Final Report

Brushless Fan Motors Impact Evaluation

Part of the Massachusetts Residential Retrofit and Low Income Program Area Evaluation

June 2012

Prepared by:

The Cadmus Group, Inc. / Energy Services
720 SW Washington Street, Suite 400
Portland, OR 97205
503.228.2992

Navigant
Opinion Dynamics Corporation
Itron
ERS

Prepared for:

The Electric and Gas
Program Administrators
of Massachusetts

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1. Executive Summary

This report presents the evaluated gross impact savings of brushless fan motors (BFMs) incentivized as a part of the Cool SMART program for upgrading heating, ventilating, and air-conditioning (HVAC) units. The following companies, collectively referred to as the Evaluation Team, conducted the research: The Cadmus Group, Inc. (Cadmus), Opinion Dynamics, Navigant Consulting (Navigant), Itron, and Energy and Resource Solutions (ERS).

In this energy conservation measure, the BFM replaces an existing permanent split-capacitor induction (PSC) alternating current (AC) motor with a direct current (DC) BFM. To be eligible for the program, the motor must serve the air distribution fan in an eligible hot air furnace or heat pump. The furnace may provide heating only or be capable of providing air-conditioning as well.

The BFM is a measure offered under the COOL SMART program implemented by Conservation Services Group (CSG).   COOL SMART is offered by the Program Administrators (PAs) National Grid, NSTAR, WMECO, Unitil, and Cape Light Compact in Massachusetts and by National Grid in Rhode Island. COOL SMART provides incentives for HVAC contractors to actively promote the replacement of existing eligible forced hot air system fan motors with BFMs. This evaluation does not address the performance of a similar technology referred to as an electrically commutated motor (ECM) offered as a lost opportunity measure.

This evaluation used on-site spot measurement and long-term metering of motors to determine the savings impact of a statistically significant sample of participants. The savings results are provided in Table 1.

Table 1. Summary Heating and Cooling Results

Item	Evaluated Savings	MA TRM Savings
Annual kWh motor savings	246 kWh	600 kWh
Direct motor savings kWh	219 kWh	
Interactive cooling savings kWh	27 kWh	
Interactive heating penalty (mmbtu)	-0.676 mmBtu	-1.575 mmBtu
Connected kW	0.182 kW	0.116 kW
CF – summer	0.26	0.67
CF – winter	0.25	0.50
Summer demand savings (kW)	0.047	0.078 kW
Winter demand savings (kW)	0.038	0.058 kW
Annual Equivalent Full Load Hr	1,493 hrs measured	5,172 hrs implied

The sample precision for all units is ±18% at an estimated 90% confidence interval. The summer demand coincidence factor is calculated using ISO-NE definitions of peak period. Both the energy and demand savings include the cooling interactive effect. The energy realization rate for all units is 41% of tracking energy use.

Based on the stated wattage reduction of the tracking estimate, the deemed savings value implicitly assumes that the motors operate more than 5,000 hours per year. Logging, however, showed that the BFMs operated in Auto mode, cycling to maintain temperature set points, and averaged about 1,493 hours per year in operation. The findings are supported by other studies and findings. The 1,493 annual hours correlate well with the Massachusetts Technical Reference Manual (TRM) reported equivalent full load hours for heating (1,200 hours) and cooling (360 hours) for residential applications (sum of 1,560 hours). After the motor change out, there was no evidence of a change in user behavior that would have increased or decreased the hours of operation. That was also the conclusion of a report prepared by the same Evaluation Team earlier in 2011, based on telephone surveys of participants.

The average energy savings calculated includes interactive savings due to the reduced cooling load from a more efficient motor assuming an SEER of 8.3. The heating penalty is calculated assuming 78% forced hot air efficiency.

The savings for a heating only retrofit application is based on the same data, but excludes cooling hours of operation.

2. Background

This section describes the program, its objectives, and key elements of this project.

Evaluation Objectives

The goals of the 2011 impact evaluation are to identify the savings associated with BFM retrofits in residential HVAC applications, to quantify underlying parameters in the savings, and to determine factors that may drive the savings. To that end, the objectives include:

- Verify the energy and demand savings of BFM retrofits for the combined Massachusetts and Rhode Island programs
- Identify the relationship between demand estimates made using contractor measured volts and amps and the true kW
- Determine the total hours of operation of the motor and the contribution of the heating and cooling operation to that total
- Assess the types of systems in which the BFMs are installed and ascertain parameters that impact savings, such as system type (i.e., condensing or non-condensing) or control strategies (i.e., cycling or continuous fan control).

Program Description

After the success of a Cool SMART pilot that incentivized BFMs in new high-efficiency furnaces, BFMs were piloted as a retrofit measure in 2009 and rolled out as a program measure in Massachusetts and Rhode Island in the 2010 program year. The BFM replaces the fan's existing permanent split-capacitor induction (PSC) motor.

The BFM measure is managed by Conservation Services Group (CSG), in Massachusetts and Rhode Island, as part of COOL SMART. The program creates incentives for HVAC contractors and customers to actively promote the replacement of existing forced hot air units with well-sized, well-installed, high-efficiency units and to retrofit existing fan motors with BFMs.

About 20 qualifying HVAC contractors are authorized to offer PA customers a BFM as a replacement for the existing standard motor serving an eligible HVAC unit. HVAC contractors are required to screen sites for eligibility and record and provide a set of measurements that characterize the pre- and post-installation performance of the motor. In return, contractors are provided a fixed incentive for each completed site. Table 2 compares the key program parameter features of the 2009 pilot and the 2010-2011 program. These parameters were extracted from contractor agreements dated May 2009 and February 2010.

Table 2. BFM Program Implementation Features

	PY 2009 (pilot)	PY 2010 & 2011
Eligible equipment	Forced warm air furnaces Forced warm air heating systems with central cooling Air source heat pumps	Added: Hydro-Air Handler operating in Heat mode?
Qualifying motor	Concept 3 and Evergreen ½ hp Provided to contractor	Range increased to include 1 hp Fan must be purchased by contractor
Incentive	$225, no cost to customer	$450
Static pressure	None	Maximum of 0.8" WC
Agreement Date	May 12, 2009	Feb 18, 2010

HVAC contractors do not typically market the BFM, but offer it as an added service in conjunction with another service call.

Deemed Measure Savings

The energy and demand savings recorded in PA tracking systems is a deemed savings value documented in the Massachusetts *Technical Reference Manual for Estimating Savings from Energy Efficiency Measures (TRM)*. The 2011 version, 2011 Program Year – Plan Version, dated October 2010, reports an annual savings of 600 kWh for a BFM.

The source of the deemed savings value, according to a footnote in the TRM, is a paper titled "Saving Energy with Efficient Residential Furnace Air Handlers: A Status Report and Program Recommendations," by Harvey M. Sachs and Sandy Smith, April 2003, prepared for the American Council for an Energy-Efficient Economy (ACEEE). The purpose of that report was to examine and present the national potential for more efficient furnaces, primarily in the new construction market. Secondary estimates of savings from an ACEEE-sponsored study and GE, a motor manufacturer, were sited, both of which were intended to provide average national savings. The hours of operation implicit in the deemed savings can be back-calculated by dividing the energy savings (600 kWh) by the connected load (0.116 kW), resulting in 5,172 hours.

Because the ACEEE report focused on the new construction and national market potential, the resulting savings estimates for BFMs may not be directly applicable to retrofit applications where the furnace and its controls are not optimized to take advantage of the BFM features.

It should be noted that the HVAC contractors participating in the current BFM program measure and record amperage readings before and after the installation of the BFM. The measurements are entered into a database maintained by CSG and provided to the PAs on a regular basis. Theoretically, the amperage readings could be used as a source for estimating demand savings and, with an estimate of annual operating hours, energy savings as well. Although the data are available, the PAs do not incorporate them into their tracking estimates of savings, but use the TRM deemed savings value instead.

Brushless Fan Technology in Retrofit HVAC Applications

The BFM retrofit measure replaces an existing less efficient motor with a much more efficient motor to drive the fan in a forced hot air furnace. The motor load, controls, and supply air delivery (cubic feet per minute or CFM) are expected to remain constant both before and after the motor replacement. This measure saves demand because it uses less power to deliver the same CFM to the conditioned space. The energy savings are a function of the change in power consumption and annual hours of the fan's operation.

BFM Technology

The BFM is a brushless DC motor that controls fan speed with a microprocessor-based variable speed controller (inverter). The existing motor is a standard AC induction motor with a start-up capacitor and is, therefore, called a PSC (permanent split capacitor) motor.

Rotor slip is a requisite element of standard AC induction motor operation. The rotor must rotate at a speed below the synchronous speed determined by the number of poles and the frequency of the AC line current. The speed difference, or the slip, is what induces the currents in the rotor necessary to produce torque. It is the torque generating rotor current and the fields it produces that cause high energy losses in the rotor, which can increase dramatically if the slip is more than a few percent. Slippage increases as the motor unloads, reducing the efficiency of the motor at part loads.

Because DC motors are synchronous machines, the BFM rotor does not slip to change the speed of the rotor. The efficiency of DC motors and the BFM, in particular, is higher than induction motor efficiency because there are no losses in the rotor. Further, speed and torque can be easily changed by adjusting the voltage and current delivered to the motor, maintaining maximum efficiency over a wide operating range.

A PSC motor can have efficiencies as high as 62% when fully loaded, while the BFM can be as high as 80%. This measure saves energy because it is approximately 19% more efficient than a PSC motor at full load (percent saved is a function of 1/62% - 1/80%). At less than full load, the power savings can be even greater because the efficiency of a PSC drops off dramatically (into the 20% range), while the BFM efficiency stays relatively constant throughout the load range.

In this retrofit application, the demand on the fan motor is set by the total CFM of conditioned air delivered to serve the conditioned space and the static pressure presented by the ductwork.

The motors used are designed with four fixed-speed point settings. When the HVAC contractor installs the BFM, the 24-volt control wires corresponding to the Heating and Cooling mode operation are connected to the relays activating one of the speed point settings. These speed points are unlikely to be exactly equivalent to the existing (pre-retrofit) motor speed settings. The nature of the BFM motors, unlike standard motors, means that the power will increase to maintain the air flow as static pressure increases.

The particular motor model used by the contractors is the EverGreen IM. The motors are designed to operate at fixed torques to correspond to the typical RPM outputs of motors used for blower motor applications. The motors can be configured to match three horsepower ranges (1/5 to ¼, ¼ to 1/3, 1/3 to 1/2), with four corresponding equivalent speed points each, providing twelve output settings. When the HVAC contractor installs the BFM, the motor power is set first. Then the 24-volt control wires corresponding to the Heating and Cooling mode operation are connected to the relays activating one of the equivalent speed point settings.

Retrofit Furnace Application

The eligible HVAC units in this study are residential forced hot air furnaces with a fan for distributing warm air through the ductwork. Units may be equipped with direct expansion coils for providing central air conditioning as well. Heat pumps are also eligible.

Fans in units with cooling and heating capability are designed to operate at multiple speeds: a low speed in winter and a high speed in summer (sometimes with an additional speed for two-stage compressors and/or two-stage heating). The speed selection is typically made through the thermostat and depends on the selected mode, either Heating or Cooling. In the Heating mode, the air-conditioning is locked out, and heating is enabled. As the space temperature at the thermostat drops below the set point, the furnace is fired to provide heating until the temperature rises above the set point, at which point the gas firing is cycled off. Operation in the Cooling mode is similar.

Thermostats typically permit setting the fan operation independent of the mode. The fan can be set to run continuously in the On mode, or to cycle to meet the set temperature in the Auto mode. In the Auto mode, the fan will cycle with the furnace firing or compressor operating, and a fan in the Auto mode will operate for fewer hours than a fan in the On mode. One goal of this 2011 evaluation was to determine the fan mode of operation and to find out through interviews whether the residents of the home changed the mode as a result of the motor change out.

Other Research

As part of this study, the Evaluation Team examined other research, which is referenced in this report and listed below.

Evaluation Report Massachusetts 2010 Residential Retrofit and Low-Income Evaluation – Brushless Fan Motors, April 2011, prepared by the Evaluation Team for Gail Azulay of NSTAR.

That report included the results of interviews of customers and contractors participating in the BFM sub-program of COOL SMART. The major finding as it relates to November 2011 study was that there was minimal evidence of snapback. Snapback would have occurred, if customers had changed the way they operated the furnace as a result of the motor change out, resulting in an increase in hours of operation of the motor. The survey confirmed that the net change in customer behavior is null, with a few customers reporting an increase in hours (6%), counter balanced by a few reducing hours (3%). The majority (84%) reported no change in behavior.

Saving Energy with Efficient Residential Furnace Air Handlers: A Status Report and Program Recommendations, April 2003, prepared by Harvey M. Sachs and Sandy Smith, for the American Council for an Energy-Efficient Economy.

That report examined the national potential for more efficient furnaces, primarily in the new construction market. Secondary estimates of savings from an ACEEE-sponsored study and GE, a motor manufacturer were sited, both of which were intended to provide average national savings. The hours of operation implicit in the deemed savings can be back-calculated by dividing the energy savings (600 kWh) by the connected load (0.116 kW), resulting in 5,172 hours.

Because the report focused on the new construction and national market potential, the resulting savings estimates for BFMs may not be directly applicable to retrofit applications where the furnace and its controls are not optimized to take advantage of the BFM features.

2006 Massachusetts and Rhode Island COOL SMART Evaluation Report, April 2007, prepared by Wirtshafter Associates, Inc., for the Massachusetts PAs.

That report covered an evaluation of the COOL SMART program with an emphasis on unit sizing, installation, and maintenance of units in the replacement context. The fan motor was not addressed directly in the evaluation; however, the field findings showed inadequate ductwork in larger systems that would lead to excessive static pressure.

BPM Motors in Residential Gas Furnaces: What are the Savings?, May 2006, prepared by James Lutz, Victor Franco, Alex Lekov, and Gabrielle Wong-Parodi, Lawrence Berkley National Laboratory.

That study compared theoretical models of BFM retrofit savings as affected by existing static pressure. The study found that with a relatively high static pressure presented by the ductwork, the savings of the BFM retrofit would be less than expected because the BFM delivers a higher CFM than the standard motor, hence uses more power. Under standard test procedures with lower duct pressures and a constant airflow, BFM savings are projected to be 41%. Under higher static pressures and a constant airflow, BFM savings may be only about 10%.

Electricity Use by New Furnaces, A Wisconsin Field Study, October 2003, prepared by Scott Pigg, Contractor: Energy Center of Wisconsin for the State of Wisconsin, Department of Administration, Division of Energy, Residential Programs.

That study compared BFM and standard motors in new condensing furnaces, which are designed to operate the fan motor continuously at low flow. The BFMs in that control mode were found to contribute significant savings. Relevant to this November 2011 evaluation, the field measurements showed the BFM power factors in the 0.6 to 0.8 range, while the standard motors showed power factors in the 0.8 to 0.9 range.

3. Sampling Strategy

This section describes the sample strategy, the methods adopted to mitigate any bias introduced by the meter deployment strategy, and the final sample disposition.

Sampling Strategy Details

The prime objective of this evaluation is to verify BFM savings, with an acceptable precision, at an acceptable cost. As no data were available characterizing the variability of BFM installations, a coefficient of variation (CV) had to be assumed to calculate sample sizes. An assumed CV of 0.4 and a budget-constrained sample of 40 sites yielded a precision of about 10% at the 90% confidence interval.

Given the lack of knowledge about the site-to-site variability of realization rates and the small sample sizes allotted to this study, the results were not likely to be statistically reliable by PA or even by state. The realistic goal was to achieve reasonably good precision study-wide and identify areas that should be investigated further in future evaluations. The sample allocation by state is summarized in Table 3.

Table 3. Design Sample Allocation by State

	Massachusetts	Rhode Island
Expected number of participants in 2011	800	100
Sample allocation	30	10
Sample rate	4%	10%

To select sites for monitoring and verification (M&V) activities, the Evaluation Team considered two approaches:

- A retrospective sampling approach using the 2010 participants as the sample frame. In this approach, a random sample of past participants would be selected for on-site M&V. These customers would have to be recruited and visited twice by the Evaluation Team engineer, once to deploy the loggers and a second time to pick up the loggers.
- An in-stream deployment strategy, where the HVAC contractors would deploy loggers at homes of customers as they participate in the program. In this approach, the contractors would recruit the customer for M&V activities after the customer agreed to the motor replacement. Only one site visit would be required by the Evaluation Team engineer to pick up the loggers.

There are two advantages to having the HVAC contractor deploy the loggers: first, it saves the cost of additional customer recruitment and a site visit. Secondly, the customer is not inconvenienced by another site visit and, therefore, is more likely to agree to serve as a metered site.

The disadvantage of the in-stream approach is the contractors may change their implementation behavior as a result of participating in the deployment; and the sample is not randomly selected from all participants, but rather from within the contractors' pool of customers participating within a narrow window of time.

The in-stream methodology was selected for the following reasons. The cost of the retrospective approach is about twice that of the in-stream approach because of the two site visits. The team agreed that the value of twice as many additional customer sites per budget dollar outweighed the potential for bias with the in-stream approach and that steps could be taken to mitigate bias. Secondly, the retrospective approach would be expected to result in a much higher rate of customer refusal, introducing a self-selection bias.

To assure a high rate of compliance, both the HVAC contractor and the host participant received incentives from the PAs for their role in the M&V activities.

Mitigation of Bias from In-Stream Sampling

Bias can be a concern with an in-stream sampling strategy that depends on the installation contractor to install the loggers. To minimize the bias of any particular contractor, the Evaluation Team selected six contractors as logger deployment partners. To arrive at the six, the contractors were stratified into a very active pool, a less active pool, and an excluded pool that consisted of contractors with fewer than 10 installs through October 2010. Three active and three less active contractors were recruited and agreed to install loggers, as illustrated in Table 4.

Table 4. HVAC Contractor 2010 Installs and Site M&V Initial Allocations

Contractor	Activity Level	Total Installs - to October 2010	Initial Sites Allocated
Chaves H&AC	High	149	16
Lawrence Air Sys	High	32	10
Aair Systems	High	33	8
Northern Comfort	High	53	
Abell's One Hour	High	39	
Climate Concepts	High	32	
Eaton Mechanical	Low	15	2
Middlesex Cooling	Low	14	2
TAG HVAC	Low	17	2
Boucher Energy	Low	8	
Victory Mech	Low	7	
Providence Mechl	Excluded	5	
Tom Fricker HVAC	Excluded	5	
Acton Refrig	Excluded	4	
Mark E. Meacham	Excluded	4	
Muirfield Mech	Excluded	3	
Keyes NA	Excluded	1	
Totals		421	40

Another source of bias can be introduced by contractors in their selection of houses for logging. To minimize that, the Evaluation Team provided the contractors with a protocol for selecting a site for recruitment. The protocol had to protect against a contractor installing all the loggers in a single neighborhood, yet be simple enough that the contractor would comply. The team considered various random selection protocols, but they seemed too complex given the few loggers allocated to most contractors. In addition, the skips in a random process could defer logger placement long enough to miss the heating season.

For all but the firm Chaves H&AC, the team instructed the contractors to install loggers at every sale until all of them were distributed. The less active contractors had to install meters at every sale to ensure the loggers were deployed in the winter season.

The Evaluation Team instructed Chaves H&AC not to concentrate the loggers in a single neighborhood. Chaves has multiple installation crews, so distribution of the loggers across all of the teams and a protocol to select the first sale of the day were considered sufficient to ensure sites were not concentrated in a homogenous pocket of homes.

Final Sample Disposition

Table 5 presents monthly summary statistics of the program participation and logger installation rates by state for 2010 and 2011.

Table 5. Participation and Logger Install Rates

Item	Jan	Feb	Mar	Apr	May	Jun	Total
MA 2010 BFM installs	39	67	86	41	69	12	314
MA 2011 BFM installs	19	12	25	17	8	11	92
MA Logged Sites	1	3	5	3	3	1	16
RI 2010 BFM installs	2	4	3	2	16	4	31
RI 2011 BFM installs	5	29	12	6	8	na	60
RI Logged Sites	4	6					10
Total Logger Sites	5	9	5	3	3	1	26

Loggers were installed at 26 residences: 10 in Rhode Island and the balance in Massachusetts. The smaller than planned sample was due to the sharp downturn in program participation in Massachusetts. The Evaluation Team extended the recruitment period to pick up additional sites, but program participation was weak in the spring of 2011. Nonetheless, the sample captures about 17% of the participants in the program through June 2011 in Massachusetts and meets the Rhode Island quota of 10 sites.

According to the contractors, the more stringent screening implemented in mid- to late 2010 was a leading cause of the 80% decline in installs in 2011 in Massachusetts. The new criterion required the static pressure served by the fan to not exceed 0.80" water column (W.C.), a design change intended to ensure a minimum savings threshold. However, contractor agreements indicate the more stringent screening was implemented early in 2010 and, therefore, should have had an impact on the installation rates for most of 2010. As of this writing, the reasons for the 2011 downturn in participation are not clear to the Evaluation Team.

The HVAC contractors' disposition of loggers is summarized in Table 6.

Table 6. HVAC Contractor Site Disposition

	Initial Allocation	Installed Sites
Chaves H&AC	16	5
Lawrence Air Sys	10	10
Aair Systems	8	6
Eaton Mechanical	2	0
Middlesex Cooling	2	2
Climate Concepts	2	3
Total	40	26

4. Methodology

This section describes the on-site procedures for data gathering and the calculation methods.

On-Site Data Gathering

On-site data include measurements by the HVAC contractor at the time of the BFM installation, the one to eight months of logging by metering equipment installed by the HVAC contractor, and the subsequent spot M&V conducted by the Evaluation Team engineer.

HVAC Contractor Site Visit

Typically, the HVAC contractor presents the BFM option to a customer as part of a service call. To qualify for the program incentive, the HVAC contractor measures the amperage of the existing standard motor in both the Heating and Cooling mode, as well as the amperage of the new motor. The contractor measures voltage as well. These values are recorded on an application that is sent to CSG for processing.

The equipment used by the contractor to measure amperage is not specified by the Cool SMART program, and the make and model will vary by contractor. In most cases, the measurements are taken using a hand-held, pocket multi-meter, capable of measuring instantaneous amperage and voltage. The expected accuracy of such a device might be ±3% of the reading.

For those sites selected for M&V activities in 2011, the HVAC contractor was required to take additional steps. The contractor had to explain the purpose of the evaluation and recruit the customer, offering a $25 gift card as an inducement. The customer had to sign a consent form, and the contractor had to record information regarding the install.

The HVAC contractors installed two loggers provided by the Evaluation Team, which are described below in more detail. The HVAC contractors were paid $50 for each site with completed paperwork.

Metering Equipment

The primary objective of installing long-term metering equipment was to determine the actual hours of operation of the installed motors and to determine, through observations of operating patterns, how customers operated the fans (in Auto or On mode). It was also important to meter across the seasons – winter, summer, and swing season – to determine any seasonal differences in operation. As a consequence, the plan was to leave the metering in place from about January to August to capture the full range of seasonal performance. In addition, because almost all of the motors were multispeed, the actual amperage draw of the motor would have to be measured rather than just the on/off status, to determine the hours of operation at each speed.

The challenge of the metering plan was to select equipment that had the capacity to store all of the values acquired over an eight-month period. The solution was to install two loggers at each site: an amperage logger and a change of state logger.

- The amperage logger tracked long-term motor draw, indicating when the high and low speed modes were operating. The logger was programmed to take a snapshot recording of the amperage every six minutes. This strategy ensured that the collected data would not over run the memory limits of the device.

- The change of state logger recorded each time the motor started or stopped and was the source of the actual run hours. This logger had the memory capacity to accurately record every cycle which occurred in the logged period.
- Together, the two loggers provided redundancy if either one failed. A reasonable estimate of cycling could be derived from the amperage logger data, and the mode of the motor operation could be estimated from temperature data, if necessary.

In addition to the loggers, the Evaluation Team engineer measured the motor amps, volts, and power factor of the BFM at each site.

The equipment used in this study is summarized in Table 7.

Table 7. Evaluation Team Metering Equipment

Description	State Logger	Amp Data Logger	20 Amp CT	Hand Help Power Meter
Manufacturer	Dent Instruments	Onset	Sentranscorp	Amprobe
Model	TOUCT-3G	U12-006	4DS-20A	ACD-31P
Accuracy	0.25 Amp min trigger	+/- 0.3A		+/- 0.4A

Site Pick-up Activity

After a solid period of summer seasonal weather, beginning in August 2011, customers were contacted to arrange for logger pick-up. When the loggers were collected, the Evaluation Team interviewed the customer about the normal operation of the furnace. The team engineer re-measured the motor for true kW and the amps, volts, and power factor, and noted the thermostat control settings as well.

Savings Calculations

The savings calculations are derived from metered and observed data collected from the following sources:

- HVAC contractor measured spot amperage and voltage measures, pre and post
- Evaluation Team engineer measured power factor measurements, post
- Long-term amperage measurements, post
- Long-term motor cycling measurements, post
- Observation of thermostat control settings and discussion with the customer.

These data were gathered for each site and processed.

The BFM saves demand (kW) because it is more efficient, drawing less power than a PSC motor, assuming the same air delivery and static pressure. The annual energy savings are a function of the demand savings (kW) and the measured hours of operation, assuming the motor is operated under the same control strategy both before and after the motor installation. The actual savings calculations, therefore, consist of two distinct parts:

- Determining the motor power usage of the existing standard induction motor and the replacement BFM, the difference of which is the connected demand savings
- Determining the hours of operation of the motor.

The next section presents a disposition of the data and the protocol for estimating when one or more of the data elements is missing. That is followed by a description of the calculation methods.

Data Disposition

Table 8 summarizes the metering data that was available for analysis. As noted earlier, program participation in 2011 dropped off by 80% from 2010 in Massachusetts, and that is reflected in the fewer number of sites participating in the study. In addition, one contractor installed the loggers incorrectly, so long-term data could not be used from five sites. Some of the sites that installed BFMs late in the study timeframe only had summer data available for analysis.

Table 8. Data Collection Disposition

Item	Number of Units	Purpose
Population through June 2011	152	
Site recruitment goals	40	
Sites actually recruited with some data available	26	
Contractor spot measurements	25	Pre amps and volts
Spot measurements	25	Power factor
Sites with at least one month of good logger data	21	
Sites with at least cooling hours	21	Cooling hour calculation
Sites with heating and cooling hours	20	Cooling and heating hour calculations

Some level of site-specific data was collected from all 26 sites, whereas 17 sites had a complete set of data. The protocol for calculating savings was to use a site-specific value, if it was available, or use a population average, if the value was unavailable. Table 11 indicates where site specific or average values were used by site.

Calculation of Motor Power Savings

The motor connected demand savings is the difference between the existing (pre-retrofit) and post-installed motor wattage. Because most of the motors operated in a Heating and Cooling mode, there were two demand savings levels, one for each per mode.

The governing equation for the power draw of a single phase motor was calculated as follows:

W = V x A x PF

Where

V = volts

A = Amperage

PF = Power Factor

W = Watts

Table 9 illustrates the sources of the factors used in the CSG date set calculations (Tracking row) and those used by the Evaluation Team to calculate motor watts (Evaluated row).

Table 9. Motor Power Calculation Sources

	kW calculation	Volts	Amps	Power Factor	Notes
Tracking	Tracking pre-installation motor kW, summer and winter mode	Tracking volts measured by installers	Spot measurement, recorded and entered into CSG tracking Four measurements: pre/post in winter mode, pre/post in summer mode	Assumed to be 100% in CSG tracking	Exact state of the unit (open or closed), accuracy of the measurement, actual voltage and power factor are unknown. Taken by contractor on the day of the motor replacement
	Tracking post-installation motor kW, summer and winter mode				
Evaluated	Evaluated pre-installation motor kW, summer and winter mode	Tracking volts measured by installers	Pre-install tracking amps, with adjustment factor	78%, based on standard practice and limited testing	Power factor measurements taken with the unit opened on the day of logger pick-up
	Evaluated post-installation motor kW, summer and winter mode		Winter and summer average amperage measured over one to eight months	Site measured power factor	

Voltage

Both the tracking calculations and the evaluation calculations used the voltage measured by the vendor at the time of the motor install. Voltage can vary at particular households and seasonally. Evaluator spot measurements of voltage were close to (generally within 1%) the HVAC contractor reported values. The HVAC contractor measured voltage was used in the calculation. Where it was not available, the Evaluation Team measured voltage was used.

Amperage

The amperage measurement is often used as a primary indicator of motor loading, with the assumption that the voltage and power factor remain relatively constant between the pre- and post-case. For this to be true, the air volume delivered and static pressure must remain the same as well.

The most reliable measure of amperage in this study is the measurement recorded by the amp logger placed in the HVAC unit. The amp loggers recorded amperage under normal operating conditions in both Heating and Cooling mode for up to eight months.

The HVAC contractor measurements taken at the time of motor replacement were the only source of pre-installation amperage available. The HVAC contractors' measurements of post-installation amperage did not correlate well with the logger measure of amperage, as shown in Table 10. These values should have been very close because they both would have measured the same motor at the same load.

Table 10. Comparison of HVAC Contractor Amperage with Long Term Amperage

Site ID	Heating				Cooling			
	Average When On	Max Logger Amps	Tracking Amps	Max/ Tracking	Average When On	Max Logger Amps	Tracking Amps	Max/ Tracking
2117	1.7	2.2	2.6	84%	2.7	3.0	4.5	67%
2119	N/A	N/A	1.4	N/A	1.6	1.7	1.9	93%
2121	1.5	1.7	2.8	61%	3.2	3.6	4.1	88%
2123	2.0	2.8	3.1	92%	2.7	3.0	4.9	60%
2124	N/A	N/A	4.4	N/A	2.9	3.5	5.7	62%
2127	N/A	N/A	2.0	N/A	2.2	2.5	3.3	74%
2128	2.1	3.0	2.4	125%	3.4	3.7	5.0	74%
2129	0.9	1.0	1.1	92%	1.3	1.4	1.6	90%
2131	1.0	1.0	1.0	103%	2.2	2.3	2.7	84%
2132	N/A	N/A	3.0	N/A	2.0	2.5	4.0	61%
2133	0.4	0.4	1.2	34%	0.7	1.7	1.6	106%
2141	0.5	0.5	2.8	20%	0.5	0.6	3.1	18%
2142	1.7	1.9	2.9	65%	2.1	2.4	2.9	82%
2144	2.0	3.0	5.2	59%	3.1	3.4	6.1	55%
2145	2.7	4.1	2.4	172%	2.7	4.1	3.9	105%
2146	2.0	2.5	2.1	122%	2.3	2.9	3.2	91%
2148	N/A	N/A	2.3	N/A	2.8	3.0	2.9	103%
2150	1.5	1.9	0.3	644%	N/A	N/A	0.0	N/A
2151	2.3	2.7	1.0	267%	2.4	2.9	0.5	588%

It is not clear why there was such a poor correlation between the amperage readings. The long term amperage trends did not show an increase or decrease in amperage overtime, which would explain differences. It is possible that there were additional contributing factors to the variation, including accuracy of the contactor amperage measurement device, voltage variations, and open/closed measurements. Other HVAC components (control circuits or condenser fans) might have been included in the measurement. Regardless of the reason, the HVAC contractor pre-installation spot-measured amperage was likely overstated as well.

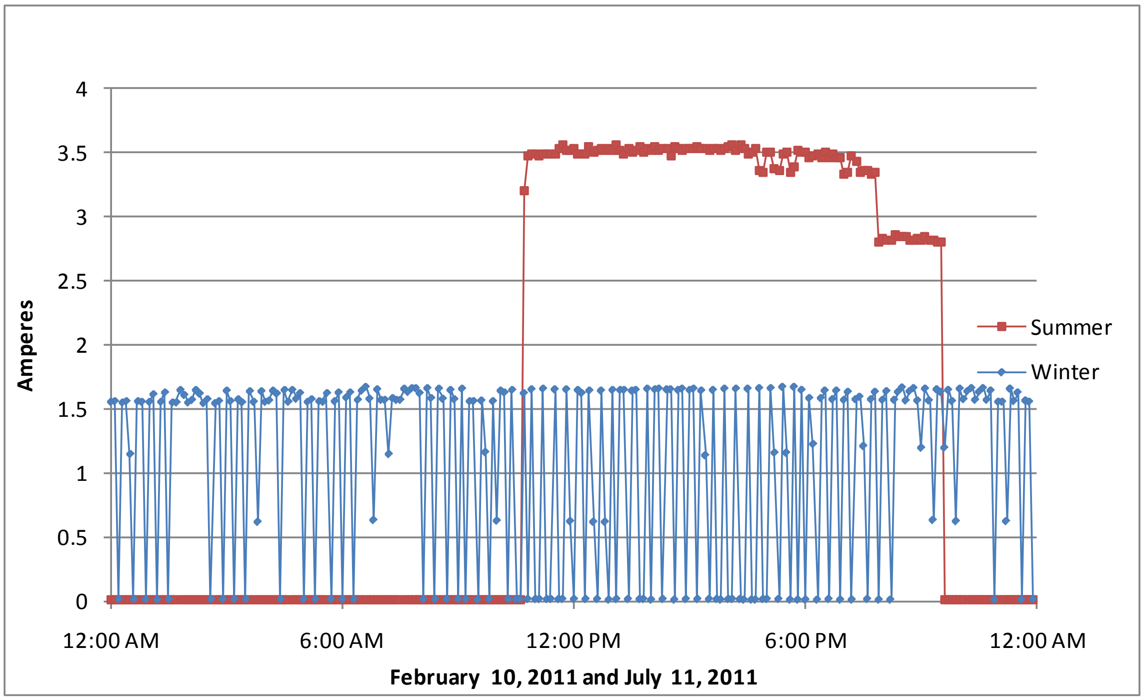
Because the HVAC contractors pre-installation amperage was the only indication of loading before the motor was replaced, it was incorporated in the analysis by necessity. The pre-installation value was calibrated using the ratio of the HVAC contractors' post-installation amperage and the long-term maximum metering amperage. If the ratio was within 20% to 125%, the ratio was used as is in the analysis, while sites outside that range were adjusted using the Evaluation Team's engineering judgment.

Post-installation amperage was derived from the amperage logger and was the average of the measured amperage when the motor was running, by season.

Multispeed Operation

Most of the BFMs operated at multiple speeds, which were clearly discernible in the metered data. Figure 1 presents a typical amperage profile graph for a winter and a summer day.

Figure 1. Typical Amperage Profile



The graph illustrates:

- Winter mode cycling – the motor cycling on and off in response to the thermostat to meet space heating needs. Note how the On periods were longer in the evening when the temperatures were cooler.
- Multiple motor speeds – where the high speed is the summer mode, and low speed is the heating mode. This particular unit appeared to operate on the second stage cooling for most of the day and cycled off to a single stage, and lower CFM, later in the day until the resident turned off the unit.

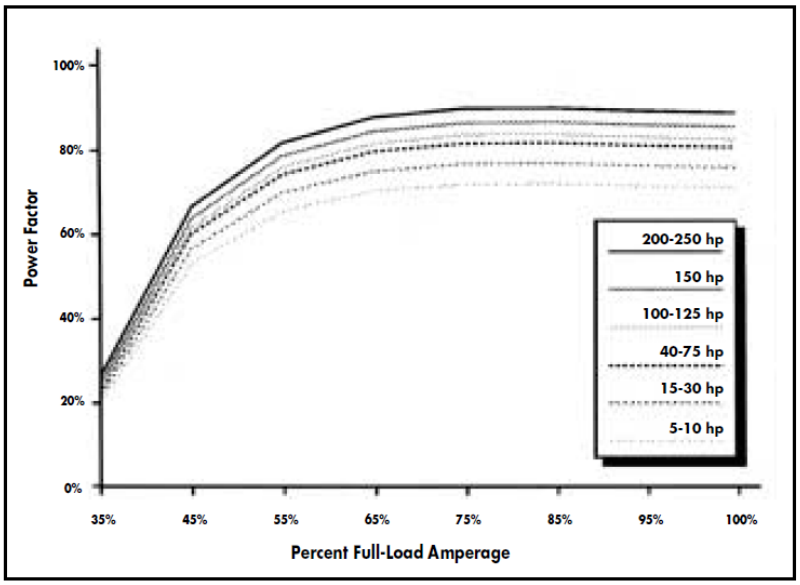
- In the summer mode, the customer ran the unit continuously during the day and shut the unit off at night on this particular day.
- In the winter mode, a few random points appear between 1.5 amps when the motor was on and 0.0 amps when the motor was off. These are artifacts of the logger measurement process. Occasionally, the instantaneous measurement is taken when the motor is ramping on or off and is, therefore, at a lower amperage than the normal running amps.

Power Factor

The power factor accounts for phase shift between the voltage and amperage wave form and is used to calculate the true power used by the unit. The CSG-maintained tracking calculations of pre- and post-installation wattages assumed a power factor of 1. In actuality, the power factor can vary significantly both between motors and over the load range.

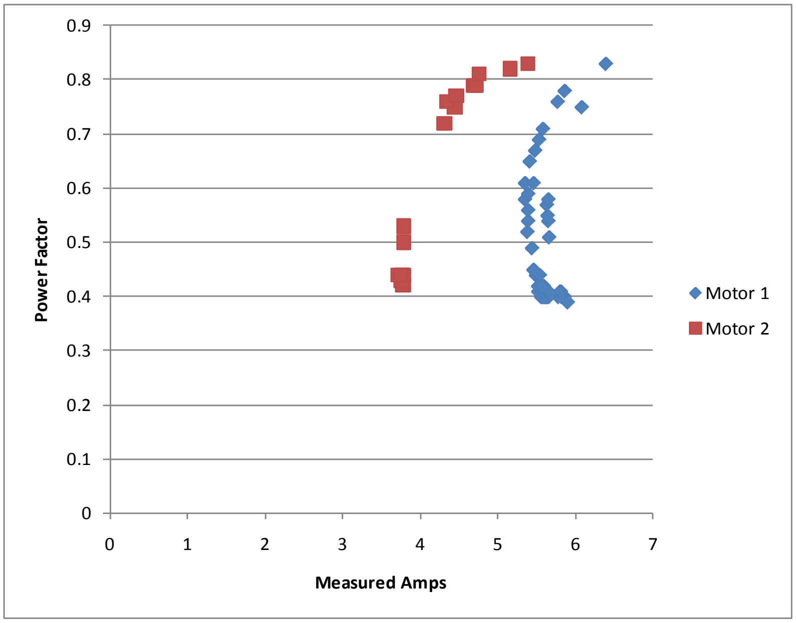
The power factor for an induction motor will typically vary through the amperage range under which the motor operates, as shown in Figure 2, taken from the U.S. Department of Energy Motor Challenge Fact Sheet. The motors depicted in this graph are larger than the BFMs in this study, but the shape of the curve characterizes smaller motors as well. Below 50 to 60%, the power factor begins to drop off dramatically. For a given load served, a change in power factor must be met by a corresponding change in amperage. An improved power factor will result in a lower amperage draw, not a reduction in power consumption.

Figure 2. Typical Power Factor Curve



The Evaluation Team was able to secure two existing motors that had been discarded by the HVAC contractors (the installers) to conduct bench-top testing of the power factor as a function of load. The results of that testing are shown in Figure 3.

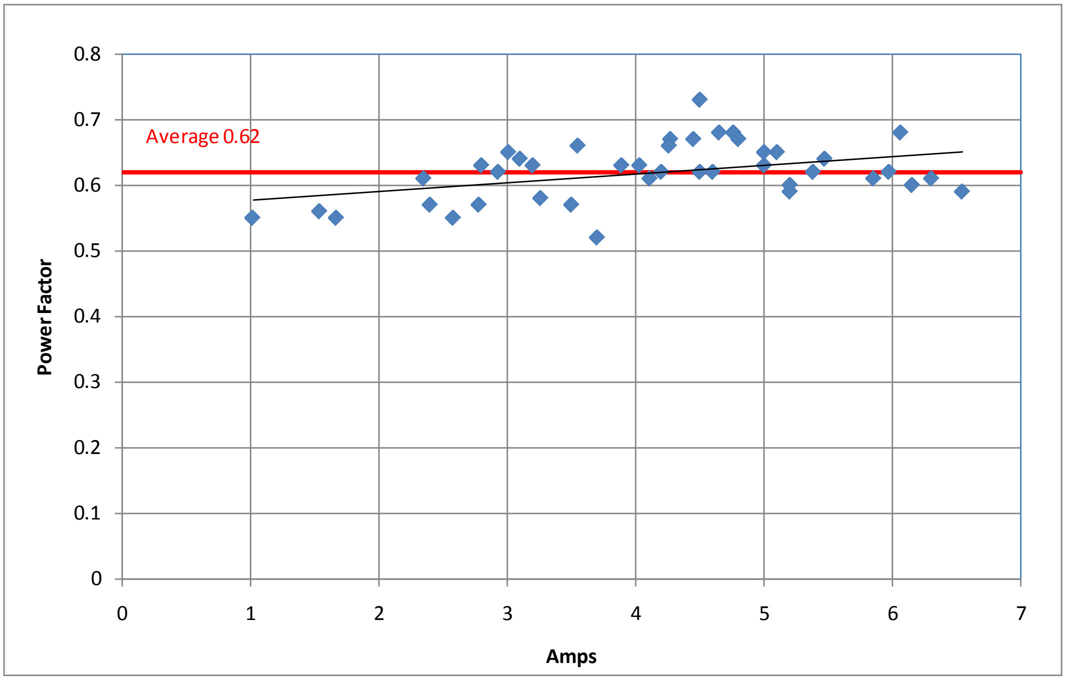
Figure 3. Bench-Top Testing of Discarded Motors



These motors have full load power factors that are typical of fractional horsepower motors and also show a characteristic drop-off in power factor as the motor is unloaded.

The power factor used to calculate the BFM power is based on the evaluator spot measurements of power factor taken at the sites. As can be seen in Figure 4, the power factor is relatively constant over the amperage range measured. The replacement motors are not equipped with a capacitor because this is not required to start the BFMs.

Figure 4. Measured Power Factor of BFM at Pick-up



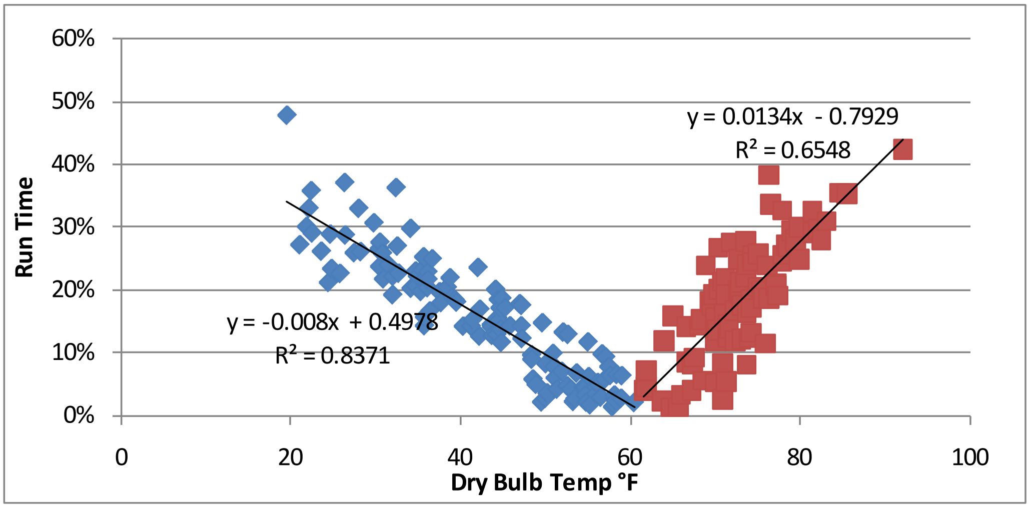
For the purposes of this study, a power factor of 0.78 was assumed for the standard motor. The power factor used for the BFM was the measured power factor, if available, or the measured site average of 0.62, if not.

Calculation of Hours of Operation

The run hours for each mode of operation (Heating, Cooling) were derived from the logged data. The status logger was the primary source for the hours of operation. For each data set that returned good data, the status data were used to produce average runtime percentages per one degree ambient dry-bulb temperature increment. The average runtime percentage was regressed against the dry-bulb temperature for each site for both the heating and cooling periods.

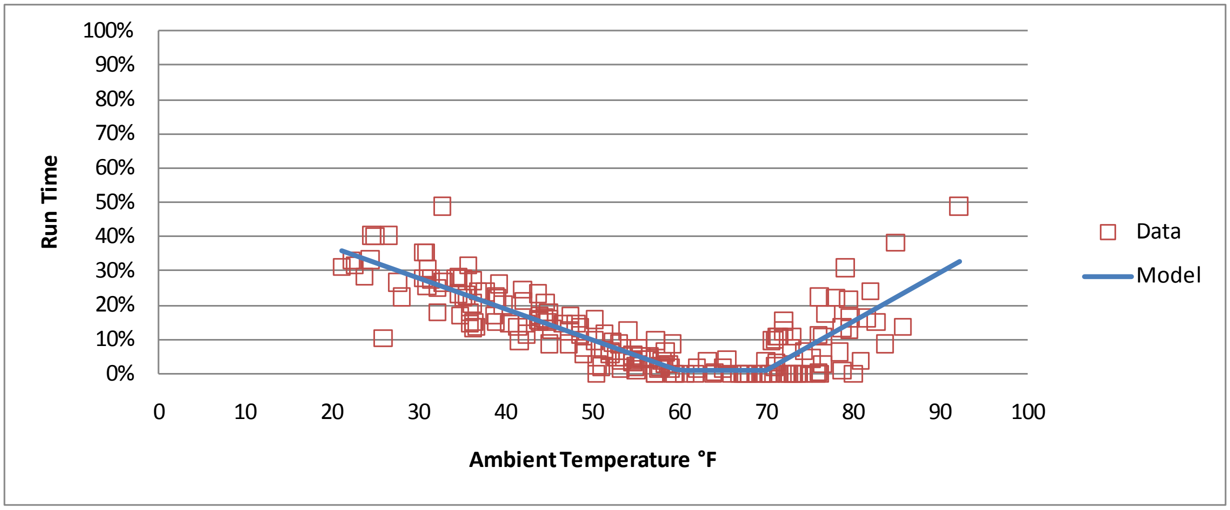
The results of the equations were applied to typical meteorological year (TMY3) hourly temperatures to produce annual hours of operation for the heating and cooling season. Figure 5 presents an example of the data and the model obtained from the regression.

Figure 5. Data Model for Calculating Run Hours Using Status Logger Data



The amperage logger data were processed in a similar manner, except that the average daily runtime percentages were regressed against the average daily temperatures. Figure 6 presents an example of the data and the model obtained from the regression.

Figure 6. Data Model for Calculating Run Hours Using Amperage Logger Data



If the status logger data were not good, the hours of operation determined from the amperage logger data were used; if no amperage logger data existed, the sample average was used.

Final Calculations of Savings

The final equations used to calculate the savings are detailed in Appendix A. As noted previously, if a site specific value was unavailable, a population value was used in place of the missing factor. Key assumptions follow:

- The peak demand calculation used the status logger regression equations applied to hourly TMY3 data to produce estimates of hourly runtimes during the peak period hours. The peak period was consistent with ISO-NE definitions of peak periods.
- Interactive effects are a result of the reduction in heat dissipated into the air stream due to the reduced load of the more efficient fan motor. A change in the motor power impacts the heating and cooling loads.
    - The heating penalty is the additional heating energy required to make up for the reduction in heat dissipated by the motor. It is a function of the heating hours of operation and the efficiency of the furnace. The analysis assumes an average furnace efficiency of 78%, which is the baseline efficiency noted in the TRM for high-efficiency furnace replacements.
    - The cooling bonus is the added electrical savings from reduced cooling load on the compressor as a result of the reduction in heat dissipated by the motor. It is a function of the cooling hours of operation and the efficiency of the air conditioning system. This analysis assumes an average SEER of 8.3, which comes from an evaluation conducted for the Long Island Power Authority in 2010, for a population of existing units replaced with high-efficiency equivalents through the Cool Homes program. The cooling bonus impacts both the energy and demand electric savings.

5. Analysis and Results

This section presents the study findings and savings results.

Individual Site Results and Analysis

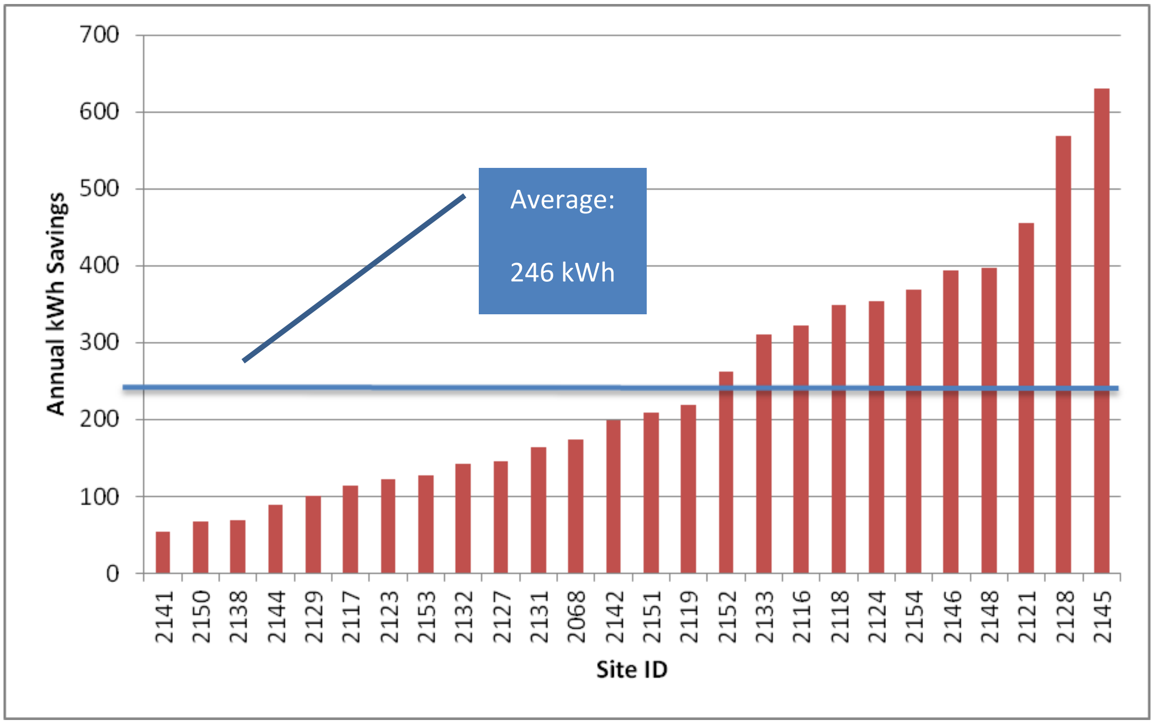
Table 11 presents individual site impact results and an indication of whether site-specific or average values were used to calculate savings. Detailed site reports are included in Appendix B.

Table 11. Site Results Summary

Site ID	Cooling Savings W	Heating savings W	Cooling Mode Savings kWh	Heating Mode Savings kWh	Total Savings kWh	Heating Penalty Therms	Cooling Hours	Heating Hours	Vent Hours	Total Hours	Have Tracking Data	Have Cooling Logged Data	Have Heating Logged Data
2127	78	50	92	53	145	2.3	837	1067	0	1904	Yes	Yes	No
2068	141	47	167	6	173	0.3	843	126	519	1488	No	Yes	Yes
2153	165	121	58	69	127	3.0	251	567	0	818	Yes	Yes	Yes
2117	-21	101	-12	125	114	5.5	396	1248	0	1644	Yes	Yes	Yes
2123	-7	142	-6	128	123	5.6	629	901	0	1530	Yes	Yes	Yes
2119	245	130	79	140	219	6.1	229	1080	0	1308	Yes	Yes	Yes
2142	303	94	96	102	198	4.5	225	1087	0	1312	Yes	Yes	Yes
2145	297	209	108	523	631	22.9	258	2499	0	2758	Yes	Yes	Yes
2141	46	55	0	53	53	2.3	0	965	0	965	Yes	Yes	Yes
2128	96	245	41	528	569	23.1	298	2154	0	2453	Yes	Yes	Yes
2131	196	114	91	73	164	3.2	328	636	0	964	Yes	Yes	Yes
2129	129	100	37	64	101	2.8	203	638	0	841	Yes	Yes	Yes
2124	266	222	70	284	353	12.4	186	1278	0	1464	Yes	Yes	Yes
2121	134	169	96	359	455	15.7	504	2124	0	2628	Yes	Yes	Yes
2146	100	246	8	387	394	16.9	55	1573	0	1628	Yes	Yes	Yes
2148	257	101	289	107	396	4.7	797	1067	0	1864	Yes	Yes	No
2144	99	157	56	33	88	1.4	396	209	0	605	Yes	Yes	Yes
2151	188	58	161	48	209	2.1	607	840	0	1446	Yes	Yes	Yes
2150	0	70	0	67	67	2.9	0	955	0	955	Yes	No	Yes
2133	92	54	306	5	311	0.2	2359	95	0	2454	Yes	Yes	Yes
2152	167	146	151	111	262	4.9	640	764	0	1404	Yes	Yes	Yes
2138	65	138	39	30	69	1.3	425	219	0	644	Yes	No	Yes
2118	306	155	183	166	349	7.2	425	1067	0	1492	Yes	No	No
2116	166	208	100	222	322	9.7	425	1067	0	1492	Yes	No	No
2132	125	100	36	107	143	4.7	205	1067	0	1272	Yes	Yes	No
2154	236	213	141	227	369	10.0	425	1067	0	1492	Yes	No	No
Avg	149	133	92	155	246	6.76	459	1,014	20	1,493			

Figure 7, on the following page, is a graph of the evaluated annual savings by site.

Figure 7. Annual Evaluated Savings by Site



As noted, there are two halves to the savings equation: the reduction in demand created by the change out to a more efficient motor and the hours of operation of the motor. It is easier to diagnose the reasons for high or low savings by examining the two components independently.

Figure 8 graphs the Heating and Cooling mode wattage reduction by site. Figure 9 presents Heating and Cooling hours of operation by site. Sites with high demand savings do not necessarily have long hours of operation; therefore, either factor alone does not explain high or low savings. For example, Site 2142 shows less than average savings, although it has the second highest demand savings.

The annual hours of operation is the component expected to be most influenced by customer behavior, although the reported behavior is not deterministic.

- Site 2138: Owners leave for the winter. The thermostat is left at the 52F setting. Hours and savings are low for both winter and summer operation.
- Site 2128: The owner enables the unit to run throughout the year at a single set point in the winter and summer, 68F and 72F, respectively. Savings are high.
- Sites 2121 and 2129: The owners report the unit is rarely operated in the Cooling mode. Savings are large in one case, small in the other.
- Site 2133: The area served has perimeter heating, which provides most of the heating, and the unit is apparently undersized. Summer hours are high, winter hours low.

Figure 8. Annual Evaluated Power Reductions by Site and by Mode

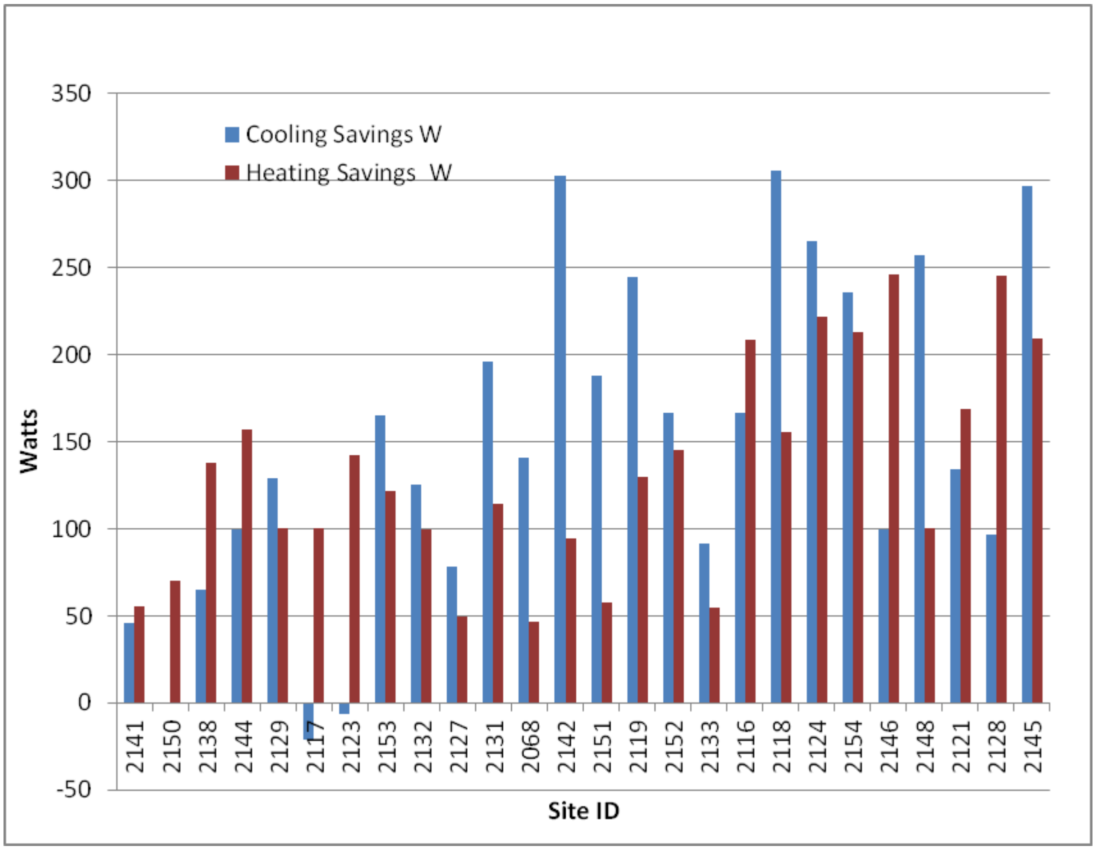
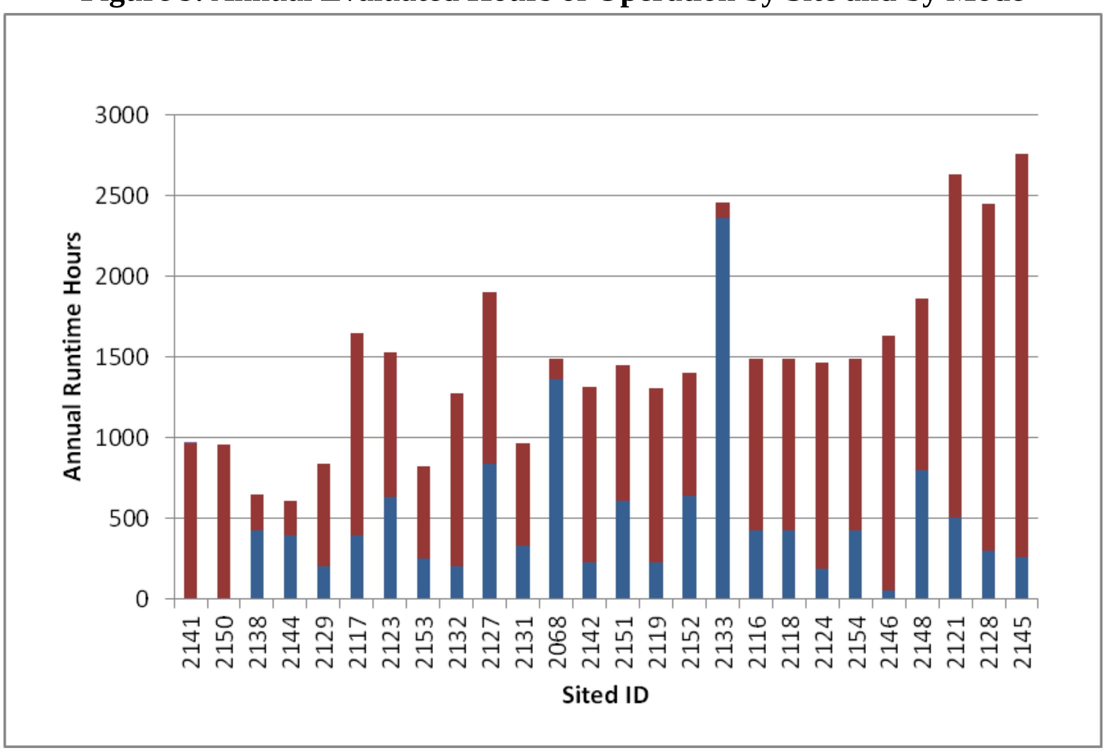


Figure 9. Annual Evaluated Hours of Operation by Site and by Mode



Aggregate Results

The evaluated average energy savings of all units in the sample is 246 kWh. This is a simple average of the energy savings of the individual site results shown in Table 11 because the sites are not weighted. Interactive effects are included. The resulting energy realization rate is 41%, which is the ratio of the evaluated savings divided by the deemed savings of 600 kWh. The relative sampling precision is 18% at the 90% confidence level.

The relative sampling precision depends upon the variance of the results, the sample size, and the size of the population. For the purposes of calculating sampling precision, the population is assumed to be the number of participants in the program through June, which is when the last metering site was recruited for M&V activities (152 sites). Alternately, the precision could be calculated based on the population of participants for 2011. That number is unknown at the writing of this report, but is expected to be less than twice the participation experienced in the first half of the year. Using a larger population (304 sites) modestly degrades the precision to 19%.

By State Results

Table 12 presents a summary of aggregate results for energy savings by state with the calculated precision at the 90% confidence level. A statistical test was performed to determine whether the estimated state level savings were significantly different from the combined results or between each other. In all cases the results indicated that the differences were not significant.

Table 12. Savings by State

Grouping	Population	Number of Sites	Average kWh Savings	Precision
All Sites	152	26	246	18%
Rhode Island, only	60	10	216	38%
Massachusetts, only	92	16	265	21%

Inclusion of Potential High Savers Only

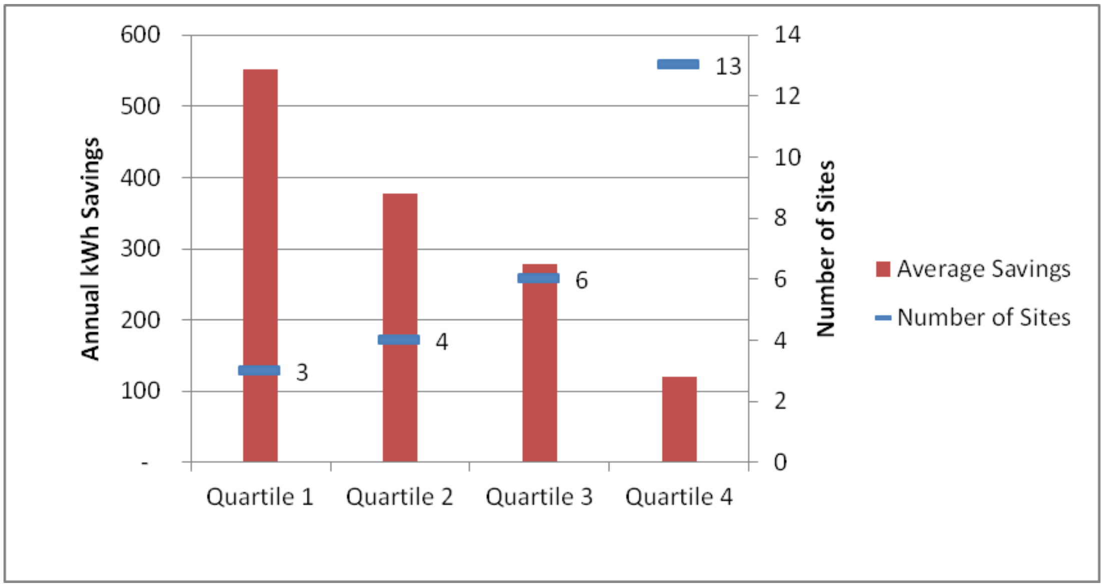
Some of the units in the sample were not operated in what might be considered a typical manner. For example, at one site, the home was unoccupied during the winter, and the unit was set to maintain a very low space temperature. At another site, the space was primarily conditioned by perimeter heat, so the furnace operated for only a few hours in the winter.

Figure 10 shows the sample sites grouped into four equal savings quartiles. The first quartile (Q1) consists of the three largest savings sites – hence highest average savings, while the fourth quartile (Q4) consists of the lowest savings sites with lowest average savings.

Ideally, participants would be more like the Q1 customers and less like the Q4 customers. However, an examination of the characteristics that could be known through *a priori* observations does not clearly identify a Q1 vs. Q4 participant. For example, four participants reported rarely running air-conditioning, but one of them is in Q1.

Of the 13 sites in the fourth quartile, three sites reported little use of the air-conditioning; one reported winter vacancy, but the nine remaining sites reported normal use during both seasons.

Figure 10. Sites by Energy by Quartile



Potential Range of Motor Demand Savings

The greatest uncertainty in the evaluation lies in the connected demand savings of the BFM. The power draw of the BFM is well characterized by the Evaluation Team's measurements. However, the conditions existing before the motor was replaced are less well known, including:

- Unknown air flow
- Unknown power factor
- Inconsistency in HVAC contractor amperage measurements.

The HVAC contractors recorded the static pressure before and after the motor change out in both the Heating and Cooling modes; however, this is not a very precise indicator of air flow because the airflow fan curves are very different for a PCS motor and a BFM. Pre and post airflow was measured and recorded in the tracking dataset for 52 of 382 sites in total. These measurements were measured by nine different contractors. The data demonstrates that although the pre and post CFM varied, the net CFM change was almost zero.

Table 13 presents the average pre-installation CFM measured by the contractor in the heating and cooling modes, the average change in the post-installation case and the minimum and maximum CFM change. Because the power varies roughly as the cube of the CFM, the average change in power due to the any change in CFM was calculated and found to have a neutral effect on the power consumption of the population as a whole.

Table 13 Pre and Post Contractor CFM Measurements

	Average Pre-install CFM	Average CFM Change in Post-install	Minimum CFM Change	Maximum CFM Change	Average Power Change Due to CFM Change
Cooling mode	948	98%	69%	128%	99%
Heating mode	894	98%	68%	122%	101%

The program design intended that the measurement of amperages taken by the HVAC contractor both before and after the motor replacement would indicate power consumption. However, as illustrated in the following example, the same amperage can produce two different power draws with two different power factors:

Case 1: Volts = 120, Amps = 5, PF = 0.8

Power = V * A * PF = 120 * 5 * 0.9 = 480 watts

Case 2: Volts = 120, Amps = 5, PF = 0.5

Power = V * A * PF = 120 * 5 * 0.5 = 300 watts

As the HVAC contractor measurements do not indicate the power factor, the actual existing motor power cannot be known with certainty.

A possible range of demand savings can be postulated assuming a part loading range of the PCS motor and a CFM change of ±15%. The part loading conditions will result in lower power factors and efficiencies for the PCS. The change in CFM will result in increased and decreased loading of the new BFM.

As shown in Table 14, that creates a potential range in savings between -19% and 61% of the PCS motor loading under these scenarios.

Table 14. Potential Range of Demand Savings

	Base Motor				New Motor Demand - in kW			Savings Percentage		
					CFM Change			CFM Change		
	PF	Eff	Motor Power (kW)	Amps	Down by 15%	No Change	Up by 15%	Down by 15%	No Change	Up by 15%
Motor is sized for 65% to 100% of range	0.80	0.65	0.77	8.01	0.393	0.625	0.918	49%	19%	-19%
Motor is sized for - 45% to 65% of range	0.60	0.60	0.83	11.57	0.393	0.625	0.918	53%	25%	-10%
Motor is sized for <45% of range	0.30	0.50	1.00	27.78	0.393	0.625	0.918	61%	38%	8%

For the sites in the sample, the range in demand savings calculated at between -11% and 67%, with an average of 47% in the summer and 52 % in the winter. This is the upper end of the range of the scenario analysis in Table 14. However, as noted in Table 13, the net effect of the CFM measurements is expected to be nil.

The literature also indicates the findings may be at the high end of the range. In the LBNL study authored by James Lutz et al., BFM savings are projected to be 41% under low static pressure and about 10% under high static pressure conditions, with no change in CFM.

Ultimately, the HVAC contractor's pre-installation measurements are site specific; and although they may not completely characterize the power consumption of the existing pre-installation motor, the readings should be correlated with that consumption. So although the savings rates are on the high side, the underlying data support that finding. In addition, the heating and cooling load served remains constant, so that any increase in CFM between the pre and post installation case, will be compensated by a reduction in hours of operation of the new motor.

One conclusion from the discussion above might be that the HVAC contractors should be required to take true power measurements and to record the pre- and post-CFM throughput of the furnaces. A true power measurement, however, requires an expensive power meter. Contractors would have to supply each installation crew with such a meter. Air flow measurements are notoriously tough to measure accurately; the nature of the relationship between power and flow means that a small change in flow can cause a larger change in power consumption. The April 2011 process evaluations carried out by the Evaluation Team indicate that the BFM replacements are barely cost-effective for the contractors, and additional requirements (to supply a power meter, for example) may lessen their participation in the program.

Potential Difference in Hours of Operation

While the CFM may vary pre and post, the hours of operation will not vary based on the CFM changes indicated in Table 13. In theory increased airflow can increase capacity of a unit somewhat, but this impact will be very minor at the values above. In a case where the BFM was set to a higher speed, the temperature of the air (in heating mode) would be lower than the slower speed, but the heat content of the air would be similar (i.e., lower temperature, higher volume). Minor changes in capacity due to air flow changes would have little effect, and would be mitigated by higher fan power due to the cube relationship between speed and power. In summary, we believe that the run times measured are representative of both the pre- and post-installed run hours.

6. Conclusions and Recommendations

The savings impact for the retrofit of furnace fan motors with BFMs is summarized in Table 1, which is repeated below as Table 15 for the reader's convenience. The results include estimates of total program average savings, the average savings for those units with heating and cooling capability, and the average savings for units with heating only capability. The sampling precision of these results is 18% at the 90% confidence interval.

Since the results for Massachusetts and Rhode Island are not statistically different, the Evaluation Team recommends using a combined estimate for both reporting jurisdictions. The PAs, however, may wish to consider separate estimates for units that provide heating and cooling and those that provide heating only.

Table 15. Summary Heating and Cooling Results

Item	All Units	Tracking
Annual kWh motor savings	246 kWh	600 kWh
Direct motor savings kWh	219 kWh	
Interactive cooling savings kWh	27 kWh	
Interactive heating penalty (mmbtu)	-0.676 mmBtu	-1.575 mmBtu
Connected kW	0.182 kW	0.116 kW
CF – summer	0.26	0.67
CF – winter	0.25	0.50
Summer demand savings (kW)	0.047	0.078 kW
Winter demand savings (kW)	0.038	0.058 kW
Annual hours	1,493 hrs measured	5,172 hrs implied

The hours of operation findings are the largest contributor to the low realization rate. The evaluated hours were about 28% of the implied tracking hours. For a furnace fan to operate 5,000 hours, it would have to be left in the On mode for extended periods of time. However, the BFMs were universally observed to operate in the Auto mode with some intermittent On periods. Fans operating in the Auto mode will cycle in response to a call for heating and cooling and, therefore, would be expected to have annual hours of operation matching the equivalent full load heating and cooling hours (EFLH) for the region.

As presented in Table 16, the hours of operation determined in this study correlate well with the estimates of heating and cooling EFLH referenced in the Massachusetts TRM.

Table 16. Comparison of the Massachusetts TRM and Study EFLH

	Heating Equivalent Full Load Hours (EFLH)	Cooling EFLH	Annual Hours
TRM: Massachusetts residential EFLH	1200	360	1560
BFM Impact Evaluation Results of this study	1049	442	1491

The Auto mode was by far the predominant control mode for the units in the post-installed state. Additional savings could have been claimed if the units had been operated in the On mode prior to the BFM installation. However, customers reported that their operation of the unit did not change with the motor retrofit. This was also the conclusion of previous work conducted by the Evaluation Team and reported in April 2011 based on customer telephone surveys: 84% of the customers did not change their behavior after the BFM installation.

As stated earlier, the greatest uncertainty in the analysis lies in the connected demand savings from the motor replacement. The power draw after the BFM retrofit is well characterized by the Evaluation Team's measurements. However, the conditions existing before the motor was replaced are less well known, including exact air flow and motor power factor and efficiency, although a sample of implementation contractor pre and post-installation measurements indicate no net change in CFM delivery. Scenario analysis suggests that the average savings rates of 47% in the summer and 52% in the winter are on the high side of the range. While there may be some questions remaining, the HVAC contractor pre-installation amperage measurements are site specific and, therefore, should be correlated with conditions at the site. The underlying data support that finding.

The Evaluation Team recognizes that additional contractor measurements of true power and CFM would provide more reliable measurements of the base case. However, the cost of compliance could be high (based on equipment costs), and contractors might not be willing to participate in the program or provide the quality of data desired.

The Evaluation Team concludes that further study of pre and post conditions may be useful in identifying better vendor measurement protocols, but such a study is unlikely to yield significantly different savings from those of this study.

APPENDIX A: DETAILED CALCULATIONS

Final Power Calculations

The power savings of the motor change out, incorporating site-specific information were calculated as shown in the equations below. The average amperage was calculated as the average of measured amperage when the motor was running (amperage > 0.2 amps). The days in a season were manually selected.

Heating Mode:

$$W_H = (V_T \text{ x } A_{PreH} \text{ x } PF_{Pre} \text{ x } ACF) - (V_T \text{ x } A_{PostH} \text{ x } PF_{Post})$$

Cooling Mode:

$$W_C = (V_T \text{ x } A_{PreC} \text{ x } PF_{Pre} \text{ x } ACF) - (V_T \text{ x } A_{PostC} \text{ x } PF_{Post})$$

Where:

W_H = Watt reduction during heating mode

W_C = Watt reduction during cooling mode

V_T = Tracking volts

A_{PreH} /A_{PreC} = HVAC contractor measured pre-install heating/cooling amps

A_{PostH} /A_{PostC} = Long-term measured post-install amps heating/cooling amps

PF_{Pre}= Pre-install power factor =0.78, all sites

PF_{Post}= Post power factor = Evaluation Team measured spot power factor

ACF = amp correction factor = Long term logger amps / HVAC contractor measured amps

Final Energy Calculations

The annual energy savings were calculated as follows:

$$E = (W_{SC} \text{ x } H_C + W_{SH} \text{ x } H_H)/1000$$

Where:

W_C = Watt reduction during cooling mode

W_H = Watt reduction during heating mode

H_C = annual hours running in cooling mode, applying regression equations of average on time vs. hourly one-degree ambient bin using TMY3 hourly data

H_H = annual hours running in heating mode, applying regression equations of average on time vs. hourly one-degree ambient bin TMY3 hourly data

E = annual fan energy savings in kWh

Peak Demand Calculation

The peak demand calculation used average runtime per one-degree temperature bin. The results of the regression were then applied to hourly TMY3 data to produce estimates of hourly runtimes during the peak period hours. The peak periods were consistent with ISO-NE and PA definitions of peak periods.

The summer peak demand impact was calculated as:

$$\text{Peak-kW}_S = W_C \text{ x } \text{PctPeak}_C / 1000$$

Where:

DS_S = Summer peak demand savings in kW

W_C = Watt reduction during Cooling mode

PctPeak_C = Average percent runtime during summer peak period of June–August from 2 p.m. to 6 p.m.

The winter peak demand impact was calculated as:

$$\text{Peak-kW}_W = W_W \text{ x } \text{PctPeak}_W / 1000$$

Where:

DS_W = Winter peak demand savings in kW

W_H = Watt reduction during Heating mode

PctPeak_H = Average percent runtime during winter peak period of December and January from 6 p.m. to 8 p.m.

The coincidence factor was then calculated as the ratio of the peak demand reduction to the connected load of the motor. For the purposes of this study, the connected load is the maximum of the cooling or heating wattage reduction, whichever is largest.

Connected load in kW, is defined as:

$$CL = Max(W_C , W_H /1000)$$

The summer and winter coincidence factors are:

$$CFs = DSs / CL$$

$$CFw = DS_W / CL$$

Interactive Effects

The motor powering the fan dissipates heat into the air stream, reducing the gas heating load and increasing the cooling load. Any change in the motor power impacts the heating and cooling loads.

Heating Penalty

The heating penalty is the additional heating energy required to make up for the reduction in heat dissipated by the motor. It is a function of the heating hours of operation and the efficiency of the furnace. The analysis underlying this report assumes an average furnace efficiency of 78%, which is the baseline efficiency noted in the TRM for high-efficiency furnace replacements.

$$E_{HP} = (W_H \times H_H)/1000 \times 3412 / Ef$$

Where:

E_{HP} = Annual heating energy penalty in Btu

W_H = Watt reduction during Heating mode

H_H = Annual hours running in Heating mode

Ef = Heating efficiency = 78%

3412 = conversion factor, 3,412 Btu per kWh

Cooling Bonus

The cooling bonus is the added electrical savings from the reduced cooling load on the compressor as a result of the reduction in heat dissipated by the motor. It is a function of the cooling hours of operation and the efficiency of the air conditioning system. This analysis assumes an average SEER of 8.3, which comes from an unpublished finding for a population of existing units replaced with high-efficiency equivalents. The cooling bonus impacts both the energy and demand electric savings.

$$E_{CB} = (W_C \times H_C)/1000 / COP$$

Where:

E_{CB} = Annual cooling energy bonus in kWh

W_{Sc} = Watt reduction during Cooling mode

H_C = Annual hours running in Cooling mode

COP = Cooling coefficient of performance = 2.4, equivalent to an SEER of 8.3

APPENDIX B: SITE REPORTS