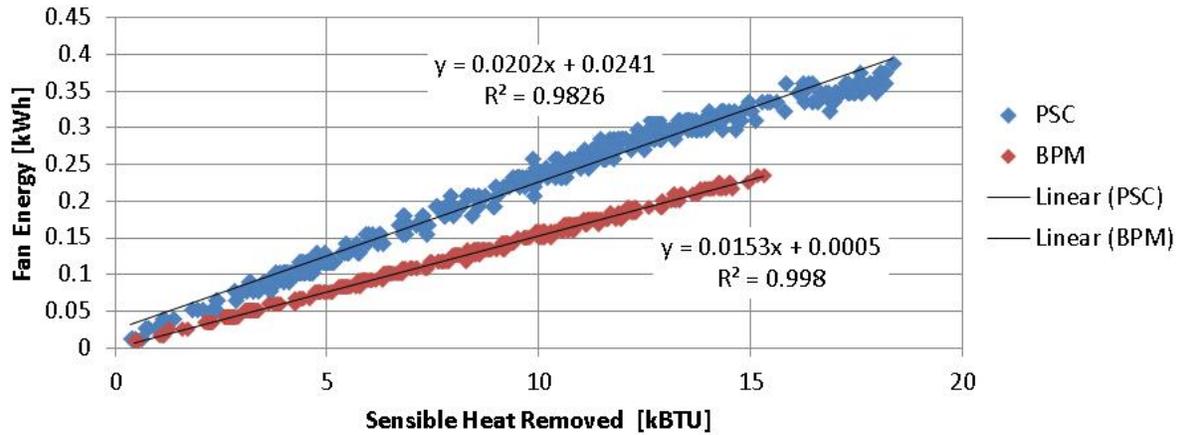
**Site 7: Fan Energy vs. Sensible Heat Removed**



Site 10: Fan Energy vs. Sensible Heat Removed

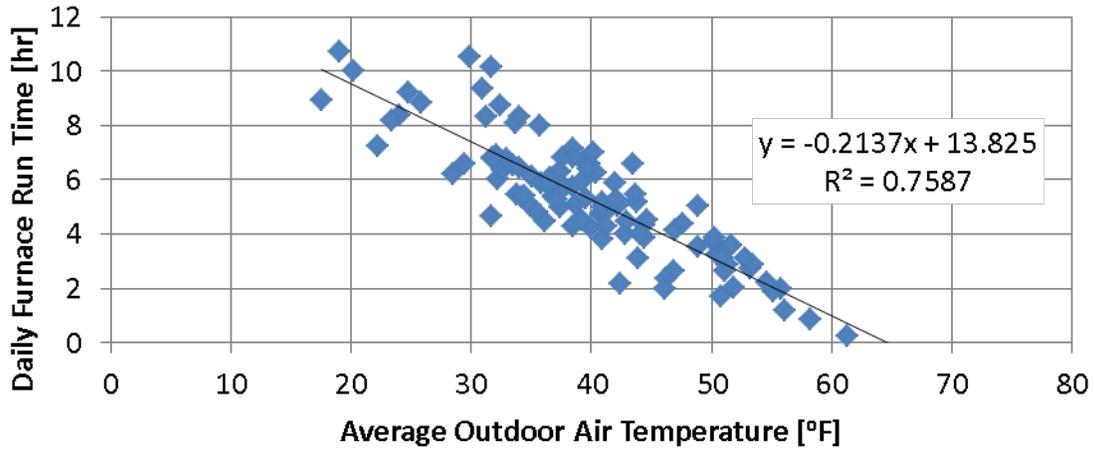


Site 12: Fan Energy vs. Sensible Heat Removed

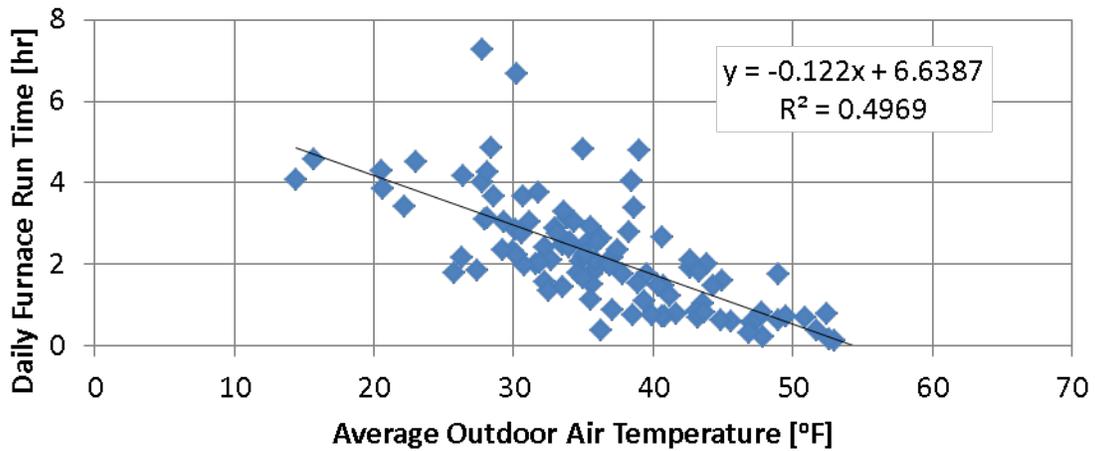


## Appendix C: Furnace Runtime Versus Average Outdoor Air Temperature

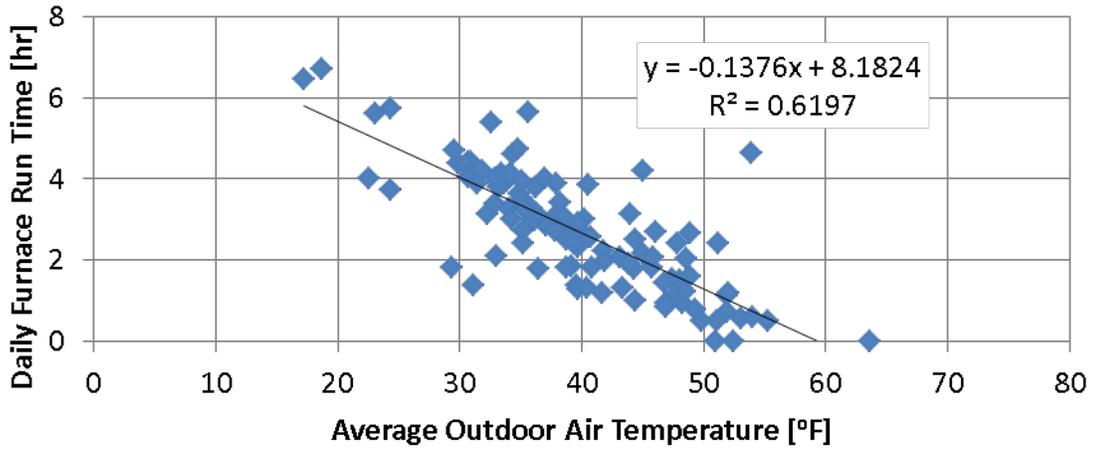
### Site 1: Furnace Runtime vs. Average Daily OAT



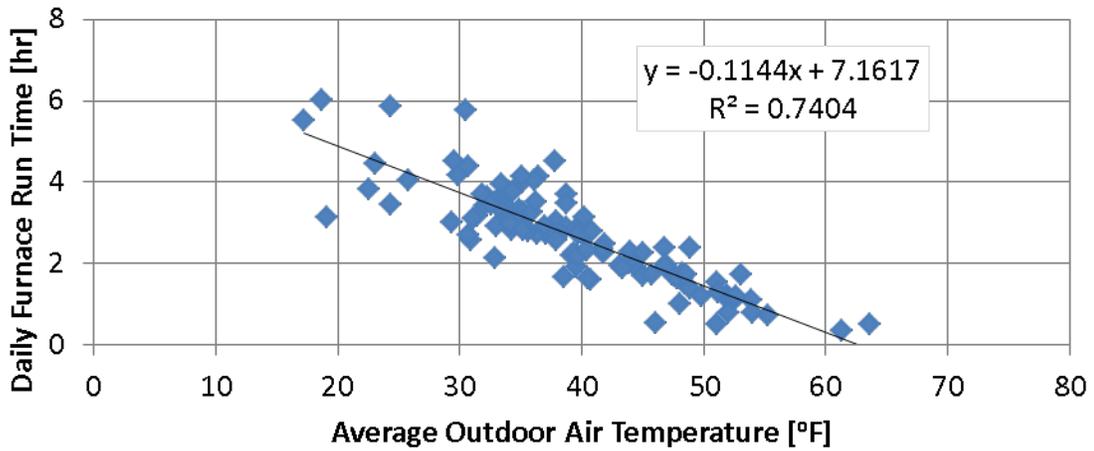
### Site 2: Furnace Run Time vs. Average Daily OAT



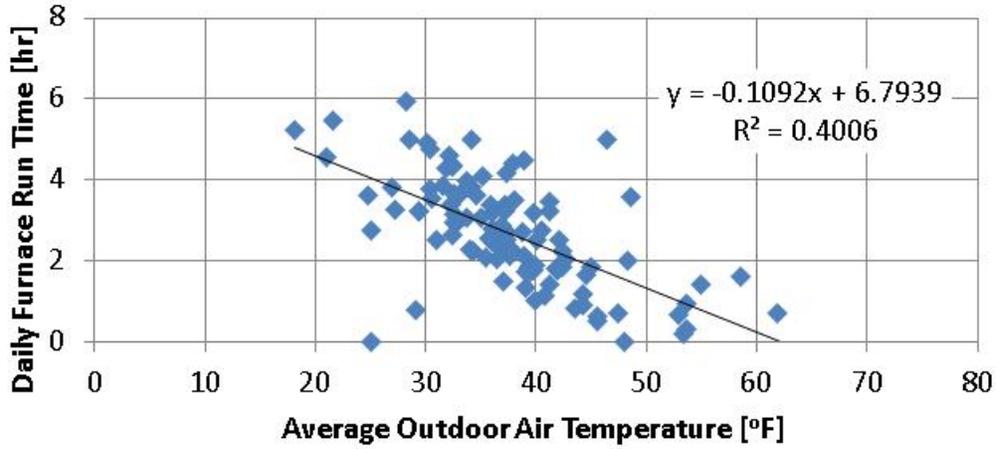
### Site 3: Furnace Run Time vs. Average Daily OAT



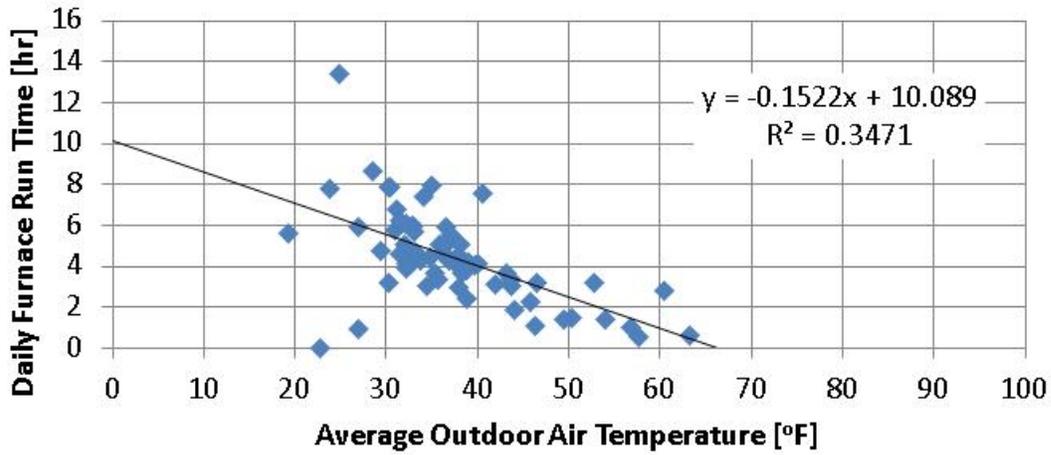
### Site 4: Furnace Run Time vs. Average Daily OAT



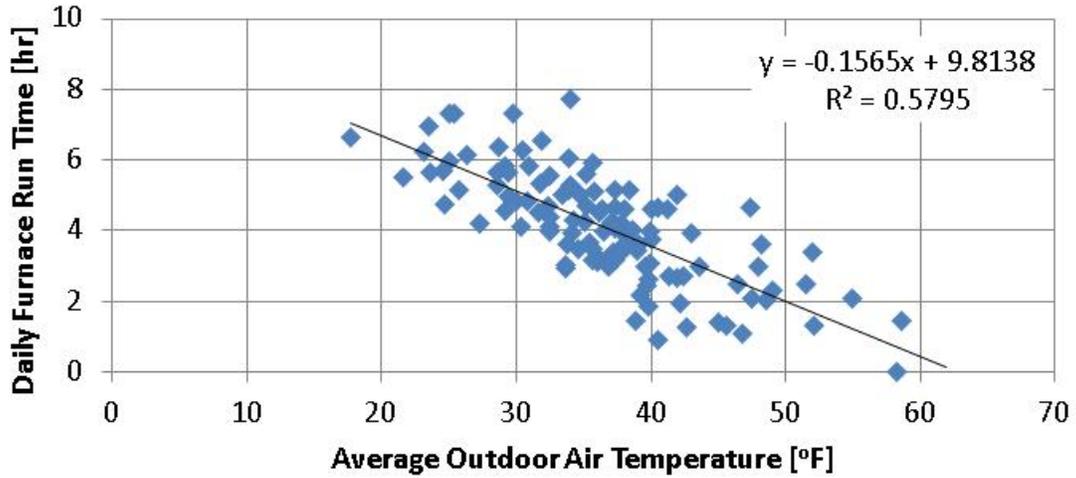
### Site 5: Furnace Run Time vs. Average Daily OAT



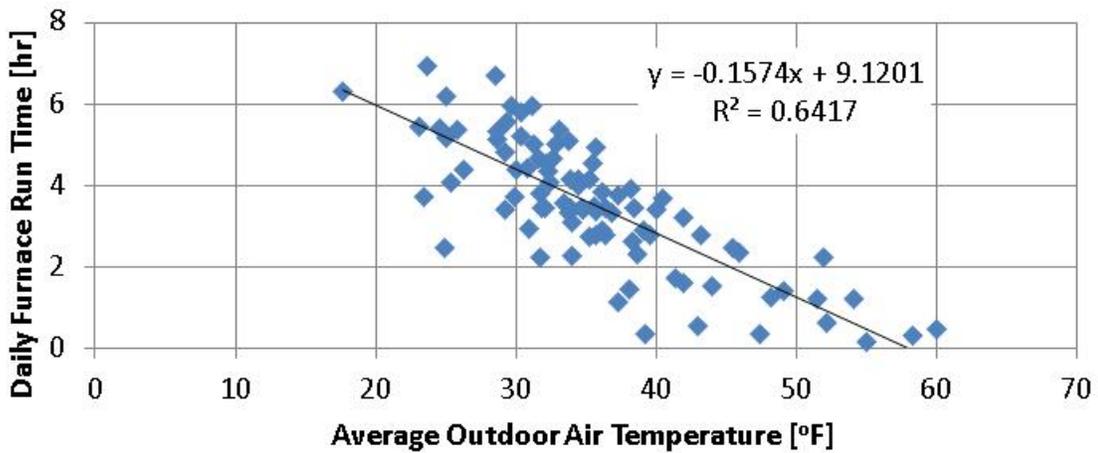
### Site 7: Furnace Run Time vs. Average Daily OAT



Site 10: Furnace Run Time vs. Average Daily OAT



Site 12: Furnace Run Time vs. Average Daily OAT



## Appendix D: Installation Questionnaire

### Replacement BPM Motor Evaluation: Installer Survey

Site name:

Address:

Site number:

Installation Date:

Installer(s):

1. How much time did it take to install the new motor? Person-hours?

2. Were there any challenges you didn't anticipate? If so, describe.

3. Were any tools or parts needed that you didn't anticipate? If so, describe.

4. Did you have documentation (manuals, e.g.) for the equipment at the home? Was this (or would this have been) helpful to the installation?

5. Did the ease or difficulty of the installation depend on the specific equipment in this home?

6. Could the installation be streamlined by knowing more about the equipment already installed? If so, describe.

7. Do you think future installations could be streamlined in other ways? How?

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