Investigation into the Reliability of Energy Efficiency/Demand Side Management Savings Estimates for Variable Frequency Drives in Commercial Applications

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Project directed by Professor Moncef Krarti.

Abstract

In light of the growing EE/DSM program offerings for VFD measures, it is worth reviewing the savings estimation methodologies currently being used to determine their reliability and investigate whether changes or updates are warranted. Although there is similarity among program offerings, the savings estimation methodologies used for VFD measures often vary significantly by VFD measure type, from state-to-state, and program-to-program. This offers opportunity for investigation to determine which methodology is the most reliable for program implementation, or if a new method is needed. This paper compares the reliability of 13 different existing protocols for estimating savings for VFD installations on HVAC fans. Each protocol was used to estimate savings for seven case studies and the results compared to the verified savings that had previously been determined. This showed that most of the TRM protocols were not reliable. The results were also compared to savings estimates derived using U.S. DOE EnergyPlus commercial building prototype models. Finally a new simple protocol was developed and validated as a more reliable alternative to existing protocols for estimating savings for VFD installations on HVAC fan motors. As such the protocol developed in this paper is recommended for adoption in TRMs across the country for use in energy efficiency program implementation to estimate savings for installations of VFDs on HVAC fan motors as a preferred alternative to most existing protocols.

Dedication

This report is dedicated to my wife Jamie, oldest child Aviella (daughter, 6), middle child Caelen (son, 4), and youngest Adler (son, 1). First and foremost I would like to express my unending love, gratitude and thanks to my beautiful wife Jamie for your tremendous sacrifice and love in supporting my graduate studies. I could not have done this without you. I am sorry it took so long and I look forward to spending my new free time with you and the kids. And to my beautiful and creative daughter Aviella, perpetually joyful and curious son Caelen, and youngest son Adler who lights up a room with his infectious smile, thank you for your continued love and support even though you were all forced to sacrifice time with your daddy so I could finish this work. I love you all deeply and hope to make it up to you now that I am finished.

Acknowledgements

There are several people who contributed to the completion of this project report. I would like to express my thanks and gratitude to all those who helped influence this work. I want to thank my project advisor Moncef Krarti for helping me to focus and get it done and for continued support and guidance through my studies. Thanks also for his willingness to accept me as a TA in my first semester as a graduate student. I also want to thank my research assistant advisor Professor John Zhai and fellowship advisor Professor Ronald Pak for their help providing funding, direction, and encouragement to take on new challenges.

Thank you to the entire faculty of the Building Systems Program for the knowledge they have passed on to me through my coursework and research, to all the students of the BSP for bringing some fun into the Engineering Center, and to all our friends at Smiley Court for all the memories and for making us feel at home.

I would also like to acknowledge my employer Navigant for providing additional funding in order to finish my degree.

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Chapter 1

1.1 Introduction

In 2010, the U.S. consumed 97.8 quads of energy (U.S. Department of Energy, 2011). This accounted for roughly 19% of global consumption, second only to China. Of this total U.S. energy consumption, buildings accounted for 41% of the primary energy, transportation was 29%, and industry accounted for the remaining 30%. Within the building sector itself, commercial buildings consumed 19% of the total U.S. energy consumption. See Figure 1 below.

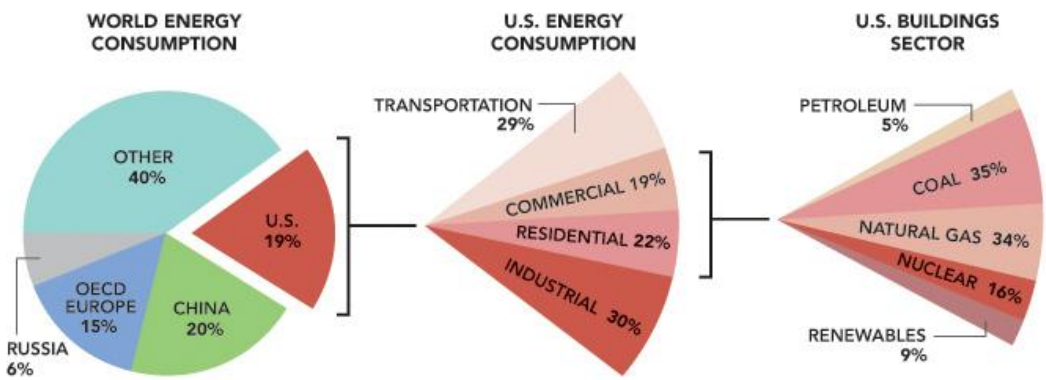

Figure 1. World Energy Consumption. (U.S. Department of Energy, 2011)

Breaking this down further shows that 42.1% of the energy used by the commercial building sector goes towards space conditioning, including space cooling (10.1%), space heating (26.6%), and ventilation (6.1%). This is by far the greatest end-use of energy in commercial buildings with the next largest end-use being lighting at only 13.6%.

It is widely recognized today that energy efficiency is one of the most cost effective means to reduce our nation's overall energy demand. The effects of this recognition can be seen in the number of states that have adopted energy efficiency resource standards or goals as shown in Figure 2. As seen in the figure, twenty states have already adopted some sort of standard or goal, and more are in the process.

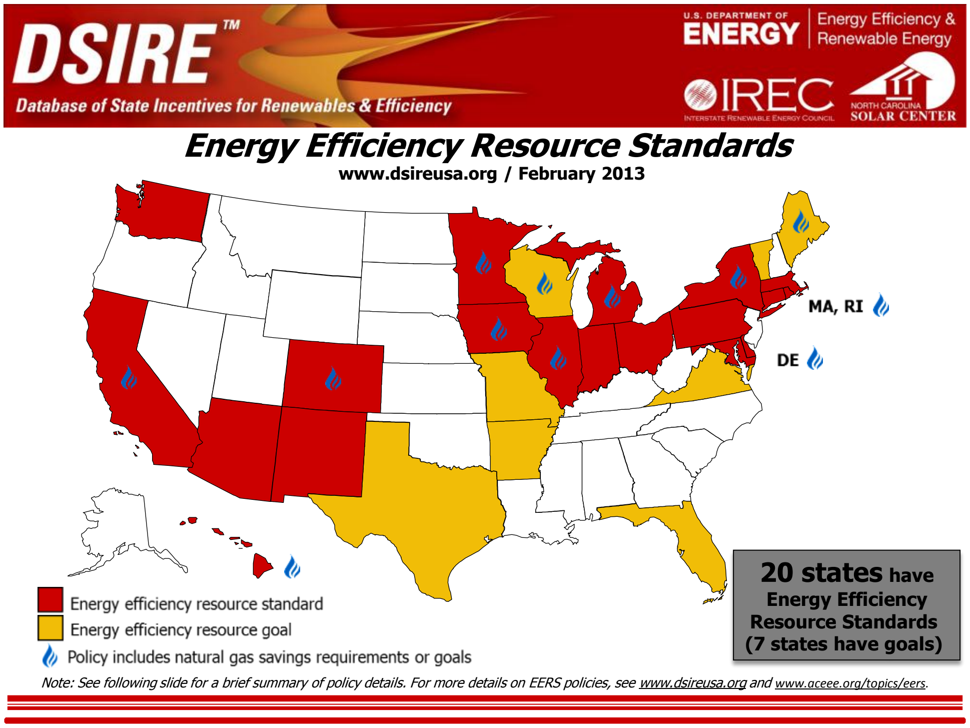

Figure 2. Map of States with Energy Efficiency Resource Standards and Goals. (DSIRE USA, 2012)

But in the commercial building sector, where is the energy savings through energy efficiency going to come from? Although it only accounts for 13.6% of building consumption vs 42.1% for space conditioning, lighting retrofits currently account for a vast majority of the commercial building stock energy savings through efficiency improvements. This is because they are the lowest hanging fruit in terms of upfront cost, ease of installation and relatively short payback period. Although lighting retrofits will still dominate energy efficiency program savings in the near future, code and standard changes requiring more efficient lighting than in the past are having a significant impact. Utilities will eventually need to look to other technologies to get their required savings towards their energy efficiency resource standard goals.

One of today's largest areas for potential energy savings after lighting retrofits in existing commercial and industrial buildings is motor measures. For example, in Pennsylvania, an energy efficiency potential study(GDS Associates, Inc and Nexant, 2012) showed that while lighting still accounts for 40.3% of achievable program potential savings by 2018, motor measures was a strong second showing a potential of 23.6% of achievable program savings. This includes replacement of low efficiency motors with premium efficiency motors, and also includes installation of adjustable speed drives (ASD) for motor applications. Many energy efficiency and demand side management (EE/DSM) programs across the country include incentives for installation of ASD measures in their program offerings. Although current participation in ASD measures is relatively small compared to lighting retrofits, participation is growing and is expected to grow even more in the future as lighting savings and incentives are reduced due to the code and standard changes.

For EE/DSM programs, as measures grow in their overall impacts, it is important to have reliable savings estimates to ensure ratepayer money is being spent wisely and to verify whether programs are meeting their compliance goals with real energy savings. In light of the growing EE/DSM program offerings for ASD measures, it is worth reviewing the savings estimation methodologies currently being used across the country to determine their reliability and investigate whether changes or updates are warranted. Although there is similarity among the program offerings, the savings estimation methodologies used for ASD measures often vary significantly by ASD measure type, and from state-to-state, and program-to-program.

For ASD installations on industrial process motors almost all programs require custom calculations for each measure due to the high uncertainty and variability between projects. This generally leads to fairly reliable savings estimates.

For ASD installations on HVAC fan and pump motors many EE/DSM programs use a simplified savings estimation method which is applied to all projects within certain parameters. Some jurisdictions use a very simplified approach using a single deemed savings estimate (kWh per horsepower), a few jurisdictions require use of hourly energy simulation models for every building application, but most programs use methods that fall somewhere in between these two extremes, using a partially deemed algorithm with default hours of use by building type and ASD application type, and a deemed savings factor for each application type. Each method has their advantages and disadvantages, with custom simulations for each project being the most reliable, but most costly to implement. The single deemed savings estimate using kWh per horsepower is the least costly to implement, but is also the least reliable. The methods in between these two try to strike a balance between reliability and cost.

Many states continue to grapple with how to best estimate savings for ASD applications. As more and more states implement EE/DSM programs the challenge of reliably estimating savings for ASD applications using simple methodologies continues to grow. This paper reviews the methodologies used to estimate savings for ASD installations on HVAC fans and pumps which do not require a custom energy simulation for each project.

1.2 Project Objectives

The various savings estimation methodologies for ASD installations in HVAC applications used for EE/DSM program implementation across the country offer opportunity for investigation to determine which savings estimation method is the most reliable for use on a macro scale, or if a new method is needed.

The project objectives were to determine whether there is an existing reliable, yet simple, measure savings estimation methodology to estimate savings for ASD installations on HVAC applications that can be recommended for states and utilities to follow for implementing ASD measures in EE/DSM programs, or if a more robust methodology is warranted. If it is determined that there is not an existing protocol that could be recommended, the project will develop a new protocol and validate whether it can be recommended over existing protocols.

The final objective is to make a recommendation for EE/DSM program stakeholders as to how ASD measure savings should be estimated.

1.3 Report Organization

The report is organized as follows. Chapter 1 provides the rational for why this study was undertaken. Chapter 2 describes how ASDs work and save energy. Chapter 3 details how EE/DSM programs used Technical Reference Manuals (TRMs) to estimate measure savings, provides a literature review of the topic, and describes 13 different TRM savings protocols that are used to estimate savings from ASD installations and which were reviewed for this project. Chapter 4 describes how case studies were selected, how the TRMs were used, and how EnergyPlus models were developed. Chapter 5 goes into detail on each case study, the results from the TRM savings estimates and the EnergyPlus modeling. Chapter 6 compares the results from all the TRM protocols and EnergyPlus models for each case study. Chapter 7 develops a new savings estimation protocol while Chapter 8 uses that protocol to estimate savings for all the case studies to validate the protocol. Chapter 9 provides final recommendations and conclusions and includes suggestions for future work.

Chapter 2

2 HVAC Fan and Pump Motors

Motors account for a significant portion of the energy consumption of building HVAC systems. In HVAC systems, motors drive chillers, compressors, fans and pumps which are used for meeting both cooling and heating loads of the buildings they serve. Most existing installed motors in HVAC systems are single speed motors that run at a constant full speed all the time regardless of the actual load on the system. When the load is constant and the motor is well matched to it this is not a problem and energy is not wasted. However, when the load on the motor varies throughout the day, week, month or year, running the motor at a constant full speed can be a significant waste of energy.

2.1 Fan Affinity Laws

Focusing on fan motors, the potential energy that can be saved is related to the fan affinity laws (ASHRAE, 2012) through the reduction of rotational speed.

$$CFM_{New} = CFM_{Initial} \times \left(\frac{RPM_{New}}{RPM_{Initial}}\right) \quad [1]$$

$$Pressure_{New} = Pressure_{Initial} \times \left(\frac{RPM_{New}}{RPM_{Initial}}\right)^2 \quad [2]$$

$$Power_{New} = Power_{Initial} \times \left(\frac{RPM_{New}}{RPM_{Initial}}\right)^3 \quad [3]$$

The result of these fan laws is that a slight reduction in CFM through lower fan speed results in a significant reduction in power needed to drive the fan. This can yield significant savings over a baseline constant volume system or an existing VAV system by installing an adjustable ASD. The above relationships are ideal. In practice the power relationship to reduction in speed is less than three. There is not an agreed upon power factor, but many references use power factors of around 2.0 to 2.7 as reasonable estimates (Consortium for Energy Efficiency (CEE), 2011).

2.2 Pump Affinity Laws

Similar to the fan affinity laws, there are also pump affinity laws (ASHRAE, 2012) which can be used to understand the potential energy that can be saved through the reduction of pump rotational speed.

$$GPM_{New} = GPM_{Initial} \times \left(\frac{RPM_{New}}{RPM_{Initial}}\right) \quad [4]$$

$$Head_{New} = \quad Head_{Initial} \times \left(\frac{RPM_{New}}{RPM_{Initial}}\right)^2 \qquad [5]$$

$$Power_{New} = \quad Power_{Initial} \times \left(\frac{RPM_{New}}{RPM_{Initial}}\right)^3 \qquad [6]$$

As with the fan laws, the pump laws show that a small reduction in pump rotational speed can result in a large reduction in power needed to drive the pump. For systems that do not need to run at full capacity all the time significant energy savings can be achieved by reducing the pump speed through installation of an ASD.

2.3 Variable Flow Systems

Variable volume/variable flow HVAC systems try to take advantage of the first two affinity laws. In fan systems, adjusting air volume can be accomplished many ways thus saving energy. The fan can be allowed to ride its system curve as variable air volume (VAV) boxes are opened and closed to serve the space conditioning loads. The flow and pressure can be further adjusted by means of outlet dampers, inlet dampers, or inlet guide vanes at the fan itself, thus changing the CFM and pressure and saving energy. In pump systems, adjusting the flow with throttling valves changes the GPM and head, thus saving energy as well.

These methods can save significant amounts of energy as compared to a constant volume/flow baseline system, but by changing the speed of the fan or pump, even more energy could be saved. Motor speed control devices can be used to do just that.(Lawrence Berkeley National Laboratory, and Resource Dynamics Corporation, 2003)(Lawrence Berkeley National Laboratory, Resource Dynamics Corporation, and Alliance to Save Energy, 2006)

2.3.1 Motor Speed Control Devices

Motor speed control devices used to control the speed of a motor through a continuous range. There are many forms of motor speed control devices including mechanical or hydraulic controllers, and ASD’s. ASD’s are more efficient than mechanical or hydraulic controllers and have mostly replaced the others except in certain applications.

Mechanical and Hydraulic control devices don’t actually change the speed of the motor, but rather the speed for the applied load. Mechanical controllers include devices such as adjustable belts and pulleys, gears, throttling valves, fan dampers and magnetic clutches. Hydraulic controllers include hydraulic clutches and fluid couplings. (Ontario Hydro, 1997)

ASD's on the other hand control the speed of the motor itself resulting in higher efficiencies than the mechanical or hydraulic controls. ASD's include electronic AC motor variable frequency drives (VFD), AC motor variable voltage controllers, eddy current clutches, switched reluctance drives, vector drives, wound-rotor motor controllers, cycloconverters, and DC motor controllers.(Ontario Hydro, 1997)(Rouse, 2009)

2.3.2 Variable Frequency Drives

To understand the efficiency a fan is operating at, one needs to plot the fan curve an overlay the system curve to identify the operating point. There are several forms of fan curves, but generally the curves used plot percent of pressure against percent of flow rate. The system curve shows the pressure and flow relationship of the entire duct system at a given location, including the effects of the ducts, dampers, filters, etc. It basically shows the pressure requirements to overcome system losses to produce flow. In other words, how much pressure the fan must overcome to induce flow in the system. (Stebbins, 1994)

The use of outlet dampers and inlet dampers essentially changes the system curve as the dampers are opened and closed, but do not change the fan curve. These changes affect the system curve by increasing or decreasing resistance to air flow. Energy is saved because changing the system curve changes the operating point on the fan curve (see Figure 3). (Stebbins, 1994)

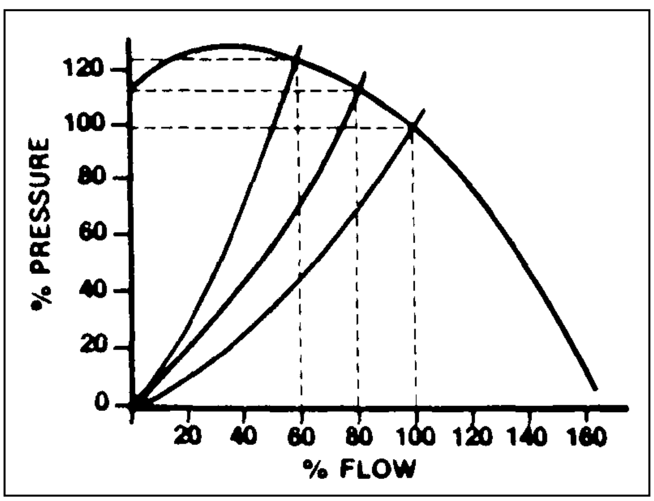

Figure 3. Outlet damper affect on system curves. (Cassidy & Stack, 1988), (Stebbins, 1994)

Inlet guide vanes instead save energy by altering the fan curve itself by affecting the incoming airflow as it enters the fan rather than altering the system curve (see Figure 4). Affecting the flow coming into the fan changes the fan characteristics, thus changing the fan curve. Inlet guide vanes are generally more efficient than outlet dampers or inlet dampers. (Stebbins, 1994)

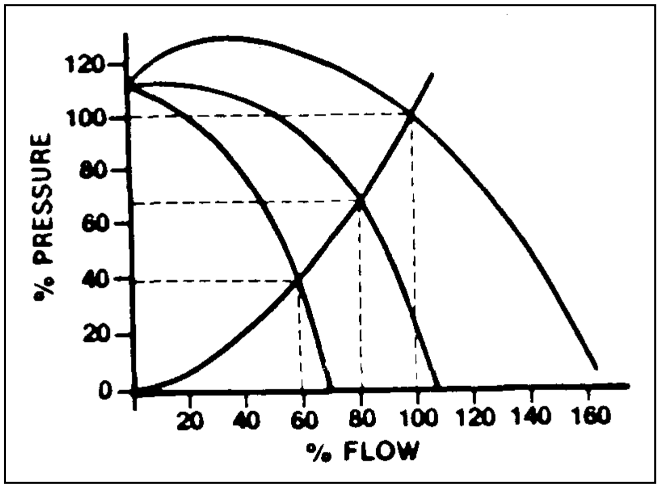

Figure 4. Inlet guide vane affect on fan curves. (Cassidy & Stack, 1988), (Stebbins, 1994)

ASD's can save more energy than either dampers or inlet guide vanes because rather than changing the system curve, or the fan curve, they are able to operate the fan at different speeds. This maintains the fan at roughly the same efficiency point on its fan curve while also maintaining the system curve (see Figure 5). The main difference is that it is operating at a different speed. This allows the designers to optimize the fan's efficiency operating point and the system's operating efficiency point throughout the full operational range.

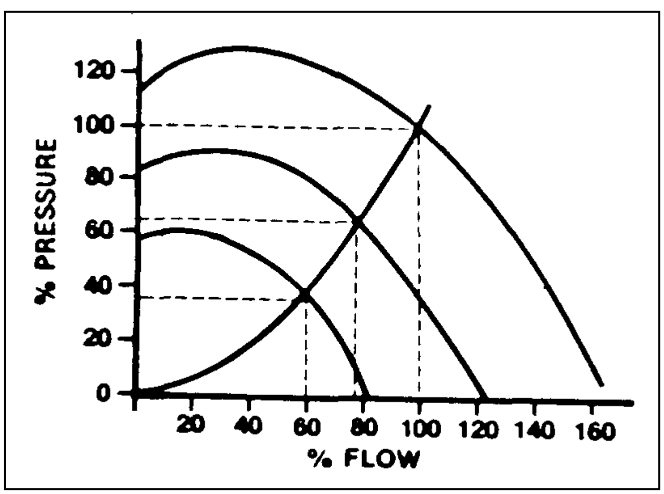

Figure 5. ASD maintains fan efficiency operating point.(Cassidy & Stack, 1988), (Stebbins, 1994)

The changing of the fan curve through the ASD's adjustment of fan speed results in a power reduction reflected in the fan affinity laws; where the power is proportional to the cube of the speed. This is a theoretical relationship and would hold true if the efficiencies of each component held constant throughout the operating range and there was no minimum system requirements. This is not reality though, and the relationship in practice is somewhat less than a cube relationship as discussed in Section 2.1 above. Figure 6 shows the effect on the system curve with a 30% back pressure. This is the minimum pressure required for the fan to overcome just to induce flow. This has a significant impact on the theoretical cubed relationship and brings it closer to a squared relationship. This is generally the case for systems with static back pressure. Systems with minimal static back pressure, such as cooling tower fans or domed roof vent fans are able to operate closer to the cubed law. These differences should be taken into account when estimating savings from ASD installations. (Stebbins, 1994)

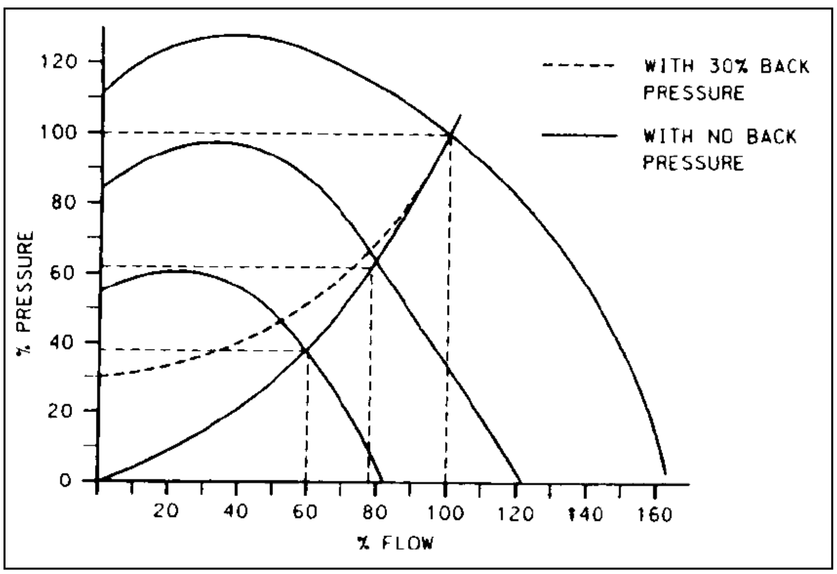

Figure 6. System curve effects due to system efficiencies. (Stebbins, 1994)

Of the various types of ASD's, VFDs are the most efficient and have become the primary ASD of choice for most commercial HVAC fan and pump applications. VFDs control motor speed through use of power conversion. Power comes into the drive at a constant 60 Hz and flows through a rectifier which converts the AC power to DC power. The DC power then flows through an inverter which switches the DC power on and off to simulate AC power at the desired frequency and voltage. The inverters are generally of three basic types. The first type includes a variable voltage inverter (VVI) and a square-wave six-step voltage source inverter (VSI). The second type is a current source inverter (CSI). The third type is a pulse width modulated inverter (PWM). (Ontario Hydro, 1997)

The PWM VFD is the most common in HVAC applications as it offers several advantages over the other types. The primary benefits are that they produce better waveforms than the alternatives, resulting in smoother motor operation at all speeds and less filtering requirements. They are, however, the most expensive of the three main VFD types.(Ontario Hydro, 1997)

Although much energy can be saved through installation of a VFD on HVAC fans and pumps, the energy savings do not necessarily translate into significant demand reductions as well. In some cases, installation of a VFD can increase peak demand because the efficiency of the VFD itself at maximum load reduces the overall efficiency of the system. VFD efficiency at full load rated output power is typically between 94% to 97%, between 91% to 96% at 50% power, between 83% and 93% at 20% power, and between 72% and 87% at 10% power (Krukowski & Wray, 2013). Below 10% power VFD efficiency drops substantially. Lower horsepower rated drives tend to be less efficient than larger drives, but this can vary by manufacturer.

Even with the reduced efficiencies at lower power ranges, motors with VFD's installed still save significant amounts of energy at lower speed due to the cubed relationship of the power to speed per the affinity laws.

Care must be taken when choosing to install a VFD on a motor as not all applications will be appropriate. There must be an opportunity for reduced speed over the existing conditions to save energy. Applications with varying loads generally present the greatest opportunity for savings. Applications where the load is constant, but the existing motor is just oversized will typically see greater savings by replacing the motor with a more appropriately sized motor than by installing a VFD.

The motor type should also be considered as not all motors and applications are suitable for the installation of a VFD. VFDs can cause significant harmonics and if not properly considered and designed for, this can drastically reduce the lifetime of the motor, thus negating any savings the VFD installation may have otherwise achieved.

Also, some motors are not designed to handle the increased heat that occurs when controlled with a VFD. Motor cooling systems are generally rated for full speed operation and as the motor speed is reduced, so is the ability of the motor to dissipate heat. This can lead to premature degradation of the insulation. Motors should be checked to confirm they have insulation levels capable of handling a VFD before a decision is made to install the VFD.

There are too many considerations that must be made when choosing to install a VFD on a motor application to list here. Many books are devoted to this topic alone. More detailed information can be found in the National Electrical Manufacturers Association (NEMA) guidebook titled, “Application Guide for AC Adjustable Speed Drive Systems” summarized by Bezesky and Kreitzer (Bezesky & Kreitzer, 2001).

When carefully planned and designed, installation of a VFD on an HVAC fan or pump can save significant energy, even as much as 70% or greater, although more commonly in the 35% to 65% range. Because of this they can have very short payback periods (often less than a year) and should be considered as an energy efficiency measure for many building managers/owners.

The rest of this paper focuses on potential energy savings associated with installation of a VFD on commercial HVAC fan applications.

2.4 Baseline System Options

The savings that can be achieved by installing a VFD on an HVAC fan motor depends significantly on what the baseline system was prior to the VFD installation. Energy savings estimates must include both the physical component options as well as the various control options.

2.4.1 Baseline Components

There are several possibilities including constant volume (CV) systems with reheat, VAV systems with discharge dampers allowing the constant speed fan to ride the fan curve, VAV systems with outlet damper controls, VAV systems with inlet damper controls, VAV systems with inlet guide vane (IGV) controls, or VAV systems with eddy current clutches. As most energy efficiency programs do not include prescriptive savings for eddy current clutches we will focus here on savings from the other alternatives.

Within these various system types, there are still significant energy savings potential differences depending on the fan type used with each system. For example, does the system use an axial fan or a centrifugal fan, if a centrifugal fan is it a forward-curved (FC) blade, radial-blade, radial-tip, backward-inclined (BI) flat, backward-inclined curved, or backward-inclined airfoil (AF/BI)(Lawrence Berkeley National Laboratory, and Resource Dynamics Corporation, 2003)? If an axial fan, is it tubeaxial or vaneaxial? Does it have controllable pitch blades? Each of these options can have significant ramifications on energy savings potential due to baseline efficiency differences.

For example, a baseline VAV system which uses inlet guide vanes on a centrifugal fan with forward curved blades may not see much energy savings by installing a VFD because they are already fairly efficient. There may be some savings, but greater care should be put into the savings calculations to ensure a reliable estimate of simple payback period or life cycle costs to justify the cost of installing a VFD. On the other hand, there are still significant savings opportunities for installing a VFD on a baseline VAV system with IGV controls on a centrifugal fan with BI blades, whether flat, curved or airfoil (Bonneville Power Administration).

There are several other considerations that may also affect potential energy savings. Is the fan direct, gear or belt driven? Is the fan oversized or right sized? Where does the fan operate on its fan curve? Is the ductwork designed properly to allow the most efficient use of the fan, or is it poorly designed such that adding a VFD will not be useful? Is the motor oversized or right sized? What efficiency is the motor? What speed does the motor run: 1200, 1800 or 3600 RPM? Is the motor open drip proof (ODP), totally enclosed fan cooled (TEFC), or other?

2.4.2 Baseline Controls

There are also many control options that can have a significant impact on the savings potential. Although installation of a VFD by itself can save energy, when coupled with improved control strategies there can be even more significant benefits. But it is often difficult to separate out the savings between the VFD itself and the controls.

Some of the controls that should be considered include: What pressure is the system set at? Is there a static pressure setpoint at which the system tries to maintain itself? What types of system controls are used? Does the system have to maintain a minimum system pressure just to open downstream dampers that will affect the minimum fan speed? Will there be power quality issues by installation of a VFD? Are there multiple fans or just a single fan?

Murphy (Murphy, 2008) highlights a few specific energy saving control strategies that are often employed with VFD systems. “Optimal Start/Stop” strategies are used to minimize the run-time at the beginning and end of daily occupancy periods. With this strategy, a building-automation system (BAS) monitors how long each zone takes to cool down and warm up (cooling mode, opposite for heating mode) depending on the outside temperature, and waits as long as possible in the morning to start the system. At the end of day it takes advantage of occupants’ tolerance of a few degree temperature drift to turn the system down before occupants leave. These both increase energy savings from a VFD system by reducing the run-time of the systems to the minimum possible.

“Fan-pressure optimization” monitors the minimum pressure required at all of the zone VAV terminals and adjusts the system static pressure control based on the “critical” zone. This affects the energy consumption of a VFD system by bringing the fan part load curve closer to the ideal cube relationship than if a static pressure setpoint is used.

"Supply-air-temperature reset" increases the cooling supply-air-temperature based on outside air-temperature to increase use of an economizer, thus reducing the chiller load. This can negatively affect the energy savings of a VFD installation because more air flow is required to cool the space due to the higher supply temperature. When appropriate this control strategy can save more chiller energy than the associated increase in fan energy, but not in all cases.

Ventilation optimization using various "demand-controlled ventilation" (DCV) strategies also can lead to additional savings with a VFD installation, or if already employed can reduce the expected savings if not accounted for. The strategies for DCV include CO2 sensors installed in high density occupancy areas, occupancy sensors installed in lowered density occupancy areas with variable schedules, and time-of-day scheduling can be used in predictable occupancy areas.

Because of the energy savings differences with only subtle differences in system configuration (of which the customer may be unaware), it is especially important for the system retrofit designer and the program implementer (who pays incentives for installing VFDs) to take care in fully understanding the existing system configuration before estimating savings. It is also important for the independent evaluator of such a project to understand the nuances of the systems and how they affect energy savings.

2.4.3 Fan Part Load Curves

A primary way to understand the energy savings differences is to compare the fan part load ratio (PLR) curves (also referred to as power ratio curves) of each system. These part load power curves are typically based on a third order polynomial equation such as the following.

$$PLR = \quad a + b \times FF + c \times FF^2 + d \times FF^3 \qquad \textbf{[7]}$$

Where:

$PLR =$ Part Load Ratio; ratio of fan power at part load conditions to full load fan power

$FF =$ Flow Fraction; ratio of cfm at part load to full load cfm

$a, b, c, and\ d =$ constants; fan coefficients for regression equation for fan given configuration type

To model various fan control types, EnergyPlus and other simulation software generally use such curves. There is not a standard set of curves for simulations or energy calculations, however, and it therefore requires some judgment as to which is the most appropriate to use. Several fan part load curves are shown in Figure 7 with corresponding coefficients in Table 1.

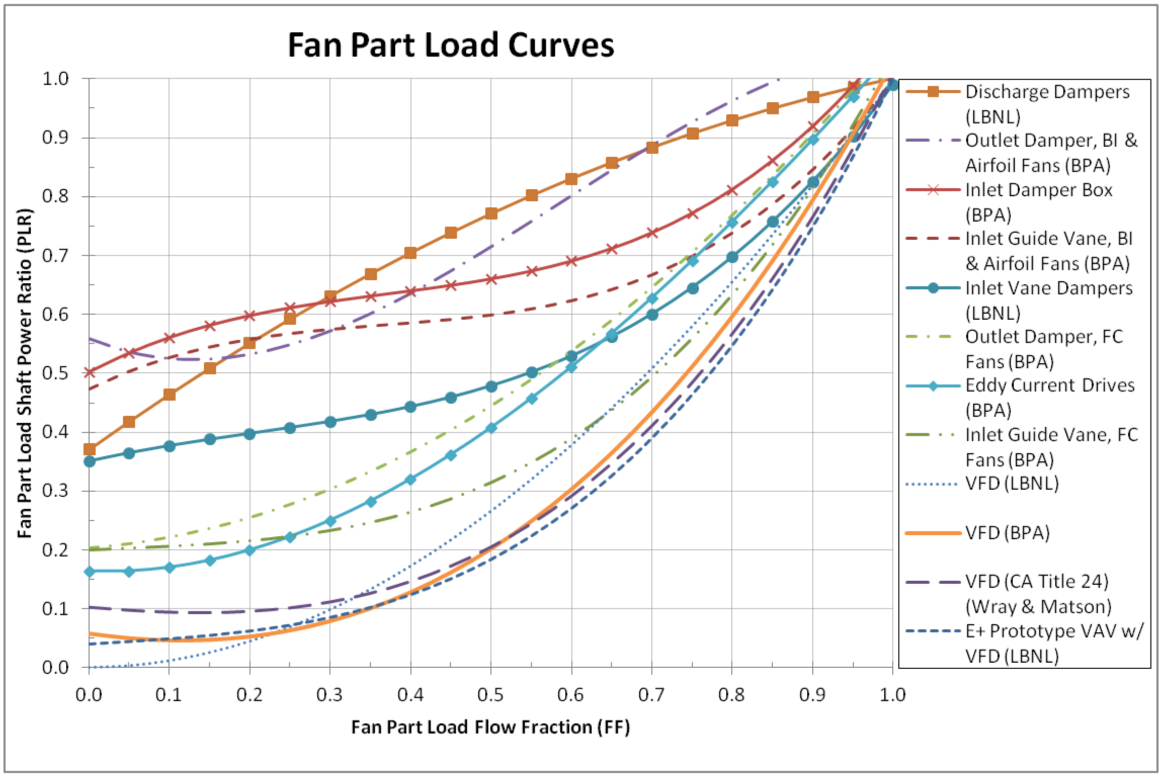

Figure 7. Fan Part Load Curves for Various Configurations.

Table 1. Fan Part Load Ratio Regression Coefficients. (Bonneville Power Administration), (Ernest Orlando Lawrence Berkeley National Laboratory (LBNL), 2013), (Wray & Matson, 2003).

Fan Control Type	Regression Coefficient			
	a	b	c	d
Discharge Dampers (LBNL)	0.37073425	0.97250253	-0.34240761	0
Outlet Damper, BI & Airfoil Fans (BPA)	0.5592857	-0.56905	2.462	-1.4
Inlet Damper Box (BPA)	0.5025833	0.71648	-1.452	1.3
Inlet Guide Vane, BI & Airfoil Fans (BPA)	0.472619	0.67944	-1.554	1.4
Inlet Vane Dampers (LBNL)	0.35071223	0.30850535	-0.54137364	0.87198823
Outlet Damper, FC Fans (BPA)	0.2041905	0.10983	0.745	0
Eddy Current Drives (BPA)	0.1639683	-0.05647	1.237	-0.3
Inlet Guide Vane, FC Fans (BPA)	0.2	0.06808	-0.128	0.9
VFD (LBNL)	*0.001530245*	*0.005208057*	*1.1086242*	*-0.11635563*
VFD (BPA)	*0.059*	*-0.19567*	*0.766*	*0.4*
VFD (CA Title 24) (Wray & Matson)	0.1021	-0.1177	0.2647	0.76
E+ Prototype VAV w/ VFD (LBNL)	*0.040759894*	*0.08804497*	*-0.07292612*	*0.943739823*

For more clarity, Figure 8 compares the fan part load curves for systems with discharge dampers and outlet dampers for easier viewing. As can be seen, FC centrifugal fans with outlet dampers have significantly lower PLR's than similar systems with BI or AF blades. When calculating savings it is important to identify which type of fan blade the system has.

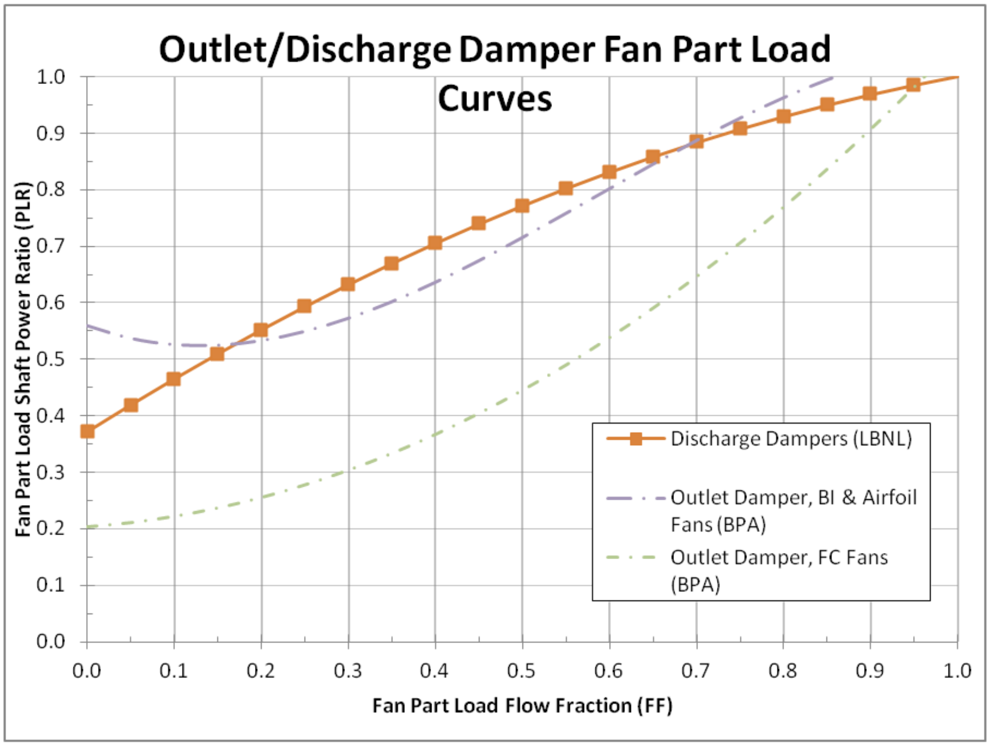

Figure 8. Fan Part Load Curves with Outlet or Discharge Dampers.

Figure 9 shows the curves for systems with inlet dampers or IGVs. Similar to the curves for outlet dampers, the systems with IGVs on FC fans have significantly lower PLR's than those with BI or AF blades.

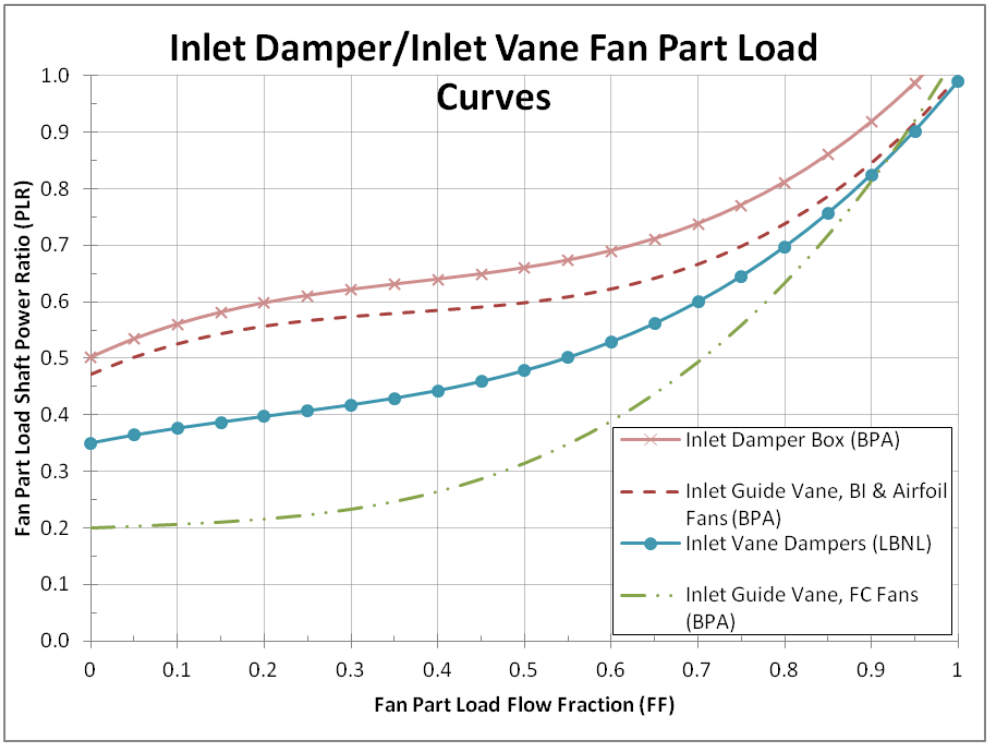

Figure 9. Fan Part Load Curves with Inlet Vanes and Inlet Dampers.

Part load curves for ASD systems are shown in Figure 10. There are several curves shown for VFD's, however, they are all quite similar. The main difference occurs below a part load flow fraction (FF) of 30%. Below this fraction the LBNL model continues to a minimum PLR of 0.0%, suggesting an idealized relationship based on the affinity laws. This is possibly appropriate for low pressure applications such as cooling tower fans or domed vent fans (Stebbins, 1994). The CA Title 24/Wray and Matson model levels out at roughly 10% PLR, which reflects a recognition of minimum static pressure requirements more in-line with actual field conditions, with the others in between. This can have a significant impact on overall estimated savings if a significant fraction of the fan run hours are below 30% FF. Because there are always friction losses that the motor must overcome just to maintain its minimum speed, the LBNL model likely underestimates the PLR in this range, whereas the CA Title 24/Wray and Matson model is more realistic. Because of these reasons the analysis and modeling for this report will use the CA Title 24/Wray and Matson VFD model as a slightly more conservative estimate rather than the others.

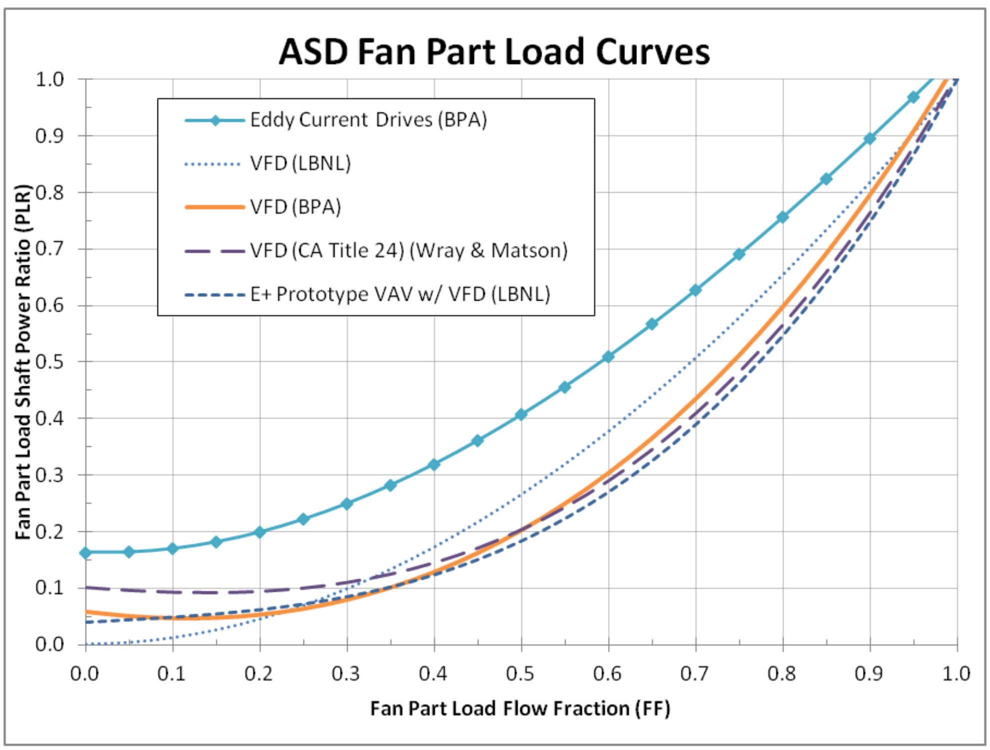

Figure 10. Fan Part Load Curves with ASDs.

There are significant differences in the energy savings potential of a VFD project depending on what the actual baseline is. When estimating potential energy savings from a VFD project it is important that the correct baseline curve is used.

Chapter 3

3 Energy Efficiency and Demand Side Management Programs

To achieve energy savings through efficiency improvements, the most common tactic states have taken is to adopt energy efficiency portfolio standards (EEPS[1]). These standards generally set specific savings goals for utilities to achieve through EE/DSM program offerings. Programs are typically differentiated by ratepayer sectors such as residential, commercial, industrial, government, etc. Some programs are separated further by technology type or by rebate type such as prescriptive measures and custom measures.

Custom measures are offered incentives based on a fixed incentive per kWh or kW saved. Prescriptive measures are commonly offered fixed incentives per unit installed, where units relates to the type of measure. For example, a program could offer a fixed incentive per installed ENERGY STAR refrigerator independent of actual energy saved, or a fixed incentive per light fixture meeting a certain criteria. Some programs offer incentives for VFD installations on HVAC fans or pumps based on a fixed incentive per HP controlled, or incentive per kWh saved using a fixed formula for the kWh saved. Other programs offer incentives based on a percent of incremental cost of the VFD installation. Still others may offer a fixed incentive for different motor size categories such as an incentive for VFDs on motors 1-5 HP, another for 6-10 HP, another for 10-20 HP, etc.

3.1 Ex Ante Savings versus Ex Post Savings Estimates

Regardless of how the incentive is paid, the programs must always provide an estimate of the energy savings for each measure incented. To do this, many jurisdictions use a standard document which specifies a methodology which must be used by the program implementers to estimate savings by measure type. These documents take many forms, but the most common is to use a Technical Reference Manual (TRM) or its equivalent. These savings estimates are used as reported “ex ante” (claimed) savings towards the implementers’ mandated savings targets.

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[1] “EEPS” will be used throughout this paper as a general reference to all legislation, regulation requirements, or utility decisions which result in the requirement for a given entity to develop portfolios of energy efficiency programs within the applicable jurisdiction in order to meet set energy and/or demand reduction compliance targets.

An independent evaluator typically selects a statistically valid random sample of projects for the program year to verify savings and come up with "ex post" (verified) savings estimates. The ratio of project ex post savings to project ex ante savings is called the project realization rate. The sampled realization rates are combined using statistical methods to determine a program level realization rate. The program level ex ante savings are then multiplied by the program level realization rate to determine overall verified savings for compliance.

For several jurisdictions the savings are verified using the TRM, thus it is important that the TRM protocols produce savings estimates that are reliable predictors of average program savings for each measure type.

3.2 Technical Reference Manuals

[This Section 3.2 is reprinted from a previously published paper of the author's (Del Balso & Grabner, 2013)*]*

A TRM, as related to energy efficiency programs or their equivalent, is a manual that specifies a standardized methodology for implementers to estimate and claim savings (energy, demand, fuel, water, greenhouse gases, etc.) for many common, mass marketed, energy efficiency measures. They are also sometimes used by evaluators as the yardstick against which the implementers will be judged. For jurisdictions with multiple implementers offering the same measure, this ensures all parties are claiming savings for the measures in a similar manner, and sometimes using the same deemed savings estimate.

In jurisdictions without a TRM, it is typical for each implementer offering an energy efficiency program to claim measure savings using their own methodology and estimates. This commonly results in each program claiming a different savings for a given measure, even though there may be no indication of actual differences between the program offerings and measure savings. A TRM reduces this inconsistency by providing a representative average "deemed" savings value or standard "deemed" savings algorithm for each measure in the TRM to be used by all implementers.

TRMs usually include "fully deemed"[2] measures and "partially deemed"[3] measures, but rarely include protocols for custom measures. Different terminology may be used in various jurisdictions, but in general, "fully deemed" refers to measures for which a single average "deemed" savings value is provided in the TRM to be used no matter what the actual customer conditions are. No customer

[2] Sometimes referred to as "deemed," "prescriptive," "stipulated," etc.

[3] Sometimes referred to as "semi-deemed," "quasi-deemed," "quasi-prescriptive," etc.

specific inputs are required to claim savings. For example, some TRMs provide a single deemed savings estimate for all recycled refrigerators regardless of size, location, age, configuration, etc. Fully deemed measure protocols work best for large scale mass market measures where there is strong empirical data to derive an estimate for average savings for the population, or measures with conditions of installation that rarely fluctuate significantly from a known value. The advantage of fully deemed measures is that they enable very cost effective implementation due to their simplicity. Their disadvantage is that if the population of participants is relatively small, the participating population measure consumption differs in some way from the assumptions, or there is limited reliable data to support the savings estimates, then the deemed savings estimates may be inaccurate and unreliable. They also generally are not reliable predictors of savings for an individual customer.

"Partially deemed" measures are somewhere between fully deemed and custom measures. For measures which vary significantly in their installation characteristics, the TRM may use a standard "deemed" savings algorithm rather than a fully deemed savings value. The protocol may include some "deemed" variables which must be used by implementers for all customers, and some variables which have default values for each jurisdiction or measure characteristic, but which may use customer specific inputs in place of the defaults if known. Some variables may not include a default value at all, but instead the implementer is required to obtain customer specific data. These measures are not appropriate to be fully deemed because the true savings fluctuate widely from customer to customer and a representative average is difficult to determine. Examples include commercial and residential HVAC measures, non-residential lighting projects, variable speed drives, etc.

Custom measures are on the other end of the spectrum from fully deemed measures. They are generally one of a kind measures for a given customer, and/or so complicated or rare that average savings estimates cannot be reliably derived. Examples of custom measures include modifications to a unique industrial process, a large chiller plant upgrade with multiple chillers and complicated control sequences which does not fit common TRM measure parameters, or installation of a newer technology that has not yet been evaluated as part of an energy efficiency program. Custom measures generally require project specific savings estimates to be derived once the project details are known. Custom measures are more complicated to implement than fully deemed or partially deemed measures, and therefore, many implementers prefer to include as many measures as possible in a TRM as fully or partially deemed.

Due to the unique needs of each jurisdiction implementing energy efficiency programs across North America, there is a diversity of approaches to naming, developing, using and maintaining each jurisdiction's equivalent of a TRM. What is considered a "measure savings protocol" in one TRM may be termed a "measure substantiation document" in a different one, "unit energy savings" in another or a "measure estimation sheet" in yet another.

TRM's have been developed in many forms including stand-alone text documents, stand-alone spreadsheets, downloadable programs, web-based applications, and any combination of these. The most common format is a text document with or without supporting spreadsheets, however, several jurisdictions maintain databases of energy efficiency measure savings which contain similar content and serve a similar purpose as a TRM, but are not called a TRM. As an example, California has an extensive database of deemed measure savings titled the California Database for Energy Efficiency Resources (California Public Utility Commission, 2011), more commonly known as the DEER. This database has been developed overtime through significant research, metering studies, and evaluations. The Michigan Energy Measures Database (MEMD) (Morgan Marketing Partners, 2013) is another tool that is similar in purpose and function as a TRM, but which resides in a database rather than a text document. The Pacific Northwest Electric Power and Conservation Planning Council's Regional Technical Forum (RTF) uses multiple documents together which collectively serve a purpose similar to a TRM. The RTF has established four different savings estimation methods which can be used for energy efficiency measures, two of which when combined would be similar to a TRM, the "Unit Energy Savings" (UES) and "Standard Protocol" methods (Regional Technical Forum (RTF), 2012). The US Department of Energy funded Uniform Methods Project (UMP) (National Renewable Energy Laboratory (NREL) and The Cadmus Group, Inc, 2012) is an attempt to develop "a set of model protocols for determining energy and demand savings that result from specific energy-efficiency measures or programs." The vision is that the UMP protocols will serve as generally accepted industry standard framework that can be incorporated into a TRM and modified as needed.

Regardless of the terminology used, at a minimum they all include protocols to estimate savings for measures which are incented in energy efficiency programs. This typically includes residential and non-residential electric energy efficiency measures which are incented in a prescriptive manner. Some TRMs also include gas and other fuel energy efficiency measures, and even custom measure savings protocols. The type of measures (electric, gas, other) included is generally based on the needs and scope of the applicable EEPS or equivalent legislation.

Whatever the format, the content within each measure protocol includes at a minimum, the methodology for estimating energy savings, whether it is from electricity, fuel, or both. This may be in the form of a fully or partially deemed savings estimate, and in a few cases custom measure protocols.

The protocol may include a methodology for estimating electric peak-demand savings, water savings, measure lifetimes, required/allowable incentive levels, incremental measure cost assumptions, total resource cost (TRC) estimates, and/or any other information the stakeholders establish as appropriate for their jurisdiction. Some TRMs include measurement and verification (M&V) requirements in addition to the savings estimates. The scope of the TRM measure protocols will be based on the needs of the stakeholders developing the TRM.

Due to the varied nature of their development and purposes, some TRMs are quite complete and thorough in their documentation. These standalone TRMs include common cross-cutting assumptions, the purpose of the TRM and its proper application within the TRM document itself, in addition to the measure protocols. Some jurisdictions maintain several documents which collectively serve as a TRM, with each document focused on a specific measure or providing specific guidance on the use or development of the measure protocols.

3.3 Literature Review

Section 3.4 below discusses the methodologies used in each publically available TRM identified for this study. As far as the author is aware, there are no research papers comparing the different savings methodologies used in the TRMs across the country. Further, there are no studies investigating the reliability of the various TRM methodologies against the verified savings for real case studies. There are many annual energy efficiency program evaluation reports available which compare the verified savings for one program against the verified savings for a sample of projects within that program, but often those evaluations use the same methodology as the TRM to derive the verified savings. This does not provide a realistic check on the TRM methodology, but rather only provides a look at whether the implementers were correctly using the TRM.

Further, there are very few programs which include only incentives for VFD measures, thus the evaluations typically include sampled projects from all of the available measures offered. This prevents one from being able to derive VFD specific findings from the reports.

While there are several research papers investigating the savings associated with installation of VFDs in industrial applications or on pump motors, there are relatively few looking specifically at HVAC fan installations in commercial buildings. The following sub-sections summarize the findings of a literature review on this topic.

3.3.1 Overview

Although focused primarily on the industrial sector, Saidur (Saidur, A review on electrical motors energy use and energy savings, 2010) provides a good literature review on motor use and opportunities for energy savings in industrial applications. As the paper is focused primarily on energy efficient motors and their savings, it does not extensively cover the aspects of installing VFDs. The review does briefly cover the installation of VFDs on motors in HVAC applications, but does not go into much discussion on calculating energy savings from their installation.

Several of the authors referenced in the paper explained the significant opportunity for savings associated with replacing inefficient motors with efficient motors, and reported that most motors do not operate at full load. There were conflicting studies on the operating points of most motors. One author suggested that most motors in buildings and industrial facilities operate at a load factor between 50 percent to 70 percent. Another author wrote that 75 percent of motors in industrial facilities operate at load factors less than 60 percent. In a separate U.S. Department of Energy document, the load factor is assumed to be 65 percent for calculations unless otherwise known (Lawrence Berkeley National Laboratory, and Resource Dynamics Corporation, 2008). This is significant because motors are most efficient when they are at roughly 75 percent load factor or greater. Motor efficiency and power factors drop significantly at less than 50 percent of full load. Because most motors are operating at such low load factors there is much potential for energy savings when installing a VFD.

Saidur also referenced several studies in which savings from VFD installations were estimated. One author estimated savings from a VFD installation on a hospital pumping system with simple calculations using the fan affinity laws, but did not compare those to actual savings (Lonnberg, 2007). The paper looked at potential savings only, and did not compare the calculated estimates to those from an actual installation.

Another study looked at savings from VFDs in a metal plating facility, but did not describe how those savings were calculated (Galitsky & Worrell, 2008).

A third study looked at VFD installations in the pumping of machine coolant in an engine plant. Savings were calculated using metering output from an energy management system (EMS) rather than using an algorithm based approach (Price & Ross, 1989).

A fourth study looked at savings from installation of variable speed chiller plants. In this study, computer simulation modeling was used to estimate savings with the model based on the fan and pump affinity laws using a cubic relationship (Yu & Chan, 2009). The paper did not, however, compare the computer simulation estimates to actual metered savings from an actual installation.

Yet another study presented savings from installing VFDs in selected industries. Energy savings were estimated using a deemed savings percent estimate from Arizona Public Service's energy efficiency program (Saidur, et al., 2009).

Teitel et al. (Teitel, et al., 2008) performed an experiment to estimate energy savings from the retrofit of poultry house ventilation fans with a VFD. Two identical poultry houses were metered using an ON-OFF fan operation in one of the poultry houses, and using a fan controlled by a VFD for the other poultry house. Metered energy consumption was compared to show energy savings from the VFD. No model or algorithm was used or developed however.

None of the studies listed investigated different savings methodologies for installing VFDs in commercial office HVAC applications as is the focus of this report. Nor did they compare different savings estimation methodologies to other methods, or compare metered savings results to predicted estimates. The author was not able to find any studies which did such a comparison.

3.3.2 Case Study Paper Reviews

Some of the reviewed papers did include case study comparisons. An early paper reported the on the consideration of installing a VFD on an new industrial plant process cooling tower fan motors as compared to installing a constant volume fan (Cassidy & Stack, 1988). Also considered were outlet damper controls and inlet guide vane controls. Calculations were performed using the simple fan affinity laws and a cubed relationship. More robust analyses and evaluations performed since 1988 have shown the cubic relationship to overstate realized savings due to efficiency losses.

A study was reported on in 2002 which compared the economics of various cooling tower capacity control methodologies (Stout Jr. & Leach, 2002). This study focused on the overall cooling tower efficiency changes based on water temperature and flow control rather than on different methodologies to estimate fan motor savings from a VFD installation. Comparisons were made between different control strategies with each analyzed using a single speed fan, two speed fan, and a variable speed fan. The study was primarily interested in savings due to the different control methods rather than the differences in fan operation.

Wang and Liu (Wang & Liu, 2003) estimated energy savings from installation of VFDs on a non-makeup-air laboratory fume hood system. They showed how savings can be estimated compared to a constant volume fume hood system. In addition they showed how savings can be calculated in a three fan system and provided algorithms to optimize fan operation between the three fans as compared to the baseline system. Although the study shows significant fan energy savings, the study focused on laboratory fume hood retrofits only.

3.3.3 Savings Estimation Techniques

As shown in the Section 3.4 there are various methodologies employed across the country used to estimate savings from VFD installations. A few papers used one or more of these methodologies to compare savings to case study projects as described further below.

3.3.3.1 Simple Engineering Algorithms / Affinity Laws

One of the most fundamental methodologies to estimate energy savings from VFD installations is to use the fan affinity laws. Calculations using the affinity laws are commonplace. There are, however, several ways to overestimate savings when using the ideal fan or pump affinity laws. These issues must be accounted for to avoid significantly over-estimating savings. Maxwell summarized several of these issues: system elements that affect system head pressure independently of flow rate; system elements that change head pressure in proportion to less than the square of the flow rate; dynamic system elements such as downstream dampers; changes in fan efficiency with modulating flow, pressure, or speed; decrease in motor efficiency at low part loads; more efficient existing part load controls than expected; drive efficiency curves; and low load factor at full flow. Individually each of these can cause savings estimates to be off by at least 2% and up to 10% or more in some cases. (Maxwell, 2005)

Rice (Rice, 1988) suggests energy savings are best estimated by separately calculating the baseline and retrofit energy consumption, then taking the difference. He describes that to use the affinity laws to estimate savings, one must first account for the system static head or static pressure requirements as anything above zero will affect the intersection point of the system curve on the pump or fan curve. If this is not accounted for savings will be overestimated. To estimate savings the evaluator must understand the baseline method of flow control, gather the pump or fan data, gather the process information which affects savings such as: specific gravity or density, system resistance (static head/pressure versus frictional), and pump/fan efficiency curves. One also needs efficiency curves for all the electrical components such as the motor, drive, gears, transformers, etc.

Reasonable assumptions can be made for the pump/fan curves and electrical efficiency curves without drastically affecting savings estimates, however, project specific data is needed on the other data points to reliably estimate savings. It is critical to have not just full load efficiencies, but part load efficiencies as well in order to estimate baseline and retrofit consumption and therefore savings. This often requires metering.

Lee (Lee, 2001) compared savings estimates from VFD installations for several case studies in various industrial applications using estimated energy savings based on metering results and energy savings estimates made using the fan affinity laws and engineering calculations. For the simplified calculations, the base kW estimates were made using an assumed load factor, the nominal nameplate HP, nameplate efficiency, and the following algorithm:

$$Pre - retrofit\ baseline\ kW = \frac{hp\ x\ 0.746\ \left(\frac{kw}{hp}\right) x\ Load\ Factor}{Motor\ efficiency} \quad \textbf{[8]}$$

Energy consumption and savings were based on projected baseline run-hours determined through interviews with plant/facility maintenance managers. All baseline systems were constant speed/volume applications. These reported run hours were used with the pre-retrofit baseline kW to project baseline energy consumption.

Post retrofit projected consumption was calculated using the affinity laws with a 2.5 power rather than a cubed power based on Stebbins' (Stebbins, 1994) work showing the affects of static pressure/head on the ideal relationship. The following algorithm was used:

$$\frac{Power2}{Power1} = \left(\frac{Speed2}{Speed1}\right)^{2.5} \quad \textbf{[9]}$$

It appears that post retrofit metering data was used to estimate the percent time the motors spent in various speed bins, but this was not clarified in the paper.

The calculated baseline kW, run hours, and calculated energy savings estimates were compared to the estimates using the pre and post retrofit metering data. The conclusion was that the run hour estimates made from facility maintenance manager interviews were not that reliable. The predicted energy savings from the simplified calculations varied significantly from the metered results. As such, the author recommend VSD savings should be estimated using metered results to determine baseline power, run-time hours, and speed bins rather than using interviews and nameplate data. There was not a judgment made on the use of the 2.5 power on the affinity law. It is important to note that these were industrial applications which tend to have more variation than HVAC applications.

3.3.3.2 Spreadsheet Calculations

The more reliable methods to estimate savings that do not rely on computer simulations generally require input of a system load profile which looks at the time a fan motor spends in various ranges (bins) of percent flow (Rouse, 2009). Minimum and maximum allowable speed/flow and the amount of throttling that occurs within the full operating range over the course of a year determine how much energy can be saved by installing a VFD (Ontario Hydro, 1997). The hours spent within each speed/flow range are recorded in a spreadsheet. The affinity laws or a regression equation for the power/flow relationship for the system are applied to each bin. The energy consumption for each bin are then added up and compared to the baseline energy consumption to determine savings.

It is recognized that demand savings estimates are difficult to predict on a system level basis when comparing multiple different system configurations. It is best not to look at individual components, but the combined efficiency of each system considered. Although not specifically focused on VFD savings, Kavanaugh developed a simplified spreadsheet calculation to do a quick early design comparison of different system types to compare design day max efficiency (Kavanaugh, 2003).

3.3.3.3 Computer Simulation Energy Modeling

One of the advantages of a building computer simulation methodology to estimate savings from VFD installations is that the computer simulations can model efficiency and consumption changes that occur in the different parts of the HVAC system as a result of installing a VFD on the fan. For example, on systems with the motor in conditioned spaces, running the motors at reduced speeds can not only save energy from the fan motor, but can reduce the cooling load on the building HVAC system due to lower motor heat losses. During the heating season, however, the lower fan motor heat losses may require increased heating energy consumption to meet the heating load.

Computer energy simulations also have the ability to isolate savings from installation of the VFD from the savings associated with various control methods. This is often not possible when using billing data or metered data.

When determining savings from VFD’s it is important to consider not just the nominal efficiency of the motor at full load, as this may represent only a small fraction or (or even none of) the annual operating points. It is necessary to look at the combination of the fan efficiency curve, the motor efficiency curve and the VFD efficiency curve. These should then be compared to the system efficiency curve to determine where on the combined fan/motor/VFD efficiency curve the system operates. Unfortunately this point is always changing as the system adjusts to load. It is difficult to make accurate energy consumption estimates based on a single two dimensional curve as it is not representative of the real complexities of the system. More advanced modeling software can use the efficiency curves for each component to determine operating conditions for annual energy simulations. (Rooks & Wallace, 2004)

Eto and Almeida (Eto & De Almeida, 1988) evaluated the potential energy savings achievable through installation of a VFD on a commercial HVAC fan and chillers as compared to using inlet guide vanes. Computer simulations were performed with different parametric runs on two prototypical commercial buildings and using five different climate zone weather files. The commercial building included in the study was a prototypical retail strip mall and a prototypical medium office building. Both building prototypes were made to meet ASHRAE Standard 90-1975.

The baseline HVAC system for the retail building was a standard VAV system with inlet guide vanes. The retrofit scenario was modeled with a VFD installed. The baseline for the office building was a dual-duct VAV system with inlet guide vanes. The retrofit scenario was modeled with VFDs installed. The office building also included retrofit of a conventional constant flow chiller with a VFD chiller. Savings from retrofitting the chiller were separated from the fan retrofit savings by running multiple model configurations.

The models were each run in five different climate zones using Weather Year for Energy Calculation (WYEC) data. Simulations were performed using the DOE-2.1C simulation program.

The simulations showed savings for both the fan and chiller applications, but also showed increased heating consumption due to the reduced heating load from running the fans at lower speeds. These HVAC interactive effects are generally not accounted for in the simplified VFD savings models. Interestingly the energy savings for the retail models differed much more between climate zones than the savings for the medium office building, primarily because the office building HVAC load was more dominated by internal loads as compared to the retail building. Both prototypes showed potential for economical energy savings, with the office building showing somewhat more potential. This study did not compare the modeling results to other savings estimation methodologies, nor to verified case studies.

3.3.3.4 Statistical Approaches

Yalcintas (Yalcintas, 2008) presents the use of an Artificial Neural Network (ANN) approach to estimating savings for two different case studies. One of the case studies was the installation of VFDs on an existing air-handling units of a hotel and the addition of energy management systems in each guest room. According to Yalcintas, the benefit of using a ANN approach as opposed to the more common Multivariable Regression (MVR) approach is that there is a faster learning time, the analysis is more simple, there is better prediction accuracy, and there is an added ability to model fluctuations in the building energy use.

This method, however, required both pre-and post metering to “train” the model before being able to use it for prediction of savings, thus limiting its application to evaluation of savings post-installation rather than prediction of savings pre-installation. This method is not available to predict savings in the absence of metering, but it is rather a method to annualize short term metering results. Although the results appeared to produce good reliability, this approach does not offer significant usability for energy efficiency program implementation, per the focus of this report. It is possible, however, that this approach could be considered for evaluation of achieved program savings.

3.4 TRM Savings Methodologies for VFD Installations on HVAC Fan or Pump Motors

Several TRMs include protocols for estimating savings associated with installing a VFD on an HVAC motor for non-residential applications. Most of the protocols include savings estimates for installations on HVAC supply, return or exhaust fans, or chilled water loop or hot water loop pump motors. A few also include estimates for installations on cooling tower fan motors.

The following TRMs include protocols for HVAC VFD installations and were included in this study for comparison. This should not be considered an exhaustive list of available TRMs. New TRMs are often under development and existing TRMs typically undergo annual or biannual updates which may supersede the documents identified for this report. Many TRMs are not posted in conspicuous public locations on the internet. Some are buried as links on a public court docket that are not accessible through normal internet search engines without previous knowledge of their existence.

Table 2 lists the TRMs included in this analysis and summarizes the calculation methodologies and source of savings estimates. The following sections go into more detail for each TRM listed including the savings algorithms used.

Table 2. TRM Calculation Methodology Comparison

TRM Source	Calculation Methodology	Source of Savings Estimates
SU 2011 MSEM	Deemed savings per horsepower regardless of building type or motor application	Based on simplified pump/fan affinity laws
CA 2011 DEER	Partially deemed algorithm with deemed savings per horsepower estimates based on building type, building vintage, motor application and climate zone	Based on DOE-2.2 energy simulations
CT 2012 TRM	Partially deemed algorithm with deemed savings per horsepower based on building type and motor application	Based on temperature bin analysis spreadsheet
IL 2012 TRM	Partially deemed algorithm with deemed savings factors based on building type and motor application	Based on temperature bin analysis spreadsheet per 2008 CT TRM
NJ 2012 TRM	Partially deemed algorithm with deemed savings factors represented as a percentage of baseline consumption based on motor application	Based on temperature bin analysis spreadsheet per 2008 CT TRM
Mid-Atlantic 2011 TRM	Partially deemed algorithm with deemed savings per horsepower based on building type and motor application	Based on temperature bin analysis spreadsheet per 2009 CT TRM
OH 2010 TRM	Partially deemed algorithm with deemed savings per horsepower based on building type and motor application	Based on temperature bin analysis spreadsheet per 2008 CT TRM
PA 2013 TRM	Partially deemed algorithm with deemed savings factors based on motor application	Based on temperature bin analysis spreadsheet per 2012 CT TRM
ME 2010 TRM	Partially deemed algorithm with deemed savings per horsepower based on motor application only	Based on National Grid 2001 values averaged from previous evaluations of VFD installations
MA 2012 TRM	Partially deemed algorithm with deemed savings per horsepower based on building type and motor application	Based on a report for NSTAR
NYSERDA 2010 TRM	Partially deemed algorithm with deemed savings per horsepower based on building type, climate, and motor application	Based on DOE-2.2 energy simulations
VT 2010 TRM	Partially deemed algorithm with deemed savings per horsepower based on motor application only	Based on National Grid 2001 values averaged from previous evaluations of VFD installation
Manufacturers' Calculators	Simple Excel based calculator with assumed savings per horsepower based on fan/pump configuration; requires input of assumed annual hours of operation	Based on manufacturer assumptions of annual average fan/pump loading and standard fan power curves

The savings methodologies used in the listed TRMs can be generally categorized into the following methods with the number of TRMs using the method recorded in parentheses:

- Simple calculations using fan affinity laws (1)
- DOE-2.2 energy simulation outputs (2)
- Temperature bin spreadsheet analysis (6)
- Empirical evaluation results (2)
- Fan part load curves (1)
- Unknown/from non-public report (1)

Each of the TRM protocols for VFD’s are summarized in the following sub-sections. It is interesting to note that of the six TRMs using temperature bin spreadsheet analysis, Connecticut is the only jurisdiction that actually did the analysis and the other five are based on different years of the CT TRM. With the differences shown in the description of each TRM, it is very interesting to see how they all come up with different savings estimates even though they are based on the same source and did not make climate adjustments.

Unfortunately none of the TRM's provide estimates of savings uncertainty, thus it is impossible to predict the uncertainty associated with each method. It is likely that there is a large uncertainty associated with each method given the methodologies used to estimate savings, none of which are based on metered results.

3.4.1 Southwest Utility Measure Savings Estimation Methodology 2011 (based on pump/fan affinity laws)

The SU 2011 MSEM (Confidential, 2011) is perhaps the most simplistic savings methodology used across the country. This is a utility specific TRM used for implementation and program evaluation purposes. Although a more complete algorithm is provided, all factors except motor horsepower are deemed resulting in a deemed savings per horsepower value regardless of building type or motor application. The deemed savings factors are based on pump/fan affinity laws assuming: kW ≈ Flowrate^2.5. All other inputs are provided as deemed values except nominal horsepower.

The algorithms provided to estimate energy and demand savings are as follows:

Annual Energy Savings[4]:

$$VSD_{i,pk,kWh} = 0.746 * \left(\frac{1}{Eff_{motor}}\right) * LF * ESF * Hours_{pk} * HP \quad \textbf{[10]}$$

Summer Peak Demand Savings:

$$VSD_{i,kW} = 0.746 * \left(\frac{1}{Eff_{motor}}\right) * LF * DSF * HP \quad \textbf{[11]}$$

Where:

$VSD_{i,pk,kWh}$	= Annual energy savings
$VSD_{i,kW}$	= Summer peak demand savings
0.746	= Conversion factor for HP to kWh
Eff_{motor}	= Installed motor efficiency; deemed based on HP
LF	= Load factor; deemed

4 Actual formula listed in the SU 2011 MSEM for energy savings incorrectly listed DSF instead of ESF. The formula listed here has been corrected to provide clarity based on intent of the MSEM.

ESF = Energy savings factor (percent); single deemed value based on pump/fan affinity laws assuming: kW ≈ Flowrate^2.5

DSF = Demand savings factor (percent); single deemed value based on pump/fan affinity laws assuming: kW ≈ Flowrate^2.5

$Hours_{pk}$ = Annual hours of operation; deemed

HP = Nominal horsepower of controlled motor

3.4.2 California Database for Energy Efficiency Resources (DEER) 2011

The California 2011 DEER (California Public Utility Commission, 2011) uses a partially deemed algorithm with deemed savings per horsepower estimates based on building type, building vintage, motor application and climate zone. Deemed savings factors were developed using DOE-2.2 (James J. Hirsch & Associates and Lawrence Berkely National Laboratory) energy simulations for prototypical buildings and established measure characterizations. Deemed savings estimates are provided for each measure type, building type, vintage and climate zone. (Itron, Inc., JJ Hirsch & Associates, Synergy Consulting, and Quantum, Inc., 2005)

The algorithms provided to estimate energy and demand savings are as follows:

Annual Energy Savings:

$$\Delta kWh = HP * \left(\frac{kWh}{HP}\right) \quad [12]$$

Summer Peak Demand Savings:

$$\Delta kW = HP * \left(\frac{kW}{HP}\right) \quad [13]$$

Annual Gas Savings:

$$\Delta therms = HP * \left(\frac{therms}{HP}\right) \quad [14]$$

Where:

ΔkWh = Annual energy savings

ΔkW = Summer peak demand savings

$\Delta therms$ = Annual fuel savings

HP = Nominal horsepower of controlled motor

$\frac{kWh}{HP}$ = Energy savings factor based on motor application, building type, building vintage, and climate zone; deemed

$\frac{kW}{HP}$ = Summer peak demand savings factor based on motor application, building type, building vintage, and climate zone; deemed

$\frac{therms}{HP}$ = Fuel savings factor based on motor application, building type, building vintage, and climate zone; deemed

The CA DEER provides deemed savings factors for VFDs installed in the following applications:

- HVAC supply VAV box with constant volume baseline
- HVAC Supply Fan with baseline VAV fan without VFD (measure assumes baseline forward curved fan with discharge dampers)
- HVAC cooling tower fans with baseline two-speed tower fans
- HVAC Pump with constant flow baseline pump for:
    - Hot water loop
    - Chilled water loop
- HVAC Pump with variable flow baseline pump for:
    - Hot water loop
    - Chilled water loop

The CA DEER provides a value for deemed savings to be used for the above applications in multiple climate zones and various vintages for each of the following building types:

- Education - Community College
- Education - Secondary School
- Education – University
- Health/Medical – Hospital
- Lodging – Hotel
- Health/Medical - Nursing Home
- Office – Large
- Retail - Multistory Large
- Commercial
- SCE Health/Medical Clinic
- SCE Transportation - Communication – Utilities

3.4.3 Connecticut 2012 TRM (based on temperature bin analysis)

The CT 2012 TRM (UI and CL&P, 2011) uses a partially deemed algorithm with deemed savings per horsepower based on building type and motor application. Deemed savings factors are based on ASHRAE 90.1-1989 User's Manual derived using a temperature bin analysis spreadsheet with typical heating, cooling and fan load profiles.

The algorithms provided to estimate energy and demand savings are as follows:

Annual Energy Savings:

$$AkWh = \left(\frac{BHP}{EFF_i}\right) * H * SF_{kWh} \quad \textbf{[15]}$$

Summer Peak Demand Savings:

$$SkW = \left(\frac{BHP}{EFF_i}\right) * SF_{kW,S} \quad \textbf{[16]}$$

Winter Peak Demand Savings:

$$WkW = \left(\frac{BHP}{EFF_i}\right) * SF_{kW,W} \quad \textbf{[17]}$$

Where:

$AkWh$	= Annual energy savings
SkW	= Summer peak demand savings
WkW	= Winter peak demand savings
BHP	= System brake horsepower
H	= Annual hours of operation; deemed
EFF_i	= Installed motor efficiency
SF_{kWh}	= Annual kilowatt hour savings factor based on typical load profile for application; deemed
$SF_{kW,S}$	= Summer kW savings factor based on typical peak load of application, includes coincident factors within deemed values; deemed
$SF_{kW,W}$	= Winter kW savings factor based on typical peak load of application, includes coincident factors within deemed values; deemed

The CT TRM provides deemed savings factors for VFDs installed in the following applications[5]:

[5] The 2012 version of the CT TRM removed the savings factors for constant volume baselines.

- HVAC Fan with baseline fan type of:
    - AF/BI: Airfoil/backward inclined
    - AF/BI IGV: Airfoil/backward inclined with inlet guide vane
    - FC: Forward curved
    - FC IGV: Forward curved with inlet guide vane
- HVAC Pump with baseline pump type of:
    - CHWP: Chilled water pump
    - HWP: Hot water pump

The TRM provides deemed annual hours of operation for fan motors, CHWP motors and HWP motors for a large number of building types too numerous to list here. It is not clear how the hours of operation are derived.

3.4.4 Illinois 2012 TRM (based on 2008 CT TRM)

The IL 2012 TRM (Vermont Energy Investment Corporation, 2012) uses a partially deemed algorithm with deemed savings factors based on building type and motor application. Deemed savings factors are based on the 2008 CT TRM (CL&P and UI, 2007) which used ASHRAE 90.1-1989 User's Manual to derive the factors using a temperature bin analysis spreadsheet with typical heating, cooling and fan load profiles. It is important to note that although the IL TRM protocol is based on the 2008 CT TRM, a few modifications were made in the IL TRM protocol.

First, the 2008 CT TRM uses brake horse power in the equation, but the IL TRM uses nominal horsepower with a load factor (LF) adjustment. This should provide similar results.

Further, the IL TRM does not include a coincidence factor (CF) in the demand savings algorithm. The protocol states that the CF is already incorporated into the DSF from the 2008 CT TRM, however, this is not entirely clear. It appears in fact that this may not be the case. The 2008 CT TRM provides CF values in the appendix as a way to convert measure peak demand savings to system peak demand savings. This would affect system peak demand savings calculated using the IL TRM.

The IL TRM also includes a factor for conversion of HP to kWh. This factor is not used in the 2008 CT TRM as it is presumably included in the savings factors directly. Given that the IL TRM did not adjust the savings factors to account for this factor it will lead to results which differ from the source document and will likely be unreliable as a result.

Lastly, deemed operating hours in the IL TRM are based on averages by building type from simulation modeling, performed for ComEd, of pump and fan motors rather than using the operating hours from the 2008 CT TRM which the savings factors are based on. Because the IL TRM uses different hours than what the savings factors are based on, this further leads to questionable savings estimates.

Given the changes the IL TRM makes to the algorithms and deemed variables as compared to the source document, it renders the savings estimates in the IL TRM to be suspect and likely unreliable.

The algorithms provided to estimate energy and demand savings are as follows:

Annual Energy Savings:

$$\Delta kWh = kW_{connected} * Hours * ESF \quad \textbf{[18]}$$

Summer Peak Demand Savings:

$$\Delta kW = kW_{connected} * DSF \quad \textbf{[19]}$$

Where:

$$kW_{connected} = HP * 0.746 * \frac{LF}{\eta_{motor}} \quad \textbf{[20]}$$

And:

ΔkWh	= Annual energy savings
ΔkW	= Summer coincident peak demand savings
$kW_{connected}$	= kW of equipment calculated using motor efficiency
$Hours$	= Annual hours of operation based on building type; deemed
ESF	= Energy savings factor based on motor application; deemed
DSF	= Demand savings factor based on motor application; deemed
HP	= Nominal horsepower of controlled motor
0.746	= Conversion factor for HP to kWh
LF	= Load factor
η_{motor}	= Installed motor efficiency

The IL TRM provides deemed savings factors for VFDs installed in the following applications:

- HVAC Fan with baseline fan type of:
    - Constant volume
    - Airfoil with inlet guide vane
    - Forward curved with discharge dampers
    - Forward curved with inlet guide vane
- HVAC Pump with baseline pump type of:
    - Chilled water pump

- Hot water pump

The IL TRM provides a value for deemed operating hours to be used for both fan and pump applications for each of the following building types:

- College/University
- Grocery
- Heavy Industry
- Hotel/Motel
- Light Industry
- Medical
- Office
- Restaurant
- Retail/Service
- School (K-12)
- Warehouse
- Average/Miscellaneous

3.4.5 New Jersey 2011 TRM (based on 2008 CT TRM)

The NJ 2011 TRM (New Jersey Clean Energy Program Protocols, 2011) uses a partially deemed algorithm with deemed savings factors represented as a percentage of baseline consumption based on motor application. Deemed savings factors are based on a CT TRM which used ASHRAE 90.1-1989 User's Manual to derive the factors using a temperature bin analysis spreadsheet with typical heating, cooling and fan load profiles. It is unclear which year of the CT TRM was used, but it was likely the 2008 CT TRM (CL&P and UI, 2007) as the ESF's can be replicated from those versions and the NJ TRM does not place HP limits on the protocol similar to the 2008 CT TRM. It is important to note that although the NJ TRM protocol is based on the CT TRM, a few modifications were made in the NJ TRM protocol.

First, the CT TRM uses brake horse power in the equation, but the NJ TRM uses nominal/nameplate horsepower with no adjustment to the energy and demand savings factors to account for the difference. This results in a different savings estimate.

Further, the NJ TRM includes a factor for conversion of HP to kWh. This factor is not used in the CT TRM, but the NJ TRM does appear to adjust the savings factors to account for this factor and should have a similar result.

The NJ TRM does not provide default operating hours based on the CT TRM and instead requires customer specific inputs for operating hours. As the ESF and DSF factors in the CT TRM are based on related operating hours per the modeling used, this adds some questions to the validity of the NJ TRM results.

Finally, the NJ TRM appears to have made an additional adjustment to the DSF values from the CT TRM when developing the protocol. It is not possible to replicate the changes and they do not appear to be consistent between motor applications. It is likely that this renders the NJ TRM protocol demand savings estimates unreliable, or at a minimum very questionable until the purpose and method of the adjustments is clarified.

The algorithms provided to estimate energy and demand savings are as follows:

Annual Energy Savings:

$$\Delta kWh = \quad 0.746 * HP * HRS * \left(\frac{ESF}{\eta_{motor}}\right) \tag{21}$$

Summer Peak Demand Savings:

$$\Delta kW = \quad 0.746 * HP * \left(\frac{DSF}{\eta_{motor}}\right) \tag{22}$$

Where:

kWh	= Annual energy savings
kW	= Peak demand savings
0.746	= Conversion factor for HP to kWh
HP	= Nominal/nameplate horsepower of controlled motor
HRS	= Annual hours of operation based on building type and motor application; default not provided
ESF	= Energy savings factor based on motor application; deemed
DSF	= Demand savings factor based on motor application, includes coincident factor within the DSF; deemed
η_{motor}	= Efficiency of motor at peak load

3.4.6 Northeast Energy Efficiency Partnerships (NEEP): Mid-Atlantic 2011 TRM (based on 2009 CT TRM)

The Mid-Atlantic 2011 TRM (Vermont Energy Investment Corporation, 2011) uses a partially deemed algorithm with deemed savings per horsepower based on building type and motor application. Use of the protocol is limited to VFDs installed on motors 10 HP or less, without a VFD control, for the following

HVAC applications: supply fans, return fans, exhaust fans, chilled water pumps, and boiler feed-water pumps. Deemed savings factors are based on the 2009 CT TRM (UI and CL&P, 2008) which used ASHRAE 90.1-1989 User's Manual to derive the factors using a temperature bin analysis spreadsheet with typical heating, cooling and fan load profiles. It is important to note that although the Mid-Atlantic TRM protocol is based on the 2009 CT TRM, a few modifications were made in the Mid-Atlantic TRM protocol.

First, the 2009 CT TRM limits the protocol's application to VFDs installed on condenser fans and cooling tower fans less than 7.5 HP, VAV fans less than 15 HP, and chilled water or hot water hydronic system pumps up to 50 HP. It is not clear why the Mid-Atlantic TRM differed in its allowed applications from the source reference to applications that were not intended by the original protocol.

Additionally, the 2009 CT TRM uses brake horse power in the equation, but the Mid-Atlantic TRM uses nominal horsepower with no adjustment to the energy and demand savings factors to account for the difference. This results in a different savings estimate.

Further, the Mid-Atlantic TRM includes a coincidence factor (CF) in the demand savings algorithm. The 2009 CT TRM does not include the CF within the DSF, but instead lists the CF's in the appendix as a way to convert measure peak demand savings to system peak demand savings. This is simply a change in where the CF is shown within the document, but should not affect system peak demand savings.

Lastly, the Mid-Atlantic TRM includes a factor for conversion of HP to kWh. This factor is not used in the CT TRM, but the Mid-Atlantic TRM did adjust the savings factors to account for this factor and should have a similar result.

The algorithms provided to estimate energy and demand savings are as follows:

Annual Energy Savings:

$$\Delta kWh = \frac{(HP * 0.746)}{\eta_{BASE}} * HOURS * ESF \qquad \textbf{[23]}$$

Summer Peak Demand Savings:

$$\Delta kW = \frac{(HP * 0.746)}{\eta_{BASE}} * DSF * CF \qquad \textbf{[24]}$$

Where:

ΔkWh	= Annual energy savings
ΔkW	= Summer peak demand savings
HP	= Nominal horsepower of controlled motor
0.746	= Conversion factor for HP to kWh
η_{BASE}	= Efficiency of baseline motor

$Hours$	= Annual hours of operation based on building type and motor application; deemed
ESF	= Energy savings factor based on motor application; deemed
DSF	= Demand savings factor based on motor application, does not include coincident demand factor; deemed
CF	= Summer peak coincidence factor; deemed by motor application

The Mid-Atlantic TRM provides deemed savings factors for VFDs installed in the following applications:

- HVAC Fan with baseline fan type of:
  - Constant Volume
  - AF/BI: Airfoil/backward inclined
  - AF/BI IGV: Airfoil/backward inclined with inlet guide vane
  - FC: Forward curved
  - FC IGV: Forward curved with inlet guide vane
- HVAC Pump with baseline pump type of:
  - CHWP: Chilled water pump
  - HWP: Hot water pump

The TRM provides deemed annual hours of operation for fan motors, chilled water pump motors and hot water pump motors for a large number of building types too numerous to list here.

3.4.7 Ohio Draft 2010 TRM (based on 2008 CT TRM)

The draft Ohio 2010 TRM (Vermont Energy Investment Corporation, 2010) uses a partially deemed algorithm with deemed savings per horsepower based on building type and motor application. Deemed savings factors are based on the 2008 CT TRM (CL&P and UI, 2007) which used ASHRAE 90.1-1989 User's Manual to derive the factors using a temperature bin analysis spreadsheet with typical heating, cooling and fan load profiles. It is important to note that although the IL TRM protocol is based on the 2008 CT TRM, a few modifications were made in the IL TRM protocol.

The primary difference is that in the Ohio TRM deemed operating hours are based on averages of hours from all building types in the CT TRM by motor application, rather than using the operating hours by building type and motor application from the 2008 CT TRM which the savings factors are based on. By averaging the operating hours across all building types, the Ohio TRM will yield less reliable savings estimates for each project. It is possible that due to differences in participation, this will also result in less reliable savings for the program as a whole.

Further, the Ohio TRM does not include a coincidence factor (CF) in the demand savings algorithm. The protocol states that the CF is already incorporated into the DSF from the 2008 CT TRM, however, this is not entirely clear in the CT TRM. It appears in fact that this may not be the case. The 2008 CT TRM provides CF values in the appendix as a way to convert measure peak demand savings to system peak demand savings. If the CT TRM doesn't include a CF in the DSF, this would affect system peak demand savings calculated using the Ohio TRM.

Given the changes the Ohio TRM makes to the algorithms and deemed variables as compared to the source document, it renders the savings estimates in the Ohio TRM to be slightly suspect. The changes are minor and may not have a significant impact, but should be understood.

The algorithms provided to estimate energy and demand savings are as follows:

Annual Energy Savings:

$$\Delta kWh = \left(\frac{BHP}{\eta_{motor}}\right) * HOURS * ESF \qquad \textbf{[25]}$$

Summer Peak Demand Savings:

$$\Delta kW = \left(\frac{BHP}{\eta_{motor}}\right) * DSF \qquad \textbf{[26]}$$

Where:

ΔkWh	= Annual energy savings
ΔkW	= Summer coincident peak demand savings
BHP	= System brake horsepower
η_{motor}	= Installed motor efficiency
HOURS	= Annual hours of operation; deemed based on motor application
ESF	= Energy savings factor based on motor application; deemed
DSF	= Demand savings factor based on motor application, includes coincident demand factor; deemed

The Ohio TRM provides deemed savings factors for VFDs installed in the following applications:

- HVAC Fan with baseline fan type of:
    - Constant volume

- Airfoil/backward inclined
- Airfoil with inlet guide vane
- Forward curved
- Forward curved with inlet guide vane

- HVAC Pump with baseline pump type of:
    - Chilled water pump
    - Hot water pump

The Ohio TRM provides a single deemed operating hour value for each of the following:

- Fans
- Hot water pump
- Chilled water pump

3.4.8 Pennsylvania 2013 TRM (based on 2012 CT TRM)

The PA 2013 TRM (Pennsylvania Public Utility Commission, 2013) uses a partially deemed algorithm with deemed savings factors based on motor application. Use of the protocol is limited to VFDs installed on without a VFD control, for the following HVAC applications: HVAC fans, chilled water pumps, and hot water pumps. Deemed savings factors are based on the 2012 CT TRM (UI and CL&P, 2011) which used ASHRAE 90.1-1989 User's Manual to derive the factors using a temperature bin analysis spreadsheet with typical heating, cooling and fan load profiles. It is important to note that although the PA TRM protocol is based on the 2012 CT TRM, a few modifications were made in the PA TRM protocol.

First, the 2012 CT TRM uses brake horse power in the equation, but the PA TRM uses nominal horsepower with a load factor (LF) adjustment. This should provide similar results.

Additionally, the PA TRM also includes a factor for conversion of HP to kWh. This factor is not used in the 2012 CT TRM as it is presumably included in the savings factors directly. Given that the PA TRM did not adjust the savings factors to account for this factor it will lead to results which differ from the source document and will likely be unreliable as a result.

Further, the PA TRM includes a CF in the demand savings algorithm. The 2012 CT TRM does not include a separate CF, but instead appears to have included the CF within the DSF itself, thus directly calculating coincident peak demand savings. This difference may double count the affects of the CF in the PA TRM, thus lowering savings estimates.

The combined effect of these modifications the PA TRM makes to the algorithms and deemed variables as compared to the source document, it renders the savings estimates in the IL TRM to be suspect and likely unreliable.

The algorithms provided to estimate energy and demand savings are as follows:

Annual Energy Savings:

$$\Delta kWh = \quad 0.746 * HP * \frac{LF}{\eta_{motor}} * RHRS_{base} * ESF \qquad \textbf{[27]}$$

Summer Peak Demand Savings:

$$\Delta kW = \quad 0.746 * HP * \frac{LF}{\eta_{motor}} * CF * DSF \qquad \textbf{[28]}$$

Where:

ΔkWh	= Annual energy savings
ΔkW	= Summer coincident peak demand savings
0.746	= Conversion factor for HP to kWh
HP	= Nominal horsepower of controlled motor
LF	= Load factor; ratio between the actual load and rated load
η_{motor}	= Efficiency of motor at full-rated load
$RHRS_{base}$	= Annual hours of operation based on building type and motor application; deemed
ESF	= Energy savings factor based on motor application; deemed
DSF	= Demand savings factor based on motor application, does not include coincident demand factor; deemed
CF	= Summer peak coincidence factor; deemed by motor application

The PA TRM provides deemed savings factors for VFDs installed in the following applications:

- HVAC Fan with baseline fan type of:
    - Constant Volume
    - Airfoil/backward inclined
    - Airfoil/backward inclined with inlet guide vane
    - Forward curved
    - Forward curved with inlet guide vane
- HVAC Pump with baseline pump type of:

- Chilled water pump
- Hot water pump

The TRM provides deemed annual hours of operation for fan motors, chilled water pump motors and hot water pump motors for a large number of building types too numerous to list here.

3.4.9 Maine 2010 TRM (based on National Grid 2001 study, same as VT 2010 TRM)

The ME 2010 TRM (Efficiency Maine, 2010) uses a partially deemed algorithm with deemed savings per horsepower based on motor application only. Deemed savings factors are based on National Grid 2001 values averaged from previous evaluations of VFD installations, but the National Grid source document is publically unavailable and the details of the evaluation methods used to determine savings are unknown. It is not clear how the savings factors were derived.

Use of the following algorithms is limited to VFDs installed on motors 5 HP through 30 HP, on HVAC supply, return and exhaust fans, chilled water pumps, and heating hot water circulation pumps, with baseline control system that is no-control or bypass. All other control systems such as on/off, inlet vanes, dampers, throttling valves, Eddy current, magnetic coupling, etc. must use a custom calculation. The ME 2010 TRM also provides a more robust algorithm to use with VFDs installed on HVAC supply, return and exhaust fans, chilled water pumps, and boiler feed water pumps (5 HP to 30 HP) with baseline conditions including no control, inlet guide vanes, outlet guide vanes, and throttling valves. However, the algorithm requires custom inputs for all variables and is therefore not provided here as a prescriptive protocol.

The algorithms provided to estimate energy and demand savings are as follows:

Annual Energy Savings:

$$\Delta kWh = ESVG * HP * CXS \quad \textbf{[29]}$$

Summer Peak Demand Savings:

$$\Delta kW = DSVG * HP * CXS \quad \textbf{[30]}$$

Where:

ΔkWh = Annual energy savings

ΔkW = Maximum of either summer or winter peak demand savings

$ESVG$ = Energy savings factor (kWh/HP) based on motor application; deemed

$DSVG$ = Winter peak demand savings factor (kW/HP) based on motor application except summer peak demand savings factor for chilled water pumps; deemed

HP = Nominal horsepower of controlled motor

CXS = Commissioning factor. CXS = 1.10 when the project undergoes commissioning services, 1.0 otherwise.

The MA TRM provides deemed savings factors for VFDs installed in the following applications:

- Supply Fan
- Return Fan
- Exhaust Fan
- Chilled Water Pump
- Heating Hot Water Circulating Pump

3.4.10 Massachusetts 2012 TRM (based on 2010 NSTAR study)

The Massachusetts 2012 TRM (Mass Save, 2012) uses a partially deemed algorithm with deemed savings per horsepower based on building type and motor application. Deemed savings factors are based on a report for NSTAR, but the report is not publically available and the details of the report are unknown. It is not clear how the savings factors were derived.

The algorithms provided to estimate energy and demand savings are as follows:

Annual Energy Savings:

$$\Delta kWh = (HP) * \left(\frac{1}{\eta_{motor}}\right) * \left(\frac{kWh}{HP}\right) \quad \textbf{[31]}$$

Summer Peak Demand Savings:

$$\Delta kW = (HP) * \left(\frac{1}{\eta_{motor}}\right) * \left(\frac{kW}{HP}\right)_{SP} \quad \textbf{[32]}$$

Where:

ΔkWh = Annual energy savings

ΔkW = Summer peak demand savings

HP = Nominal horsepower of controlled motor

η_{motor} = Nameplate motor efficiency

$\frac{kWh}{HP}$ = Energy savings factor based on motor application and building type; deemed

$\left(\frac{kW}{HP}\right)_{SP}$ = Summer peak demand savings factor based on motor application and building type; deemed

The MA TRM provides deemed savings factors for VFDs installed in the following applications:

- Building Exhaust Fan
- Cooling Tower Fan
- Chilled Water Pump
- Boiler Feed Water Pump
- Hot Water Circulating Pump
- MAF – Make-up Air Fan
- Return Fan
- Supply Fan
- WS Heat Pump Circulating Loop

And for the following building types:

- University/College
- Elementary/High School
- Multi-Family
- Hotel/Motel
- Health
- Warehouse
- Restaurant
- Retail
- Grocery
- Offices

3.4.11 New York 2010 TRM (based on DOE-2.2 simulation modeling)

The NY 2010 TRM (New York Evaluation Advisory Contractor Team and TecMarket Works, 2010) uses a partially deemed algorithm with deemed savings per horsepower based on building type, climate, and motor application. Deemed savings factors were developed using DOE-2.2 energy simulations and prototypical buildings with three different built-up systems. Results were then averaged together for the final factors.

The algorithms provided to estimate energy and demand savings are as follows:

Annual Energy Savings:

$$\Delta kWh = HP * \left(\frac{\Delta kWh}{HP}\right) \quad [33]$$

Summer Peak Demand Savings:

$$\Delta kW = HP * \left(\frac{\Delta kW}{HP}\right) * CF_S \quad \textbf{[34]}$$

Where:

ΔkWh = Annual energy savings

ΔkW = Summer peak demand savings

HP = Nominal horsepower of controlled motor

$\frac{\Delta kWh}{HP}$ = Energy savings factor based on climate, building type and motor application; deemed

$\frac{\Delta kW}{HP}$ = Summer peak demand savings factor based on climate, building type and motor application; deemed

CF_S = Coincidence factor

The NY TRM provides deemed savings factors for VFDs installed in the following applications:

- Chilled Water Pump
- Hot Water Pump
- Cooling Tower Fan
- Return Fan
- Supply Fan
- Condenser water pump

And for the following building types:

- Hotel
- Office
- Hospital
- Community college
- High school
- Large retail
- Dormitory
- University

The protocol also provides energy and demand savings factors supplied by National Grid based on data developed by NSTAR for the Massachusetts TRM and trued up by National Grid based on NSTAR data. The details of the works by NSTAR and National Grid are publically unavailable. The savings factors provided based on NSTAR data cover the following motor applications:

- Exhaust fan
- Cooling tower fan
- Chilled water pump
- Boiler feed-water pump
- Hot water pump
- Make-up air fan
- Return fan
- Supply fan
- Water loop heat pump circulating pump

The savings factors provided based on NSTAR data cover the following building types:

- University/College
- Elementary/High School
- Multi-Family
- Hotel/Motel
- Health
- Warehouse
- Restaurant
- Retail
- Grocery
- Offices

3.4.12 Vermont 2010 TRM (based on National Grid 2001 study, same as ME 2010 TRM)

The VT 2010 TRM (Efficiency Vermont, 2010) uses a partially deemed algorithm with deemed savings per horsepower based on motor application only. Deemed savings factors are based on National Grid 2001 values averaged from previous evaluations of VFD installations, but the National Grid source document is publically unavailable and the details of the evaluation methods used to determine savings are unknown. It is not clear how the savings factors were derived.

Use of the following algorithms is limited to VFDs installed on motors less than 10 HP, on HVAC supply, return and exhaust fans, chilled water pumps, and boiler feed-water pumps, with baseline control system that is no-control, inlet guide vanes, outlet guide vanes, and throttling valves.

The algorithms provided to estimate energy and demand savings are as follows:

Annual Energy Savings:

$$\Delta kWh = ESVG * HP * CXS \quad \textbf{[35]}$$

Summer Peak Demand Savings:

$$\Delta kW = DSVG * HP * CXS \quad \textbf{[36]}$$

Where:

ΔkWh	= Annual energy savings
ΔkW	= Maximum of either summer or winter peak demand savings
$ESVG$	= Energy savings factor (kWh/HP) based on motor application; deemed
$DSVG$	= Winter peak demand savings factor (kW/HP) based on motor application except summer peak demand savings factor for chilled water pumps; deemed
HP	= Nominal horsepower of controlled motor
CXS	= Commissioning factor. CXS = 1.10 when the project undergoes commissioning services, 1.0 otherwise.

The VT TRM provides deemed savings factors for VFDs installed in the following applications:

- Supply Fan
- Return Fan
- Exhaust Fan
- Chilled Water Pump
- Heating Hot Water Circulating Pump

3.4.13 Manufacturers' Calculators

Several VFD manufacturers publish simple Excel based spreadsheet calculators to estimate energy savings from installing a VFD on HVAC applications. They are similar to DOE based calculators and generally use a simple partially deemed algorithm with a deemed power savings ratio based on baseline and retrofit flow control method. The basis of the assumptions is found in the ASHRAE Handbook, HVAC

Applications Volume. The calculator is intended to provide conservative estimates, but in some cases may overestimate savings.

The algorithm provided to estimate energy savings is as follows:

Annual Energy Savings:

$$\Delta kWh = \quad 0.746 * HP * (PR_{base} - PR_{VFD}) * RHRS_{base} \qquad \textbf{[37]}$$

Where:

ΔkWh	= Annual energy savings
0.746	= Conversion factor for HP to kWh
HP	= Nominal horsepower of controlled motor
PR_{base}	= Motor Power Ratio based on flow control method of baseline motor (assumed at 60% of maximum flow for fans and 70% maximum flow for pumps)
PR_{VFD}	= Motor Power Ratio based on flow control with a VFD installed (assumed at 60% of maximum flow for fans and 70% maximum flow for pumps)
$RHRS_{base}$	= Annual hours of operation based on building type and motor application; input required

The calculators generally provide Motor Power Ratios for the following flow control methods:

- HVAC Fans:
    - Bypass Damper
    - Fan Curve (VAV riding the fan curve)
    - Outlet Damper
    - Inlet Guide Vane
    - Variable Frequency Drive
- HVAC Pumps:
    - No Control
    - Bypass Valve
    - Discharge Valve
    - Variable Frequency Drive

Chapter 4

4 Case Studies and Savings Estimation Methods

Several case studies with verified savings were identified in order to compare the various TRM estimation methodologies and computer simulation modeling methods.

4.1 Selection of Case Studies

To review the reliability of the various TRM savings protocols, the plan was to have several case studies from different jurisdictions with verified savings based on pre- and post-installation metering data to compare. Given that incentives have been offered for VFDs installed on HVAC systems for several years in many jurisdictions it was believed that it would be easy to find many case studies that had been verified using metered results. For a variety of reasons this was not the case.

Many commercial and industrial programs offer a variety of measure types within one program, therefore evaluation samples rarely produce statistically valid findings for any one measure type. This means that for a large program the sampled VFD projects may only be a handful per year, if any at all. Further, because many of the evaluations in jurisdictions that use a TRM only verify that project savings estimates correctly followed the TRM, metered results are few and far between. In fact, most of the VFD projects that were verified using metering were custom projects, and because the TRM protocols did not apply these project results are generally not useful for this study.

Because a study like this needs to be able to compare apples to apples as much as possible, it was decided to focus on retrofits of existing office building HVAC fans, as these have the largest overall program potential of the primary building types in the country. This further limited the pool of available case studies to only retrofits of office building HVAC fans, with verified savings that did not use a TRM for the verification.

Although it was originally desired to have case studies with verified savings based on pre- and post-installation metering, this was shown to be unfeasible. It is very rare for project owners, program implementation contractors, or evaluators to meter post-installation conditions. It is rarer still to meter pre-installation conditions. Narrowing the study down further to office building HVAC fan projects proved impossible to find any case studies with both pre- and post-installation metering. It was even difficult to find case studies with significant post-installation metering. Because of these challenges it was determined that the study would need to be opened up to case studies that were verified with metering, billing analysis, or using a detailed bin analysis.

An exhaustive internet search was performed on both general public websites and in scholarly journals, periodicals, and research papers which only produced a small handful of potential case studies. Of the potential case studies found, none provided enough detail necessary to be able to apply the various TRM protocols to estimate savings, nor to compare to energy models.

Next, several manufacturers of VFDs were contacted to see if they had any metered case studies that may be used for the study. Only two manufacturers responded; both sent several one or two sheet summaries of case studies they use for marketing purposes. Unfortunately, all of the studies were several years old, some dating back to the late 1990's, and the background data was no longer available. It was determined that only one of these studies could be used because it provided the list of motors retrofitted with VFDs, their horsepower and building type.

The author also contacted several program evaluation firms to see if they had any potential case studies. Mr. Del Balso works for Navigant as an independent program evaluator, and therefore was able to contact several internal staff as well as staff from multiple competitor firms. Unfortunately this proved to be less fruitful than anticipated. After looking through several years worth of internally available sampled projects, a few projects were identified as possible case studies. The list was narrowed down to seven case studies which were worth attempting to estimate savings using all the available TRM protocols. One case study proved not useful as it did not fit in the limited applications each TRM has, leaving six usable case studies from evaluations and one case study from manufacturers, for a total of seven usable case studies.

Table 3 summarizes the usable seven case studies.

Table 3. Case Study Summary

Case Study Number	Source Type	Building Type	Building Location	VSD Installations[a]	Baseline System Type	Retrofit System Type	Verification Type
1	Manufacturer	County government Courthouse/Office building	Southeastern US county (Assumed Atlanta, GA for analysis)	VFD's installed on HVAC AHU fans	AHU VAV fans w/ IGVs	AHU VAV fans w/VFDs, IGVs locked open	Side by side comparison of two identical floors with baseline and retrofit; Metered and logged data extrapolated to annual
2	Utility Incentive Program Evaluation	Large Office Building	Philadelphia, PA	VFD's installed on HVAC supply and return fans	VAV fans w/ IGVs	VAV fans w/VFDs, IGVs locked open	Spot metered and logged data extrapolated to annual using bin analysis and fan curves
3	Utility Incentive Program Evaluation	Large Office Building	Philadelphia, PA	VSDs installed on HVAC AHU supply and return fans, fresh air fans, cooling tower fans, hot water loop pumps, and cold water loop pumps	VAV fresh air VAV fans w/ IGVs	VAV Fresh air fans with VFDs	Metered and logged data extrapolated to annual (only the fresh air fan motors were included comparison)
4	Utility Incentive Program Evaluation	Large Office Building	Philadelphia, PA	VSDs installed on HVAC supply and return fans, condenser water pumps and a cooling tower fan	VAV AF/BI supply fans w/ outlet dampers, and AF/BI return fans w/ outlet dampers	VAV supply fan w/ VFD, and return fans w/ VFD	EMS trend data extrapolated to annual using bin analysis (only supply and return fans were included in analysis)
5	Utility Incentive Program Evaluation	Large Mall	Philadelphia, PA	VFDs installed on existing RTU supply fans	VAV AF/BI RTUs w/ IGV serving retail space, CV RTUs serving common space	VAV RTUs w/ VFDs serving retail space, and VAV RTUs w/ VFDs serving common space	EMS trend data extrapolated to annual using bin analysis
6	Utility Incentive Program Evaluation	Medium Office Building	Chicago, IL	VFDs installed on RTU supply fans	VAV RTU supply fans w/ IGVs	VAV RTU supply fans w/ VFDs	Metered and logging data extrapolated to annual
7	Utility Incentive Program Evaluation	Medium Office Building	Chicago, IL	VFDs installed on HVAC supply fans	VAV supply fans w/ outlet dampers	VAV supply fans w/ VFDs	Metered and logged data extrapolated to annual

[a] For all cases where fan type is unknown, Air Foil/Backward Inclined fan is assumed.

Because most of the case studies did not provide all the details necessary to apply the various TRM's, several assumptions needed to be made. This is not atypical for use of TRM protocols, or for evaluation activities, as it is common that many project details are unavailable to the implementation contractor and evaluator. This does indicate some of the limitations of program implementation and evaluation, however. The following assumptions were used when case study specific data was unavailable.

- Motors:
  - EPact efficiency for given nominal motor HP
  - ODP motor assumed with 4 poles (1800 RPM)
- Fan Type:
  - Centrifugal fan
  - BI/AF blades for VAV systems
- Run Hours:
  - For all cases, run hours were assumed based on building type and/or fan application type per the CT TRM table of HVAC Hours of Use. For TRM's with their own tables, hours from those were used instead. In a few case studies where actual project specific run hours were determined through metered or logged data, the actual hours were not used in the TRM analyses because the goal of the project is to compare savings estimates using simplified TRM protocols without metering to verified savings. In such cases, metered/logged run hours will not typically be available at the time the TRM is used to estimate savings.

4.2 Estimating Savings Using Technical Reference Manuals

The 13 TRM/simple savings methodologies were used to estimate savings for each of the seven case studies and compared to the verified savings estimates. The results are summarized with each case study.

4.2.1 TRM Limitations

Several of the TRMs have limitations which limit the protocols' application to certain conditions. There was no clear justification for why the limitations were placed in any of the TRM protocols, and for a few TRMs the limitations appear to be arbitrary. In some instances where the case study was outside the TRM limitations the protocols were used to estimate savings anyway to see how the methodology would compare to the other protocols if the limitations were not in place. The following notes apply to the superscripts in each summary table.

a. The 2011 Mid-Atlantic TRM limits the protocol to VSDs installed on motors 10 HP or less for HVAC supply fans, return fans, exhaust fans, chilled water pumps, and boiler feed-water pumps. Case studies labeled with this note are technically not eligible to use the Mid-Atlantic TRM, however, the protocol was applied anyway for comparison only as the original source document does not place similar restrictions on the savings factors.
b. The ME 2010 TRM is limited to VFDs installed on motors 5 HP through 30 HP, on HVAC supply, return and exhaust fans, chilled water pumps, and heating hot water circulation pumps, with baseline control system that is no-control or bypass. All other control systems such as on/off, inlet vanes, dampers, throttling valves, Eddy current, magnetic coupling, etc. must use a custom calculation. Case studies labeled with this note are technically not eligible to use the ME TRM, however, the protocol was applied anyway for comparison purposes only.
c. The VT 2010 TRM is limited to VFDs installed on motors less than 10 HP, on HVAC supply, return and exhaust fans, chilled water pumps, and boiler feed-water pumps, with baseline control system that is no-control, inlet guide vanes, outlet guide vanes, and throttling valves. Case studies labeled with this note are technically not eligible to use the VT TRM, however, the protocol was applied anyway for comparison purposes only.

4.2.2 TRM Demand Savings Estimates

Although all the TRM's offer an estimate of peak demand savings, it is not worthwhile to analyze the differences between the estimates as the demand savings depends entirely on the defined peak demand period which differs significantly between many of the TRMs. To properly estimate peak demand savings for a given project an hourly load profile and seasonal average load profile are necessary in addition to a defined peak period. As these differ from jurisdiction to jurisdiction an apples to apples comparison cannot be made.

The demand savings estimates are shown for each case study for informational purposes only to show the diversity of demand predictions. No further analysis was done beyond this.

4.3 Estimating Savings Using EnergyPlus Modeling

A goal of this project was to compare energy savings estimates from EnergyPlus simulations for the various case studies to the verified savings and the TRM estimated savings. These results will be used to determine if simplified prototypical computer simulation models will be better predictors of energy savings than the TRM based estimates.

The CA DEER and NY TRM's essentially use energy modeling results as a basis for the TRM savings estimation protocol. It is not clear whether these savings estimates based on energy modeling results are more reliable than an algorithm based approach.

Because the case studies used for this study are in different cities than the CA DEER and NY TRM models are based on, it is important to develop savings estimates by running the models with weather files from the case study specific cities. This study will be a bit more project specific as well because the models will be run with simulations of the actual baseline system type to the retrofit system type and control type without averaging multiple types together such as the CA DEER does.

4.3.1 DOE EnergyPlus Commercial Building Prototypes

The energy simulation models for each case study are based on the U.S. Department of Energy Commercial Reference Building prototypical models (U.S. Department of Energy (DOE), 2012). There are 16 different building types that are available, and each is available with construction based on either "New Construction", "Existing buildings constructed in or after 1980 ("post-1980")", or "Existing buildings constructed before 1980 ("pre-1980")". All prototypical models are pre-programmed using 16 different climate zones, although each model can be run in any climate zone with available EnergyPlus weather data.

For this study, the "Large Office" and "Medium Office" building prototypes were used to estimate savings for case studies 1, 2, 3, 4, 6, and 7. For case study 5, which was a large mall, the "Stand-alone Retail" prototype was used as the best available fit. It is recognized that this is not a great representation of a large mall, however, it is a common occurrence in energy efficiency programs for a non-conforming building to apply for incentives. This is a good test to see if a prototypical model can be used to estimate savings for a non-conforming building. It may be that it is more appropriate to assign non-conforming buildings to a custom measure with custom energy calculations/modeling performed, rather than to use prescriptive methodologies.

Because the case study files did not include any indication of building age, it is assumed that all buildings were built post-1980 for the energy modeling. Therefore, all case studies utilized the post-1980 prototypes as the starting point. Models were simulated using Typical Meteorological Year 3 (TMY3) weather data for the specific city of each case study.

The results of the prototype simulations were used to determine energy savings per motor horsepower (kWh/hp). The resulting savings estimate was then used to estimate savings for the actual case study based on the total retrofitted motor horsepower.

4.3.2 EnergyPlus Modeling of HVAC Systems

The Medium Office and Large Office building prototypes both were initially designed as using single duct VAV systems with VFDs installed on the fans. The default fan part load curve was based on an LBNL generic curve for VFDs (Curve no. 12), however, as discussed in the sections above, this likely overestimates savings as it does not fully account for system back pressure. The default fan curve for VFDs will be replaced with the CA Title 24 VFD fan curve (Curve no. 11) using the coefficients shown in Table 1 above and duplicated in Table 4 below. To model the baseline condition the most appropriate fan curve from the table will be used for each case study.

Table 4. Fan Part Load Ratio Regression Coefficients. (Bonneville Power Administration), (Ernest Orlando Lawrence Berkeley National Laboratory (LBNL), 2013), (Wray & Matson, 2003). (Duplicate of Table 1)

Curve No.	Fan Control Type	Regression Coefficient			
		a	b	c	d
1	Discharge Dampers (LBNL)	0.37073425	0.97250253	-0.34240761	0
2	Outlet Damper, BI & Airfoil Fans (BPA)	0.5592857	-0.56905	2.462	-1.4
3	Inlet Damper Box (BPA)	0.5025833	0.71648	-1.452	1.3
4	Inlet Guide Vane, BI & Airfoil Fans (BPA)	0.472619	0.67944	-1.554	1.4
5	Inlet Vane Dampers (LBNL)	0.35071223	0.30850535	-0.54137364	0.87198823
6	Outlet Damper, FC Fans (BPA)	0.2041905	0.10983	0.745	0
7	Eddy Current Drives (BPA)	0.1639683	-0.05647	1.237	-0.3
8	Inlet Guide Vane, FC Fans (BPA)	0.2	0.06808	-0.128	0.9
9	*VFD (LBNL)*	*0.001530245*	*0.005208057*	*1.1086242*	*-0.11635563*
10	*VFD (BPA)*	*0.059*	*-0.19567*	*0.766*	*0.4*
11	VFD (CA Title 24) (Wray & Matson)	0.1021	-0.1177	0.2647	0.76
12	*E+ Prototype VAV w/ VFD (LBNL)*	*0.040759894*	*0.08804497*	*-0.07292612*	*0.943739823*

The Medium Office building prototype uses packaged rooftop air conditioners for cooling and a gas furnace in the packaged rooftop unit for heating. The VAV terminal boxes have electric resistance reheat and dampers.

The Large Office building prototype uses two water-cooled centrifugal chillers with an open cooling tower for cooling and a gas boiler for heating. The VAV terminal boxes have hot-water coil reheat and dampers.

The Stand-alone Retail building prototype was initially designed as a Constant Volume (CV) system with four packaged rooftop units with air conditioners for cooling and a gas furnace in the packaged rooftop unit for heating. To estimate savings for the Large Mall case study, the HVAC system type was converted to a VAV system. The packaged rooftop units were maintained, however.

Chapter 5

5 Case Study Details and Savings Estimates

The following sections describe the details of each case study and the results from applying each TRM methodology, and the EnergyPlus modeling. Case study numbering was in order of convenience only.

5.1 Case Study 1

Case study number 1 was provided by Yaskawa, a VFD manufacturer, as part of their marketing materials. The project was a test project to show proof to a southeastern US county government that retrofitting an existing county courthouse and law enforcement building HVAC system with VFDs would save energy. The test project was a requirement of the county to allow the larger project to move forward. The project was published in two periodicals as white papers (Yaskawa, 2004) (Phillips, 2004).

The test project consisted of a comparison of the energy consumption of the seventh and eighth floors of an existing courthouse building after retrofitting the air-handling unit (AHU) of the seventh floor only with VFDs. After the retrofit, the two floors were metered and logged for a 13-day test period, from August 30, 2002 through September 11, 2002, and the consumption for each floor was then annualized and compared. Since both floors have similar floor plans and occupancy patterns, with cooling required around the clock for seven days a week serving courtrooms and law-enforcement facilities, this study provided a unique side-by-side energy consumption comparison. This offers a more reliable way of estimating energy savings than most alternatives.

5.1.1 System Setup

The baseline system was a VAV AHU with a 25-HP fan motor with IGVs for each of the comparison floors. The fan motor operated at constant speed. The seventh floor's main existing AHU was retrofit with a VFD on the existing fan motor and the IGVs were locked open. The system was controlled to maintain a duct static pressure setpoint of 1 inch wg measured using a pressure transducer installed in the ductwork. The total annual run hours of the fan were estimated stated as 8760 based on the occupancy type.

There is limited information in the reports and so it is difficult to identify all necessary inputs for the TRM comparisons and modeling. In particular, the motor efficiency is unknown, but assumed as EPact efficiency for comparison purposes. The report did not specify the fan type as axial or centrifugal, nor did it mention the type of fan blade. For purposes of analysis it is assumed that the fan was centrifugal with BI/AF blades as a common fan type for this type of system.

The location was not specified other than to say it was located in a major Southeastern governmental organization. For purposes of analysis it is assumed to be in Atlanta, GA. It is recognized that this assumption is significant for the analysis since climate zone can have a large impact on energy savings. Because deemed savings estimation methods are trying to get in the rough ballpark of verified savings estimates this limitation is acknowledged and accepted as a reasonable risk.

Table 5 summarizes the baseline system setup for Case Study 1.

Table 5. Case Study 1 Project Summary

Motor Application	Motor Quantity	Motor HP	Motor Efficiency	Baseline Fan Type	Fan Blade Type	Baseline VAV Control Type	Operating Hours (actual/assumed for analysis)
AHU Supply Fan	1	25	91.7% (EPact assumed)	Centrifugal	BI/AF blades (assumed)	IGV's	8760/7665 (Police/fire stations 24 hr)

5.1.2 Verified Savings

Verified savings from the project were estimated at 77,948 kWh per year based on the monitoring period metered results extrapolated to a year.

5.1.3 TRM Savings Estimates

Table 6 shows the results of the estimates using the TRM protocols. The minimum ratio of predicted to verified energy savings is 18% (OH 2010 TRM) and the maximum is 95% (NJ 2012 TRM), with an average of 47%. All of the TRM's underestimated the energy savings for this project. This is not entirely surprising given that the case study was likely selected by the manufacturer to show maximum savings in order to convince the county government to install more VFD's in their facilities.

Table 6. Case Study 1 TRM Savings Estimates

TRM Source	Energy Savings (kWh)	Peak Demand Savings Summer (kW)	Predicted / Verified Energy Savings Ratio	Predicted / Verified Demand Savings Ratio
Verified Savings	77,948	NA	NA	NA
SU 2011 MSEM	58,050	1.100	74%	NA
CA DEER 2011	24,842	5.000	32%	NA
CT 2012 TRM	37,892	2.825	49%	NA
IL 2012 TRM	15,154	2.115	19%	NA
NJ 2012 TRM	74,048	9.111	95%	NA
Mid-Atlantic 2011 TRM[a]	47,391	0.991	61%	NA
OH 2010 TRM	13,798	1.983	18%	NA
PA 2013 TRM	26,540	1.467	34%	NA
ME 2010 TRM[b]	22,247	3.845	29%	NA
MA 2012 TRM	29,335	1.745	38%	NA
NY 2010 TRM	40,125	1.400	51%	NA
VT 2010 TRM[c]	25,025	4.325	32%	NA
Manufacturers' Calculators	48,604	6.341	62%	NA

5.1.4 EnergyPlus Modeling Results

Case Study 1 was modeled using the Large Office prototype. The baseline model fans were set to a VAV system with IGVs and BI/AF blades using fan curve number 4 from Table 4. The retrofit model fans were set to a VAV system with VFDs using fan curve number 11. Both cases were run using TMY3 data for Atlanta, GA.

The results from the modeling are shown below. Table 7 shows the total building electric energy savings predicted using the models.

Table 7. Case Study 1 EnergyPlus Model Total Electric Energy Savings Estimates.

Variable	Results
Model Total Fan Motor break kW =	371
Model Total Fan Motor BHP =	497
Baseline Model Total Electric Consumption (kWh) =	8,172,872
Retrofit Model Total Electric Consumption (kWh) =	7,135,158
Total Electric Energy Savings (kWh) =	1,037,714
Total Electric Energy Savings per BHP (kWh/BHP) =	2,087
Assumed Load Factor =	0.6
Model Total Electric Energy Savings per Nominal HP (kWh/HP) =	1,252
Case Study Total Fan Retrofit Nominal HP =	25
Case Study Model Estimated Total Electric Energy Savings (kWh/yr) =	**31,301**
Verified Electric Energy Savings (kWh/yr) =	**77,948**
Model Predicted / Verified Energy Savings Ratio =	**0.40**

Table 8 shows the fan only electric energy savings. The non-fan electric energy savings is 14.7% of the total electric energy savings. This is a significant difference. With the exception of the CA DEER and NY TRM, none of the TRM's account for additional system energy savings or penalties beyond the fan motor itself. Given these results it is possible that this is a significant underestimation of potential savings.

Table 8. Case Study 1 EnergyPlus Model Fan Only Electric Energy Savings Estimates.

Variable	Results
Model Total Fan Motor break kW =	371
Model Total Fan Motor BHP =	497
Baseline Model Fan Electric Consumption (kWh) =	1,121,806
Retrofit Model Fan Electric Consumption (kWh) =	236,278
Fan Electric Energy Savings (kWh) =	885,528
Fan Electric Energy Savings per BHP (kWh/BHP) =	1,781
Assumed Load Factor =	0.6
Model Fan Electric Energy Savings per Nominal HP (kWh/HP) =	1,068.41
Case Study Total Fan Retrofit Nominal HP =	25
Case Study Model Estimated Fan Electric Energy Savings (kWh/yr) =	**26,710**
Verified Electric Energy Savings (kWh/yr) =	**77,948**
Model Predicted / Verified Fan Only Energy Savings Ratio =	**0.34**

Table 9 shows the fuel heating impact. There is a slight increase in fuel consumption to make up for the reduced motor and fan heat load with the VFD installed. The models assume a natural gas boiler with hot water reheat. If the building used electric resistance reheat this would reduce the total electric energy savings. The electric penalty would be about 848 kWh/yr or roughly 3% of total savings. However, this would be offset by reduced pumping energy for the water loop and therefore may not be a significant enough concern to worry about. The details on the case study do not provide any information on the type of reheat used, but water coil reheat with a natural gas boiler is a common system type and is a reasonable assumption.

Table 9. Case Study 1 EnergyPlus Model Fuel Savings Estimates.

Variable	Results
Model Total Fan Motor break kW =	371
Model Total Fan Motor BHP =	497
Baseline Model Fuel Consumption (MMBtu) =	3,192
Retrofit Model Fuel Consumption (MMBtu) =	3,326
Fuel Savings (MMBtu) =	(133)
Fuel Savings per BHP (MMBtu/BHP) =	(0.27)
Assumed Load Factor =	0.6
Model Fuel Savings per Nominal HP (MMBtu/HP) =	(0.16)
Case Study Total Retrofit Nominal HP =	25
Case Study Model Estimated Total Fuel Savings (MMBtu/yr) =	**(4.02)**

Although a predicted to verified energy savings ratio of 0.40 is not very good, this is not entirely unexpected for this case study. The details of the case study indicate this facility runs 24/7/365, but the Large Office prototype uses the more typical office occupancy pattern of weekdays during 8am to 5pm. Given the number of operating hours for the case study outside this range, a ratio of 0.40 is realistic. This is in fact similar to the average TRM predicted to verified energy savings ratio of 0.47.

5.1.5 Summary

Figure 11 shows a comparison of all the TRM and EnergyPlus model results versus the verified savings. With the exception of the NJ 2012 TRM, all of the methods predicted much lower savings than the verified results. Given that the NJ 2012 TRM appears to be an outlier in relation to the other TRMs it is not likely that it was giving more reliable results, but more that it is just different than the others.

These results indicate there is a significant difference in the actual project details versus what the models assumed. As stated above, it is likely a result of the case study having operating hours of 24/7/365 which is much higher than the standard hours for an office building. Overall, for this project none of the methods yielded results that could be considered reliable for this case study.

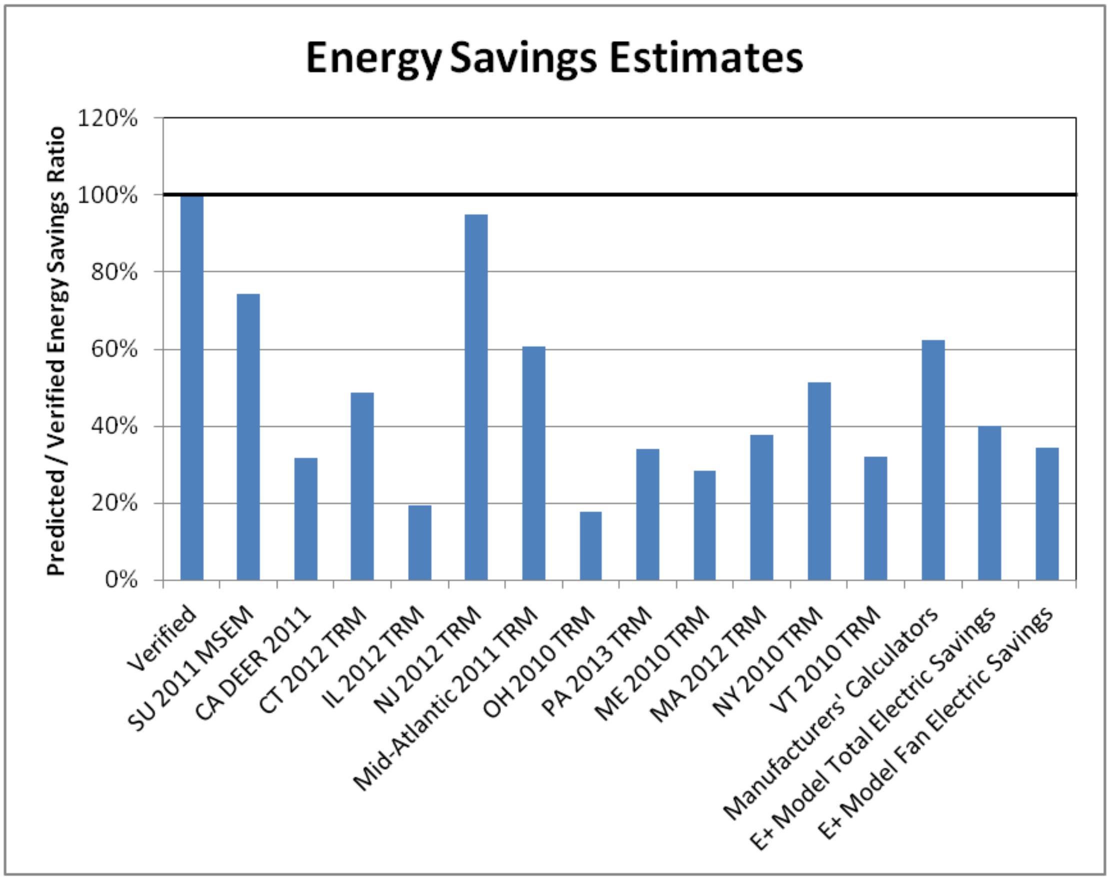

Figure 11. Case Study 1 Energy Savings Prediction Comparison

5.2 Case Study 2

Case study number 2 was from an independent evaluation of a Mid-Atlantic energy efficiency incentive program. The project was in a large downtown office building located in Philadelphia, PA, and included retrofit of existing HVAC supply and return fans with VFDs. A total of 16 new VFDs were installed, eight on supply fans and eight on return fans.

The project was verified using spot power measurements at various VFD frequencies and runtime logging to determine operation characteristics and run hours. The data was weather normalized and extrapolated to a full year using bin analysis to estimate annual verified savings. WattNode/Hobo power meters were installed to meter the fan motors over a period of time, however, all data came back unusable and the spot measurements and trend logging was used to verify savings estimates.

5.2.1 System Setup

The baseline system was eight VAV AHUs with 125-HP supply fan motors and 40-HP return fan motors. Each fan was controlled with IGVs. The fan motors operated at constant speed. All AHUs were retrofit with VFDs on both the existing supply and return fan motors, and the IGVs were locked open. The system was controlled to maintain a duct static pressure. The fans schedules were verified as set to off during unoccupied hours. The total annual run hours of the fans were verified as 4004 hours based on the logger data extrapolated to a year.

There is limited information in the reports and so it is difficult to identify all necessary inputs for the TRM comparisons and modeling. In particular, the motor efficiency is unknown, but assumed as EPact efficiency for comparison purposes. The report did specify the fan type as centrifugal, but it did not mention the type of fan blade. For purposes of analysis it is assumed that the fan was centrifugal with BI/AF blades as a common fan type for this type of system.

Table 10 summarizes the baseline system setup for Case Study 2.

Table 10. Case Study 2 Project Summary

Motor Application	Motor Quantity	Motor HP	Motor Efficiency	Baseline Fan Type	Fan Blade Type	Baseline VAV Control Type	Operating Hours (actual/assumed for analysis)
AHU Supply Fans	8	125	94.5% (EPact assumed)	Centrifugal	BI/AF blades (assumed)	IGV's	4004/3748 (office)
AHU Return Fans	8	40	93.0% (EPact assumed)	Centrifugal	BI/AF blades (assumed)	IGV's	4004/3748 (office)

5.2.2 Verified Savings

Verified savings for the project were estimated at 940,051 kWh per year based on the monitoring period metered results extrapolated to a year. Verified peak demand savings were estimated at 95.324 kW per PA Act 129 requirements which require estimating demand savings over the top 100 hours of maximum system demand.

5.2.3 TRM Savings Estimates

Table 11 shows the results of the estimates using the TRM protocols. The minimum ratio of predicted to verified energy savings is 36% (IL 2012 TRM) and the maximum is 326% (SU 2011 MSEM), with an average of 148%. Most TRMs overestimated savings, although the CT 2012 TRM prediction was quite close to the verified savings estimates at 101%. Given that the actual hours of use were fairly close to the assumed hours of use for analysis purposes, it is not somewhat surprising to see how much higher the TRM estimates are.

Table 11. Case Study 2 TRM Savings Estimates

TRM Source	Energy Savings (kWh)	Peak Demand Savings Summer (kW)	Predicted / Verified Energy Savings Ratio	Predicted / Verified Demand Savings Ratio
Verified Savings	**940,051**	**95.324**	NA	NA
SU 2011 MSEM	3,065,033	58.055	326%	61%
CA DEER 2011	1,310,760	273.240	139%	287%
CT 2012 TRM	953,028	145.331	101%	152%
IL 2012 TRM	335,492	108.795	36%	114%
NJ 2012 TRM	1,862,383	468.656	198%	492%
Mid-Atlantic 2011 TRM[a]	1,191,925	50.966	127%	53%
OH 2010 TRM	1,106,799	203.991	118%	214%
PA 2013 TRM	667,517	75.477	71%	79%
ME 2010 TRM[b]	NA	NA	NA	NA
MA 2012 TRM	1,529,162	102.822	163%	108%
NY 2010 TRM	2,007,560	84.416	214%	89%
VT 2010 TRM[c]	1,488,680	257.160	158%	270%
Manufacturers' Calculators	1,254,848	334.805	133%	351%

5.2.4 EnergyPlus Modeling Results

Case Study 2 was modeled using the Large Office prototype. The baseline model fans were set to a VAV system with IGVs and BI/AF blades using fan curve number 4 from Table 4. The retrofit model fans were set to a VAV system with VFDs using fan curve number 11. Both cases were run using TMY3 data for Philadelphia, PA.

The results from the modeling are shown below. Table 12 shows the total building electric energy savings predicted using the models. With a predicted to verified energy savings ratio of 1.88, the energy models significantly over predicted savings relatively to the verified savings.

Table 12. Case Study 2 EnergyPlus Model Total Electric Energy Savings Estimates.

Variable	Results

Model Total Fan Motor break kW =	365
Model Total Fan Motor BHP =	489
Baseline Model Total Electric Consumption (kWh) =	8,012,447
Retrofit Model Total Electric Consumption (kWh) =	6,918,922
Total Electric Energy Savings (kWh) =	1,093,525
Total Electric Energy Savings per BHP (kWh/BHP) =	2,237
Assumed Load Factor =	0.6
Model Total Electric Energy Savings per Nominal HP (kWh/HP) =	1,342
Case Study Total Fan Retrofit Nominal HP =	1320
Case Study Model Estimated Total Electric Energy Savings (kWh/yr) =	**1,771,585**
Verified Electric Energy Savings (kWh/yr) =	**940,051**
Model Predicted / Verified Energy Savings Ratio =	**1.88**

Table 13 shows the fan only electric energy savings. The non-fan electric energy savings is 15.7% of the total model predicted electric energy savings. Again, this is a significant difference and may indicate that savings for the non-fan benefits should be considered when estimating VFD savings.

Table 13. Case Study 2 EnergyPlus Model Fan Only Electric Energy Savings Estimates.

Variable	Results
Model Total Fan Motor break kW =	365
Model Total Fan Motor BHP =	489
Baseline Model Fan Electric Consumption (kWh) =	1,157,875
Retrofit Model Fan Electric Consumption (kWh) =	236,342
Fan Electric Energy Savings (kWh) =	921,533
Fan Electric Energy Savings per BHP	1,885

(kWh/BHP) =	
Assumed Load Factor =	0.6
Model Fan Electric Energy Savings per Nominal HP (kWh/HP) =	1,131
Case Study Total Fan Retrofit Nominal HP =	1320
Case Study Model Estimated Fan Electric Energy Savings (kWh/yr) =	**1,492,947**
Verified Electric Energy Savings (kWh/yr) =	**940,051**
Model Predicted / Verified Fan Only Energy Savings Ratio =	**1.59**

Table 14 shows the fuel heating impact. There is a noticeable increase in fuel consumption to make up for the reduced motor and fan heat load with the VFD installed. The models assume a natural gas boiler with hot water reheat. If the building used electric resistance reheat this would reduce the total electric energy savings. The electric penalty would be about 169,600 kWh/yr or roughly 9.6% of total savings. This would be offset by reduced pumping energy for the water loop. It is likely the offset would be less than the 9.6% and therefore this may be a significant impact which should be considered. The details on the case study do not provide any information on the type of reheat used, but water coil reheat with a natural gas boiler is a common system type and is a reasonable assumption.

Table 14. Case Study 2 EnergyPlus Model Fuel Savings Estimates.

Variable	Results
Model Total Fan Motor break kW =	365
Model Total Fan Motor BHP =	489
Baseline Model Fuel Consumption (MMBtu) =	6,555
Retrofit Model Fuel Consumption (MMBtu) =	7,051
Fuel Savings (MMBtu) =	(497)
Fuel Savings per BHP (MMBtu/BHP) =	(1.02)
Assumed Load Factor =	0.6
Model Fuel Savings per Nominal HP (MMBtu/HP) =	(0.61)

Case Study Total Retrofit Nominal HP =	1,320
Case Study Model Estimated Total Fuel Savings (MMBtu/yr) =	**(804.72)**

The model predictions for Case Study 2 are almost the exact opposite of the Case Study 1 outcome. The EnergyPlus prototype outcomes result in a predicted to verified energy savings ratio of 1.88, which is again not very good, but because it is too high. For this case study, both the prototype and the case study building are large office buildings. The prototype was run using Philadelphia, PA TMY3 weather data so this is not an issue of applying results from one climate zone to another. Both the case study and the prototype should have similar occupancy schedules as there is nothing in the project data to suggest a 24/7/365 occupancy as in Case Study 1. The results point to significant differences between the prototype model and the case study building, but without more details on the building itself, it is impossible to narrow it down to the driving source of the discrepancy.

While not quite as drastic, the average TRM predicted to verified energy savings ratio was similarly high at 1.48. There appears to be something inherent in this project which leads the non-customized prediction methodologies to overestimate savings. It could be that the TRM estimates are closer because for the most part they only consider the fan savings whereas the modeling estimates total building savings.

5.2.5 Summary

Figure 12 shows a comparison of all the TRM and EnergyPlus model results versus the verified savings. Most of the predictions overestimate savings as compared to the verified estimates. For this case study the SU 2011 MSEM significantly overestimates savings at a ratio of 326%. One of the primary limitations of that TRM protocol is no ability to adjust savings based on project type. This clearly affects the savings predictions for this case study as the SU 2011 MSEM is really an outlier.

On average the TRM results (average TRM predicted to verified ratio of 148%) are less than the modeled results for both the total savings (ratio of 188%) and the fan only savings (ratio of 159%). There was a wide range of estimates from the TRM protocols though so it is hard to say for this project none of the methods yielded results that could be considered reliable for this case study. The fan only savings was in a similar range as the TRM average though.

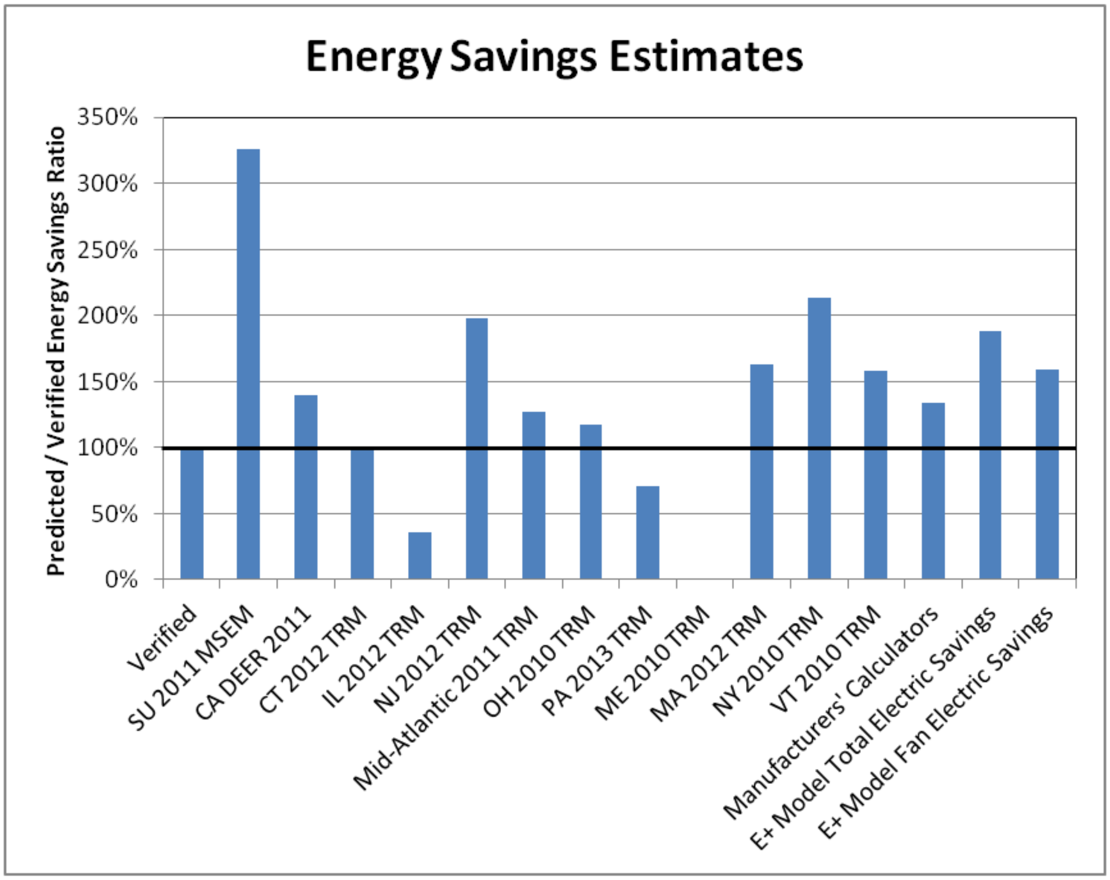

Figure 12. Case Study 2 Energy Savings Prediction Comparison

5.3 Case Study 3

Case study number 3 was also from an independent evaluation of a Mid-Atlantic energy efficiency incentive program. The project was a major retrofit project in a large downtown office building located in Philadelphia, PA, and included retrofit of existing HVAC AHU supply fans, fresh air intake fans, cooling tower fans, hot water loop pumps, and cold water loop pumps with VFDs.

The project included VFD retrofits to the following motors:

- AHU VAV supply fan motors
  - 36-7.5 HP hi/low
- HVAC fresh air intake fans
  - 1-40 HP VAV fan with IGV's
  - 1-30 HP VAV fan with IGV's
- Cooling tower fans
  - 3-60 HP hi/low

- hot water loop pumps
    - 2-20 HP outlet valves riding pump curve
    - 1-40 HP summer only, 3-way valve, constant 50% flow
    - 3-75 HP winter only, one pump at a time, outlet valves riding pump curve
    - 2-15 HP operate over 50F, outlet valves riding pump curve
- domestic cold water loop pumps
    - 1-15 HP with outlet damper riding pump curve
    - 1-20 HP with outlet damper riding pump curve

Only the AHU supply fans and fresh air intake fans were verified using trend data and logging to determine bins and EFLH to extrapolate to weather normalized annual savings. The baseline and retrofit fan kW was estimated based on the part load efficiency curves of a system with IGV's and a VFD. The VFD displayed kW, however, the EMS did not allow logging of power. Spot power measurements and speed were compared to estimates from the fan part load curves and were found to match well with the panel. A majority of the TRMs do not apply to two-speed motor baselines, however, therefore, only the fresh air intake fan motors are included for comparison.

5.3.1 System Setup

The baseline system under consideration was 1-40 HP VAV fresh air intake fan and 1-30 HP VAV fresh air intake fan. Each fan was controlled with IGVs. The fan motors operated at constant speed. Both fan motors were retrofit with VFDs, and the IGVs were locked open or removed. The system was controlled to maintain a scheduled duct static pressure operating at constant speed most of the time. The total annual run hours of the fans were verified as 5270 hours for the 40 HP fan and 4720 hours for the 30 HP fan based on the trend data extrapolated to a year. The motor efficiency was verified as NEMA premium.

There is limited information in the reports and so it is difficult to identify all necessary inputs for the TRM comparisons and modeling. The report did not specify the fan type. For purposes of analysis it is assumed that the fan was centrifugal with BI/AF blades as a common fan type for this type of system.

Table 15 summarizes the baseline system setup for Case Study 3.

Table 15. Case Study 3 Project Summary

Motor Application	Motor Quantity	Motor HP	Motor Efficiency	Baseline Fan Type	Fan Blade Type	Baseline VAV Control Type	Operating Hours (actual/assumed

							for analysis)
Fresh Air Intake Fan	1	40	94.1%	Centrifugal	BI/AF blades (assumed)	IGV's	5270/3748 (office)
Fresh Air Intake Fan	1	30	94.1%	Centrifugal	BI/AF blades (assumed)	IGV's	4720/3748 (office)

5.3.2 Verified Savings

Verified savings for the fresh air intake fans portion of this project were estimated at 108,940 kWh per year based on the monitoring period metered results extrapolated to a year. Verified peak demand savings were estimated at 25.363 kW per PA Act 129 requirements which require estimating demand savings over the top 100 hours of maximum system demand.

5.3.3 TRM Savings Estimates

Case study 3 was another project in a large office building in downtown Philadelphia, PA, however, the project consisted of multiple HVAC measures. The TRM were used to estimate savings for the fresh air intake fan retrofits only. Table 16 shows the minimum ratio of predicted to verified energy savings is 16% (IL 2012 TRM) and the maximum is 149% (SU 2011 MSEM), with an average of 67%. Similar to all other case studies, there is a wide deviation of estimates. In this instance the NY 2010 TRM prediction was quite close to the verified savings estimates at 103%.

Table 16. Case Study 3 TRM Savings Estimates

TRM Source	Energy Savings (kWh)	Peak Demand Savings Summer (kW)	Predicted / Verified Energy Savings Ratio	Predicted / Verified Demand Savings Ratio
Verified Savings	**108,940**	**25.363**	NA	NA
SU 2011 MSEM	162,540	3.079	149%	12%
CA DEER 2011	69,510	14	64%	57%
CT 2012 TRM	50,557	7.710	46%	30%
IL 2012 TRM	17,797	5.771	16%	23%
NJ 2012 TRM	98,796	24.861	91%	98%
Mid-Atlantic 2011 TRM[a]	63,230	2.704	58%	11%
OH 2010 TRM	58,714	10.821	54%	43%
PA 2013 TRM	35,411	4.004	33%	16%
ME 2010 TRM[b]	NA	NA	NA	NA
MA 2012 TRM	80,043	4.761	73%	19%
NY 2010 TRM	112,350	3.920	103%	15%
VT 2010 TRM[c]	70,070	12.110	64%	48%
Manufacturers' Calculators	66,545	17.755	61%	70%

5.3.4 EnergyPlus Modeling Results

Case Study 3 was modeled using the Large Office prototype. The baseline model fans were set to a VAV system with IGVs and BI/AF blades using fan curve number 4 from Table 4. The retrofit model fans were set to a VAV system with VFDs using fan curve number 11. Both cases were run using TMY3 data for Philadelphia, PA.

The results from the modeling are shown below. Table 17 shows the total building electric energy savings predicted using the models. With a predicted to verified energy savings ratio of 0.86, the energy models were in an acceptable range for energy efficiency program implementation and evaluation. It would be unrealistic to expect a generic method to consistently have more reliable savings than this.

Table 17. Case Study 3 EnergyPlus Model Total Electric Energy Savings Estimates.

Variable	Results
Model Total Fan Motor break kW =	365
Model Total Fan Motor BHP =	489
Baseline Model Total Electric Consumption (kWh) =	8,012,447
Retrofit Model Total Electric Consumption (kWh) =	6,918,922
Total Electric Energy Savings (kWh) =	1,093,525
Total Electric Energy Savings per BHP (kWh/BHP) =	2,237
Assumed Load Factor =	0.6
Model Total Electric Energy Savings per Nominal HP (kWh/HP) =	1,342
Case Study Total Fan Retrofit Nominal HP =	70
Case Study Model Estimated Total Electric Energy Savings (kWh/yr) =	**93,948**
Verified Electric Energy Savings (kWh/yr) =	**108,940**
Model Predicted / Verified Energy Savings Ratio =	**0.86**

Table 18 shows the fan only electric energy savings. The non-fan electric energy savings is again 15.7% of the total model predicted electric energy savings. This is a significant difference and may indicate that savings for the non-fan benefits should be considered when estimating VFD savings.

Table 18. Case Study 3 EnergyPlus Model Fan Only Electric Energy Savings Estimates.

Variable	Results
Model Total Fan Motor break kW =	365
Model Total Fan Motor BHP =	489
Baseline Model Fan Electric Consumption (kWh) =	1,157,875
Retrofit Model Fan Electric Consumption (kWh) =	236,342
Fan Electric Energy Savings (kWh) =	921,533
Fan Electric Energy Savings per BHP (kWh/BHP) =	1,885
Assumed Load Factor =	0.6
Model Fan Electric Energy Savings per Nominal HP (kWh/HP) =	1,131
Case Study Total Fan Retrofit Nominal HP =	70
Case Study Model Estimated Fan Electric Energy Savings (kWh/yr) =	**79,171**
Verified Electric Energy Savings (kWh/yr) =	**108,940**
Model Predicted / Verified Fan Only Energy Savings Ratio =	**0.73**

Table 19 shows the fuel heating impact. There is a noticeable increase in fuel consumption to make up for the reduced motor and fan heat load with the VFD installed. The models assume a natural gas boiler with hot water reheat. If the building used electric resistance reheat this would reduce the total electric energy savings. The electric penalty would be about 8,990 kWh/yr or roughly 9.6% of total savings. This would be offset by reduced pumping energy for the water loop. It is likely the offset would be less than the 9.6% and therefore this may be a significant impact which should be considered. The details on the case study do not provide any information on the type of reheat used, but water coil reheat with a natural gas boiler is a common system type and is a reasonable assumption.

Table 19. Case Study 3 EnergyPlus Model Fuel Savings Estimates.

Variable	Results
Model Total Fan Motor break kW =	365
Model Total Fan Motor BHP =	489
Baseline Model Fuel Consumption (MMBtu) =	6,555
Retrofit Model Fuel Consumption (MMBtu) =	7,051
Fuel Savings (MMBtu) =	(497)
Fuel Savings per BHP (MMBtu/BHP) =	(1.02)
Assumed Load Factor =	0.6
Model Fuel Savings per Nominal HP (MMBtu/HP) =	(0.61)
Case Study Total Retrofit Nominal HP =	70
Case Study Model Estimated Total Fuel Savings (MMBtu/yr) =	**(42.67)**

The model predictions for Case Study 3 are much more reasonable than those for Case Studies 1 and 2. A total model predicted to verified energy savings ratio of 0.86 is acceptable among energy efficiency program evaluations. However, a more realistic comparison to the TRM protocols would be to look at the fan only energy savings with a ratio of 0.73, which is slightly below the acceptability range for efficiency program evaluations. There is no set range for acceptability, but typically a ratio of 0.85 to 1.15 is considered reasonable. Without more project level details it is difficult to know why Case Study 3 results were so much better than Case Studies 1 and 2. These modeling results are both better than the average TRM predicted energy savings predicted to verified energy savings ratio of 67%.

5.3.5 Summary

Figure 13 shows a comparison of all the TRM and EnergyPlus model results versus the verified savings. As with the energy models, most of the TRM savings estimates underestimate savings as compared to the verified estimates, with the exception of the SU 2011 MSEM which is again an outlier, and the NY 2010 TRM.

On average the TRM results (average TRM predicted to verified ratio of 67%) are less than the modeled results for both the total savings (ratio of 86%) and the fan only savings (ratio of 73%). There was a wide range of estimates from the TRM protocols though so it is hard to say for this project none of the methods yielded results that could be considered reliable for this case study. Again, the energy model fan only savings estimate was closer to the TRM average than the energy model total savings estimate.

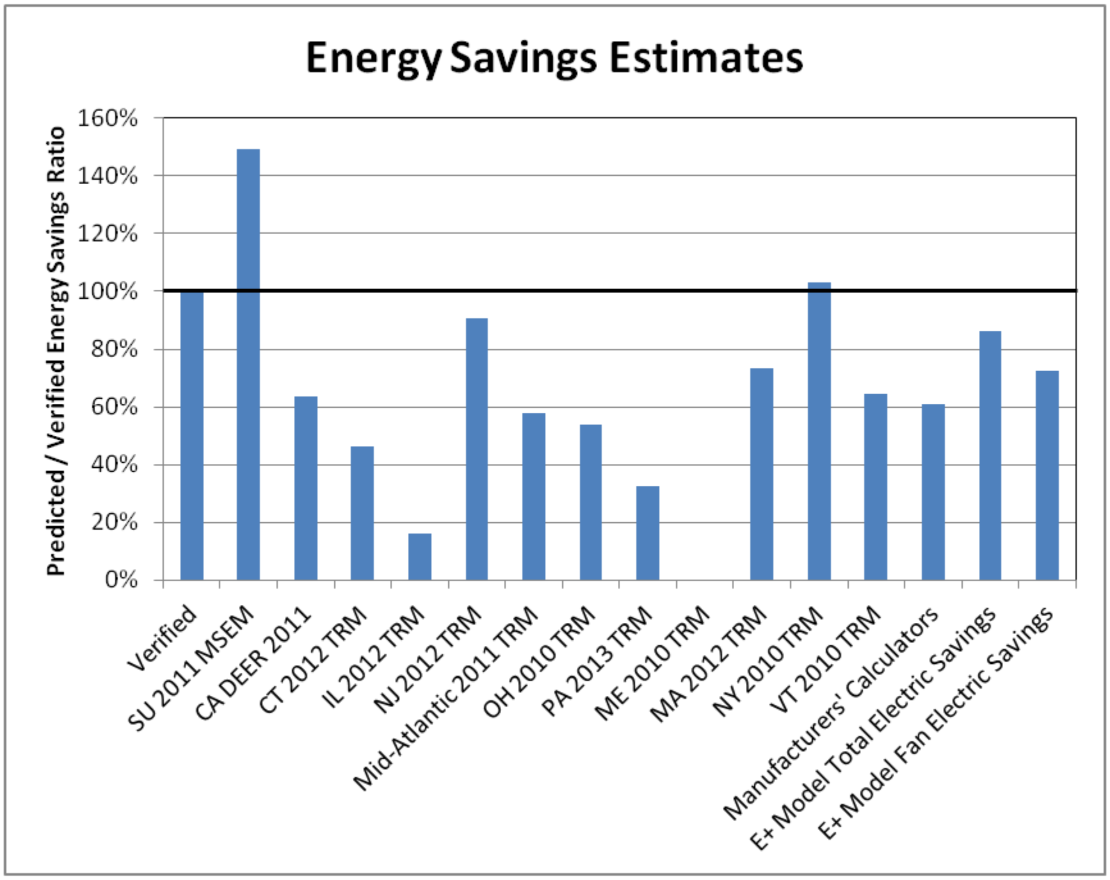

Figure 13. Case Study 3 Energy Savings Prediction Comparison

5.4 Case Study 4

Case study number 4 was also from an independent evaluation of a Mid-Atlantic energy efficiency incentive program. The project was a major retrofit project in a large downtown office building located in Philadelphia, PA, and included retrofit of existing HVAC AHU supply and return fans, cooling tower fan, and condenser water pumps with VFDs. The verification determined that only the supply and return fan retrofits saw energy savings and thus are the only retrofits considered here.

The project included VFD retrofits to the following motors:

- VAV Supply Fans
    - 1-200 HP with outlet dampers
- VAV Return Fans
    - 1-50 HP with outlet dampers
    - 1-60 HP with outlet dampers
    - 1-100 HP with outlet dampers

Savings were verified using analysis of trend data for a sample of the motors from EMS to establish run hours and power. Power was estimated using VFD frequency trend data and DOE-2 fan part load curves for VFDs and outlet dampers. Power was weather normalized and extrapolated to annual energy savings using a bin analysis.

5.4.1 System Setup

The baseline system under consideration was 1-200 HP VAV supply fan, 1-50 HP VAV return fan, 1-60 HP VAV return fan, and 1-100 HP VAV return fan. Each fan was controlled with outlet dampers. The fan motors operated at constant speed. All fan motors were retrofit with VFDs, and the outlet dampers were locked open or removed. The system was controlled on a time of day schedule. The total annual run hours of the fans were verified as 3865 hours for the 200 HP supply fan and 3943 hours for the return fans based on the trend data extrapolated to a year. The motor efficiency was verified per the site visit reports.

There is limited information in the reports and so it is difficult to identify all necessary inputs for the TRM comparisons and modeling. The report did not specify the fan type. For purposes of analysis it is assumed that the fan was centrifugal with BI/AF blades as a common fan type for this type of system.

Table 20 summarizes the baseline system setup for Case Study 4.

Table 20. Case Study 4 Project Summary

Motor Application	Motor Quantity	Motor HP	Motor Efficiency	Baseline Fan Type	Fan Blade Type	Baseline VAV Control Type	Operating Hours (actual/assumed for analysis)
Supply Fan	1	200	95.0%	Centrifugal	BI/AF blades (assumed)	Outlet Dampers	3865/3748 (office)
Return Fan	1	50	89.7%	Centrifugal	BI/AF blades (assumed)	Outlet Dampers	3943/3748 (office)

Return Fan	1	60	90.6%	Centrifugal	BI/AF blades (assumed)	Outlet Dampers	3943/3748 (office)
Return Fan	1	100	95.0%	Centrifugal	BI/AF blades (assumed)	Outlet Dampers	3943/3748 (office)

5.4.2 Verified Savings

Verified savings for the project were estimated at 1,218,846 kWh per year based on the monitoring period metered results extrapolated to a year. Verified peak demand savings were estimated at 109.204 kW per PA Act 129 requirements which require estimating demand savings over the top 100 hours of maximum system demand.

5.4.3 TRM Savings Estimates

Table 21 shows the minimum ratio of predicted to verified energy savings was 9% (IL 2012 TRM) and the maximum was 78% (SU 2011 MSEM), with an average of 43%. Similar to all other case studies, there was a wide deviation of estimates. As was seen for case study 1, all of the TRM's underestimated the energy savings for this project and no TRM was within 20% of the verified savings estimate.

Table 21. Case Study 4 TRM Savings Estimates

TRM Source	Energy Savings (kWh)	Peak Demand Savings Summer (kW)	Predicted / Verified Energy Savings Ratio	Predicted / Verified Demand Savings Ratio
Verified Savings	**1,218,846**	**109.204**	NA	NA
SU 2011 MSEM	952,018	18.032	78%	17%
CA DEER 2011	407,130	85	33%	78%
CT 2012 TRM	505,724	99.217	41%	91%
IL 2012 TRM	104,732	33.963	9%	31%
NJ 2012 TRM	581,385	146.302	48%	134%
Mid-Atlantic 2011 TRM[a]	582,268	31.960	48%	29%
OH 2010 TRM	345,513	63.680	28%	58%
PA 2013 TRM	325,457	47.195	27%	43%
ME 2010 TRM[b]	NA	NA	NA	NA
MA 2012 TRM	484,432	36.651	40%	34%
NY 2010 TRM	585,180	29.848	48%	27%
VT 2010 TRM[c]	520,240	89.830	43%	82%
Manufacturers' Calculators	687,818	183.516	56%	168%

5.4.4 EnergyPlus Modeling Results

Case Study 4 was modeled using the Large Office prototype. The baseline model fans were set to a VAV system with Outlet Dampers and BI/AF blades using fan curve number 2 from Table 4. The retrofit model fans were set to a VAV system with VFDs using fan curve number 11. Both cases were run using TMY3 data for Philadelphia, PA.

The results from the modeling are shown below. Table 22 shows the total building electric energy savings predicted using the models. The energy model predictions were fairly low with a predicted to verified total electric energy savings ratio of 0.46.

Table 22. Case Study 4 EnergyPlus Model Total Electric Energy Savings Estimates.

Variable	Results
Model Total Fan Motor break kW =	365
Model Total Fan Motor BHP =	489
Baseline Model Total Electric Consumption (kWh) =	8,030,267
Retrofit Model Total Electric Consumption (kWh) =	6,918,922
Total Electric Energy Savings (kWh) =	1,111,344
Total Electric Energy Savings per BHP (kWh/BHP) =	2,273
Assumed Load Factor =	0.6
Model Total Electric Energy Savings per Nominal HP (kWh/HP) =	1,364
Case Study Total Fan Retrofit Nominal HP =	410
Case Study Model Estimated Total Electric Energy Savings (kWh/yr) =	**559,232**
Verified Electric Energy Savings (kWh/yr) =	**1,218,846**
Model Predicted / Verified Energy Savings Ratio =	**0.46**

Table 23 shows the fan only electric energy savings. The non-fan electric energy savings is again 15.7% of the total model predicted electric energy savings. This is a significant difference and may indicate that savings for the non-fan benefits should be considered when estimating VFD savings.

Table 23. Case Study 4 EnergyPlus Model Fan Only Electric Energy Savings Estimates.

Variable	Results
Model Total Fan Motor break kW =	365
Model Total Fan Motor BHP =	489
Baseline Model Fan Electric Consumption (kWh) =	1,172,931
Retrofit Model Fan Electric Consumption (kWh) =	236,342
Fan Electric Energy Savings (kWh) =	936,589
Fan Electric Energy Savings per BHP (kWh/BHP) =	1,916
Assumed Load Factor =	0.6
Model Fan Electric Energy Savings per Nominal HP (kWh/HP) =	1,149
Case Study Total Fan Retrofit Nominal HP =	410
Case Study Model Estimated Fan Electric Energy Savings (kWh/yr) =	**471,294**
Verified Electric Energy Savings (kWh/yr) =	**1,218,846**
Model Predicted / Verified Fan Only Energy Savings Ratio =	**0.39**

Table 24 shows the fuel heating impact. There is a noticeable increase in fuel consumption to make up for the reduced motor and fan heat load with the VFD installed. The models assume a natural gas boiler with hot water reheat. If the building used electric resistance reheat this would reduce the total electric energy savings. The electric penalty would be about 52,520 kWh/yr or roughly 9.4% of total savings. This would be offset by reduced pumping energy for the water loop. It is likely the offset would be less than the 9.4% and therefore this may be a significant impact which should be considered. The details on the case study do not provide any information on the type of reheat used, but water coil reheat with a natural gas boiler is a common system type and is a reasonable assumption.

Table 24. Case Study 4 EnergyPlus Model Fuel Savings Estimates.

Variable	Results
Model Total Fan Motor break kW =	365
Model Total Fan Motor BHP =	489
Baseline Model Fuel Consumption (MMBtu) =	6,556
Retrofit Model Fuel Consumption (MMBtu) =	7,051
Fuel Savings (MMBtu) =	(495)
Fuel Savings per BHP (MMBtu/BHP) =	(1.01)
Assumed Load Factor =	0.6
Model Fuel Savings per Nominal HP (MMBtu/HP) =	(0.61)
Case Study Total Retrofit Nominal HP =	410
Case Study Model Estimated Total Fuel Savings (MMBtu/yr) =	**(249.21)**

The model predictions for Case Study 4 are again not very good. A total model predicted to verified energy savings ratio of 0.46 is quite low for energy efficiency program evaluations. It is interesting to note that the average TRM predicted to verified energy savings ratio was 0.43, very similar to the savings predicted using the prototypes. Without more project level details it is difficult to know what is driving all of the prediction methodologies to be so low relative to the verified savings estimates.

5.4.5 Summary

Figure 14 shows a comparison of all the TRM and EnergyPlus model results versus the verified savings. As with the energy models, all of the TRM savings estimates underestimate savings as compared to the verified savings estimates. The SU 2011 MSEM is again an outlier with much higher predicted savings than the other TRMs. It is unclear what caused the predicted savings estimates to generally be so low from both the TRM protocols and the energy modeling method. It is a bit surprising given that the verified run hours were so similar to the typical TRM run hours.

On average the TRM results (average TRM predicted to verified ratio of 43%) are similar to the modeled results for both the total savings (ratio of 46%) and the fan only savings (ratio of 39%). There appears to be closer agreement across the predicting methods than for other case studies.

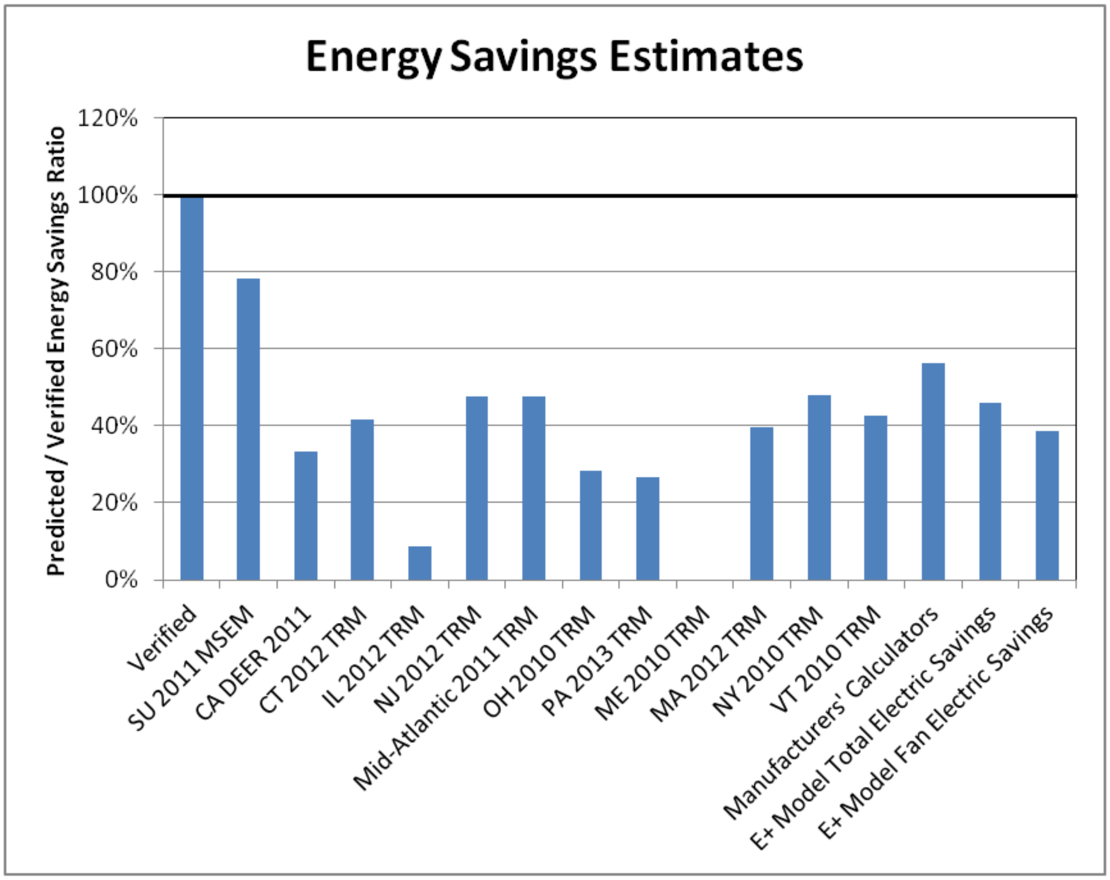

Figure 14. Case Study 4 Energy Savings Prediction Comparison

5.5 Case Study 5

Case study number 5 was also from an independent evaluation of a Mid-Atlantic energy efficiency incentive program. The project was a retrofit project in a large mall building located in the Philadelphia, PA area, and included retrofit of all 30 existing VAV RTUs with VFDs and 19 existing CV RTUs with VFDs.

The project included VFD retrofits to the following motors:

- 30 VAV RTU Supply Fans serving retail space
  - 2-60 HP with IGVs
  - 5-50 HP with IGVs
  - 17-40 HP with IGVs
  - 2-30 HP with IGVs

    - 1-25 HP with IGVs
    - 2-20 HP with IGVs
    - 1-15 HP with IGVs
- 19 CV RTU Supply fans serving common space
    - 9-40 HP
    - 4-30 HP
    - 4-25 HP
    - 2-15 HP

Savings were verified using analysis of trend data for a sample of the motors from EMS to establish run hours and power. Two units were also selected for direct amp logging. Power was estimated using VFD frequency trend data and DOE-2 fan part load curves for VFDs and outlet dampers. Power was weather normalized and extrapolated to annual energy savings using a bin analysis.

5.5.1 System Setup

The baseline system under consideration consisted of 30 existing VAV RTU supply fans with IGVs ranging from 15 to 60 HP, and 19 existing CV RTU supply fans ranging from 15 to 40 HP. The fan motors all operated at constant speed. All fan motors were retrofit with VFDs, and the IGVs on the existing VAV units were locked open or removed. The system was controlled to maintain a duct static pressure setpoint of 1 inch wg and on a time of day schedule. The total annual run hours of the VAV fans were verified as 6791 hours, and of the CV fans were verified as 1696 hours based on the trend data extrapolated to a year.

There is limited information in the reports and so it is difficult to identify all necessary inputs for the TRM comparisons and modeling. The motor efficiency is unknown, but assumed as EPact efficiency for comparison purposes. The report did not specify the fan type. For purposes of analysis it is assumed that the fan was centrifugal with BI/AF blades as a common fan type for this type of system.

Table 25 summarizes the baseline system setup for Case Study 5.

Table 25. Case Study 5 Project Summary

Motor Application	Motor Quantity	Motor HP	Motor Efficiency	Baseline Fan Type	Fan Blade Type	Baseline VAV Control Type	Operating Hours (actual/assumed for analysis)
VAV RTU Supply Fan	2	60	93.6%	Centrifugal	BI/AF blades (assumed)	IGVs	6791/4833 (Mall Concourse)
VAV RTU Supply Fan	5	50	93.0%	Centrifugal	BI/AF blades (assumed)	IGVs	6791/4833 (Mall Concourse)
VAV RTU Supply Fan	17	40	93.0%	Centrifugal	BI/AF blades (assumed)	IGVs	6791/4833 (Mall Concourse)
VAV RTU Supply Fan	2	30	92.4%	Centrifugal	BI/AF blades (assumed)	IGVs	6791/4833 (Mall Concourse)
VAV RTU Supply Fan	1	25	91.7%	Centrifugal	BI/AF blades (assumed)	IGVs	6791/4833 (Mall Concourse)
VAV RTU Supply Fan	2	20	91.0%	Centrifugal	BI/AF blades (assumed)	IGVs	6791/4833 (Mall Concourse)
VAV RTU Supply Fan	1	15	91.0%	Centrifugal	BI/AF blades (assumed)	IGVs	6791/4833 (Mall Concourse)
CV RTU Supply Fan	9	40	93.0%	Centrifugal	BI/AF blades (assumed)	None	1696/4833 (Mall Concourse)
CV RTU Supply Fan	4	30	92.4%	Centrifugal	BI/AF blades (assumed)	None	1696/4833 (Mall Concourse)
CV RTU Supply Fan	4	25	91.7%	Centrifugal	BI/AF blades (assumed)	None	1696/4833 (Mall Concourse)
CV RTU Supply Fan	2	15	91.0%	Centrifugal	BI/AF blades (assumed)	None	1696/4833 (Mall Concourse)

5.5.2 Verified Savings

Verified savings for the project were estimated at 1,444,584 kWh per year based on the monitoring period metered results extrapolated to a year. Verified peak demand savings were estimated at 206.100 kW per PA Act 129 requirements which require estimating demand savings over the top 100 hours of maximum system demand.

5.5.3 TRM Savings Estimates

Table 26 shows the minimum ratio of predicted to verified energy savings was 91% (IL 2012 TRM) and the maximum was 352% (CA DEER 2011), with an average of 177%. Similar to all other case studies, there is a wide difference across the savings estimates, however, the distribution among the various TRMs is somewhat different for this case study than the others. This is the only case study for which the CA DEER 2011 had the highest prediction to verified savings ratio. For this project the closest TRM prediction was the OH 2010 TRM with predicted savings estimates at 99% of the verified estimates.

Table 26. Case Study 5 TRM Savings Estimates

TRM Source	Energy Savings (kWh)	Peak Demand Savings Summer (kW)	Predicted / Verified Energy Savings Ratio	Predicted / Verified Demand Savings Ratio
Verified Savings	**1,444,584**	**206.100**	NA	NA
SU 2011 MSEM	4,179,600	79.161	289%	38%
CA DEER 2011	5,080,229	739.984	352%	359%
CT 2012 TRM	2,024,636	270.001	140%	131%
IL 2012 TRM	1,319,939	236.235	91%	115%
NJ 2012 TRM	3,322,098	648.306	230%	315%
Mid-Atlantic 2011 TRM[a]	3,107,396	110.697	215%	54%
OH 2010 TRM	1,434,325	221.470	99%	107%
PA 2013 TRM	1,737,765	163.615	120%	79%
ME 2010 TRM[b]	NA	NA	NA	NA
MA 2012 TRM	2,223,043	124.149	154%	60%
NY 2010 TRM	2,358,000	100.800	163%	49%
VT 2010 TRM[c]	1,801,800	311.400	125%	151%
Manufacturers' Calculators	2,359,272	629.475	163%	305%

5.5.4 EnergyPlus Modeling Results

Case Study 5 was modeled using the Stand-Alone Retail prototype. The case study had fans with both a CV baseline and a VAV with IGV baseline. To predict savings for these different fan configurations, the baseline model was run two ways. First the baseline model fans were set to a CV system. This CV baseline model was used to predict savings for the motors serving the common areas totaling 610 hp. Second the baseline model fans were set to a VAV system with IGVs and BI/AF blades using fan curve number 4 from Table 4. This VAV baseline model was used to predict savings for the motors serving the retail spaces totaling 1190 hp. The retrofit model fans were set to a VAV system with VFDs using fan curve number 11. The baseline and retrofit cases were all run using TMY3 data for Philadelphia, PA.

The results from the modeling are shown below. Table 27, Table 28, and Table 29 show the total building electric energy savings predicted using the models. The energy model predictions were fairly high with a predicted to verified total electric energy savings ratio of 2.13.

Table 27. Case Study 5 EnergyPlus Model Total Electric Energy Savings Estimates - CV Baseline Motors Only.

Variable	Results
Model Total Fan Motor break kW =	18
Model Total Fan Motor BHP =	24
Baseline Model Total Electric Consumption (kWh) =	509,639
Retrofit Model Total Electric Consumption (kWh) =	421,328
Total Electric Energy Savings (kWh) =	88,311
Total Electric Energy Savings per BHP (kWh/BHP) =	3,739
Assumed Load Factor =	0.6
Model Total Electric Energy Savings per Nominal HP (kWh/HP) =	2,243
Case Study Total Fan Retrofit Nominal HP =	610
Case Study Model Estimated Total Electric Energy Savings (kWh/yr) =	**1,368,477**

Table 28. Case Study 5 EnergyPlus Model Total Electric Energy Savings Estimates - VAV Baseline Motors Only.

Variable	Results
Model Total Fan Motor break kW =	18
Model Total Fan Motor BHP =	24
Baseline Model Total Electric Consumption (kWh) =	478,067
Retrofit Model Total Electric Consumption (kWh) =	421,328
Total Electric Energy Savings (kWh) =	56,739
Total Electric Energy Savings per BHP (kWh/BHP) =	2,402
Assumed Load Factor =	0.6
Model Total Electric Energy Savings per Nominal HP (kWh/HP) =	1,441
Case Study Total Fan Retrofit Nominal HP =	1190
Case Study Model Estimated Total Electric Energy Savings (kWh/yr) =	**1,715,221**

Table 29. Case Study 5 EnergyPlus Model Total Electric Energy Savings Estimates Versus Verified Savings.

Variable	Results
Case Study Model Estimated Total Electric Energy Savings (kWh/yr) =	**3,083,698**
Verified Savings (kWh/yr) =	**1,444,584**
Model Predicted / Verified Energy Savings Ratio =	**2.13**

Table 30, Table 31, and Table 32 show the fan only electric energy savings. The non-fan electric energy savings is 12.4% of the total model predicted electric energy savings. This is a significant difference and may indicate that savings for the non-fan benefits should be considered when estimating VFD savings.

Table 30. Case Study 5 EnergyPlus Model Fan Only Electric Energy Savings Estimates - CV Baseline Motors Only.

Variable	Results
Model Total Fan Motor break kW =	18
Model Total Fan Motor BHP =	24
Baseline Model Fan Electric Consumption (kWh) =	95,072
Retrofit Model Fan Electric Consumption (kWh) =	12,822
Fan Electric Energy Savings (kWh) =	82,250
Fan Electric Energy Savings per BHP (kWh/BHP) =	3,482
Assumed Load Factor =	0.6
Model Fan Electric Energy Savings per Nominal HP (kWh/HP) =	2,089
Case Study Total Fan Retrofit Nominal HP =	610
Case Study Model Estimated Fan Electric Energy Savings (kWh/yr) =	**1,274,553**

Table 31. Case Study 5 EnergyPlus Model Fan Only Electric Energy Savings Estimates - VAV Baseline Motors Only.

Variable	Results
Model Total Fan Motor break kW =	18
Model Total Fan Motor BHP =	24
Baseline Model Fan Electric Consumption (kWh) =	60,067
Retrofit Model Fan Electric Consumption (kWh) =	12,822
Fan Electric Energy Savings (kWh) =	47,244
Fan Electric Energy Savings per BHP (kWh/BHP) =	2,000
Assumed Load Factor =	0.6
Model Fan Electric Energy Savings per Nominal HP (kWh/HP) =	1,200
Case Study Total Fan Retrofit Nominal HP =	1190
Case Study Model Estimated Fan Electric Energy Savings (kWh/yr) =	**1,428,203**

Table 32. Case Study 5 EnergyPlus Model Fan Only Electric Energy Savings Estimates Versus Verified Savings.

Variable	Results
Case Study Model Estimated Fan Electric Energy Savings (kWh/yr) =	**2,702,757**
Verified Savings (kWh/yr) =	**1,444,584**
Model Predicted / Verified Fan Only Energy Savings Ratio =	**1.87**

Table 33, Table 34, and Table 35 show the fuel heating impact. There is a noticeable increase in fuel consumption to make up for the reduced motor and fan heat load with the VFD installed. The models assume natural gas fired reheat. If the building used electric resistance reheat this would reduce the total electric energy savings. The electric penalty would be about 725,100 kWh/yr or roughly 23.5% of total savings. This is quite a high heating penalty. This is clearly a significant impact which should be considered. In this case the details on the case study noted the type of reheat used and therefore this penalty should be accounted for on the fuel side, but the models reflected the actual system type so there would be no electric penalty for the actual case study. Other projects which do use electric reheat would need to include this factor so as not to greatly overstate savings.

Before basing any actual adjustments on this value, it is important to recognize the significant differences between the modeled building and the case study building. The modeled building used a Stand-Alone Retail prototypical model because there were no U.S. DOE prototypical models for a large mall. Prior to making such an adjustment to an actual large mall project, it may be prudent to develop a more project specific energy model.

Table 33. Case Study 5 EnergyPlus Model Fuel Savings Estimates - CV Baseline Motors Only.

Variable	Results
Model Total Fan Motor break kW =	18
Model Total Fan Motor BHP =	24
Baseline Model Fuel Consumption (MMBtu) =	1,060
Retrofit Model Fuel Consumption (MMBtu) =	1,227
Fuel Savings (MMBtu) =	(167)
Fuel Savings per BHP (MMBtu/BHP) =	(7.06)
Assumed Load Factor =	0.6
Model Fuel Savings per Nominal HP (MMBtu/HP) =	(4.24)
Case Study Total Retrofit Nominal HP =	610
Case Study Model Estimated Total Fuel Savings (MMBtu/yr) =	**(2,584.75)**

Table 34. Case Study 5 EnergyPlus Model Fuel Savings Estimates - VAV Baseline Motors Only.

Variable	Results
Model Total Fan Motor break kW =	18
Model Total Fan Motor BHP =	24
Baseline Model Fuel Consumption (MMBtu) =	1,199
Retrofit Model Fuel Consumption (MMBtu) =	1,227
Fuel Savings (MMBtu) =	(28)
Fuel Savings per BHP (MMBtu/BHP) =	(1.20)
Assumed Load Factor =	0.6
Model Fuel Savings per Nominal HP (MMBtu/HP) =	(0.72)
Case Study Total Retrofit Nominal HP =	1,190
Case Study Model Estimated Total Fuel Savings (MMBtu/yr) =	**(855.92)**

Table 35. Case Study 5 EnergyPlus Model Fuel Savings Estimates Versus Verified Savings.

Variable	Results
Case Study Model Estimated Total Fuel Savings (MMBtu/yr) =	**(3,441)**

The model predictions for Case Study 5 are again not very good. A total model predicted to verified energy savings ratio of 2.13 is very high for energy efficiency program evaluations. It is interesting to note that the average TRM predicted to verified energy savings ratio was 1.77, which was somewhat similar to the savings predicted using the prototypes. There are many reasons this case study is being overestimated, but because the model estimates are fairly similar in scale to the TRM average estimates, it may be that the building is just not suited very well to prescriptive predictions. Without more project level details it is difficult to know.

5.5.5 Summary

Figure 15 shows a comparison of all the TRM and EnergyPlus model results versus the verified savings. As with the energy models, most of the TRM savings estimates overestimate savings by a wide margin as compared to the verified savings estimates. This time both the SU 2011 MSEM and the CA DEER 2011 are outliers with much higher predicted savings than the other TRMs. It is unclear what caused the predicted savings estimates to generally be so high from both the TRM protocols and the energy modeling method.

It is possible that one factor causing the predictions to be high is that the verified hours on the constant volume baseline units were much lower than the assumed hours and modeled hours. Given that those units accounted for just under half the predicted savings this may account for some of the overestimation, but it would not be able to account for all of it. Especially considering the verified hours from the VAV baseline units were much higher than the assumed/modeled hours of use.

On average the TRM results (average TRM predicted to verified ratio of 177%) are somewhat lower than the modeled results for the total savings (ratio of 213%) and slightly lower than the fan only savings (ratio of 187%). There is fairly wide distribution of estimates across all the methodologies for this case study.

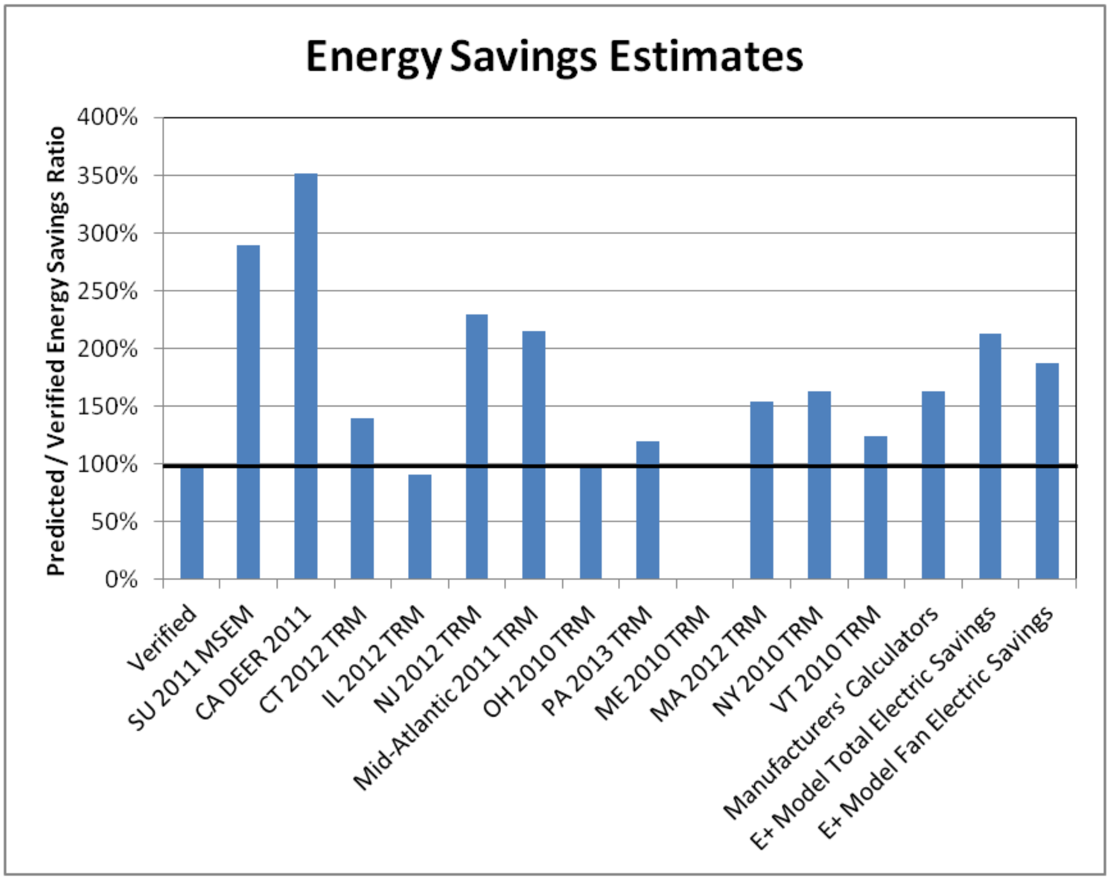

Figure 15. Case Study 5 Energy Savings Prediction Comparison

5.6 Case Study 6

Case study number 6 was also from an independent evaluation of a Midwestern energy efficiency incentive program. The project was a retrofit project in a medium office building located in the Chicago, IL area, and included retrofit of all four existing VAV RTUs with VFDs. Each RTU had two supply fans with IGVs and both were retrofit.

The project included VFD retrofits to the following motors:

- VAV RTU Supply Fans
  - 4-50 HP with IGVs
  - 4-20 HP with IGVs

Savings were verified using analysis of metered data of fan motor power to establish run hours and power curves. Power was weather normalized and extrapolated to annual energy savings using a bin analysis.

5.6.1 System Setup

The baseline system under consideration consisted of four existing VAV RTUs, each with 1-50 HP supply fan with IGVs and 1-20 HP supply fan with IGVs for a total of eight fan motors. The fan motors all operated at constant speed. All fan motors were retrofit with VFDs, and the IGVs on the existing VAV units were locked open or removed.

There is limited information in the reports and so it is difficult to identify all necessary inputs for the TRM comparisons and modeling. The total annual run hours of the VAV fans were not specified in the analysis documents. It is unclear how the system was controlled. The motor efficiency is unknown, but assumed as NEMA Premium per notes in the verification report for comparison purposes. The report did not specify the fan type. For purposes of analysis it is assumed that the fan was centrifugal with BI/AF blades as a common fan type for this type of system.

Table 36 summarizes the baseline system setup for Case Study 6.

Table 36. Case Study 6 Project Summary

Motor Application	Motor Quantity	Motor HP	Motor Efficiency	Baseline Fan Type	Fan Blade Type	Baseline VAV Control Type	Operating Hours (actual/assumed for analysis)
VAV RTU Supply Fan	4	50	94.5%	Centrifugal	BI/AF blades (assumed)	IGVs	NA/3748 (office)
VAV RTU Supply Fan	4	20	93.0%	Centrifugal	BI/AF blades (assumed)	IGVs	NA/3748 (office)

5.6.2 Verified Savings

Verified savings for the project were estimated at 272,642 kWh per year based on the monitoring period metered results extrapolated to a year. Verified peak demand savings were estimated at 72.342 kW per IL requirements which require estimating demand savings over the PJM peak period.

5.6.3 TRM Savings Estimates

Table 37 shows the minimum ratio of predicted to verified energy savings was 26% (IL 2012 TRM) and the maximum was 238% (SU 2011 MSEM), with an average of 107%. Similar to all other case studies, there is a wide range of estimates. For this project the closest TRM prediction was the VT 2010 TRM with predicted savings estimates at 103% of the verified estimates. This was the case even though this project was technically was outside the VT 2010 TRM limitations.

Table 37. Case Study 6 TRM Savings Estimates

TRM Source	Energy Savings (kWh)	Peak Demand Savings Summer (kW)	Predicted / Verified Energy Savings Ratio	Predicted / Verified Demand Savings Ratio
Verified Savings	**272,642**	**72.342**	NA	NA
SU 2011 MSEM	650,158	12.315	238%	17%
CA DEER 2011	335,966	60	123%	83%
CT 2012 TRM	202,298	30.849	74%	43%
IL 2012 TRM	71,214	23.094	26%	32%
NJ 2012 TRM	395,326	99.481	145%	138%
Mid-Atlantic 2011 TRM[a]	253,008	10.819	93%	15%
OH 2010 TRM	150,653	21.650	55%	30%
PA 2013 TRM	141,693	16.021	52%	22%
ME 2010 TRM[b]	NA	NA	NA	NA
MA 2012 TRM	320,284	19.050	117%	26%
NY 2010 TRM	449,400	15.680	165%	22%
VT 2010 TRM[c]	280,280	48.440	103%	67%
Manufacturers' Calculators	266,180	71.019	98%	98%

5.6.4 EnergyPlus Modeling Results

Case Study 6 was modeled using the Medium Office prototype. The baseline model fans were set to a VAV system with IGVs and BI/AF blades using fan curve number 4 from Table 4. The retrofit model fans were set to a VAV system with VFDs using fan curve number 11. Both cases were run using TMY3 data for Chicago, IL.

The results from the modeling are shown below. Table 38 shows the total building electric energy savings predicted using the models. The energy model predictions were somewhat high with a predicted to verified total electric energy savings ratio of 1.44.

Table 38. Case Study 6 EnergyPlus Model Total Electric Energy Savings Estimates.

Variable	Results
Model Total Fan Motor break kW =	41
Model Total Fan Motor BHP =	55
Baseline Model Total Electric Consumption (kWh) =	1,112,669
Retrofit Model Total Electric Consumption (kWh) =	983,519
Total Electric Energy Savings (kWh) =	129,150
Total Electric Energy Savings per BHP (kWh/BHP) =	2,333
Assumed Load Factor =	0.6
Model Total Electric Energy Savings per Nominal HP (kWh/HP) =	1,400
Case Study Total Fan Retrofit Nominal HP =	280
Case Study Model Estimated Total Electric Energy Savings (kWh/yr) =	**391,964**
Verified Electric Energy Savings (kWh/yr) =	**272,642**
Model Predicted / Verified Energy Savings Ratio =	**1.44**

Table 39 shows the fan only electric energy savings. The non-fan electric energy savings is 17.7% of the total model predicted electric energy savings. This is a significant difference and may indicate that savings for the non-fan benefits should be considered when estimating VFD savings.

Table 39. Case Study 6 EnergyPlus Model Fan Only Electric Energy Savings Estimates.

Variable	Results
Model Total Fan Motor break kW =	41
Model Total Fan Motor BHP =	55
Baseline Model Fan Electric Consumption (kWh) =	133,786
Retrofit Model Fan Electric Consumption (kWh) =	27,486
Fan Electric Energy Savings (kWh) =	106,300
Fan Electric Energy Savings per BHP (kWh/BHP) =	1,920
Assumed Load Factor =	0.6
Model Fan Electric Energy Savings per Nominal HP (kWh/HP) =	1,152
Case Study Total Fan Retrofit Nominal HP =	280
Case Study Model Estimated Fan Electric Energy Savings (kWh/yr) =	**322,615**
Verified Electric Energy Savings (kWh/yr) =	**272,642**
Model Predicted / Verified Fan Only Energy Savings Ratio =	**1.18**

Table 40 shows the fuel heating impact. There is a noticeable increase in fuel consumption to make up for the reduced motor and fan heat load with the VFD installed. The models assume natural gas fired main heating coils and electric resistance reheat. It would be possible, but unlikely, a building of this size would use electric resistance main heating coils so this penalty would likely remain as a fuel only penalty. It is possible this type of building would use a main natural gas boiler with a hot water coil. If this were the case there may be a slight increase in pumping energy with the retrofit.

This fuel heating penalty is equivalent to about 69,200 kWh/yr of electric resistance heat, or roughly 17.7% of total savings. This is quite a high heating penalty. This is clearly a significant impact which should be considered. Regardless whether or not this penalty is fuel or electric, it is sizable enough that it should be considered in reviewing the cost effectiveness of the measure.

Table 40. Case Study 6 EnergyPlus Model Fuel Savings Estimates.

Variable	Results
Model Total Fan Motor break kW =	41
Model Total Fan Motor BHP =	55
Baseline Model Fuel Consumption (MMBtu) =	142
Retrofit Model Fuel Consumption (MMBtu) =	250
Fuel Savings (MMBtu) =	(108)
Fuel Savings per BHP (MMBtu/BHP) =	(1.96)
Assumed Load Factor =	0.6
Model Fuel Savings per Nominal HP (MMBtu/HP) =	(1.17)
Case Study Total Retrofit Nominal HP =	280
Case Study Model Estimated Total Fuel Savings (MMBtu/yr) =	**(328.44)**

The model predictions for Case Study 6 are again not great. A predicted to verified total electric energy savings ratio of 1.44 is fairly high among energy efficiency program evaluations. Without more project level details it is difficult to know what is driving the results. These results are particularly worse than the average TRM predicted to verified total electric energy savings ratio of 1.07. As noted for some of the other case studies, the model predicted to verified fan only electric energy savings ratio may be a better comparison to most of the TRMs. In this case the ratio was 1.18 which is reasonably close to the average TRM ratio. It is unclear why these would be worse than the average TRM savings. Without more project level details it is difficult to know what is driving the prototypical energy simulation estimates to be so much higher relative to the verified savings estimates and the various TRMs.

5.6.5 Summary

Figure 16 shows a comparison of all the TRM and EnergyPlus model results versus the verified savings. On average the TRM results (average TRM predicted to verified ratio of 107%) were slightly better than the modeled results for both the total savings (ratio of 144%) and the fan only savings (ratio of 118%).

This case study had the best overall prediction results as compared to the verified estimates. This held true for both the TRMs and the energy modeling results, except for a couple outliers including the SU 2011 MSEM and the IL 2012 TRM, with predictions that were extremely high and low respectively.

It is possible that the predictions were generally better for this case study than others because the actual building was fairly similar to the prototypical model used in the analysis. Most of the other case studies were fairly different or more unique relative to the prototypes. It may speak to the need for accurate modeling of the actual building to get reliable results.

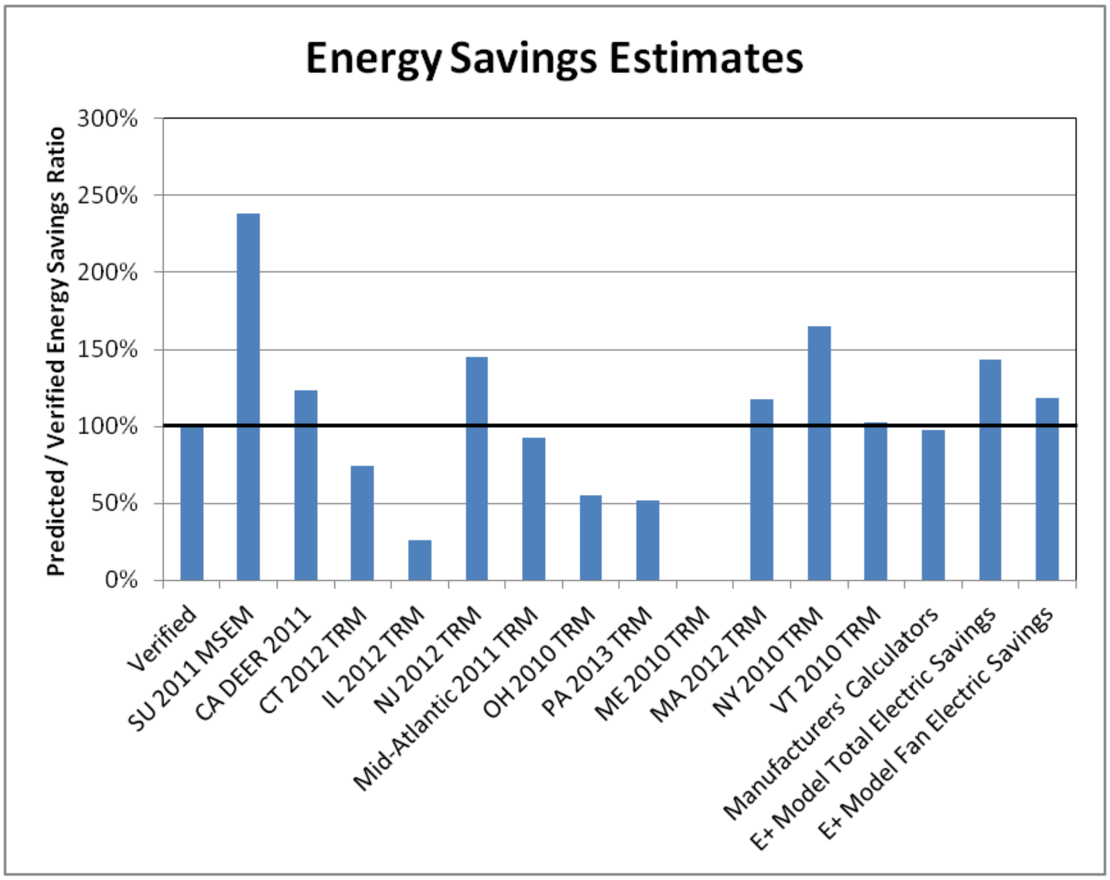

Figure 16. Case Study 6 Energy Savings Prediction Comparison

5.7 Case Study 7

Case study number 7 was also from an independent evaluation of a Midwestern energy efficiency incentive program. The project was a retrofit project in a medium office building located in the Chicago, IL area, and included retrofit of 18 existing VAV HVAC supply fans with VFDs.

The project included VFD retrofits to the following motors:

- VAV Supply Fans

- 6-40 HP with outlet dampers
- 3-50 HP with outlet dampers
- 6-100 HP with outlet dampers
- 3-150 HP with outlet dampers

Savings were verified using analysis of metered data of fan motor power to establish run hours and power curves. Power was weather normalized and extrapolated to annual energy savings using a bin analysis.

5.7.1 System Setup

The baseline system under consideration consisted of 18 existing VAV supply fans with outlet dampers. The fan motors all operated at constant speed. All fan motors were retrofit with VFDs, and the outlet dampers on the existing VAV units were locked open or removed. The total annual run hours of the 150-HP and 50-HP fans were verified as 3716 hours, and of the 100-HP and 40-HP fans were verified as 3095 hours based on the metered data extrapolated to a year.

There is limited information in the reports and so it is difficult to identify all necessary inputs for the TRM comparisons and modeling, however, this is not dissimilar from how TRMs are typically used by program implementation contractors. It is unclear how the system was controlled. The motor efficiency is unknown, but assumed as NEMA Premium per notes in the verification report for comparison purposes. The report did not specify the fan type. For purposes of analysis it is assumed that the fan was centrifugal with BI/AF blades as a common fan type for this type of system.

Table 41 summarizes the baseline system setup for Case Study 7.

Table 41. Case Study 7 Project Summary

Motor Application	Motor Quantity	Motor HP	Motor Efficiency	Baseline Fan Type	Fan Blade Type	Baseline VAV Control Type	Operating Hours (actual/assumed for analysis)
VAV Supply Fan	6	40	94.1%	Centrifugal	BI/AF blades (assumed)	Outlet dampers	3095/3748 (office)
VAV Supply Fan	3	50	94.5%	Centrifugal	BI/AF blades (assumed)	Outlet dampers	3716/3748 (office)
VAV Supply Fan	6	100	95.4%	Centrifugal	BI/AF blades (assumed)	Outlet dampers	3095/3748 (office)
VAV Supply Fan	3	150	95.8%	Centrifugal	BI/AF blades	Outlet	3716/3748

		(assumed)	dampers	(office)

5.7.2 Verified Savings

Verified savings for the project were estimated at 1,195,946 kWh per year based on the monitoring period metered results extrapolated to a year. Verified peak demand savings were estimated at 192.844 kW per IL requirements which require estimating demand savings over the PJM peak period.

5.7.3 TRM Savings Estimates

Table 42 shows the minimum ratio of predicted to verified energy savings was 30% (IL 2012 TRM) and the maximum was 280% (SU 2011 MSEM), with an average of 138%. Similar to all other case studies, there is a wide range of estimates. For this project the closest TRM prediction was the Mid-Atlantic 2011 TRM with predicted savings estimates at 107% of the verified estimates. This was the case even though this project was technically was outside the Mid-Atlantic 2011 TRM limitations.

Table 42. Case Study 7 TRM Savings Estimates

TRM Source	Energy Savings (kWh)	Peak Demand Savings Summer (kW)	Predicted / Verified Energy Savings Ratio	Predicted / Verified Demand Savings Ratio
Verified Savings	**1,195,946**	**192.844**	NA	NA
SU 2011 MSEM	3,343,672	63.332	280%	33%
CA DEER 2011	1,727,824	308.336	144%	160%
CT 2012 TRM	1,027,889	156.747	86%	81%
IL 2012 TRM	361,845	117.341	30%	61%
NJ 2012 TRM	2,008,674	505.469	168%	262%
Mid-Atlantic 2011 TRM[a]	1,285,551	54.970	107%	29%
OH 2010 TRM	765,476	110.007	64%	57%
PA 2013 TRM	719,951	81.405	60%	42%
ME 2010 TRM[b]	NA	NA	NA	NA
MA 2012 TRM	1,627,383	96.796	136%	50%
NY 2010 TRM	2,311,200	80.640	193%	42%
VT 2010 TRM[c]	1,441,440	249.120	121%	129%
Manufacturers' Calculators	2,415,751	644.544	202%	334%

5.7.4 EnergyPlus Modeling Results

Case Study 7 was modeled using the Medium Office prototype. The baseline model fans were set to a VAV system with Outlet Dampers and BI/AF blades using fan curve number 2 from Table 4. The retrofit model fans were set to a VAV system with VFDs using fan curve number 11. Both cases were run using TMY3 data for Chicago, IL.

The results from the modeling are shown below. Table 43 shows the total building electric energy savings predicted using the models. The energy model predictions were fairly high with a predicted to verified total electric energy savings ratio of 1.72.

Table 43. Case Study 7 EnergyPlus Model Total Electric Energy Savings Estimates.

Variable	Results
Model Total Fan Motor break kW =	41
Model Total Fan Motor BHP =	55
Baseline Model Total Electric Consumption (kWh) =	1,115,669
Retrofit Model Total Electric Consumption (kWh) =	983,519
Total Electric Energy Savings (kWh) =	132,150
Total Electric Energy Savings per BHP (kWh/BHP) =	2,387
Assumed Load Factor =	0.6
Model Total Electric Energy Savings per Nominal HP (kWh/HP) =	1,432
Case Study Total Fan Retrofit Nominal HP =	1440
Case Study Model Estimated Total Electric Energy Savings (kWh/yr) =	**2,062,640**
Verified Electric Energy Savings (kWh/yr) =	**1,195,946**
Model Predicted / Verified Energy Savings Ratio =	**1.72**

Table 44 shows the fan only electric energy savings. The non-fan electric energy savings is 18.1% of the total model predicted electric energy savings. This is a significant difference and may indicate that savings for the non-fan benefits should be considered when estimating VFD savings.

Table 44. Case Study 7 EnergyPlus Model Fan Only Electric Energy Savings Estimates.

Variable	Results
Model Total Fan Motor break kW =	41
Model Total Fan Motor BHP =	55
Baseline Model Fan Electric Consumption (kWh) =	135,722
Retrofit Model Fan Electric Consumption (kWh) =	27,486

Fan Electric Energy Savings (kWh) =	108,236
Fan Electric Energy Savings per BHP (kWh/BHP) =	1,955
Assumed Load Factor =	0.6
Model Fan Electric Energy Savings per Nominal HP (kWh/HP) =	1,173
Case Study Total Fan Retrofit Nominal HP =	1440
Case Study Model Estimated Fan Electric Energy Savings (kWh/yr) =	**1,689,384**
Verified Electric Energy Savings (kWh/yr) =	**1,195,946**
Model Predicted / Verified Fan Only Energy Savings Ratio =	**1.41**

Table 45 shows the fuel heating impact. There is a noticeable increase in fuel consumption to make up for the reduced motor and fan heat load with the VFD installed. The models assume natural gas fired main heating coils and electric resistance reheat. It would be possible, but unlikely, a building of this size would use electric resistance main heating coils, so this penalty would likely remain as a fuel only penalty. It is possible this type of building would use a main natural gas boiler with a hot water coil. If this were the case there may be a slight increase in pumping energy with the retrofit.

This fuel heating penalty is equivalent to about 355,006 kWh/yr of electric resistance heat, or roughly 17.2% of total savings. This is quite a high heating penalty. This is clearly a significant impact which should be considered. Regardless whether or not this penalty is fuel or electric, it is sizable enough that it should be considered in reviewing the cost effectiveness of the measure.

Table 45. Case Study 7 EnergyPlus Model Fuel Savings Estimates.

Variable	Results
Model Total Fan Motor break kW =	41
Model Total Fan Motor BHP =	55
Baseline Model Fuel Consumption (MMBtu) =	142
Retrofit Model Fuel Consumption (MMBtu) =	250
Fuel Savings (MMBtu) =	(108)

Fuel Savings per BHP (MMBtu/BHP) =	(2)
Assumed Load Factor =	0.60
Model Fuel Savings per Nominal HP (MMBtu/HP) =	(1)
Case Study Total Retrofit Nominal HP =	1,440
Case Study Model Estimated Total Fuel Savings (MMBtu/yr) =	**(1,685)**

Similar to Case Studies 2 and 6, the model predictions for Case Study 7 are much higher the verified savings, and higher than the average TRM predicted to verified total electric energy savings ratio of 1.38. A predicted to verified total electric energy savings ratio of 1.72 is relatively unusual for energy efficiency program evaluations for projects of this size, but not unheard of. Without more project level details it is difficult to know why Case Study 7 predictions were so poor relative to verified savings.

As noted for some of the other case studies, the model predicted to verified fan only electric energy savings ratio may be a better comparison to most of the TRMs. In this case the ratio was 1.41 which is quite close to the average TRM ratio of 1.38. Clearly there are a lot of energy impacts outside of just the fan energy savings that should be considered.

5.7.5 Summary

Figure 17 shows a comparison of all the TRM and EnergyPlus model results versus the verified savings. On average the TRM results (average TRM predicted to verified ratio of 138%) were somewhat better than the modeled results for both the total savings (ratio of 172%) and roughly the same as the fan only savings (ratio of 141%).

The results for this case study varied widely as with other case studies. While the Mid-Atlantic 2011 TRM savings estimates were quite close to the verified savings it was likely just circumstantial rather than being a better predictor.

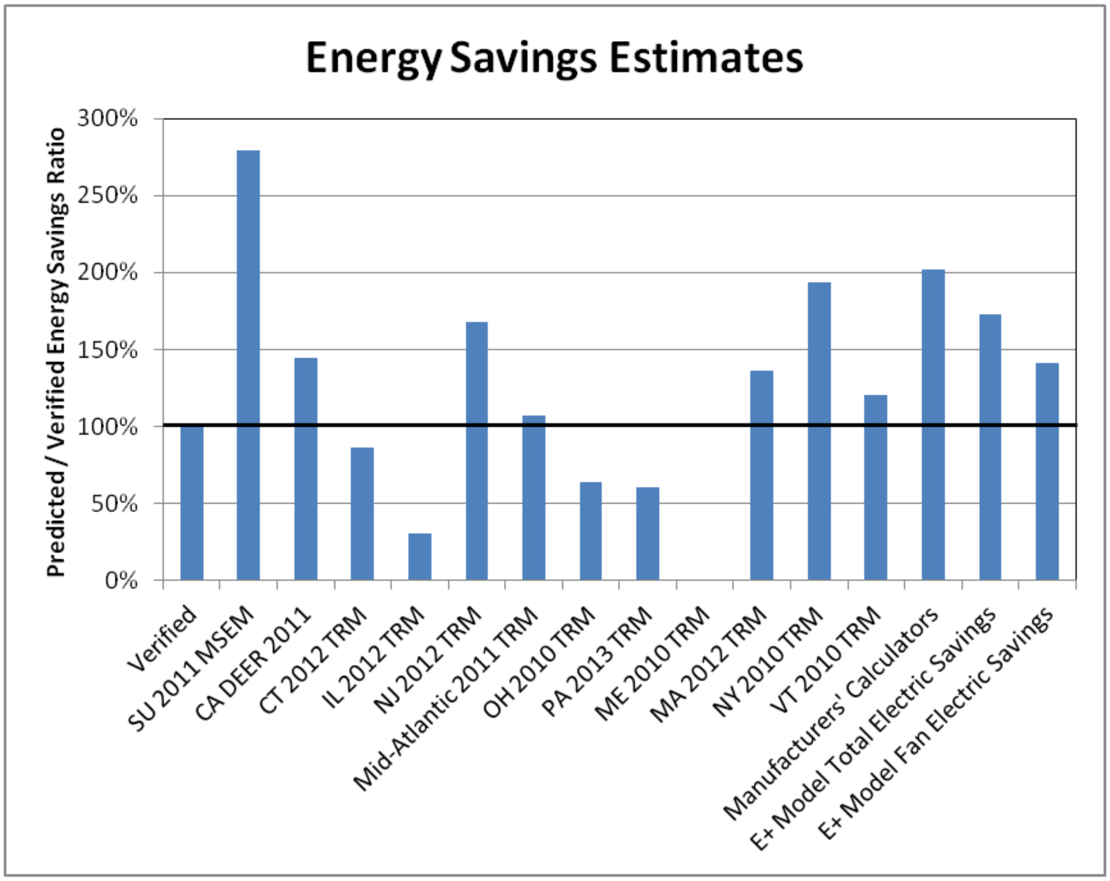

Figure 17. Case Study 7 Energy Savings Prediction Comparison

Chapter 6

6 Savings Prediction Results

It is informative to look at the savings estimates for each individual case study, but to determine if one method is more reliable than the others at predicting project savings, it is necessary to look at a comparison of each TRM and the energy model results across all the case studies.

6.1 Initial Observations

One of the most interesting findings from the TRM comparisons is the range of savings estimates seen coming out of the TRMs based on the CT TRM. From the six TRMs using the CT methodology (CT, IL, NJ, Mid-Atlantic, OH, and PA), the range of predicted to verified energy savings ratios was from 33% all the way up to 139%, with the CT 2012 TRM at 77%. This clearly shows the differences between the TRMs which cause significant concern as to the reliability of any of the TRMs using the CT methodology, other than maybe the CT TRM itself being the original source. Although the Mid-Atlantic 2011 TRM was one of the best predictors on a whole, it is more likely from chance that it was so close rather than because it was reliable.

Another interesting finding is that for the TRMs in the comparison, it appears that the more complex methodologies do not seem to lead to more reliable results. The Manufacturers' Calculators used one of the simplest methods with single motor power ratio assumptions for pre/post installations based on assumed average flow ratios and fan part load power curves, but yielded relatively similar results to the more complicated TRM and energy modeling methodologies.

One of the more complicated was the NY 2010 TRM, which used DOE-2.2 energy simulations to derive deemed savings estimates per motor HP depending on building type and fan type. The MA 2012 TRM also used a savings per motor HP, but it is unclear how those factors were derived. The Mid-Atlantic 2011 TRM was based on the CT TRM which used a bin analysis to estimate savings factors by fan configuration, but as discussed previously, there are concerns as to the reliability of the Mid-Atlantic TRM methodology. Finally, the CA DEER 2011 also used complicated energy savings factors established through extensive modeling techniques and had similar results, but had a significantly larger standard deviation and more limited application options.

In many ways the manufacturers' calculator methodology based on fan motor power ratios was the best in terms of simplicity and reliability. The one caveat is that motor run hours are required to be input into the calculation, but default run hours are not provided in the calculators. For this study run hours were assumed based on other methods that did include estimated run hours by building type and motor configuration. It is likely that this calculation would be even more reliable if savings were based on customer specific run hours based on metering, although this might defeat the purpose of a simplified savings estimation method.

Even though some of the TRMs had ratios of predicted energy savings to verified savings that were close to 100% on average, it is unlikely that this is because they are using a more sound methodology than the others. It is more likely that it was random chance due to the small sample size of case studies. A larger, statistically valid sample comparing metered results to TRM estimates would be required within each TRM jurisdiction to confidently say that one method is more reliable than the others. With the large standard deviations and differences between each TRM attempting to predict the same project savings, it does create doubt that any one TRM protocol is better than the other. It appears likely that they all have significant flaws.

One of the most glaring flaws observed during this study was that none of the TRMs cover enough configurations to be able to adequately estimate savings for just these seven case studies. As discussed in Chapter 2, there are a significant number of parameters which all affect VFD project savings, but all the TRMs have attempted to simplify the differences to just a handful of parameters, and in some cases grouping them all together as one. This does not recognize the realities of VFD projects and the differences between HVAC systems. The author believes these simplifications provide a false sense of predictability in VFD project savings that just does not exist.

As shown in Figure 7 and Table 1, there are at least nine different main baseline fan control types (constant volume is not shown in the figure and table, but is in addition to the eight shown) for which fan part load curves are available and that affect energy savings, but as discussed in Chapter 2 there are many more parameters to consider. Of all the TRMs included in this study, five options was the most given for selection of the fan control type, with some having no options at all. That is not enough to cover just the basic fan control options. Given the wide variety of fan types and blade types available, this cannot possibly predict reliable savings for VFD projects.

Further, none of the TRMs included static pressure differences in the calculations, but this can have a big impact on where the fans’ operating efficiency is. It is very common for system operating parameters to be modified after installation of a VFD which needs to be taken into consideration when estimating savings. None of the TRMs provide such an option.

Some of the TRMs do include adjustments for motor efficiency, but none included adjustments for fan efficiency or VFD efficiency, which both affect overall system efficiency. Also, as the fan changes speed or the system back pressure changes, the efficiency of all three parameters (fan, motor, and VFD) change as well. This simply cannot be considered in a highly simplified methodology such as a TRM protocol must adopt.

Another factor on efficiency is the motor type and number of poles (which affects the baseline motor speed). None of the TRMs or case studies included this information. Motor to fan drive connection such as direct drive, belt drive, or gear drive, was also not included. Neither was the baseline fan speed, although the affects of this should be accounted for in the power calculations. These concerns are relatively small compared to the other more major issues that are ignored. Until the more major issues are dealt with it is probably acceptable to ignore these.

None of the TRMs ask about the minimum allowable flow percentage required by the system to maintain minimum necessary system pressure. This affects the low end of the VFD frequency and how far down the fan part load curve the system can go, which in turn affects the maximum savings that can be achieved. This can have a significant impact on potential energy savings, particularly in motors that are oversized and start out at a relatively low load factor. In cases like this, if a motor is brought to too slow a speed and it is lightly loaded, the efficiency of the motor can drop precipitously thus negating savings.

As VFDs become a larger and larger portion of EE/DSM programs, it is important that a more reliable and accurate savings methodology than the current TRM protocols be employed to ensure that ratepayer money is being spent wisely. There are more complex methodologies already available, but program implementers tend to prefer more simplified methods. The question remains, can a simplified method reliably predict VFD savings?

6.2 TRM Estimation Results

Table 46 compares the average ratio of predicted energy savings over verified savings between each TRM. It also shows the standard deviation of the ratio by TRM.

Table 46. Average Energy Predicted / Verified Ratios by TRM

TRM Source	Average Energy Predicted / Verified Ratio	Standard Deviation of Energy Predicted / Verified Ratio
SU 2011 MSEM	205%	104%
CA DEER 2011	127%	110%
CT 2012 TRM	77%	36%
IL 2012 TRM	33%	27%
NJ 2012 TRM	139%	65%
Mid-Atlantic 2011 TRM[a]	101%	58%
OH 2010 TRM	62%	36%
PA 2013 TRM	57%	32%
ME 2010 TRM[b]	29%	NA
MA 2012 TRM	100%	49%
NY 2010 TRM	121%	72%
VT 2010 TRM[c]	92%	47%
Manufacturers' Calculators	111%	57%
TRM Average	**96%**	**58%**
E+ Model Total Electric Savings	**127%**	**70%**
E+ Model Fan Electric Savings	**107%**	**60%**

Figure 18 graphs the average predicted savings to verified savings ratio for all the case studies for each methodology, and one standard deviation of the results.

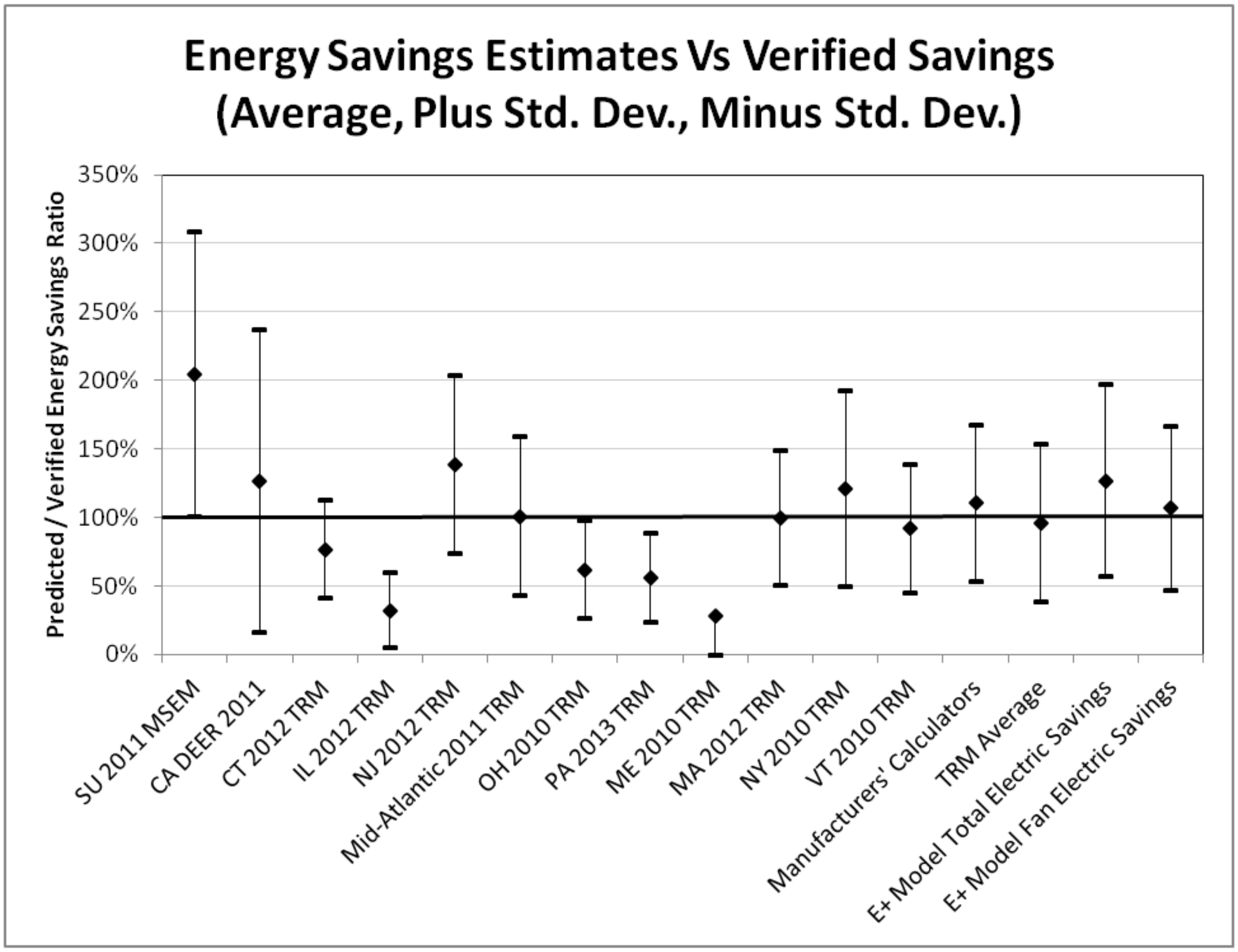

Figure 18. Comparison of Average TRM Predicted Savings vs Verified Savings Estimates; plus or minus one Standard Deviation of Predictions.

Figure 19 is similar to the previous graph, however, it shows the average predicted savings to verified savings ratio for all the case studies for each methodology, plus the highest and the lowest ratios.

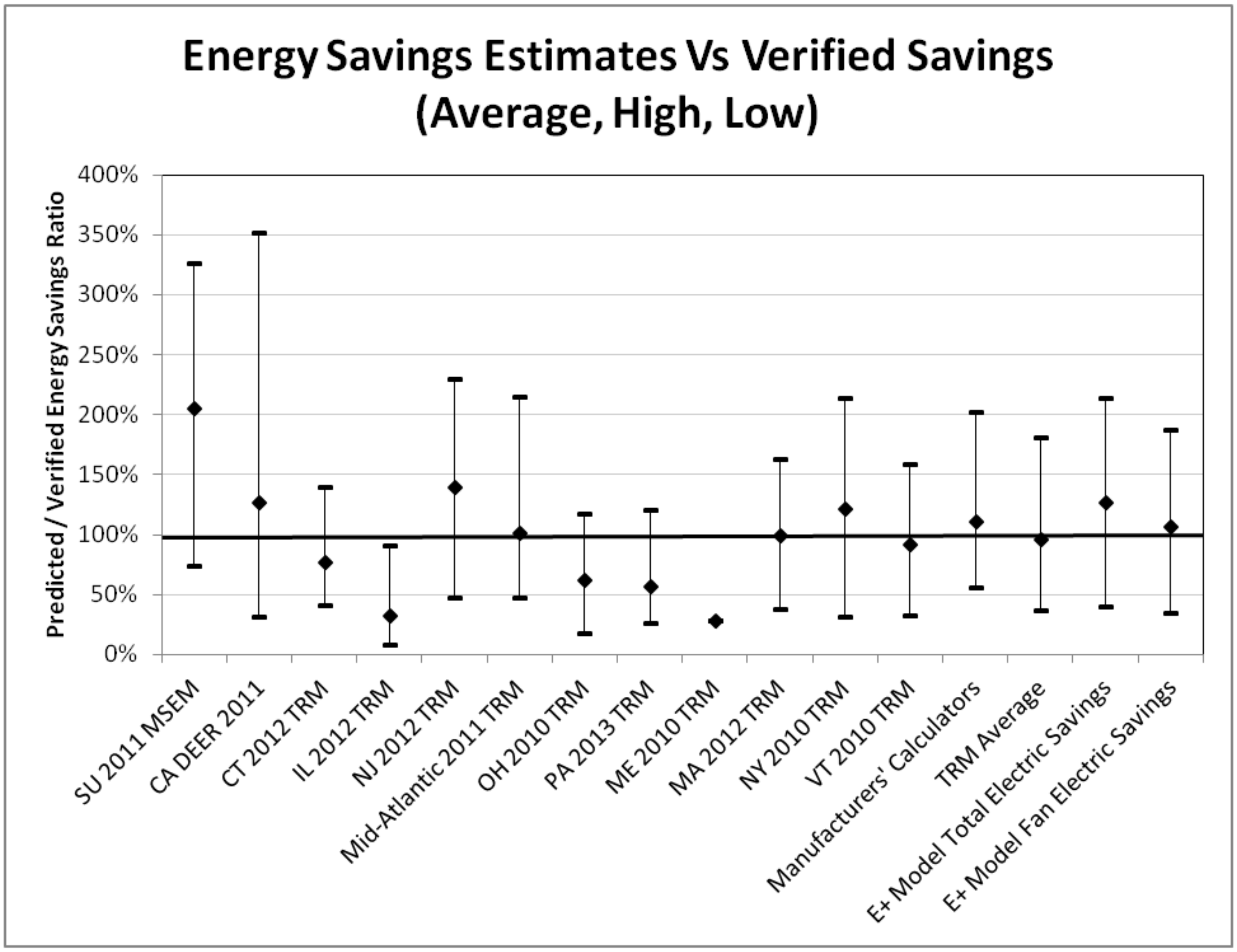

Figure 19. Comparison of Average TRM Predicted Savings vs Verified Savings Estimates; including High and Low Estimates.

The TRMs that did the best job of predicting savings were the MA 2012 TRM with an average predicted to verified energy savings ratio of 100% and the Mid-Atlantic 2011 TRM with an average ratio of 101%. The VT 2010 TRM at a ratio of 92% and the Manufacturers' Calculators at a ratio of 111% also did a decent job of predicting an average savings. The EnergyPlus fan only estimates were fairly similar to these four TRMs with an average ratio of 107%. These all, however, have standard deviations around the ratios of roughly 50% or higher. As a whole, the combined results of all the TRMs had an average predicted to verified energy savings ratio of 96% with a standard deviation of 58%, very similar to the results of just the best TRMs.

The SU 2011 MSEM had the highest overall predicted to verified energy savings ratio at 205% with a standard deviation of 104%. Given the simplicity of the SU 2011 MSEM protocol, and the fact that it is from a very different climate zone than the case studies, it is not entirely surprising. On the other hand it is still predicting savings significantly over what the CA DEER 2011 predicted which has a reasonably similar climate to the SU 2011 MSEM. This shows that these two very different protocols are not predicting savings anywhere near close to each other, even though they are for somewhat similar climates.

On the other end of the spectrum was the ME 2010 TRM with a ratio of only 29%, but this protocol could only be used for one case study and so is not comparative to the rest of the protocols. The IL 2012 TRM was used for all the case studies and on a whole it significantly underestimated savings with a ratio of 33%. The IL 2012 TRM, also had the lowest standard of deviation at 27%, however, thus it is at least consistently predicting low savings, unlike some of the other TRMs.

6.3 TRM Results by Case Study

Table 47 compares the average TRM predicted savings to the verified savings by case study. If all the TRMs had a methodology that could compare apples to apples for all case studies, one would expect to see very similar standard deviation of the ratios across the case studies. This was not the case. Standard deviations ranged from 17% for case study 4 to 76% for case study 5 rather than being fairly consistent between case studies.

Table 47. Average TRM Estimates by Case Study

Case Study	Verified Energy Savings (kWh/yr)	Average TRM Energy Savings (kWh/yr)	Average Energy Predicted / Verified Ratio	Standard Deviation of Energy Predicted / Verified Ratio
Case Study 1	77,948	36,547	47%	22%
Case Study 2	940,051	1,386,772	148%	72%
Case Study 3	108,940	73,239	67%	33%
Case Study 4	1,218,846	520,747	43%	17%
Case Study 5	1,444,584	2,562,106	177%	76%
Case Study 6	272,642	290,972	107%	55%
Case Study 7	1,195,946	1,650,185	138%	70%

This is likely a result of the different options each TRM offers to predict savings. For projects that do not fit cleanly into one of the few options a TRM offers, the next closest option must be selected. This is done in practice by program implementers, and, as the standard deviations shows, this may not be a good practice to follow because the predicted savings can be far off the verified. From the experience of applying the different TRMs to the seven case studies, this is clearly a limitation of TRMs. Even with only seven case studies, none of the compared TRMs had enough baseline configuration options to cover the actual configurations, let alone all of the possible projects an energy efficiency program will see.

If the differences in prediction capabilities could be clearly linked to a specific project type or fan configuration it could help understand which type of projects the TRMs have difficulty predicting. Unfortunately, the results show there was no consistency and it appears that the TRMs do no better at predicting one project type versus another, but instead have difficulty predicting savings for all projects. For the given case studies, the average predictions had a minimum predicted to verified energy savings ratio of 43% for case study 4 and a maximum of 177% for case study 5.

6.4 EnergyPlus Simulation Results

Each case study was run using the prototype models for the baseline and retrofit scenario and the results compared. Models were not calibrated beyond the calibration already performed by the US DOE to develop the prototypes. Further calibration was not done because the models are intended to be generic representations of the typical buildings rather than case study specific models.

The simulations give total fan motor brake-wattage, which was converted to motor brake-horsepower (bhp). Because energy efficiency program implementers typically do not know the bhp unless spot metering is performed, savings must be estimated using motor nominal horsepower (nhp or hp) of the actual motors. This requires some estimates of a load factor to convert hp to bhp for savings estimates. Only four of the TRMs included a conversion from hp to bhp in the algorithms. The rest of the TRMs included any adjustments made within the savings factors themselves, or did not include an adjustment at all. Of the four using a load factor to adjust hp to bhp, only three provided a default with defaults of 0.682, 0.75, and 0.8. The fourth did not include a default. Using the findings from the literature review a default load factor of 0.65 appears to be more appropriate (Saidur, A review on electrical motors energy use and energy savings, 2010), (Lawrence Berkeley National Laboratory, and Resource Dynamics Corporation, 2008).

This assumption has a significant impact however. Since it has a linear relationship on the savings, a difference in assumption or actual load factor of 0.05 has a 5% impact on savings estimates. Given the range of load factors in practice, this one assumption may be significantly over or under estimating savings for a given project. It would be much more reliable to require spot metering of all retrofit motors at maximum load to verify the load factor and use this as an input to the calculations.

In most cases the energy modeling results also showed a fairly substantial heating fuel penalty which is also not typically accounted for. For the case studies the average equivalent electric fuel penalty was 12.8% of total model predicted energy savings. While most TRMs are interested primarily in electricity savings, it is important that the project owner understand this penalty which will show up as an offsetting utility bill increase. This can affect the owners' cost effectiveness analysis, but it can affect the utilities' cost analyses as well. Given the typically short payback VFDs have, it is unlikely this would be a problem for most installations, but there will be some projects that this would affect. Of all the TRMs included in this study, only the CA DEER 2011 incorporated a fuel penalty. This possibly reflects a lack of understanding of the full impacts of VFD retrofits.

6.5 TRM versus EnergyPlus Modeling Comparisons

Another issue that can be seen when comparing the EnergyPlus modeling results to the verified and the TRM savings results is the difference between the fan only savings estimates and the total electric energy savings. For the case studies modeled there was an average impact from non-fan energy savings of 15.7% of the total project savings. This is a significant percentage of savings not being accounted for.

Figure 20 shows how the model predicted to verified total energy savings ratio was generally much farther from the average TRM ratio than the model predicted fan only ratio.

This is not only an issue with the TRM methodologies, but it is also an issue with the verified savings estimates. As could be seen in Figure 18 and Figure 19, at 127%, the average predicted to verified model total energy savings ratio was further from the verified savings than the fan only ratio of 107%. There is a need to account for this energy savings when verifying project savings. The difficultly is that the non-fan energy savings are hard to verify because it is generally not possible to put a power meter on all the affected equipment. Alternatively one could use whole facility billing analysis to estimate the total project savings, but these measures often save only a small fraction of the overall building energy consumption. This means it is often not possible to identify the savings with this method because the noise in the data often overshadows the savings.

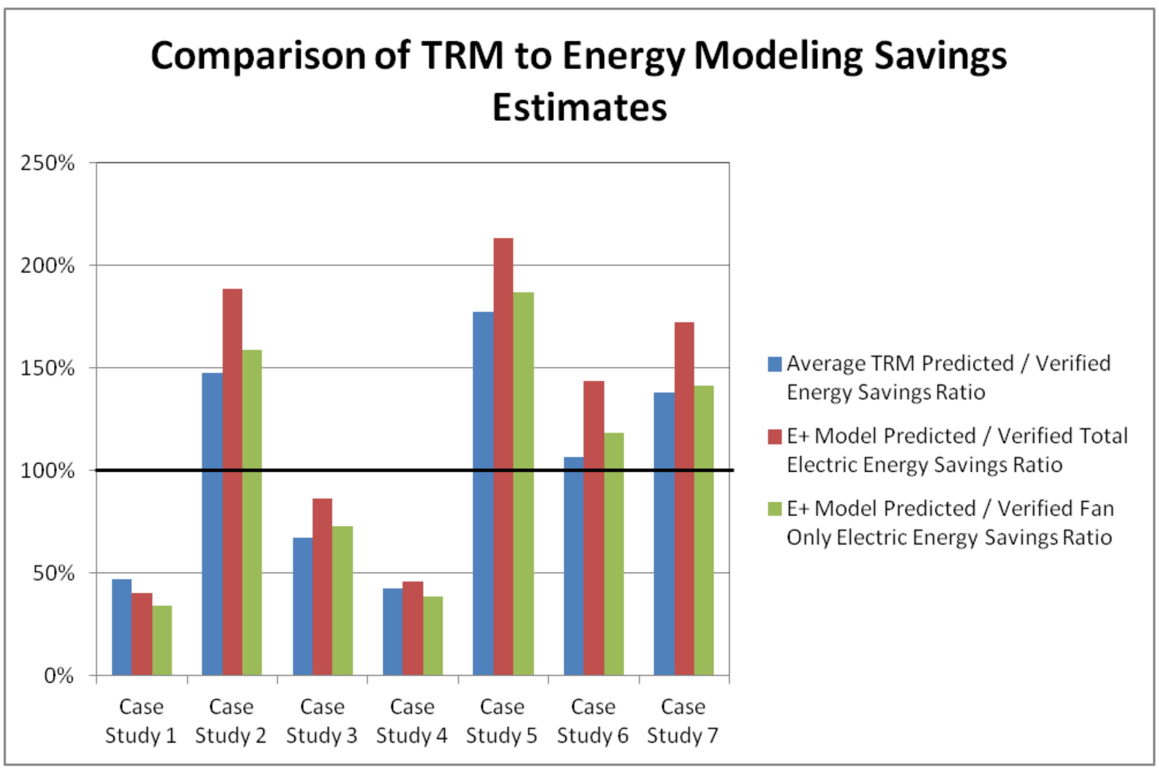

Figure 20. Comparison of Verified, TRM, and Modeling Savings Estimates.

What Figure 20 also shows is a general trend that the average of all the TRMs provides relatively similar results to the fan-only savings predicted using the generic prototypical energy models. The problem is that it is difficult to call any of the TRM methodologies reliable due to the errors within so many of them.

6.6 Program Evaluation Results

From an energy efficiency program perspective, the most important metric that an evaluation of the program produces is the program level Realization Rate (RR). This metric is generally used to verify the utility complied with its regulatory savings goals. If a RR is too high or low the utility may face financial penalties for having missed their target (too low) or may face significant program redesign issues if they greatly exceeded their target (too high). The goal is to have a RR around 1.0, but usually an acceptable range is around 0.85 to 1.15. The RR is calculated as: RR = ex post verified savings / ex ante estimated savings. The program level RR is calculated using a statistical weighted average of the ratios for a sample of projects if the evaluation did not verify a census of the program projects.

In this study we are considering how the various TRM and energy modeling methodologies will serve for determining the ex ante savings for a program. To check how each method performed in this study we can look at the total RR for each method by summing the verified savings and dividing by the sum of the predicted savings for all case studies. This will give us an indication of how well the methodology performed relative to the verified savings. This is a bit different than the previous comparisons in this paper where the comparison was looking at the average predicted to verified savings ratios. Utilities, implementers, evaluators and regulators will be most interested in how close to 1.0 the RRs will be when using a particular methodology.

Figure 21 shows the RRs calculated for the sum of all the case studies based on ex ante methodology compared to the verified savings. The solid line is set at 100% or a RR of 1.0 which would mean the ex ante savings perfectly predicted the verified savings. The dashed lines are set at roughly 85% and 115% or a RR of 0.85 and 1.15 which are roughly the acceptable range for program RRs from a utility planning perspective. When a RR is below 1.0 it means the ex ante methodology overestimated savings. When the RR is over 1.0 it means the ex ante methodology underestimated savings.

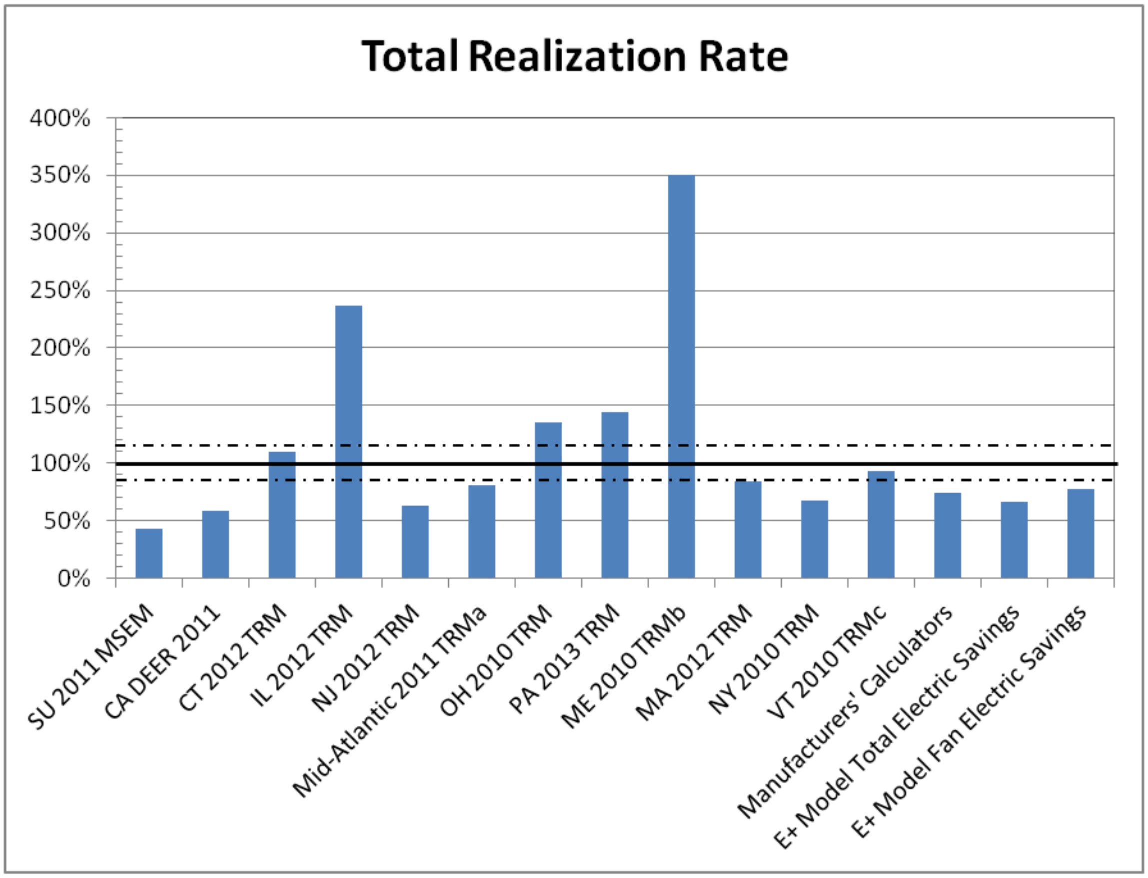

Figure 21. Evaluation Realization Rate Comparison by Ex Ante Methodology.

Figure 22 shows why one cannot simply take the average RR of each evaluated case study. Public Utility Commissions (PUC), or their equivalent, are interested in knowing whether a utility met their energy savings compliance targets in megawatt hours (MWh). Because each project can have vastly different savings, just taking the average RR would only inform the PUC how well the implementer/utility predicted savings, but it would not tell them how much total energy was saved. As shown in the figure the weighted average RR (Evaluation RR) does not produce the same result as the average RR.

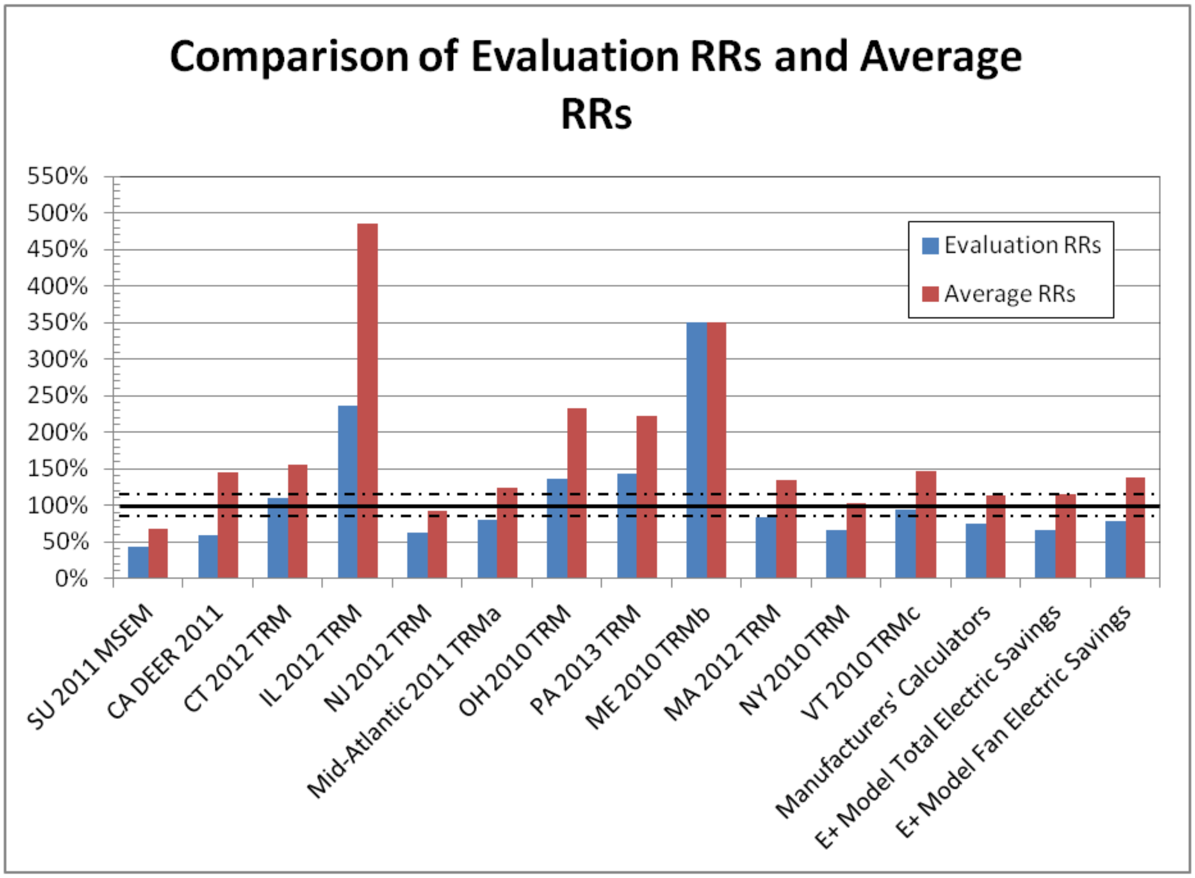

Figure 22. Comparison of Evaluation RRs and Average Case Study Level RRs.

As pointed out earlier, most TRMs and the verified savings for all the case studies focused on the fan-only savings, but the energy models showed this is likely underestimating savings by a large fraction. For the case studies in this study, the average non-fan savings from the EnergyPlus models was 15.7%. This additional savings can be considered HVAC Interactive Effects. If the PUC is interested in total savings from the VFD measures it is important to make an adjustment to the verified fan only savings to account for this additional HVAC savings. Although the EnergyPlus models did not consistently predict the case study savings accurately, the relative percentage is likely reasonable to apply to the verified fan-only project savings. Further, if the verified savings are accounting for the HVAC interactive effects, the it would be a more useful comparison if the TRM estimates that did not account for these effects were adjusted as well. This includes the SU 2011 MSEM, CT 2012 TRM, IL 2012 TRM, NJ 2012 TRM, Mid-Atlantic 2011 TRM, OH 2010 TRM, PA 2013 TRM, and the Manufacturers' Calculators. The CA 2011 DEER and NY 2010 TRM already include interactive effects as they are based on DOE-2.2 energy models. It is assumed that the ME 2010 TRM, MA 2012 TRM and VT 2010 TRM already include such factors, but this is not known. It is not appropriate to make such an adjustment without knowing whether or not it is already included.

Figure 23 shows the evaluation RRs adjusted for HVAC interactive effects by multiplying the verified savings and the appropriate TRM savings by (1+0.157). This specific adjustment factor should not be used for actual evaluations, but a more reliable average factor should be developed and used based on a more complete set of energy modeling results for a given jurisdiction. For this study the 15.7% average is reasonable. Again, a solid line was plotted at the 100% mark and a dashed line at 85% and 115%.

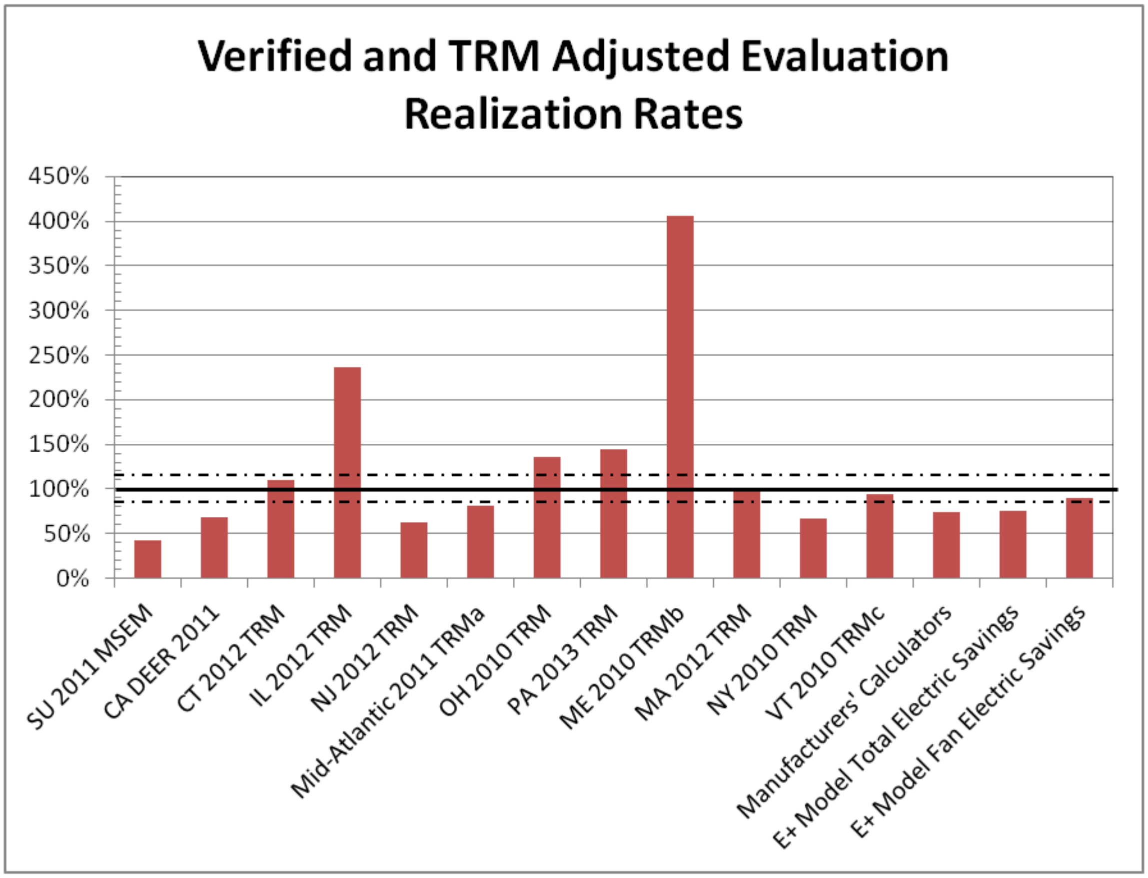

Figure 23. Adjusted Evaluation Realization Rate Comparison by Ex Ante Methodology.

Using these adjusted evaluation RRs three TRM methodologies and the EnergyPlus Model fan-only savings estimates fall within the acceptable RR range. This includes the CT 2012 TRM, the MA 2012 TRM, and the VT 2010 TRM. Because we are looking for an apples to apples comparison and the EnergyPlus Model fan-only savings ignores the HVAC interactive effects this method will not be considered as acceptable.

Chapter 7

7 Recommended TRM Model

The results of this study are not entirely conclusive. Due to the inaccuracy of the savings estimation methods as a whole when predicting savings for the case studies it is difficult to recommend that a prescriptive method should be used at all. Clearly a custom project specific detailed bin analysis, energy model, or metering approach would result in much more reliable savings estimates than any of the other methods used in this study.

While a custom method would yield more reliable results, it is expected that this will not be a sufficient recommendation for energy efficiency program implementers. They need simplicity to be able to process as many incentives as possible. As such, a recommendation is still in order, albeit with reservations.

Although the CT 2012 TRM, the MA 2012 TRM, and the VT 2010 TRM all yielded results within acceptable ranges to program stakeholders, they cannot be recommended for use in other jurisdictions given the lack of full transparency behind the savings factors. It is possible that if there were more transparency and reproducibility in these protocols, then the methodologies may be worth adopting in other jurisdictions. While it may be possible to recommend those TRMs if they were more transparent, there are some additional drawbacks worth considering; mainly the difficulty in developing climate specific factors to adopt the protocols in other jurisdictions.

As a result, a more simple method is recommended. The recommendation is to use a methodology similar to the Manufacturers' Calculators, but with some modifications to make it more robust. The Manufacturers' Calculators produced results that were fairly similar to the other three acceptable methods and with a similar standard deviation, but the calculators were somewhat limited. The primary advantage of this method is that it is fairly customizable if actual project level details are known, and it is very simple to employ.

7.1 Calculator Adjustments

The are several concerns with the existing calculators that should be addressed to make it the calculator more reliable. First, the original calculators were fairly limited in their baseline control options, only including factors for bypass dampers, outlet dampers, IGV and VFDs. This can be expanded using the available regression curves previously discussed in Section 2.4.3. The following Table 48 is recommended for use with the calculator. This includes options for an increased number of control options and for some, options for fan type. This greatly expands the usability and customizability of the protocol to better meet the needs of program implementers.

Table 48. Control Options for VFD Savings Calculator

Fan Control Type	Regression Coefficient				Minimum Flow Ratio	Coefficient Source
	a	b	c	d		
No Control or Bypass Damper	1.0	0.0	0.0	0.0	100%	NA
Discharge Dampers	0.37073425	0.97250253	-0.34240761	0	70%	1
Outlet Damper, BI & Airfoil Fans	0.5592857	-0.56905	2.462	-1.4	70%	2
Inlet Damper Box	0.5025833	0.71648	-1.452	1.3	50%	2
Inlet Guide Vane, BI & Airfoil Fans	0.472619	0.67944	-1.554	1.4	50%	2
Inlet Vane Dampers	0.35071223	0.30850535	-0.54137364	0.87198823	30%	1
Outlet Damper, FC Fans	0.2041905	0.10983	0.745	0	70%	2
Eddy Current Drives	0.1639683	-0.05647	1.237	-0.3	20%	2
Inlet Guide Vane, FC Fans	0.2	0.06808	-0.128	0.9	30%	2
VFD with duct static pressure controls	0.1021	-0.1177	0.2647	0.76	20%	3
VFD with low/no duct static pressure (<1" w.g.)	0.040759894	0.08804497	-0.07292612	0.943739823	20%	4

Sources:
1. LBNL: EnergyPlus Engineering Reference Manual Table 29. Fan Coefficient Values.
2. BPA: DOE VSD Calculator for Fans from BPA Energy Efficiency & Renewable Energy website. Accessed 6/7/13. https://ecenter.ee.doe.gov/EM/tools/Pages/VSDCalcFans.aspx
3. CA Title 24 (Wray & Matson): http://epb.lbl.gov/publications/pdf/lbnl-53605.pdf
4. LBNL: EnergyPlus DOE Medium Office Building Post 1980 v1.4_7.2 Chicago Ohare_Prototypical Model

As may be noticed, the recommended table only includes two of the possible VFD regression curves that were listed in Section 2.4.3. While one could argue for including all four as possible options, this is not recommended at this time unless more research is done into the differences between each model. The models are fairly similar, but program evaluation has shown that there are almost no real case studies where a VFD installed on an HVAC system can get below a 10% part load ratio. This is primarily a result of all HVAC systems having at least some back pressure than must be overcome and the fans, drives and motors have some friction that must be overcome to just run at a minimum speed.

The regression equation used for “VFD with duct static pressure controls” represents a curve which levels out at about a 10% part load ratio at roughly 30% flow fraction. This curve should be used for most VFD installations in an HVAC system that use duct static pressure to control the flow rate.

The equation used for the “VFD with low/no duct static pressure (<1” w.g.)” represent a curve which levels does not quite level out, but goes down to a minimum part load ratio of roughly 5% at 0% flow fraction. This curve may be used for VFD installations that may have a low or no static duct pressure to overcome. An example where this is appropriate to use is for an un-ducted fan.

These regression coefficients can be used to develop a part load ratio table at different flow rates. Table 49 shows these part load ratios at different flow fractions based on control and fan type. There is no default baseline assumption for control type to require project specific selection. Without this information, a proper savings estimate cannot be made.

Table 49. Part Load Ratios by Control and Fan Type and Flow Fraction.

Control Type	Flow Fraction									
	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
No Control or Bypass Damper	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Discharge Dampers	0.46	0.55	0.63	0.70	0.77	0.83	0.88	0.93	0.97	1.00
Outlet Damper, BI & Airfoil Fans	0.53	0.53	0.57	0.64	0.72	0.80	0.89	0.96	1.02	1.05
Inlet Damper Box	0.56	0.60	0.62	0.64	0.66	0.69	0.74	0.81	0.92	1.07
Inlet Guide Vane, BI & Airfoil Fans	0.53	0.56	0.57	0.59	0.60	0.62	0.67	0.74	0.85	1.00
Inlet Vane Dampers	0.38	0.40	0.42	0.44	0.48	0.53	0.60	0.70	0.83	0.99
Outlet Damper, FC Fans	0.22	0.26	0.30	0.37	0.45	0.54	0.65	0.77	0.91	1.06
Eddy Current Drives	0.17	0.20	0.25	0.32	0.41	0.51	0.63	0.76	0.90	1.04
Inlet Guide Vane, FC Fans	0.21	0.22	0.23	0.26	0.31	0.39	0.49	0.63	0.81	1.04
VFD with duct static pressure controls	0.09	0.10	0.11	0.15	0.20	0.29	0.41	0.57	0.76	1.01
VFD with low/no duct static pressure	0.05	0.06	0.09	0.12	0.18	0.27	0.39	0.55	0.75	1.00

Second, the existing calculators do not include default hours of use, nor do they include default motor types and efficiencies. Again, these are both easy to add and will facilitate implementation.

For default hours of use, several of the TRMs included long tables with fan run hours by building type. There is little indication of where these tables came from, but it can be assumed for the most part they are reasonable. These tables can be adopted as a default unless jurisdiction specific hours are known or developed. The table from the CT 2012 TRM is recommended for adoption here and is shown in Table 50. Although energy simulation models could be used to develop climate specific default run hours, to do so would require an exorbitant number of building type specific models to be developed. This may not be a cost effective solution to just using the CT 2012 TRM RHRS as an initial default and updating the table over time using logger data from evaluations and implementation.

Table 50. Default Hours of Use for VFD Savings Calculator (UI and CL&P, 2011).

Facility type	Fan motor hours	Facility type	Fan motor hours
Auto related	4,056	Medical offices	3,748
Bakery	2,854	Motion picture theater	1,954
Banks, financial centers	3,748	Multi-family (common areas)	7,665
Church	1,955	Museum	3,748
College-cafeteria	6,376	Nursing homes	5,840
College-classes / administrative	2,586	Office (general office types)	3,748
College-dormitory	3,066	Office/Retail	3,748
Commercial condos	4,055	Parking garages & lots	4,368
Convenience stores	6,376	Penitentiary	5,477
Convention center	1,954	Performing arts theater	2,586
Courthouse	3,748	Police/fire stations (24 Hr)	7,665
Dining: bar lounge/leisure	4,182	Post office	3,748
Dining: cafeteria/fast food	6,456	Pump stations	1,949
Dining: family	4,182	Refrigerated warehouse	2,602
Entertainment	1,952	Religious building	1,955
Exercise center	5,836	Residential (except nursing homes)	3,066
Fast food restaurants	6,376	Restaurants	4,182
Fire station (unmanned)	1,953	Retail	4,057
Food stores	4,055	School/University	2,187
Gymnasium	2,586	Schools (Jr./Sr. high)	2,187
Hospitals	7,674	Schools (preschool/elementary)	2,187
Hospitals/healthcare	7,666	Schools (technical/vocational)	2,187
Industrial-1 shift	2,857	Small services	3,750
Industrial-2 shift	4,730	Sports arena	1,954
Industrial-3 shift	6,631	Townhall	3,748
Laundromats	4,056	Transportation	6,456
Library	3,748	Warehouse (not refrigerated)	2,602
Light manufacturers	2,857	Wastewater treatment plant	6,631
Lodging (hotels/motels)	3,064	Workshop	3,750
Mall concourse	4,833	24/7/365	8,760
Manufacturing facility	2,857	Other	Custom

There are several motor efficiency levels that may be found on projects. They include older standard efficiency motors, NEMA pre-EPact efficient motors, NEMA EPact high efficiency motors, NEMA Premium efficiency motors, and motors with a variety of non-standard efficiencies. Table 51, Table 52, Table 53, and Table 54 provide default efficiency levels by motor type, enclosure type, speed, and HP. As a conservative assumption, the recommended default motor is a NEMA Premium efficiency, ODP, 4-pole/1800 RPM fan motor.

Table 51. Standard Motor Default Efficiencies.(Chirakalwasan, 2006-2007)

	Open Drip Proof (ODP) # of Poles			Totally Enclosed Fan-Cooled (TEFC) # of Poles		
	6	4	2	6	4	2
	Speed (RPM)			Speed (RPM)		
Size HP	1200	1800	3600	1200	1800	3600
1						
1.5						
2						
3						
5						
7.5						
10	87.30%	86.30%	86.30%	87.10%	87.00%	86.10%
15	87.40%	88.00%	87.90%	88.20%	88.20%	86.80%
20	88.50%	88.60%	89.10%	89.10%	89.60%	87.80%
25	89.40%	89.50%	89.00%	89.80%	90.00%	88.60%
30	89.20%	89.70%	89.20%	90.10%	90.60%	89.20%
40	90.10%	90.10%	90.00%	90.30%	90.70%	89.00%
50	90.70%	90.40%	90.10%	91.60%	91.60%	89.30%
60						
75	92.00%	91.70%	90.70%	91.90%	92.20%	90.50%
100	92.30%	92.20%	91.90%	92.80%	92.30%	90.40%
125	92.60%	92.80%	91.60%	93.00%	92.60%	90.80%
150	93.10%	93.30%	92.00%	93.30%	93.30%	91.70%
200	94.10%	93.40%	93.00%	94.00%	94.20%	92.20%

Table 52. NEMA Pre-EPact Efficient Motors Default Efficiencies.(Douglass, 2005)

Size HP	Open Drip Proof (ODP) # of Poles			Totally Enclosed Fan-Cooled (TEFC) # of Poles		
	6	4	2	6	4	2
	Speed (RPM)			Speed (RPM)		
	1200	1800	3600	1200	1800	3600
1	77.00%	82.50%		75.50%	80.00%	
1.5	82.50%	82.50%	80.00%	82.50%	81.50%	78.50%
2	84.00%	82.50%	82.50%	82.50%	82.50%	81.50%
3	85.50%	86.50%	82.50%	84.00%	84.00%	82.50%
5	86.50%	86.50%	85.50%	85.50%	85.50%	85.50%
7.5	88.50%	88.50%	85.50%	87.50%	87.50%	85.50%
10	90.20%	88.50%	87.50%	87.50%	87.50%	87.50%
15	89.50%	90.20%	89.50%	89.50%	88.50%	87.50%
20	90.20%	91.00%	90.20%	89.50%	90.20%	88.50%
25	91.00%	91.70%	91.00%	90.20%	91.00%	89.50%
30	91.70%	91.70%	91.00%	91.00%	91.00%	89.50%
40	91.70%	92.40%	91.70%	91.70%	91.70%	90.20%
50	91.70%	92.40%	91.70%	91.70%	92.40%	90.20%
60	92.40%	93.00%	93.00%	91.70%	93.00%	91.70%
75	93.00%	93.60%	93.00%	93.00%	93.00%	92.40%
100	93.60%	93.60%	93.00%	93.00%	93.60%	93.00%
125	93.60%	93.60%	93.00%	93.00%	93.60%	93.00%
150	93.60%	94.10%	93.60%	94.10%	94.10%	93.00%
200	94.10%	94.10%	93.60%	94.10%	94.50%	94.10%

Table 53. NEMA EPact High Efficiency Motors Default Efficiencies.(Douglass, 2005)

	Open Drip Proof (ODP) # of Poles			**Totally Enclosed Fan-Cooled (TEFC) # of Poles**		
	6	**4**	**2**	**6**	**4**	**2**
	Speed (RPM)			Speed (RPM)		
Size HP	1200	1800	3600	1200	1800	3600
1	80.00%	82.50%	75.50%	80.00%	82.50%	75.50%
1.5	84.00%	84.00%	82.50%	85.50%	84.00%	82.50%
2	85.50%	84.00%	84.00%	86.50%	84.00%	84.00%
3	86.50%	86.50%	84.00%	87.50%	87.50%	85.50%
5	87.50%	87.50%	85.50%	87.50%	87.50%	87.50%
7.5	88.50%	88.50%	87.50%	89.50%	89.50%	88.50%
10	90.20%	89.50%	88.50%	89.50%	89.50%	89.50%
15	90.20%	91.00%	89.50%	90.20%	91.00%	90.20%
20	91.00%	91.00%	90.20%	90.20%	91.00%	90.20%
25	91.70%	91.70%	91.00%	91.70%	92.40%	91.00%
30	92.40%	92.40%	91.00%	91.70%	92.40%	91.00%
40	93.00%	93.00%	91.70%	93.00%	93.00%	91.70%
50	93.00%	93.00%	92.40%	93.00%	93.00%	92.40%
60	93.60%	93.60%	93.00%	93.60%	93.60%	93.00%
75	93.60%	94.10%	93.00%	93.60%	94.10%	93.00%
100	94.10%	94.10%	93.00%	94.10%	94.50%	93.60%
125	94.10%	94.50%	93.60%	94.10%	94.50%	94.50%
150	94.50%	95.00%	93.60%	95.00%	95.00%	94.50%
200	94.50%	95.00%	94.50%	95.00%	95.00%	95.00%

Table 54. NEMA Premium Efficiency Motors Default Efficiencies.(Douglass, 2005)

	Open Drip Proof (ODP) # of Poles			Totally Enclosed Fan-Cooled (TEFC) # of Poles		
	6	**4**	**2**	**6**	**4**	**2**
	Speed (RPM)			Speed (RPM)		
Size HP	1200	1800	3600	1200	1800	3600
1	82.50%	85.50%	77.00%	82.50%	85.50%	77.00%
1.5	86.50%	86.50%	84.00%	87.50%	86.50%	84.00%
2	87.50%	86.50%	85.50%	88.50%	86.50%	85.50%
3	88.50%	89.50%	85.50%	89.50%	89.50%	86.50%
5	89.50%	89.50%	86.50%	89.50%	89.50%	88.50%
7.5	90.20%	91.00%	88.50%	91.00%	91.70%	89.50%
10	91.70%	91.70%	89.50%	91.00%	91.70%	90.20%
15	91.70%	93.00%	90.20%	91.70%	92.40%	91.00%
20	92.40%	93.00%	91.00%	91.70%	93.00%	91.00%
25	93.00%	93.60%	91.70%	93.00%	93.60%	91.70%
30	93.60%	94.10%	91.70%	93.00%	93.60%	91.70%
40	94.10%	94.10%	92.40%	94.10%	94.10%	92.40%
50	94.10%	94.50%	93.00%	94.10%	94.50%	93.00%
60	94.50%	95.00%	93.60%	94.50%	95.00%	93.60%
75	94.50%	95.00%	93.60%	94.50%	95.40%	93.60%
100	95.00%	95.40%	93.60%	95.00%	95.40%	94.10%
125	95.00%	95.40%	94.10%	95.00%	95.40%	95.00%
150	95.40%	95.80%	94.10%	95.80%	95.80%	95.00%
200	95.40%	95.80%	95.00%	95.80%	96.20%	95.40%
250	95.40%	95.80%	95.00%	95.80%	96.20%	95.80%
300	95.40%	95.80%	95.40%	95.80%	96.20%	95.80%
350	95.40%	95.80%	95.40%	95.80%	96.20%	95.80%
400	95.80%	95.80%	95.80%	95.80%	96.20%	95.80%
450	96.20%	96.20%	95.80%	95.80%	96.20%	95.80%
500	96.20%	96.20%	95.80%	95.80%	96.20%	95.80%

Further, the existing calculators use nominal HP, but do not make an adjustment for motor load factor, nor efficiency. It is easy to include both these adjustments. As recommended in the previous sections, a reasonable default load factor is 65%. Many load factors may be higher or lower than this value, but this is a reasonable assumption. Multiplying the nominal/nameplate HP by the load factor gives the needed BHP.

The existing calculators assume a constant loading of 60% of maximum flow for fans. While this may be the average flow, it is not a good representation of a typical load profile. By adding a default load profile with the option to use customer specific data if available, the calculator can be more robust and reliable. Figure 24 shows a typical fan duty cycle for a VAV HVAC system from the ASHRAE Handbook; HVAC Systems and Equipment. This can be used as a default load profile for the calculator to provide reasonable savings estimates or specific building type load profiles could be developed.

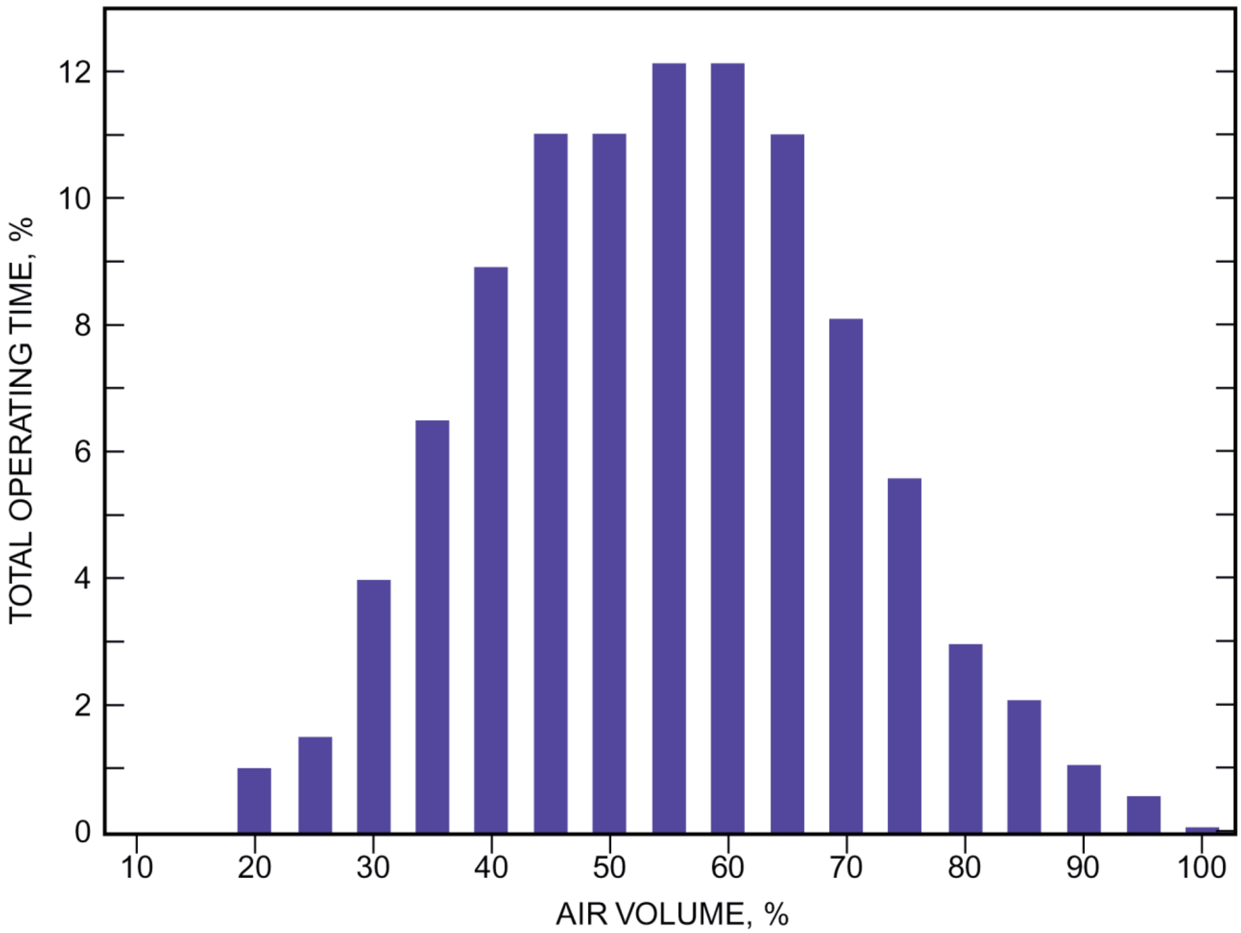

Figure 24. Typical Fan Duty Cycle for a VAV System (From ASHRAE Handbook; HVAC Systems and Equipment, page 45.11, Figure 12.(ASHRAE, 2012))

Using the ASHRAE fan duty cycle shown above, a bin analysis can be easily developed and fan motor part load ratios determined for each bin. Table 55 shows a possible default load profile using the ASHRAE duty cycle.

Table 55. Default Fan Duty Cycle.

Flow Fraction (% of design cfm)	Percent of Time at Flow Fraction
0% to 10%	0%
10% to 20%	1%
20% to 30%	6%
30% to 40%	16%
40% to 50%	22%
50% to 60%	25%
60% to 70%	19%
70% to 80%	9%
80% to 90%	3%
90% to 100%	1%

Lastly, as described in previous sections, using an appropriate algorithm and the above defaults will yield fan-only savings. These need to be adjusted to include savings from the HVAC Interactive Effects. For the purposes of this study the average Interactive Effects Factor was 15.7%. This will be used for this study, but a larger analysis should be completed to derive a more appropriate jurisdiction specific average HVAC interactive effects factor.

All of these adjustments can be made and a new algorithm developed. The following algorithms are recommended for use to estimate annual baseline and retrofit electric energy consumption and then used to estimate total project savings for VFD retrofits on HVAC fan motors.

Baseline Energy Consumption (kWh_{Base}) =

$$\left(0.746 \times HP \times \frac{LF}{\eta_{motor}}\right) \times RHRS_{Base} \times \sum_{0\%}^{100\%} (\%\ of\ Time\ at\ Flow\ Fraction \times PLR_{Base}) \quad [38]$$

Retrofit Energy Consumption ($kWh_{Retrofit}$) =

$$\left(0.746 \times HP \times \frac{LF}{\eta_{motor}}\right) \times RHRS_{base} \times \sum_{0\%}^{100\%} (\%\ of\ Time\ at\ Flow\ Fraction \times PLR_{Retrofit}) \quad [39]$$

Fan-Only Energy Savings

$$(\Delta kWh_{fan}) = kWh_{Base} - kWh_{Retrofit} \quad [40]$$

Total Project Electric

$$\text{Energy Savings } (\Delta kWh_{total}) = \Delta kWh_{fan} \times (1 + IE_{energy}) \quad [41]$$

Where:

ΔkWh_{total} = Total project annual energy savings

ΔkWh_{fan} = Fan-only annual energy savings

0.746 = Conversion factor for HP to kWh

HP = Nominal horsepower of controlled motor

LF = Load Factor; Motor Load at Fan Design CFM (Default = 65%)

η_{motor} = Installed nominal/nameplate motor efficiency

$RHRS_{Base}$ = Annual operating hours for fan motor based on building type

$\%\ of\ Time\ at\ Flow\ Fraction$ = Percentage of run-time spent within a given flow fraction range

PLR_{Base} = Part load ratio for a given flow fraction range based on the baseline flow control type

$PLR_{Retrofit}$ = Part load ratio for a given flow fraction range based on the retrofit flow control type

IE_{energy} = HVAC interactive effects factor for energy (default = 15.7%)

Note that none of the factors are fully deemed. Using a fully deemed value only serves to limit the potential reliability of a measure protocol by forcing the program implementer to use a deemed value rather than a known project-specific value when available. Default values may be used when project specific data is unknown, but as will be seen in the next chapter, project specific data leads to much more reliable savings estimates. If available either through metering, logging, trend data, or simulation, project specific data should be used in place of the default RHRS, motor efficiency, load factor, and load profiles.

Chapter 8

8 Validation

To validate the viability of the recommended protocol detailed in Chapter 7, the protocol was used to estimate savings for each of the seven case studies. The results are explained here.

8.1 Assumptions

Energy savings estimates were derived for each case study using the default RHRS based on building type from Table 50. For those projects with verified operating hours, the custom RHRS were also used to see if there is an improvement in the estimates when using more project specific knowledge. The default RHRS for the office buildings (Case studies 1, 2, 3, 4, 6 and 7) were based on the “Office (general office types)” building type. For case study 5, the “Mall Concourse” building type was used for the constant volume baseline systems serving the common areas. The “Retail” building type was used for the VAV baseline systems serving the shops and retail spaces.

For all cases the same assumptions that were used for the previous TRM estimates as described in Chapter 5 were used with this method. This included assuming an ODP motor enclosure at 1800 RPM. Motor efficiency was selected per the project specific details as described in the previous sections. A default Load Factor of 65% was assumed. The retrofit fan control type was set to the default “VFD with duct static pressure controls” for all case studies. For all case studies, the control type was selected based on the known control option with backward-inclined or air-foil fans rather than FC fans because this was not generally listed in the individual case study evaluation reports.

Initial analysis of the EnergyPlus results showed a significant HVAC interactive effect from the installation of the VFDs. This was not taken into account in most of the savings protocols, nor was it accounted for in any of the case study verified savings, but it is real savings that should be accounted for. To ensure a fair comparison, all savings estimates made with the existing protocols that did not account for HVAC interactive effects were adjusted using the average HVAC interactive effect factor from the EnergyPlus modeling results by multiplying the predicted or verified savings by (1+0.157). This specific adjustment factor should not be used for actual program implementation, but such a factor should be developed and used based on a more complete set of energy modeling results for a given jurisdiction.

8.2 Case Study Validation Results

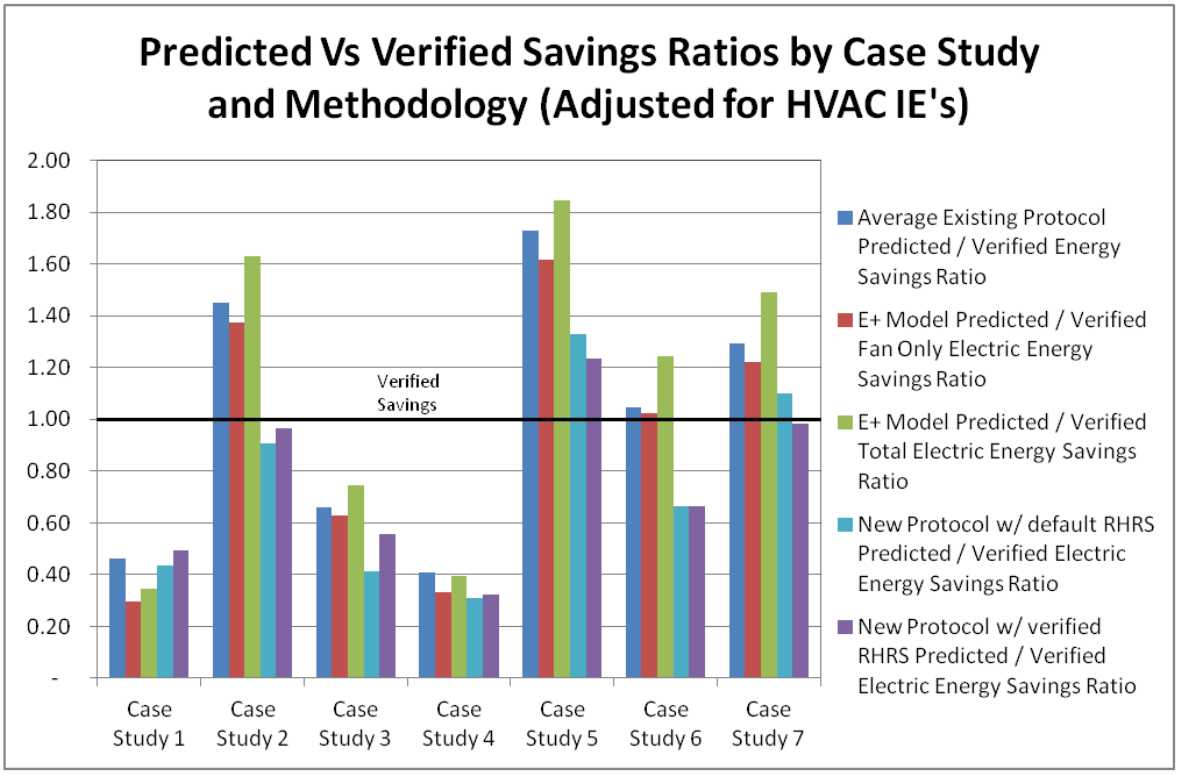

Figure 25 again shows the prediction accuracy of the savings estimates for each case study by methodology with the results of the new protocol included, and with savings estimates adjusted for HVAC IEs. The figure shows the predicted to verified energy savings ratio by each case study for the average TRM results, the EnergyPlus model results and the new protocol using default RHRS and verified RHRS where available.

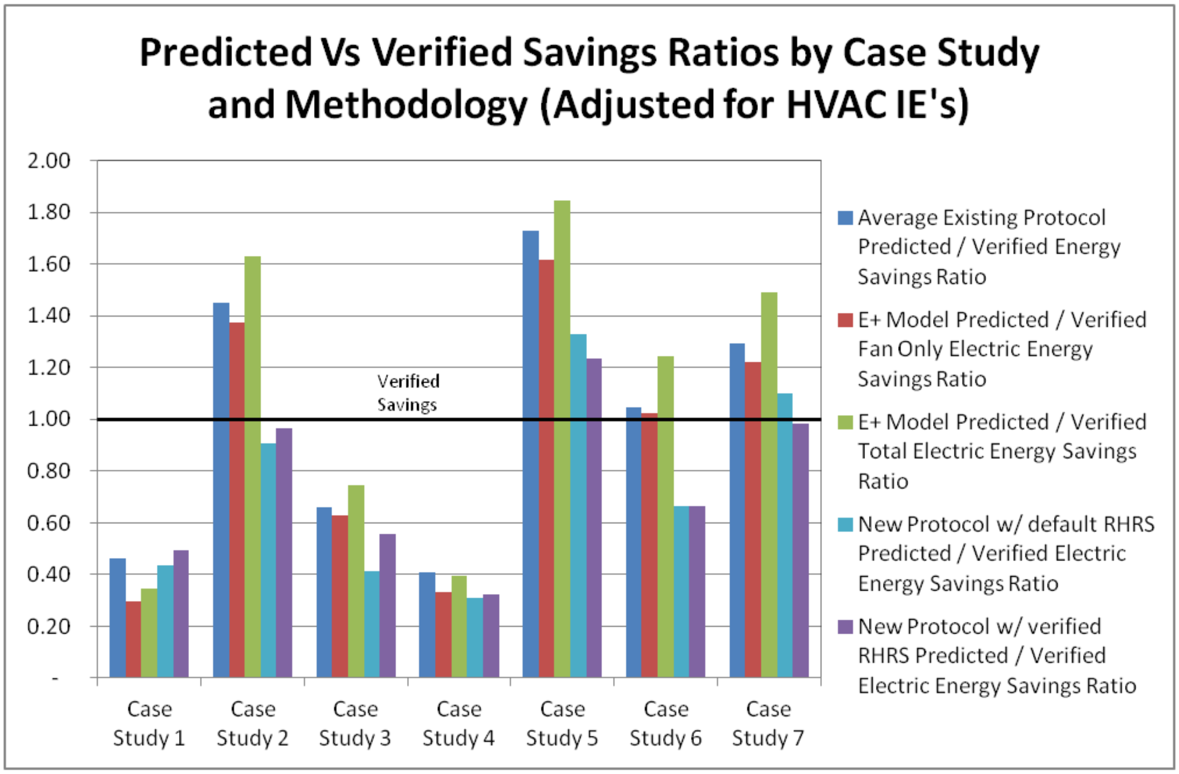

Figure 25. Case Study Savings Prediction Accuracy Relative to Verified Savings – Adjusted for HVAC IE's.

In four of seven cases, the results using the default hours with the new protocol were as good as, or better than the average existing protocol estimates and the EnergyPlus models. Using the verified RHRS the new protocol was even better than when using the default RHRS. This shows the value of using customer specific RHRS to allow more accurate prediction of savings. While the results show the calculator is not accurate for all case studies, it does show significant improvement overall as compared to using the EnergyPlus DOE prototypical models, and compared to the average of all the existing protocols.

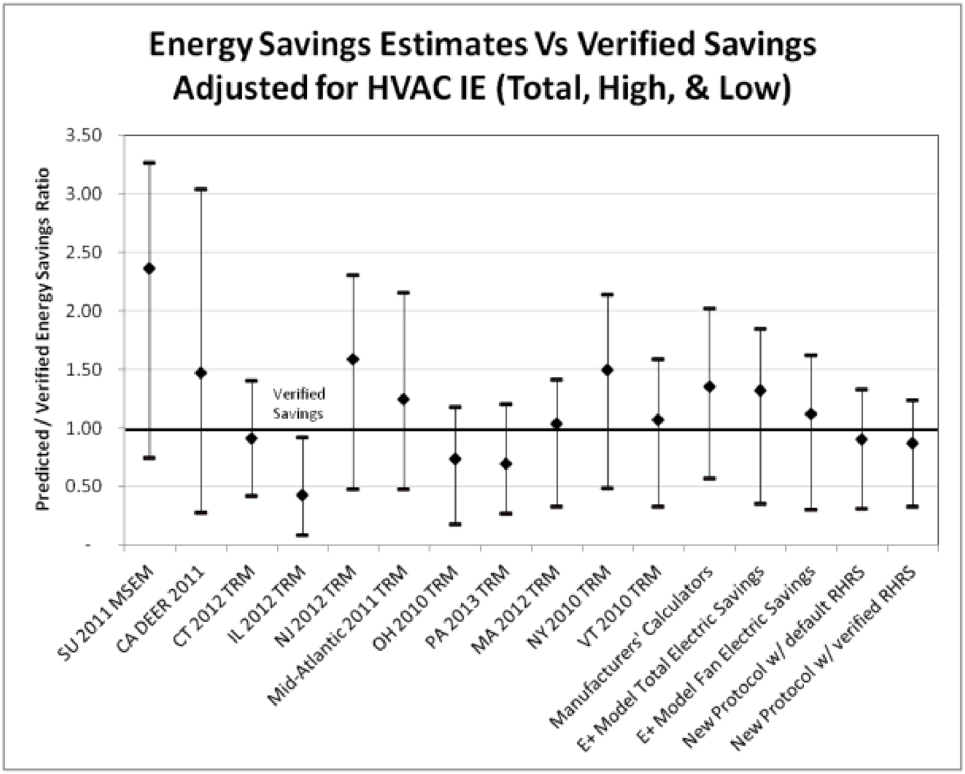

Figure 26 confirms this improvement showing the total predicted to verified savings ratio (sum of predicted / sum of verified savings) for the new model being close to that for the best TRM results, but with a reduced range of estimates. The standard deviation of the case study ratios was similarly lower than for the existing protocols. This indicates the new protocol consistently produced more reliable results than any of the existing TRM methodologies.

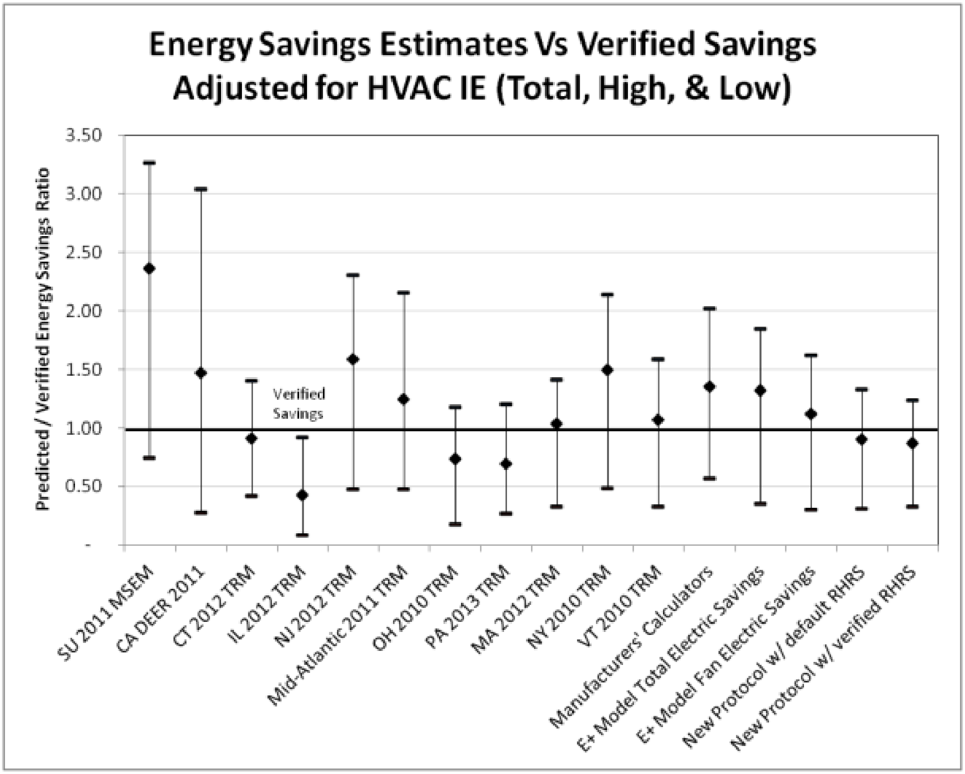

Figure 26. Energy Savings Estimation Accuracy by Methodology – Adjusted for HVAC Interactive Effects.

The previous figures focused on the predicted to verified savings ratios without the adjustments for HVAC interaction effects. Figure 27 shows the evaluation RRs using the adjusted verified savings estimates as previously described in Section 6.6. The total evaluation RR for the new protocol using the default RHRS was 1.11, within the acceptable range. Using the verified RHRS, the total evaluation RR increased slightly to 1.16. These are both significantly better than the EnergyPlus total project savings RR of 0.76 and the Manufacturers' Calculator RR of 0.74. It is not quite as good as the MA 2012 TRM RR of 0.97, but it does have a reduced standard deviation.

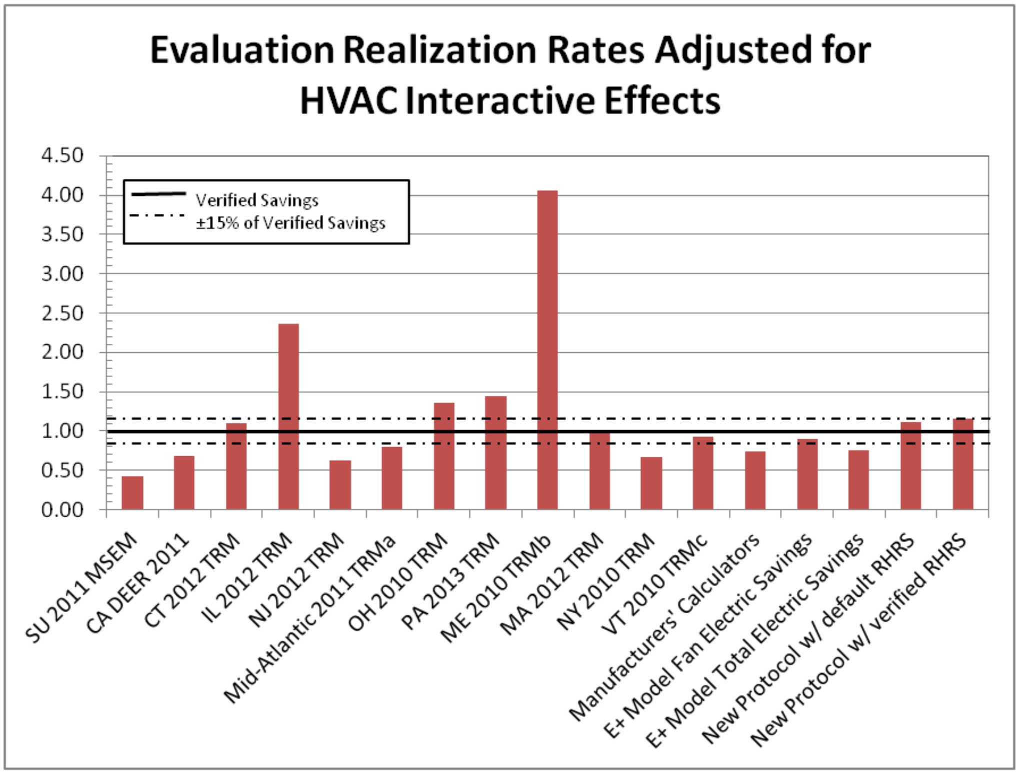

Figure 27. Comparison of Evaluation Realization Rates – Adjusted for HVAC Interactive Effects.

An additional check on the reliability of the new protocol is to compare the root mean square error (RMSE) of the predicted savings versus the verified savings. shows the verified savings for each case study and the predicted savings estimated using each protocol, each adjusted for HVAC interactive effects as needed. As expected from previous comparisons, the existing protocol with the worst (highest) RMSE was the SU 2011 MSEM, the best was the CT 2012 TRM. The RMSE for the new protocol using default RHRS was almost as good as the CT 2012 TRM and better than all other protocols. Results from the new protocol were improved further with the use of verified RHRS, producing a lower RMSE than all other methods. This confirms the benefit of using project specific RHRS rather than default values.

Table 56 shows the verified savings for each case study and the predicted savings estimated using each protocol, each adjusted for HVAC interactive effects as needed. As expected from previous comparisons, the existing protocol with the worst (highest) RMSE was the SU 2011 MSEM, the best was the CT 2012 TRM. The RMSE for the new protocol using default RHRS was almost as good as the CT 2012 TRM and better than all other protocols. Results from the new protocol were improved further with the use of verified RHRS, producing a lower RMSE than all other methods. This confirms the benefit of using project specific RHRS rather than default values.

Table 56. Estimated Savings (kWh/yr) and RMSE by Estimation Methodology – Adjusted for HVAC IE's.

Evaluation Methodology	Case Study 1	Case Study 2	Case Study 3	Case Study 4	Case Study 5	Case Study 6	Case Study 7	RMSE
Verified Savings	90,186	1,087,639	126,044	1,410,205	1,671,384	315,447	1,383,710	-
SU 2011 MSEM	67,164	3,546,243	188,058	1,101,484	4,835,797	752,233	3,868,628	**4,745,896**
CA DEER 2011	24,842	1,310,760	69,510	407,130	5,080,229	335,966	1,727,824	3,578,054
CT 2012 TRM	43,841	1,102,654	58,494	585,122	2,342,503	234,059	1,189,268	**1,087,442**
IL 2012 TRM	17,533	388,164	20,591	121,174	1,527,169	82,395	418,655	1,781,489
NJ 2012 TRM	85,674	2,154,777	114,307	672,663	3,843,667	457,392	2,324,036	2,702,977
Mid-Atlantic 2011 TRM	54,831	1,379,057	73,157	673,684	3,595,258	292,731	1,487,383	2,084,224
OH 2010 TRM	15,965	1,280,566	67,932	399,758	1,659,514	174,305	885,656	1,155,521
PA 2013 TRM	30,707	772,317	40,970	376,554	2,010,594	163,939	832,983	1,272,774
MA 2012 TRM	29,335	1,529,162	80,043	484,432	2,223,043	320,284	1,627,383	1,192,285
NY 2010 TRM	46,425	2,322,747	129,989	677,053	2,728,206	519,956	2,674,058	2,211,025
VT 2010 TRM	28,954	1,722,403	81,071	601,918	2,084,683	324,284	1,667,746	1,146,122
Manufacturers' Calculators	56,235	1,451,860	76,993	795,805	2,729,677	307,970	2,795,024	1,904,088
E+ Model Fan Electric Savings	31,301	1,771,585	93,948	559,232	3,083,698	391,964	2,062,640	1,912,555
E+ Model Total Electric Savings	26,710	1,492,947	79,171	471,294	2,702,757	322,615	1,689,384	1,486,362
New Protocol w/ default RHRS	39,141	984,422	52,222	437,073	2,221,465	208,962	1,520,224	**1,139,412**
New Protocol w/ verified RHRS	44,732	1,051,661	70,144	455,446	2,067,208	208,962	1,360,026	**1,042,414**

Overall, these results validate that this new calculator is a viable alternative to the existing TRM protocols while still providing a simple, yet robust energy savings protocol for VFD measures.

Chapter 9

9 Conclusions and Recommendations

This study has shown that while VFD technology does not change significantly across the country, prescriptive methods for claiming VFD measure savings does. Unfortunately this does not result in more reliable savings estimates, and in some cases leads to wildly inaccurate estimates.

9.1 Existing TRM Findings and Recommendations

Although this study cannot be considered statistically valid from a program evaluation perspective for all of the savings protocols, it does give an indication of which methods are definitely not producing reliable results and which may be more reasonable than others.

Three methods produced results that were in an acceptable evaluation range. These included the CT 2012 TRM with HVAC interactive effects adjustments, the MA 2012 with no interactive effects adjustments, and the VT 2010 TRM, also without adjustments. While it cannot be said that these three methods will always yield results in the acceptable range for program implementation and evaluation, there is more confidence that the SU 2011 MSEM, the IL 2012 TRM, NJ 2012 TRM, OH 2010 TRM, PA 2013 TRM, and ME 2010 TRM are not estimating savings in a reliable manner. In each case the results are either far outside the range of expected savings, or there is a mistake in their savings estimation methods that inherently produces unreliable savings estimates. Looking at each of these methodologies will help understand where the deviations are occurring.

9.1.1 SU 2011 MSEM Recommendations

There were no specific errors in the SU 2011 MSEM algorithm which would cause the discrepancies. One of the biggest problems with the SU 2011 MSEM method is that all factors were deemed except for motor horsepower. This resulted in a fully deemed savings per horsepower calculation with no adjustment for motor efficiency, fan application type, building type or hours of use. It is possible that given a large enough population of participants, using this methodology may produce reliable results. That is an unrealistic burden to place on TRM protocol, however, as there are few programs that incent a large enough number of VFDs to get to a high enough population for this to be reliable. The program would be better off revising their prescriptive algorithms.

It is recommended that this protocol be revised to a more reliable method.

9.1.2 IL 2012 TRM Recommendations

As discussed in Section 3.4.4, the IL 2012 TRM had several errors from the start. This TRM was based on a version of the CT TRM. It was an earlier version than the CT 2012 TRM which was included in this study, but they were very similar. While the CT 2012 TRM did not have the best results of the group, it was one of only three protocols with overall evaluation realization rates within acceptable limits. Given that the IL TRM was based on the same methodology one would expect it to be in the same ballpark of savings, but it was significantly different and one of the worst performers.

One of the primary contributors to the poor results was that the IL TRM used the savings factors from the CT TRM, but then used different hours of use values. Because these two factors are related in the CT TRM the saving factors should not be adopted elsewhere without using the same hours of use unless an adjustment is made to both (although this is not recommended because of the potential errors associated with such an adjustment).

Another major issue with the IL TRM is that it included a conversion factor for HP to kWh. Although the CT TRM did not explicitly state so, it is presumed that this conversion was already included in the savings factors directly. Given the CT TRM's much better predictions than the IL TRM, this is likely to be a correct assumption. These two errors caused the savings estimates from the IL TRM to be very unreliable.

It is recommended that this protocol be revised to a more reliable method.

9.1.3 NJ 2011 TRM Recommendations

The NJ 2011 TRM was also based on a version of the CT TRM and it too had several unacceptable adjustments. One of the errors made in adopting the CT TRM was that the NJ TRM uses nominal motor horsepower in the equation without making a load factor adjustment to convert to brake horsepower which the CT TRM savings factors are based on. Another error is that the NJ TRM includes a factor to convert HP to kWh, but it appears this conversion is already included in the CT TRM savings factors. These two adjustments make the NJ 2011 TRM unreliable.

It is recommended that this protocol be revised to a more reliable method.

9.1.4 OH 2010 TRM Recommendations

The OH 2010 TRM was based on the same version of the CT TRM as the IL 2012 TRM, yet these two TRMs resulted in significantly different savings estimates. The biggest difference between the CT TRM and the OH 2010 TRM was that the OH protocol used an average of all the building type run hours as a deemed value rather than allowing building type specific hours to be used. This clearly had a big impact on savings estimates. Similar to the SU 2011 MSEM needing a large number of participants to possibly yield reliable results, this assumption of average HOU will only work for an energy efficiency program if there are a sufficiently large number of VFD projects in the program and the buildings included in the program each had an equal number of projects and weighted savings. This is not a good strategy for such a high impact measure. The OH 2010 TRM would be better off adjusting to a more building type and application specific methodology.

It is recommended that this protocol be revised to a more reliable method.

9.1.5 PA 2013 TRM Recommendations

The PA 2013 TRM was based on the CT 2012 TRM. It is somewhat surprising to see such substantial differences, but they can be explained. The PA 2013 TRM added an adjustment to convert HP to kWh similar to the IL 2012 TRM. As stated above, this adjustment may not be appropriate as it appears this conversion was already included in the CT savings factors. There are other differences between the PA 2013 TRM and the CT 2012 TRM, but those are on the demand algorithm. This adjustment is the primary difference and led to a much higher total RR than was seen for the CT 2012 TRM. This conversion factor should be removed.

It is recommended that this protocol be revised to a more reliable method.

9.1.6 ME 2010 TRM Recommendations

Because the ME 2010 TRM could only be used for estimating savings for one case study it is difficult to make any generalizations on its validity. The most obvious generalization that can be made is that it is a very restricted protocol which leads to limited usefulness for program implementation. This is its most distinct drawback as compared to the others.

For the one project that the TRM was able to be used, the savings predictions were very low relative to the verified savings at only 29%. This was in a similar range as most of the TRMs for this project and therefore further extrapolation to programs as a whole cannot be made.

To be a more useful tool for program implementation, it is recommended that the protocol be revised to be less restrictive or replaced altogether with the new protocol recommended from this study.

9.1.7 Cross Cutting Recommendations

One overarching recommendation that can be made is that it is never good to base a TRM protocol on an existing protocol from another jurisdiction that is not fully understood. This can be seen with all of the protocols based on a version of the CT TRM. Each of them made some adjustments that led to less reliability of savings, and in most cases, much less reliability. These adjustments were made primarily as a result of not fully understanding what the savings factors in the CT TRM represented. Because of this mistakes were made. It is best practice to make sure a TRM protocol is based on fully transparent methodologies.

9.2 EnergyPlus Prototypical Model Findings and Recommendations

Although the EnergyPlus prototypical model total savings estimates were not within the desired range, they were not that far off either. This method is not recommended to be used as the basis for a TRM however. The main reason for this is because there are a limited number of building types with US DOE prototypical models. As a result, this method will not yield reliable results for the large range of building types that energy efficiency programs regularly encounter without significant additional modeling adjustments. While this method has the potential for being very reliable if custom building models are made, it would be costly and time prohibitive to do so for program implementation.

It is recommended that energy simulation models be reserved for large custom projects or evaluation and verification where custom models can afford to be developed for a smaller number of projects.

9.3 New Protocol Findings and Recommendations

A new protocol was developed for this study which is based on simple algorithms, yet it provides a robust and more reliable methodology than existing TRM protocols for estimating savings from VFD installations on HVAC fan motors for program implementation. This methodology was validated using seven case studies and comparing the protocol derived energy savings estimates to verified savings estimates. This was confirmed by looking at a metric used for evaluation of energy efficiency programs called a realization rate. This savings estimates from this protocol were as reliable as the best existing methods, but did so with greater accuracy. The new protocol is recommended for adoption in TRMs across the country as a simple and reasonably reliable, cost effective savings estimation tool for VFD installations on HVAC fan motors.

While this new protocol is recommended for adoption in energy efficiency TRMs for use by program implementers, it is not recommended for use by evaluators. As budgets allow, evaluators should use more robust methodologies to verify savings from VFD installations. Evaluators do not always suffer from the same time and budget constraints per project as program implementation does. They should be able to produce more reliable results by including more detailed consideration of pre and post controls such as such as static pressure control settings, and the physical system configurations including motor, fan, and VFD efficiency curves, drive type, etc.

The goal of a TRM protocol for an energy efficiency program is to estimate savings within a reasonable range of the real project savings for a population of installations. The smaller the population and larger the savings, the more important it is to have a reliable TRM protocol. VFDs are one of those measures. This new protocol showed that it is capable of producing reasonably reliable savings estimates in a very simple manner, which will translate to a cost effective implementation.

9.4 Other Recommendations

Regardless of the method used, careful consideration of the additional savings associated with HVAC interactive effects should be included in the analysis. The energy models showed this to be a significant portion of the overall savings and many of the existing TRM protocols simply ignored this aspect.

Another important consideration is the heating penalty that often occurs with the installation of a VFD. Only one of the protocols examined included any consideration of a heating penalty. When considering the cost effectiveness of VFD measures this can have a significant effect and should not be ignored. While it may not help the utilities from an electric energy reduction perspective, it does affect the building owner.

9.5 Future Work

This study focused on VFD installations in commercial office building HVAC fan applications. TRM protocols for VFDs typically include savings estimates for VFDs in many other building types, as well as other applications. Other applications include cooling tower fans, water pumps, and chillers. A similar analysis could be performed to determine the reliability of the existing protocols for those applications. The recommended protocol could be further validated for other building types as well and expanded to other applications.

One of the inputs that did not have a lot of supporting studies is the default load factor of 65%. The average load factor should be investigated further, and differentiated based on application and motor size.

There are many ways the recommended protocol could be expanded and made more robust. Further investigations as to the sensitivity of different inputs and system configurations or control types could be completed to improve the reliability of the method.

Other future related studies could include reviewing what information or data from energy models could be used to develop more reliable VFD measure savings protocols. Is it enough to simply use pre/post consumption data to develop a single ESF/DSF estimates, or should more detailed output data such as percent time in different temperature/efficiency bins, or efficiency improvements in each temperature bin be used?

Further investigation could be done to determine if the regression curves identified and included in the recommended protocol are the best curves to use. There were four regression curves identified for VFD driven fans, but there is not a lot of information describing these curves. One reference document did mention that some of these curves are very old and have not been updated in decades. A study could look at how closely these curves represent current technology and system energy consumption.

Another future study could review whether or not heating degree day, heating degree hour, cooling degree day or cooling degree hour data could be used to improve the reliability of VFD measure savings estimation protocols.

9.6 Final Conclusions

This study looked at 13 existing TRM protocols for estimating savings from VFD installations on HVAC fan motors. Seven case studies were identified to compare the TRM protocols to determine if one method was more reliable than the others. Each protocol was used to estimate savings for all the case studies and the results compared to the verified savings that had previously been determined. Comparison of these results showed that most of the TRM protocols were not reliable, with only a few providing overall results within an acceptable range. They did so, however, with a large standard deviation of predicted savings to verified savings. This indicated a need to develop a more reliable savings estimation protocol.

EnergyPlus models were run using prototypical building type models developed by the US DOE, but adjusted to reflect the baseline and retrofit HVAC system type for each case study. Savings estimates were calculated for each case study from the model outputs and compared to the results from the TRM analysis. The EnergyPlus prototypical model estimates proved to be no more reliable than the existing TRM protocols.

This warranted the development of a new protocol. Based on the review of the existing protocols, one of the simplest existing methods appeared to offer the potential for improvement. This simple calculator was revised and expanded to be a more robust, yet still simple calculation protocol to estimate savings for VFD installations on HVAC fan motors. Adjustments were made and the new protocol was used to estimate savings for all seven case studies. Savings were estimated using default building type run hours, and using known run hours developed from logging or metering for the energy efficiency program evaluations.

These results were compared to the results from all the TRM protocols and the EnergyPlus prototypical models. This new protocol was validated to provide overall savings estimates that were as good as the best TRM protocols, but which showed more reliability on a project specific basis. As such the protocol developed in this paper is recommended for adoption in TRMs across the country for use in energy efficiency program implementation to estimate savings for installations of VFDs on HVAC fan motors.

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Appendix

The following screen shots in Figure 28 and Figure 29 of the new protocol as implemented in Excel show how easy it is to estimate savings for a given project.

Inputs

Building Type	Office (general office types)	Select building type
Default Annual Operating Hours	3748	
Project Specific Annual Operating Hours	8760	Optional if known
Baseline Fan Control Type	Inlet Guide Vane, BI & Airfoil Fans	Select baseline fan control type
Retrofit Fan Control Type	VFD with duct static pressure controls	Select retrofit fan control type; Default = VFD with duct static pressure controls
Nameplate Horsepower	25	Enter HP
Motor Enclosure Type	Open Drip Proof (ODP)	Select motor enclosure type; Default = Open Drip Proof (ODP)
Motor Efficiency Type	NEMA motors (pre-EPact)	Select motor efficiency; Default = NEMA Premium Efficiency
Motor Speed (RPM)	1800	Select motor speed in RPM; Default = 1800 RPM
Nominal Efficiency	91.7%	Output cell based on motor selections
Nameplate Efficiency		Enter actual efficiency if known; Optional
Motor Load at Fan Design CFM (Load Factor)	65%	Enter actual load factor if known; Default = 65%

Flow Fraction (% of design cfm)	Percent of Time at Flow Fraction	Baseline Part Load Ratio	Retrofit Part Load Ratio
0% to 10%	0%	0.53	0.09
10% to 20%	1%	0.56	0.10
20% to 30%	6%	0.57	0.11
30% to 40%	16%	0.59	0.15
40% to 50%	22%	0.60	0.20
50% to 60%	25%	0.62	0.29
60% to 70%	19%	0.67	0.41
70% to 80%	9%	0.74	0.57
80% to 90%	3%	0.85	0.76
90% to 100%	1%	1.00	1.01
	100%	Ok, Capacity = 100%	

Source: Default Flow Fraction profile from 2012 ASHRAE Handbook; HVAC Systems and Equipment, page 45.11, Figure 12.

Required Input Cell
Optional Input Cell
Output Cell
Verification Check Cell
Total Savings

Outputs

kWh_{Base} =	73,572	kWh/yr
$kWh_{Retrofit}$ =	34,910	kWh/yr
ΔkWh_{fan} =	38,662	kWh/yr
ΔkWh_{total} =	44,732	kWh/yr

Figure 28. Print Screen of new protocol with savings estimates for Case Study 1.

Algorithms

$$kWh_{Base} = (0.746 * HP * LF / \eta_{motor}) * RHRS_{Base} * \sum (\%FF * PLR_{Base})$$

$$kWh_{Retrofit} = (0.746 * HP * LF / \eta_{motor}) * RHRS_{Base} * \sum (\%FF * PLR_{Retrofit})$$

$$\Delta kWh_{fan} = kWh_{Base} - kWh_{Retrofit}$$

$$\Delta kWh_{total} = \Delta kWh_{fan} * (1 + IE_{energy})$$

Where:

kWh_{Base} = Baseline annual energy consumption (kWh/yr)

$kWh_{Retrofit}$ = Retrofit annual energy consumption (kWh/yr)

ΔkWh_{fan} = Fan-only annual energy savings

ΔkWh_{total} = Total project annual energy savings

0.746 = Conversion factor for HP to kWh

HP = Nominal horsepower of controlled motor

LF = Load Factor; Motor Load at Fan Design CFM (Default = 65% (Lawrence Berkeley National Laboratory, and Resource Dynamics Corporation, 2008))

η_{motor} = Installed nominal/nameplate motor efficiency (default motor is a NEMA Premium efficiency, ODP, 4-pole/1800 RPM fan motor)

$RHRS_{Base}$ = Annual operating hours for fan motor based on building type

%FF = Percentage of run-time spent within a given flow fraction range

PLR_{Base} = Part load ratio for a given flow fraction range based on the baseline flow control type

$PLR_{Retrofit}$ = Part load ratio for a given flow fraction range based on the retrofit flow control type

IE_{energy} = HVAC interactive effects factor for energy (default = 15.7% for this study only based on EnergyPlus results for the seven case studies)

Figure 29. Print Screen of New Protocol Algorithms.