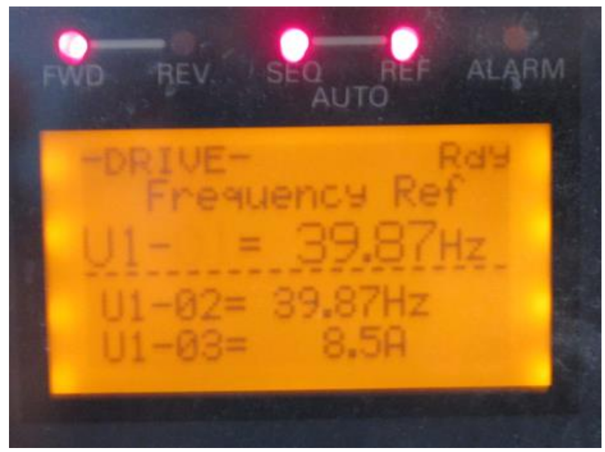
Northeast Energy Efficiency Partnerships



Variable Speed Drive Loadshape Project

August 2014

About NEEP & the Regional EM&V Forum

REGIONAL EVALUATION,
MEASUREMENT & VERIFICATION FORUM

NEEP was founded in 1996 as a non-profit whose mission is to serve the Northeast and Mid-Atlantic to accelerate energy efficiency in the building sector through public policy, program strategies and education. Our vision is that the region will fully embrace energy efficiency as a cornerstone of sustainable energy policy to help achieve a cleaner environment and a more reliable and affordable energy system.

The Regional Evaluation, Measurement and Verification Forum (EM&V Forum or Forum) is a project facilitated by Northeast Energy Efficiency Partnerships, Inc. (NEEP). The Forum's purpose is to provide a framework for the development and use of common and/or consistent protocols to measure, verify, track, and report energy efficiency and other demand resource savings, costs, and emission impacts to support the role and credibility of these resources in current and emerging energy and environmental policies and markets in the Northeast, New York, and the Mid-Atlantic region.

About Cadmus

CADMUS

The Cadmus Group, Inc. (Cadmus) is a nationally recognized energy and environmental consulting firm committed to delivering services and solutions that create social and economic value and improve people's lives. Our multidisciplinary staff of professionals provides technical expertise across the full spectrum of energy, environmental, public health, and sustainability consulting. The Energy Services Division at Cadmus works with utilities, regulatory commissions, and other organizations to provide comprehensive services that encompass all aspects of energy efficiency and demand response program planning, design, and evaluation; renewables and distributed generation; and carbon and greenhouse gas emissions.

Variable Speed Drive Loadshape Project FINAL REPORT

August 15, 2014

Northeast Energy Efficiency Partnerships
Regional Evaluation, Measurement and Verification Forum
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0 Executive Summary

The Northeast Energy Efficiency Partnerships (NEEP) Evaluation, Measurement, and Verification Forum (EM&V Forum) conducts research studies to support energy-efficiency programs and policy in the Northeast and Mid-Atlantic states. In 2012, the EM&V Forum and its Sponsors commissioned this Variable Speed Drive (VSD) Loadshape study to determine the hourly energy and demand impacts of variable speed drives installed on HVAC equipment in existing nonresidential buildings throughout the Northeast and Mid-Atlantic.

Between 2013 and 2014, Cadmus and DMI (the evaluation team) worked with the EM&V Forum's Technical Committee to complete this study. This report describes the study objective, methods, and results, and the evaluation team's recommendations for future implementation and evaluation of variable speed drive projects.

0.1 Objective

The EM&V Forum commissioned this study to assess the annual, peak, and hourly demand impacts from VSD installations. The study focused on VSD retrofit projects on heating, ventilation, and air conditioning (HVAC) equipment in existing commercial buildings using rebates from the Sponsor's prescriptive VSD programs. Through primary and secondary data collection and analysis, the evaluation team developed hourly demand savings estimates—savings loadshapes—for VSDs installed on various HVAC equipment types across the Northeast and Mid-Atlantic states.[1] The study uses these loadshapes to calculate key savings metrics, including average annual energy savings and demand savings during peak periods, attributed to VSD retrofit projects across the NEEP states.

The EM&V Forum provides these study results and primary data to its members to support Sponsor activities including regulatory filings for energy-efficiency programs, demand resource values submitted to forward-capacity markets, and air quality research.

0.2 Methods

The study results rely on extensive on-site data collection and metering, including more than 400 VSD installations across eight states, and thorough engineering and statistical analysis for the population of prescriptive VSD retrofit projects installed by NEEP Sponsors in 2010 and 2011. The study also leveraged data from the 2013 Massachusetts study of VSD installations that included both pre-retrofit and post-retrofit metering (Massachusetts Pre/Post VSD Study).[2]

[1] The Northeast and Mid-Atlantic states include Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, Connecticut, Delaware, New York, Pennsylvania, Maryland, and Washington D.C.
[2] KEMA, Inc. and DMI, Inc., Impact Evaluation of 2011-2012 Prescriptive VSDs, May 2013.

0.2.1 Population Analysis

The evaluation team analyzed program tracking data for VSD installations from 12 participating program administrators in eight states (Table 1). For each participating Sponsor, the table indicates the associated state(s) and weather region(s) for implemented projects. We used the six weather regions defined in the previous NEEP EM&V loadshape project.[3]

Table 1. Participating Program Administrators, States, and Weather Regions

Program Administrator (Sponsor)	State								Weather Region**					
	Connecticut	Maine	Maryland	Massachusetts	New Hampshire	New York	Rhode Island	Vermont	Downstate New York (DNY)	Mid-Atlantic (MAT)	New England East (NEE)	New England North (NES)	New England South (NES)	Upstate New York (UNY)
Baltimore Gas and Electric (BG&E)			◆							●				
Connecticut Light and Power (CL&P)*	◆												●	
Consolidated Edison of New York (Con Edison)						◆			●					
Efficiency Maine Trust (EMT)		◆										●		
Efficiency Vermont (EV)								◆				●		
First Energy			◆							●				
Long Island Power Authority (LIPA)						◆			●					
National Grid				◆			◆				●		●	
NSTAR Electric (NSTAR)*				◆							●			
NYSERDA						◆			●					●
Pepco			◆							●				
Public Service of New Hampshire (PSNH)*					◆							●		

* CL&P, NSTAR, and PSNH are part of Northeast Utilities.

Based on this review, the EM&V forum agreed to focus the study on prescriptive VSD installations completed in 2010 or 2011 on the following equipment types:

- Supply Fans (SF)
- Return Fans (RF)
- Cooling Water Pumps (CWP)
- Heating Water Pumps (HWP)

[3] KEMA, Inc., C&I Unitary HVAC Load Shape Project Final Report, June 2011.

- Water Source Heat Pump Circulation Pumps (WHP)

These five equipment types represent the VSD installations with the largest annual energy savings across the NEEP Sponsor territories.

0.2.2 Sampling

Due to the objectives to capture five equipment types and analyze regional differences, the desire to represent each study Sponsor, and limited auxiliary data for the study population, the evaluation team developed a unique multi-stage, multi-phase sampling strategy. We implemented this staged and phased sampling approach to develop the study sample of VSD projects (tracked projects with VSD installations) and units (specific VSD installations). This approach enabled the team to conduct targeted sampling to pursue adequate representation for each Sponsor, weather region, and equipment type, while ensuring that the sample was representative of the regional population of VSD installation within each equipment type category.

Sampling Stages

We performed two stages of sampling because the only relevant auxiliary variables for the population were project size (tracked annual energy savings) and weather region. Although the sampling objective was to collect a representative sample of the five selected equipment types, the evaluation team could not sample based on equipment type because some program tracking data did not include these data.

In the first stage, we sampled projects based on project size and weather region. In the second stage, we sampled units within each sampled project to target the appropriate equipment type for this study.

Sampling Phases

Because the tracking data did not include equipment type information for all projects and some equipment types were more prevalent than others, we performed multiple phases of sampling to ensure adequate representation of all five selected equipment types in the study sample.

In the first phase, we sampled projects (with the sample size set to 50% of the total project sample size) and then analyzed the distribution of equipment types from those Phase 1 projects. For subsequent sampling phases, we minimized selection of the equipment types (SF and CWP) that were most common in the previous sampling phases, to maximize selection of the less-common equipment types (RF, HWP, and WHP).

0.2.3 Data Collection

The study required extensive data collection—including on-site data collection and long-term metering for over 400 VSD installations—to support this study. Table 2 summarizes the primary and secondary data collection activities we completed between June 2012 and September 2013.

Table 2. Data Collection Activities

Activity	Description
Primary Data	
Sponsor Tracking Data	The evaluation team collected and reviewed the tracking data for VSD installations completed through the Sponsor's programs. We used these data to define the study population and design the study sample.
On-Site Survey and Metering	**Equipment Inspection and Survey** The evaluation team surveyed facility staff for sampled projects to collect information about normal facility and equipment operation and baseline conditions. We used these data to develop our models for both VSD and baseline loadshapes.
	Metering The team installed power-metering equipment on sampled units to measure the energy consumption of VSD-controlled equipment throughout the year between August 2012 and September 2013. We used these data to model the hourly operation and electric demand of VSD-controlled units.
Secondary Data	
Existing Savings Values, Methods or Assumptions for VSDs	**TRM Review** The team reviewed the existing savings methods and assumption in the Sponsors' Technical Reference Manuals. We used this information to compare the results of our study to existing savings claims.
	Review of Existing VSD Savings Methods The team reviewed common methods for estimating energy and demand savings from VSD installations. We used this information to develop our baseline demand model.
	Massachusetts Pre/Post Metering Study The team reviewed the meter data and analysis results from the Massachusetts Pre/Post Installation VSD Study. We used these data and findings to develop and verify our baseline demand model.
Historical and Actual Weather Data	The team collected actual and TMY hourly weather data for the Northeast and Mid-Atlantic weather regions. We used actual hourly data to examine relationships between VSD power and ambient weather conditions. We applied those relationships to TMY data to predict VSD power during typical weather years.

0.2.4 Data Analysis

The evaluation team used primary and secondary data to develop estimates of the savings loadshapes and savings metrics for each sampled unit, based on models that use the hourly operation and power schedules for the pre- and post-retrofit conditions as well as typical calendar year weather conditions. We used these unit-level models to estimate savings loadshapes and metrics based on typical weather year conditions.

Hourly Operating Schedule

The hourly operating schedule indicates the percentage of time in each hour of the year that we expect the unit to operate. Taking into consideration factors such as operating season, operating schedules, and unit type, we used our meter and survey data to develop the post-retrofit operating schedule for each unit.

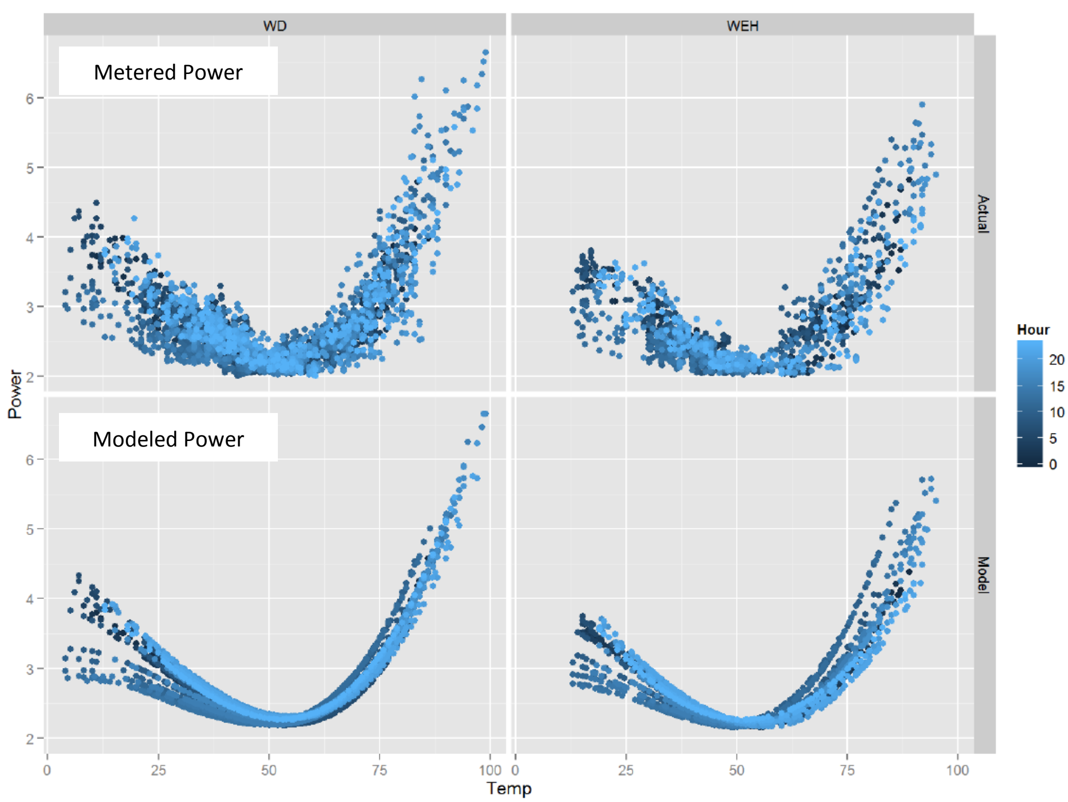
Due to limited information about pre-retrofit operation, we assumed that the pre-retrofit (baseline) operating schedule was the same as the observed post-retrofit (VSD) operating schedule. Although we confirmed that a VSD installation could change both the operating power and the operating hours of the connected equipment, we determined through discussions with the NEEP Technical Committee that this study would focus only on the savings achieved by power reductions resulting from the VSD installation.

Hourly VSD Power Model

We developed a VSD power model for each unit to estimate the electric demand required by the unit when it operates with the connected VSD. We analyzed relationships between measured operating power and four variables: operating season, day type, hour, and outdoor temperature. We used the relationships to develop a set of hourly models for each unit that predict the unit's hourly power demand based on a typical calendar year weather.

Figure 1 shows an example of our hourly modeling approach for a unit that exhibited temperature dependence. The first row shows the actual hourly VSD demand plotted by temperature for weekdays and weekends. The second row shows our modeled hourly output for the same temperature data. In each figure, the colors indicate the different hourly models.

Figure 1. Examples of Hourly Models for Temperature-Dependent Units



Hourly Pre-Retrofit Power Model

Because this study did not include pre-retrofit observations or measurements, we developed a baseline model using a combination of primary and secondary data to estimate the typical hourly operating power. In particular, we used meter data from the Massachusetts Pre/Post VSD Study to guide and verify our baseline assumptions. Table 3 summarizes our modeling approach for pre-retrofit systems.

Table 3. Baseline Model Approach on Baseline System Type

Baseline Category*	Approach for Estimating the Pre-Retrofit Performance Curve
Constant Volume (CV)	Equipment operates at constant full load power (100% FLP) during all operating hours.
Variable Volume (VV)	Equipment operates at same flow rate as post-retrofit equipment. Estimate pre-retrofit power using measured hourly post-retrofit power and DOE-2 eQUEST performance curves.[4]

* Based on information provided by facility staff; otherwise, determined based on distribution of known baseline types within the equipment category.

We assigned all units to one of two baseline categories—constant volume (CV) or variable volume (VV)—based on information provided by the facility staff during our on-site surveys. This baseline category determined the baseline performance curve we used to estimate pre-retrofit operating power.

Several key observations from our on-site surveys, secondary data reviews, and experience with existing commercial buildings shaped this baseline model. These are:

- The majority of HVAC fan and pump motors operate at constant power in the pre-retrofit condition, where we defined the pre-retrofit condition as the period immediately before participating in a prescriptive VSD retrofit program.
- Pre-retrofit meter data from the Massachusetts Pre/Post VSD Study indicated a strong correlation between the measured average pre-retrofit operating power and the rated motor horsepower.
- Although VSDs are able to reduce both operating power and operating hours, changes in the operating schedule between the pre- and post-retrofit conditions are difficult to quantify without adequate pre-retrofit data. For this study, we assumed the pre-retrofit operating hours matched the post-retrofit operating hours.[5]

Unit-Level Loadshapes and Savings Metrics

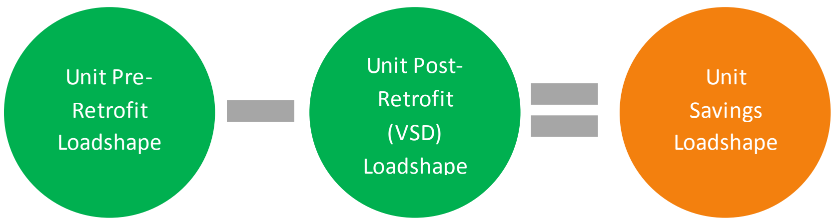
We used our models for operating schedule, VSD power, and baseline power to estimate the pre-retrofit (baseline) and post-retrofit (VSD) hourly demand loadshape for each unit. As indicated in Figure 2, we

[4] http://www.doe2.com/equest/

[5] This assumption likely results in understated savings for VSD retrofit installations since we do not account for any impacts of reduced schedules but expect that VSD retrofits allow for these additional savings.

calculated the savings loadshape by subtracting the hourly VSD loadshape from the hourly baseline loadshape.

Figure 2. Calculation for the Unit-Level Savings Loadshape



We then used these unit-level savings loadshapes to calculate key savings metrics for each unit, including annual energy and peak demand savings.

0.2.5 Aggregation Analysis

In a typical evaluation study, the evaluation team predefines the aggregation method based on the sample design. This approach typically involves using sampling weights to aggregate the sampled unit observations in order to produce a population-level estimate of the result. In this study, due to the observed diversity in unit-level operating characteristics and distinct populations of temperature-dependent and temperature-independent units, we developed and compared four different methods of aggregation to analyze these differences in an aggregation analysis.

We worked with the NEEP Technical Committee to develop four methods as options for aggregating the unit-level data into population results. Each method uses a different combination of unit-level data to develop the population results, representing different assumptions that can be made about differentiating or combining unit subpopulations across weather regions.

We developed a set of formulas to estimate the aggregated results for subpopulations of units (e.g., temperature-dependent supply fans in the Mid-Atlantic weather region) and to combine those subpopulation results to obtain overall population results (e.g., supply fans in the Northeast). For each aggregation method, we used these formulas to produce population-level savings estimates with populations defined by equipment type and weather region.

In collaboration with the NEEP Technical Committee, we examined and compared the results of these calculations to select the aggregation method that provides the most accurate and useful result to the study Sponsors. We selected the aggregation method (Method D) that combines all unit data within each equipment category across weather regions. We used aggregation Method D to develop a single set of weighted average loadshapes and savings metrics for each equipment type that applies across the northeast region.

0.3 Results

Using the results of the aggregation analysis, the evaluation team combined the unit-level savings results to develop average savings results for VSDs installed across the NEEP region. Although we expected to observe significant regional differences in VSD performance, our observations and analysis highlighted unexpected findings that guided our final approach and presentation of results. The final study results represent the average per-horsepower savings achieved from VSD retrofits on key HVAC systems in existing nonresidential buildings.

In this section, we describe the final study sample, our observations about the performance of the sampled units, our findings about baseline systems, key assumptions that shape the analysis and results, and our estimates of the average energy and peak demand savings achieved by VSD installations. We follow the presentation of results with a discussion of the how the Sponsors may use the results for future programs and the key findings that influenced the final analysis.

0.3.1 Final Sample

The savings results in this study rely on the primary data the evaluation team collected from the final sample of VSD projects and units. Table 4 shows the final sample of metered units by equipment type and weather region.

Table 4. Final Sample of Equipment Type by Weather Region

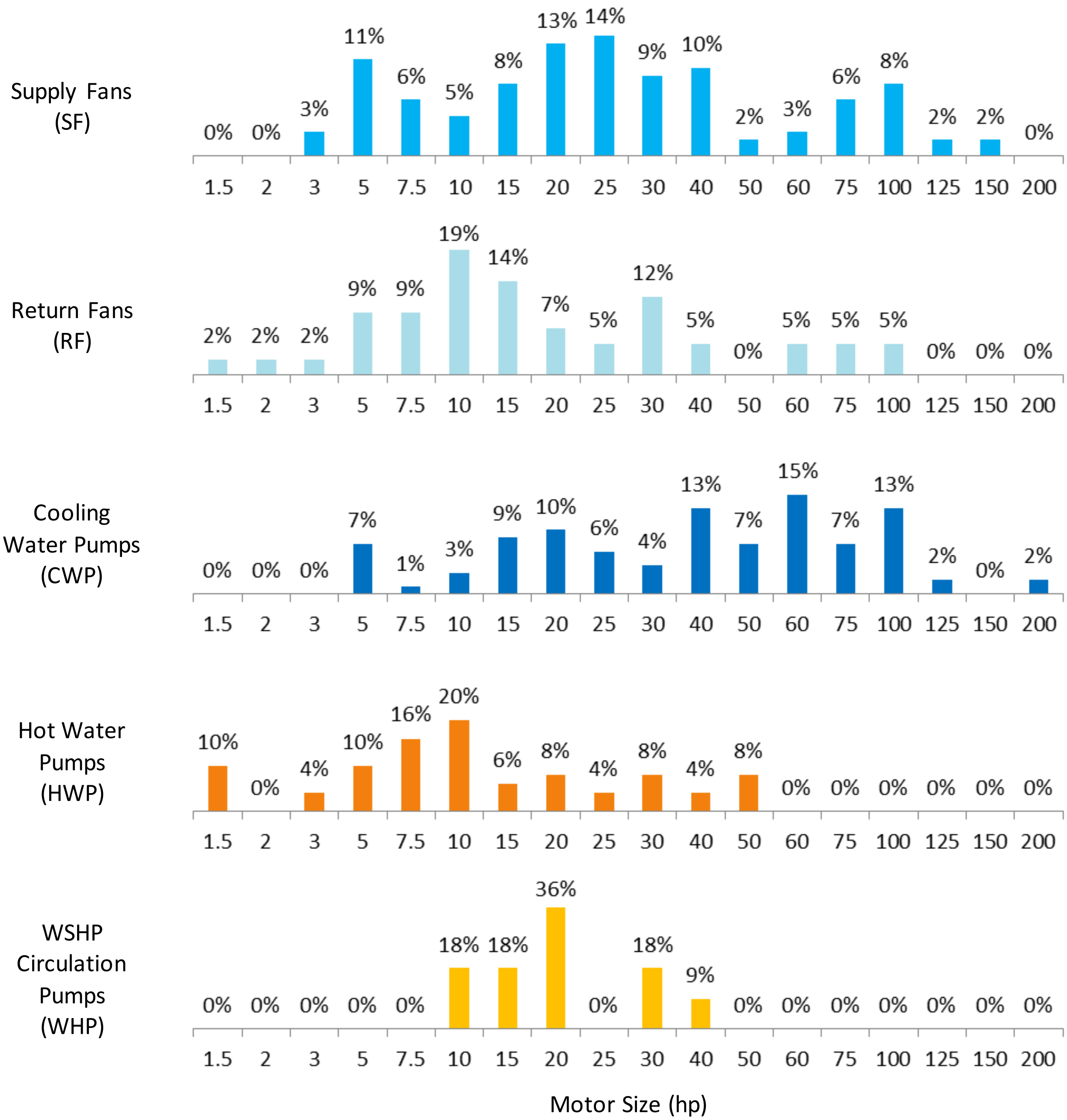
Equipment Type	DNY	MAT	NEE	NEN	NES	UNY	Total	Pct. of Total
Supply Fans (SF)	35	24	21	23	20	8	131	33%
Return Fans (RF)	9	15	13	17	4	2	60	15%
Cooling Water Pumps (CWP)	4	20	22	53	3	7	109	28%
Hot Water Pumps (HWP)	5	6	3	40	11	12	77	20%
Water Source Heat Pump Circulation Pumps (WHP)	3	0	1	8	3	0	15	4%
Total	56	65	60	141	41	29	392	100%
Percent of Total	14%	17%	15%	36%	10%	7%	100%	NA

Weather Regions: DNY = Downstate New York; MAT = Mid-Atlantic; NEE = New England East; NEN = New England North; NES = New England South; UNY = Upstate New York

The final sample includes 392 VSD installations across all weather regions and equipment types. We stratified by weather region in our sampling approach, so that the number of sampled projects across the weather regions would be representative of the distribution in the population. Due to our phased sampling approach, the overall distribution of equipment types may not represent of the overall population of prescriptive VSD installations (i.e., supply fans likely represent more than 33% of the installations overall). However, *within* each equipment type category, the distribution of units across weather regions likely represents the distribution in the population. We used sampling weights at both the project and unit levels to account for any differences in the sampling and population distributions.

Figure 3 shows the distribution of motor sizes in the final sample. In each figure, the x-axis shows the range of motor sizes eligible for the study sample (0 to 200 horsepower) and the y-axis indicates the percentage of motors in the sample for each motor size.

Figure 3. Distribution of Motor Sizes (motor hp) by Equipment Type



To be consistent with the typical guidelines for prescriptive VSD incentives in the Sponsors' programs, we included all VSDs on motors up to 200 horsepower in the study population. We excluded units from the sample based on motor size only if the motor was larger than 200 hp. Other than this exclusion of large motors, this motor size distribution represents the overall population of prescriptive VSD installations for each equipment type.

Figure 4 shows the distribution of building types in the final sample. The bars in the table indicate the relative distribution of each building type compared to the others.

Figure 4. Distribution of Building Types in Final Sample

Building Types	Percent of Sample
Office	35%
Restaurant	0%
College/University (non-Residential)	20%
Industrial/Manufacturing	5%
Retail	2%
Hospital	8%
K-12	11%
Warehouse	1%
Grocery	0%
Multifamily/Dormitory	9%
Hotel/Motel/Lodging	4%
Other	7%

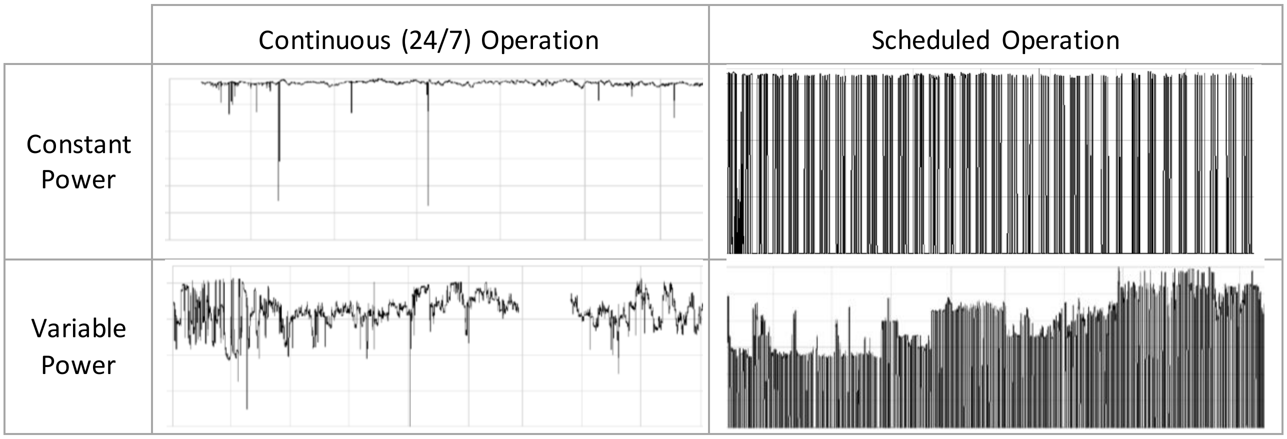
The evaluation team developed the list of 12 building types as part of the data collection protocols. During the site visits, the evaluation team verified or determined the building type for each sampled site and assigned each site to one of the 12 listed building types. We did not exclude any projects based on building type, so we believe this distribution is representative the overall population distribution.

Although we expect building type to be an influential parameter in VSD performance, we could not stratify the sample by building type due to limitations in the project scope and auxiliary data. In addition, the diversity operating schedules and strategies across the sample suggests that building type is not a reliable indicator of VSD performance.

0.3.2 Observed Variation in VSD Operation

Throughout the data collection and analysis activities, the evaluation team observed significant variation in the operating patterns of sampled units. Figure 5 shows an example of the differences in operating schedules (e.g., continuous operation vs. scheduled operation) and in operating power (e.g., constant vs. variable power).

Figure 5. Examples of Observed Variation in VSD Operation



In addition to differences in equipment schedules and power settings, factors such as motor configuration and seasonality increased the variation in our models of VSD demand and savings. We used all of these factors to develop annual estimates of energy and demand savings at the unit level.

0.3.3 Estimates of Baseline Operation

Because this study focused on post-installation operation of equipment with VSDs, we relied on facility staff to describe pre-retrofit operation for all sampled. We used this survey information to develop an initial distribution of baseline categories, then re-assigned any VSD or unknown baseline categories to develop the adjusted distribution for the savings analysis. Table 5 shows the initial and adjusted distributions of baseline categories for each equipment type.

Table 5. Reported Baseline (Pre-Retrofit) Category

Baseline Category	SF	RF	CWP	HWP	WHP	All
sample	n = 131	n = 60	n = 109	n = 77	n = 15	n = 392
Initial Distribution						
Constant volume (CV)	31%	42%	35%	25%	40%	33%
Variable volume (VV)	1%	6%	0%	0%	0%	2%
Variable speed drive*	1%	2%	0%	0%	0%	1%
Unknown**	66%	50%	65%	75%	60%	65%
Adjusted Distribution* **						
Constant volume	97%	92%	100%	100%	100%	98%
Variable volume	3%	8%	0%	0%	0%	2%

* Based on discussions with the NEEP Technical Committee, we reassigned VSD baselines to either CV or VV. Since VSDs are not an eligible baseline for any Sponsor programs, the team elected to remove this baseline category from the final analysis.

** The high percentage of units with unknown baselines is likely due to the elapsed time (minimum of one year) since the site installed the VSDs.

*** We assigned all equipment with VSD or unknown baselines by randomly assigning the unit to a CV or VV baseline based on the probably of those baselines occurring in the initial, or “known” distribution.

The initial distribution shows that facility staff could not define the baseline system for almost two-thirds of the studied units. This inability to report on the baseline conditions was prevalent for the majority of sampled units across all equipment types. This is not surprising for a data collection effort conducted a minimum of one year after the customer installed the VSD equipment.

Among those staff members who could recall the baseline system type and operation, the majority indicated that the equipment operated at constant speed and power before the customer installed the rebated VSDs. Among these, some staff indicated that although variable volume equipment existed, the site was installing VSDs because the existing variable volume equipment was not in working condition. We classified these cases in the constant volume category.

To estimate the adjusted distributions, the evaluation team re-assigned the baseline category for units with an unknown or VSD baseline in the initial distribution based on the observed distribution of CV and VV baselines among the known baseline categories within each equipment group. In other words, we randomly assigned each “unknown” or “VSD” baseline from the initial distribution to either the CV or VV baseline category using the probability of CV or VV from the initial baselines.

The final distribution demonstrates our estimate that almost all systems operated as constant volume prior to the VSD retrofit. Although contrary to many TRM approaches that assume a higher fraction of variable volume baselines, we confirmed through multiple discussions with the NEEP Technical Committee and building commissioning engineers that this high percentage of systems operating at constant volume is consistent with field observations across existing buildings and with the pre-installation findings from the MA VSD Pre/Post study. The following points support this finding:

- The CV baseline category includes systems that were designed as VV but operate as CV, because of improperly operating controls, broken equipment, etc.
- The program population of buildings does not include the full C&I building stock. Rather, the population includes only those existing buildings that participated in one of the Sponsors’ VSD retrofit programs. Existing buildings with working variable volume systems are less likely to participate in the programs since there is no need to replace the working VV equipment.
- Eligibility requirements for several Sponsor VSD programs do not allow rebates for existing VV systems in working condition. This filter likely further reduces the number VV baselines among the participant population.
- Our commissioning engineers agree that based on their experience in existing buildings, it is becoming less and less common to see non-VSD VV systems in working condition. Frequently, they will find evidence that these VV systems were part of the original design, but noted that they are often not working. For example, we see guide vanes that are locked in place so they effectively operate as constant volume systems.
- For pumping systems, pumps without VSD controls are typically constant volume by design. There are systems that use variable volume distribution in the building (e.g. two-way valves at

the coils), but they are typically configured using bypass valves at the plant so the primary loop pump would still operate at full, constant volume.

- Although the sample was small, the pre-retrofit metering results from the Massachusetts Pre/Post VSD study are consistent with these assumptions. For that study, the field team observed and metered the equipment prior to when the VSD was installed. They identified a couple systems that were designed as VV, but the meter data showed constant power on those fans.

0.3.4 Key Assumptions

Based on our findings in both the primary and secondary data and the need to develop a standard approach to estimate savings in this study, we developed several key assumptions to guide our savings analysis. In collaboration with NEEP's EM&V Technical Committee, we applied the following key assumptions in this study:

- **Pre-Retrofit Operating Power**. Due to the post-installation focus of the study, the evaluation team could not measure pre-retrofit operating power. We modeled pre-retrofit power based on a combination of the unit-rated horsepower, metered post-installation power, on-site survey data about the pre-retrofit condition, and results of the Massachusetts Pre/Post Metering Study.
- **Pre-Retrofit Schedule**. Due to the post-installation focus of the study, the evaluation team could not monitor the pre-retrofit operating schedule. We assumed the pre-retrofit operating schedule was the same as the post-retrofit operating schedule.
- **Units with Baseline VSD**. A small number of interviewed on-site staff indicated that the new VSDs replaced existing VSDs. Since replacement of existing VSDs is not eligible in the Sponsor's programs and an attribution study would likely capture these occurrences, we assigned a new baseline category for these units based on the observed proportion of baseline categories for the remaining units.
- **Non-Operating Units**. Our metering and on-site data collection indicated 52 of 392 (<14%) units that have low operating hours due to rotating, lead-lag, or back-up control strategies. We retained these units in the study sample to represent these occurrences as we observed them in the study population.

0.3.5 Savings Metrics

The team used the unit-level savings results to estimate average savings metrics for the population of prescriptive VSD projects installed through the Sponsor's energy-efficiency programs. Based on key observations and findings during the data collection and analysis tasks, we produced a single set of savings results for each equipment type to reflect the average savings across all northeast weather regions. The northeast average results account for the diversity of motor sizes, building types, HVAC loads, and control strategies observed in the study sample.

The following tables describe the estimated savings for each equipment type. In addition to the per-horsepower savings values, the tables show the relative precision for each result at both 90% and 80%

confidence levels. Although the study aimed to achieve 10% relative precision at 90% confidence for the key savings metrics, the variability of performance among sampled units resulted in higher relative precision values.

Table 6 shows the estimated annual energy savings per horsepower for units across the NEEP region. We present the annual energy savings in units of kWh per hp.

Table 6. Annual Energy Savings per Unit Horsepower

Equipment Type	kWh/hp	RP @ 90%	RP @ 80%
Supply Fans	2,033	23.5%	18.3%
Return Fans	1,788	13.8%	10.8%
Cooling Water Pumps	1,633	17.7%	13.8%
Hot Water Pumps	1,548	18.4%	14.3%
WSHP Circulation Pumps	2,562	12.8%	10.0%

* Results apply for all units across the Northeast Mid-Atlantic states.

Table 7 shows the estimated demand reduction value for the ISO-NE summer and winter on-peak periods.[6] We present these summer demand savings in units of kW per hp.

Table 7. ISO-NE Summer and Winter On-Peak Demand Savings per Unit Horsepower

Equipment Type	ISO-NE Summer On-Peak			ISO-NE Winter On-Peak		
	kW/hp	RP @ 90%	RP @ 80%	kW/hp	RP @ 90%	RP @ 80%
Supply Fans	0.288	18.8%	14.6%	0.265	21.5%	16.7%
Return Fans	0.302	11.9%	9.3%	0.274	15.3%	11.9%
Cooling Water Pumps	0.183	16.7%	13.0%	0.194	18.2%	14.1%
Hot Water Pumps	0.096	34.1%	26.5%	0.221	20.7%	16.1%
WSHP Circulation Pumps	0.229	22.0%	17.1%	0.297	12.4%	9.7%

* Results apply for all units across the Northeast and Mid-Atlantic states.

Table 8 shows the estimated demand reduction value for the PJM summer peak period.[7] We present these summer demand savings in units of kW per hp.

[6] The ISO-NE on-peak summer demand reduction is the expected average demand reduction between the hours 1 p.m. and 5 p.m. on non-holiday weekdays in June, July, and August. The ISO-NE on-peak winter demand reduction is defined as the average demand reduction between the hours of 5 p.m. and 7 p.m. on non-holiday weekdays in December and January.

[7] The PJM summer peak demand is the expected average demand reduction during the hours 2 p.m. and 6 p.m. on non-holiday weekdays in June, July, and August.

Table 8. PJM Summer Peak Demand Savings per Unit Horsepower

Equipment Type	kW/hp	RP @ 90%	RP @ 80%
Supply Fans	0.286	19.0%	14.8%
Return Fans	0.297	12.4%	9.7%
Cooling Water Pumps	0.185	16.7%	13.0%
Hot Water Pumps	0.096	34.3%	26.7%
WSHP Circulation Pumps	0.234	20.6%	16.0%

* Results apply for all units across the Northeast and Mid-Atlantic states.

The team compared the study results with the estimated savings assumptions from the Massachusetts, Mid-Atlantic, and New York Technical Reference Manuals and to the results of the Massachusetts Pre/Post VSD study. For each parameter, the savings results generally fall within the expected range of savings.

0.3.6 Key Findings that Explain the Results

We uncovered multiple important findings that guided our analysis approach and dictated our recommendation for a single set of savings results averaged across the NEEP region.

Variable speed drives frequently operate at constant speed.

Our on-site observations and metering data showed that customers operated at least one third of VSD-controlled motors at a constant speed (typically less than full speed) during the nine- to 12-month data collection period. Similarly, the Massachusetts Pre/Post VSD Study found that customers operated more than two-thirds of the metered VSDs at constant speed. When we discussed this operating strategy during our on-site interviews,[8] some facility operators indicated that they intended this constant speed operation while others indicated that they had not fully commissioned the VSD equipment. Although we expect VSDs to vary the motor speed depending on load conditions, the observed constant speed operation may result in higher energy savings during peak demand periods compared to when standard savings assumptions that VSD-controlled motors operate at or close to full speed during peak conditions.

Operators may select constant speed operation over variable speed operation.

Although we expect operators to use new variable speed drives to vary the operating speed of the motor, we found that it is not uncommon for operators to choose to operate the motor at a constant speed setting. Through discussions with facility staff in this study and our building commissioning engineers, we identified several reasons an operator may choose to use a VSD to operate a motor at constant speed:

[8] We asked these questions during removals at the end of our data collection period to minimize any influence on the facility's typical operation.

- Operators may use a VSD to dial in on a reduced constant flow requirements. Reduced constant flow could also be achieved by using a valve or damper to throttle the flow or for certain pumping applications modifications could be made to the pump impellers. Compared to the throttling option, the VSD substantially reduces power requirements, energy consumption, and energy costs. Compared to the impeller modification option, the VSD allows the operator to keep the existing equipment in place and retains the flexibility of increasing speed (and capacity) if needed in the future.
- Operators may forgo the cost of implementing the controls for variable speed operation and instead settle on a reduced constant speed that is acceptable. Implementing controls may require installing new flow or pressure sensors, connecting those sensors and the VSD to a central EMS, programming controls sequences, and commissioning the system to ensure that the controls work correctly. Due to the cost and time requirements, operators may prefer to operate the equipment at a constant speed that meets the generally meets flow requirements. This constant speed may be higher than the necessary for periods of low load, but still reduces energy consumption and costs compared to constant speed. The installation of the VSD allows them to take advantage of further operational modifications if the controls are updated in the future.

Variable speed drive performance often does not track outside temperature.
In addition to a large percentage of VSDs that operated at a constant speed setting (discussed above), our unit-level data analysis demonstrated that the operating power for more than half of the units did not correlate with ambient temperature. Unlike larger equipment that operates to meet whole-building HVAC loads, internal variables such as occupancy or occupant activity may be more influential to VSD performance than external variables such as ambient temperature.

The savings estimates for each weather region are similar and similarly diverse.
In our aggregation analysis, we calculated average savings for each weather region and compared savings estimates between regions as well as to the average across all regions combined (NEEP region). The comparison showed that the confidence intervals for the regions overlap in most cases, suggesting that the average results are not very different from region to region. The confidence interval for the combined NEEP region covered a range that lies within the other regional intervals but provided a narrower margin of error around the mean. Further, we found that the variation in operation was similar from region to region, which provided another indication that regional differences were small. Due to these findings, we present average savings across all six weather regions.

Most pre-retrofit equipment operates at constant power.
The evaluation team's on-site survey and secondary data review indicated that a majority of pre-retrofit equipment operated at constant power. As indicated in Table 5, we modeled 98% of the pre-retrofit systems at constant power (after removing several occurrences of VSD baselines from the sample). Although standard VSD assumptions often model other variable flow systems as the baseline for VSD retrofit project, our research suggests that even when these variable flow systems exist they are not in

working condition. Our research is supported by the Massachusetts Pre/Post VSD Study, which demonstrated constant power operation for 100% of the pre-retrofit systems.

0.3.7 Application of Results

Implementers in the Northeast and Mid-Atlantic states may use these results to estimate the savings for VSD installations that meet the following characteristics:

- The VSD is retrofitted on HVAC equipment in an existing nonresidential building and does not replace an existing, working VSD.
- The VSD controls a motor no larger than 200 horsepower.
- The VSD controls a motor driving one of these equipment types: (1) supply fans, (2) return fans, (3) chilled water plant distribution pumps, (4) hot water distribution pumps, and (5) water source heat pump distribution pumps.
- The controlled equipment serves an HVAC load.

When using these results, the implementer should calculate the desired savings parameter by multiplying the rated horsepower of the motor or total horsepower of the population of motors by the appropriate savings factor from the tables above. For example, to estimate the annual energy savings for a VSD retrofit project on a 50-hp supply fan, the implementer should multiply 50 (the rated horsepower of the existing motor) by the appropriate savings factor from Table 6. Similarly, the Sponsor may estimate the ISO-NE on-peak demand reduction by multiplying 50 (the rated horsepower) by the appropriate demand savings factor from Table 7.

Dissimilar to many TRM savings approaches that provide savings factors by building type or that use engineering algorithms to estimate savings using project-specific input parameters, the results of this study are averaged savings that account for the varied performance of VSD installations across building types and weather regions in the Northeast and mid-Atlantic states. This study does not deny the influence of building operating hours or ambient temperature on VSD performance; however, the diversity of equipment performance demonstrated in this study indicates that these two variables are not reliable predictors for VSD performance. As discussed in this report, many other factors such as equipment operating schedules, motor configuration, and VSD control strategy also influence VSD performance and savings estimates.

These study results are based on direct and long-term measurements of nearly 400 VSD installations and account for the diversity of motor sizes, building types, HVAC loads, and operating strategies, and seasonal differences across the northeast. The results also account for recent, measured findings about pre-retrofit performance.

0.4 Recommendations

The evaluation team offers the following recommendations for implementers and evaluators of VSD projects to improve the energy savings of VSD installations and effectiveness of VSD programs.

Recommendations for Implementers

- Continue to promote the installation of VSD on existing equipment.
  - VSD retrofit projects are achieving significant energy and demand savings across the Northeast and Mid-Atlantic regions.
- To ensure VSDs operate as intended to achieve energy and demand savings, Program Administrators should integrate VSD control and commissioning requirements into program implementation activities. Application forms should require specification of the intended control strategy, and post-installation inspection should include verification of commissioned VSD control sequences.
  - We observed during the site visits and in our reviews of the metered data that many customers operate their VSDs at constant speed. In some cases, customers intend to operate VSDs at constant speed, but for many customers this constant-speed operation is due to incomplete project commissioning. In addition, we found that a larger percentage of VSDs operated at constant power in the Massachusetts Pre/Post VSD Study (conducted immediately before and after VSD installation) compared to the NEEP study (conducted at least one year after installation). We assume that the lower percentage of constant-speed units observed in this study is due to the longer period of elapsed time after the VSD installation, which allowed more customers to complete commissioning.
- As VSDs saturate the existing building stock, the Program Administrators should take more care in screening project eligibility.
  - For several sampled projects, the rebated VSD units replaced existing VSD units at the end of their useful lives. Although we did not include those baseline occurrences in this study, these observations are evidence of projects' receiving program incentives despite ineligibility.
- To support future evaluation efforts, the Program Administrators should add pre-retrofit data collection requirements to program application forms. At minimum, the PAs should require customers to specify the baseline system type and working condition of that system and operating schedule for the baseline equipment.
  - Information about baseline operation is limited in Sponsor tracking data and difficult to collect after customers complete VSD projects. Since baseline operation is a critical component for estimating energy and peak demand savings, it is important for the programs to record the working condition of baseline systems as well as the existing operating strategy and schedule.

Recommendations for Evaluators

- The timing of the post-installation inspection and metering is important. Our findings suggest the customers may take a year or longer installing the VSD to set up the controls and fully commission the system. Performing evaluation activities within a year of installation will provide accurate first-year results, but may not accurately reflect VSD performance in the following years.

- When metering VSD power for energy analyses, the evaluator should examine seasonal operation defined for each facility. Seasons may be associated with changes in equipment purpose (e.g., heating or cooling), occupancy patterns (e.g., academic year vs. vacation periods), or other parameter such as control strategy (e.g., constant vs. variable speed).
    - Customers use HVAC motors differently throughout the year. This is especially true for equipment in seasonal facilities and for equipment that serve both heating and cooling loads.

1 Introduction

This study is the third in a series of savings loadshape studies focused on efficient technologies implemented through the energy-efficiency programs of NEEP's Sponsors. This loadshape study targets the annual, peak, and hourly electric demand savings achieved by variable speed drives (VSDs) installed on existing heating, ventilation, and air conditioning (HVAC) equipment in commercial buildings throughout the Northeast and Mid-Atlantic states, including Maryland, Maine, Massachusetts, Connecticut, Vermont, New Hampshire, and Rhode Island, and New York.

1.1 NEEP EM&V Forum

The Northeast Energy Efficiency Partnerships (NEEP) is a nonprofit organization established to promote energy-efficiency throughout the Northeast and Mid-Atlantic.[9] NEEP created the Evaluation, Measurement, and Verification (EM&V) Forum in 2008 "to support the development and use of consistent protocols to evaluate, measure, verify, and report the savings, costs, and emission impacts of energy efficiency and other demand-side resources."

In particular, the EM&V Forum facilitates joint research and evaluation by pooling funds from multiple Sponsors to conduct large-scale research studies such as the loadshape series.[10] These studies provide robust estimates of the energy and demand savings achieved by demand side resources the Northeast.

Table 9 shows Sponsors of the EM&V Forum and indicates the states included in this VSD loadshape project.

Table 9. EM&V Forum Sponsors and VSD Study Participants

State	Sponsor	Study Participant*
Connecticut	CT Energy Efficiency Fund	◆
District of Columbia	District Dept. of the Environment	
Maine (2012)	Efficiency Maine Trust	◆
Maryland	Maryland Energy Administration EmPOWER Maryland Utilities (PHI/Pepco, Delmarva, SMECO, First Energy, Baltimore Gas & Electric)	◆
Massachusetts	Cape Light Compact National Grid NSTAR Unitil Western Massachusetts Electric Company	◆

[9] www.neep.org

[10] The NEEP EM&V forum has completed two loadshape studies to date: The Commercial Lighting Loadshape Study (completed in 2011) and the Unitary AC Loadshape Study (completed in 2012).

State	Sponsor	Study Participant*
New Hampshire	NH Electric Co-op Public Service New Hampshire Unitil	◆
New York	Long Island Power Authority New York Power Authority New York State Energy Research and Development Authority	◆
Rhode Island	National Grid	◆
Vermont	Department of Public Service	◆

* Participants are Program Administrators that provided data for the study population of VSD installations.

1.2 Project Objectives and Scope

The objective of the NEEP VSD Loadshape study is to develop estimates of the annual, peak, and hourly demand savings of achieved variable speed drive (VSD) installations on existing HVAC equipment in commercial buildings. In the early stages of this project, the Subcommittee agreed to focus on the five equipment type categories that make up the majority of annual energy savings from VSD installations across the Sponsors' programs:

- Supply fans
- Return fans
- Cooling water pumps
- Heating hot water pumps
- Water source heat pump circulation pumps.

The study uses both primary data—direct power metering and data collection for a sample of VSD installations across the Sponsors' programs—and secondary data to establish the hourly savings loadshapes for each of these selected equipment type categories.

1.3 Definitions

In Table 10, we provide definitions for terms critical to understanding the sampling, data collection, and/or analysis methods we used for this study.

Table 10. Definition of Terms

Term	Definition
Variable Speed Drive (VSD)	Variable speed drives control the operating speed of connected motors based on programmed control strategies.
HVAC	Heating, Ventilation, and Air Conditioning; in this study, we focus on VSDs installed on or equipment that serve HVAC loads in existing nonresidential buildings.

Term	Definition
Loadshape	A loadshape describes the hourly electricity demand for all 8,760 hours in a year. In this study, we calculate demand loadshapes to model the hourly electric demand of HVAC equipment with or without VSDs. Similarly, we calculate savings loadshapes to model the expected hourly demand reduction achieved by VSD-controlled equipment compared to the pre-retrofit or baseline condition.
Equipment Type	Equipment type refers to the categories of commercial HVAC equipment. In this study, we focus on these five equipment type: supply fans, return fans, cooling water pumps, heating hot water pumps, and water source heat pump distribution pumps.
Project	Project refers to an activity completed by a participant in one of the Sponsors' programs and tracked in the Sponsor's database, in which one or more VSDs were installed. All projects in the study sample had at least one VSD installation on one of the five defined equipment types.
Unit	A unit refers to a unique VSD installation as part of a VSD project. All units in the study sample involved power metering for VSD-controlled equipment from one of the five selected equipment types.
Sample Phase	We performed multiple phases of sampling in order to improve the distribution of equipment types in the study sample. Each sampling phase has a different condition set for the eligible population, in order to target specific equipment types.
Sample Stage	We performed two stages of sampling within each sample phase. The first stage involved sampling projects based on project size and weather region. The second stage involved sampling the units within a sampled project for power metering.
Target Sample	The target sample describes the ideal sample of projects and units developed in the sample strategy and used to guide the sample draw.
Study Sample	The study sample is the collection of projects and units included in the analysis. Differences between the target and study samples may be due to (1) small populations of projects in some strata and weather regions, (2) inability to control for equipment type in the sample draw, and (3) differences between expected and actual units for given project.
Operating Power	We use the term operating power to describe the measured or estimated power demand from the motor during periods of operation. For example, in our analysis of metered operating power, we examine the measured power only during periods when the motor is operating.
Primary/Lead Units	Primary units operate as the primary, or lead, equipment to serve the designated load. When there is a call for heating, cooling, or ventilation, the primary unit will respond to meet the load requirements.
Lag Units	Lag units assist primary, or lead, equipment when the lead equipment reaches its maximum capacity or a maximum setting. In these scenarios, the lag units will respond to serve load any load beyond what is served by the lead unit. Because the primary equipment usually serves the full HVAC load, lag units typically only operate when the loads are unusually high.
Rotating Units	Rotating units operate in a team of similar units to serve the same load. Facility operators rotate units to lengthen the lifetime of equipment and to provide redundancy in case of failure. Since rotating units take turns serving the designated load, each unit operates for only a fraction of the team's overall schedule.

Term	Definition
Back-up Units	Back-up units rarely operate and are in place to provide redundancy for primary or rotating units. Back-up units typically operate only when the other equipment malfunctions or is turned off for regular maintenance activities.
Weather Regions	We defined the following six weather regions for this study: DNY = Downstate New York; MAT = Mid-Atlantic; NEE = New England East; NEN = New England North; NES = New England South; UNY = Upstate New York

1.4 Acknowledgements

Many parties contributed to the design and execution of this loadshape study. First, we thank the NEEP EM&V Forum for engaging the region in these complex loadshape projects and organizing the many stakeholders throughout the project.

We thank the Forum Sponsors and Loadshape Subcommittee members for recognizing and contributing to this important research. At each stage of the project, Sponsors and subcommittee members provided critical project data, reviewed project deliverables, and participated in project status meetings. We thank the subcommittee members for their diligence in responding to data requests and for contributing thoughtful feedback during each phase of the project.

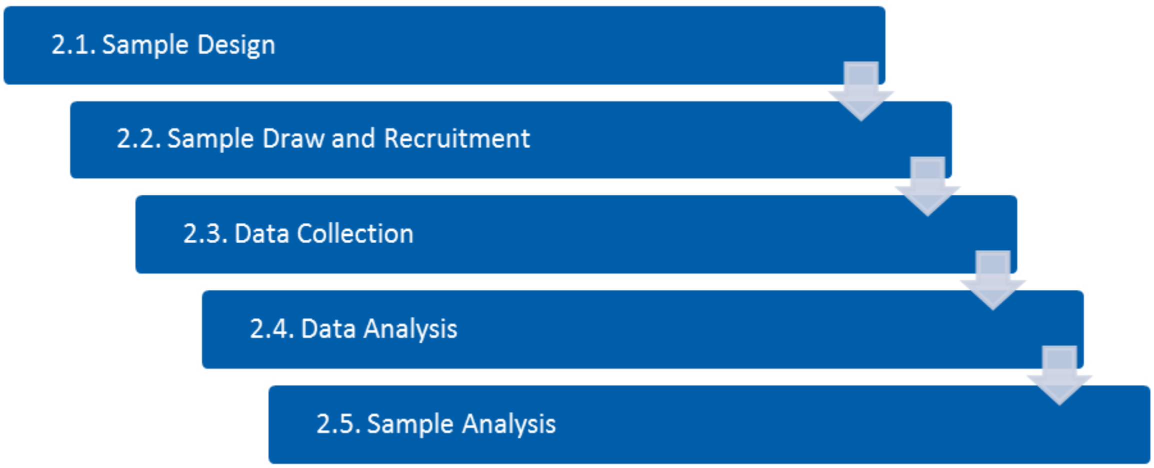
The subcommittee members include: Cheryl Hindes, Mary Straub, and Sheldon Switzer from BG&E; Kristin Graves, Michael Ihesiaba, and Mahdi Jawad from Con Edison; Kristy Fleischmann from Constellation Energy; Matt Quirk and Chris Siebens from First Energy; Bill Blake and Whitney Brougher from National Grid; Dave Bebrin, Tom Belair, Geoff Embree, Monica Kachru, Gary LaCasse, Joe Swift, and David Weber from Northeast Utilities (including CL&P, NSTAR, and WEMCo); Marilyn Brown and Mary Cahill from NYPA; Deborah Pickett from NYSEG; Judeen Byrne, Tracey DiSimone, Victoria Engel-Fowles, and Ed Kear from NYSERDA; David Sneeringer from Pepco; Paul Gray from United Illuminating; Mary Downes from Unitil; Bill Fischer and Nicola Janjic from VEIC; Jim Cunningham and Leszek Stachow from the NH PUC; Niko Dietsch from the EPA; Taresa Lawrence from the District of Columbia Energy Office; Amanda Kloid and James Leyko from the Maryland PSC; Arthur Maniaci from the New York ISO; Ralph Prahl from the Massachusetts EEAC; Allison Reilly from NESCAUM; Jennifer Chiodo from CX-Associates (Massachusetts Energy Efficiency Advisory Council); Scott Dimetrosky from Apex Analytics (Connecticut Energy Efficiency Board); Colin High from Resource Systems Group, Inc. ; Lori Lewis from Analytical Evaluation Consultants (Connecticut Energy Efficiency Board); Lisa Skumatz from SERA, Inc. (representing Connecticut Energy Efficiency Board); Doug Hurley from Synapse-Energy; and Julie Michals, Elizabeth Titus, Cecily McChalicher, and Danielle Wilson from the NEEP EM&V Forum.

Finally, we thank the members of the NEEP Loadshape Technical Committee–Elizabeth Titus, David Jacobson, and Steve Waite–who participated in many long discussions and contributed insightful questions, feedback, and recommendations throughout the project.

2 Methods

The evaluation team conducted this VSD loadshape study in the five key tasks described in Figure 6. This progression of tasks is similar to the previous loadshape studies and other EM&V research. However, the specific methods within each task are uniquely complex due to limitations in the program tracking data, elapsed time since the project completion, and variation in the operation of VSDs throughout the study sample. In this section and referenced Appendices, we describe the methods for each analysis task including our observations and key assumptions.

Figure 6. Key Tasks for Loadshape Analysis



2.1 Sample Design

For this study, the evaluation team developed a unique sampling strategy to account for varying levels of available tracking data from the Sponsors, limited information about the equipment types in the population of projects, and expected variation between weather regions and Sponsors.

In this first task, we reviewed the Sponsors' tracking data, designed the sample framework, and created the sample. This strategy is documented in the memorandum "VSD Loadshape Project – Proposed Sampling Strategy, Updated," dated August 2, 2012.

2.1.1 Analysis of Sponsor Tracking Data

After the project kick-off meeting, the evaluation team submitted a data request to the NEEP EM&V Technical Committee and study Sponsors. We received participation records from 12 Sponsors. These data included 3,845 lines accounting for 2,109 unique projects completed between 2009 and 2012.

Based on our review of these data and follow-up discussions with specific Sponsors, we developed a set of criteria to further define the dataset. We excluded all projects that met any of the following criteria:

- The project was completed in or before 2009.
- The project was not yet completed.

- The customer installed the VSD on equipment serving process loads or on chiller compressors.
- The project was new construction or major renovation.
- The project was part of a NYSERDA custom program.

These criteria reduced the qualified sampling population to 2,798 unique data lines, representing 1,582 unique projects. It is important to note that this qualified population may include some unqualified projects, since we could not remove projects for which we did not have complete tracking data.

Table 11 summarizes the tracking data provided by each Sponsor, including whether each data type was available in the Sponsor tracking data. The last column indicates the data types available across all Sponsor data.

Table 11. Tracking Data Characteristics by Sponsor

Data Type	Efficiency Maine	PSNH	Efficiency Vermont	National Grid	NSTAR	CL&P	Con Edison	NYSERDA	LIPA	Pepco	First Energy	BG&E	All
Project Energy Savings	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆
Project Demand Savings	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆
Measure Level Energy Savings	◆			◆	◆	◆	◆	◆	◆	◆	◆	◆	○
Project Type (New/Retrofit)		◆	◆	◆	◆	◆		○		◆	◆	◆	○
Prescriptive Projects	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆
Custom Projects		◆	◆	◆		◆	◆	◆					○
Equipment Type	◆	○		○	◆	○	○		◆	◆	◆	◆	○
Base Case Control Type									◆				○
Building Type	◆	○	○	○	◆	◆	◆	○	◆	○		◆	○
2010 Projects	◆	◆	◆	◆	◆	◆		◆			◆	◆	○
2011 Projects	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆
2012 Projects		◆	◆	◆		◆		◆	◆	◆		◆	○

◆ Indicates that the Sponsor provided information on almost all projects.
○ indicates that the Sponsor provided information on some projects.
A blank cell indicates that these data were not available.

The last column in Table 11 indicates that only four data types were consistently available in all Sponsors' tracking data: project energy savings, project demand savings, prescriptive projects, and 2011 projects. Therefore, when comparing data to determine the relative impact of any equipment type, building type, or Sponsor, we limited our review to only data from 2011 projects.

The following tables summarize 2011 installations by state, sponsor, equipment type, and building type.

Table 12. 2011 Records by State

State	2011 Data Lines	2011 Annual Energy Savings (kWh)	Percent of 2011 Annual Energy Savings
New York	534	52,094,873	58.70%
Massachusetts	269	16,863,715	19.00%
Maryland	152	10,875,541	12.25%
Connecticut	65	3,344,469	3.77%
Rhode Island	36	2,301,688	2.59%
Maine	107	1,566,232	1.76%
New Hampshire	18	973,232	1.10%
Vermont	39	731,616	0.82%
Total	1,220	88,751,364	100.00%

Table 13. 2011 Records by Sponsor

Sponsor	2011 Data Lines	2011 Annual Energy Savings (kWh)	Percent of 2011 Annual Energy Savings
Consolidated Edison	126	29,675,457	33.44%
NYSERDA	370	21,214,476	23.90%
Northeast Utilities (NSTAR)	161	10,128,360	11.41%
National Grid	146	9,454,766	10.65%
BG&E	120	6,742,301	7.60%
CL&P	65	3,344,469	3.77%
Pepco	21	3,093,340	3.49%
Efficiency Maine	107	1,566,232	1.76%
LIPA	38	1,204,939	1.36%
FirstEnergy	11	1,039,900	1.17%
Efficiency Vermont	39	731,616	0.82%
PSNH	16	555,508	0.63%
Total	**1,220**	**88,751,364**	**100.00%**

Table 14. 2011 Records by Equipment Type

Equipment Type	2011 Data Lines	2011 Annual Energy Savings (kWh)	Percent of 2011 Annual Energy Savings	
			All	Excluding Unknowns
UNKNOWN*	444	24,695,866	27.83%	NA
Cooling Water Pump**	148	16,711,456	18.83%	26.09%
Supply Air Fan	207	14,400,588	16.23%	22.48%
Fans, All Types***	40	11,496,292	12.95%	17.95%
Water Source Heat Pump Circulation Pump	38	3,848,103	4.34%	6.01%
Hot Water Pump	89	3,674,750	4.14%	5.74%
Boiler Feedwater Pump	37	2,888,901	3.26%	4.51%
Cooling Tower Fan	64	2,520,766	2.84%	3.94%
Pump, All Types***	10	2,443,487	2.75%	3.81%
Building Exhaust Fan	50	2,436,508	2.75%	3.80%
Return Air Fan	71	1,996,261	2.25%	3.12%
Make-Up Air Fan	20	1,559,276	1.76%	2.43%
Boiler Draft Fan	2	79,111	0.09%	0.12%

* We assigned the unknown classification in cases for which the equipment type was not available.
** Cooling Water Pumps includes Chilled Water Pumps and Condenser Water Pumps. Some sponsors separate these two technologies while others do not.
*** We used the “Fans, All Types” or “Pumps, All Types” classifications in cases for which (1) we knew the record corresponded to a fan or pump installation, but did not know the specific type, or (2) multiple fans or multiple pumps of different types were within one record.

Table 15. 2011 Records by Building Type

Building Type*	2011 Data Lines	2011 Annual Energy Savings (kWh)	Percent of 2011 Annual Energy Savings
Office	238	37,051,892	41.75%
Manufacturing	161	11,160,532	12.58%
College	151	6,760,255	7.62%
Other	92	5,303,072	5.98%
Hospital	96	5,280,259	5.95%
UNKNOWN	90	4,276,818	4.82%
Education	125	3,907,962	4.40%
Hotel	38	3,652,553	4.12%
Retail	43	2,834,414	3.19%
Multifamily	35	2,204,420	2.48%
Health	43	2,062,459	2.32%
Water Supply or Treatment	14	1,080,205	1.22%

Building Type*	2011 Data Lines	2011 Annual Energy Savings (kWh)	Percent of 2011 Annual Energy Savings
Government	28	939,441	1.06%
Amusement	10	560,935	0.63%
Warehouse	10	457,530	0.52%
Institutional	1	223,832	0.25%
Assembly	14	223,213	0.25%
Commercial	8	147,813	0.17%
Mixed	8	137,325	0.15%
Laboratory	1	122,100	0.14%
Religious	1	96,954	0.11%
Restaurant	4	81,766	0.09%
Business	3	67,200	0.08%
Museum	2	51,480	0.06%
Automotive	2	24,520	0.03%
Misc.	1	23,296	0.03%
Grocery	1	19,121	0.02%

* The team classified building types based only on the text records in the Sponsor tracking data; we did not reference SIC or NAICS codes for this stage of the project.

** It is unknown at this time if the VFD installations within each building type are serving HVAC equipment or manufacturing equipment. If one of these projects is sampled and the installation is determined to be serving manufacturing equipment, the sample point will be replaced.

The evaluation team made the following conclusions based on this review of the Sponsors' 2011 VSD projects:

- Random sampling would result in bias toward the Sponsors that provided more years of data. Furthermore, given that 88% of the stated savings occur within five service territories, the evaluation team must take additional steps to ensure that all Sponsors are represented in the study and that the results are applicable to the programs offered by each Sponsor.
  - Our framework used both weather region and size category as stratification variables to reduce this bias and ensure representation.
- There are many projects and a substantial percentage of savings for which the equipment type served is unknown (i.e., unavailable in the tracking data). Sampling must either separate unknown equipment projects from known equipment projects or occur at the project level.
  - Our framework involved an initial stage of project-level sampling followed by a second stage of unit-level sampling within sampled projects.

2.1.2 Define Sampling Framework

The evaluation team designed the sampling strategy to achieve the following objectives:

- Produce annual operation and savings loadshapes that are flexible enough to be used by all project sponsors and accurate enough to meet requirements for program reporting.
- Balance the need for accurate equipment-specific loadshapes with the desire to produce as many loadshapes as possible.
- Produce accurate loadshapes across multiple equipment types within the agreed project scope of 420 metered units.

Based on these objectives and the results of our tracking data review, the evaluation team established sample targets for the top five equipment types and developed a multi-*stage*, multi-*phase* sampling approach to meet those targets. Our framework stated the following:

1. We will calculate loadshapes for the following five equipment types: supply fans, return fans, cooling water pumps, hot water pumps, and water source heat pump circulation pumps.
    - These equipment types represent 64% to 85% of known 2011 equipment type savings, depending on what is assumed to be included from the "fans" and "pumps" classifications. We included Return Air Fans over other equipment types with similar impacts because 75% of the projects known to include a return air fan VFD also include a supply air fan VFD. The inclusion of RAF in the study increases the number of loadshapes analyzed without decreasing the overall efficiency of the study.
    - Focusing the study on these five equipment types reduces the available sampling population from 1,582 projects to 1,409 projects.
2. We will use the meter installation targets described in Table 16 for the five selected equipment types. We proposed a larger number of meter installations for supply fans and cooling water pumps for the following reasons:
    - The tracking data suggest that these two equipment types represent over 50% of the Sponsors' 2011 VSD energy savings, so we should prioritize the accuracy of their loadshapes over the other loadshapes.
    - We could subdivide both equipment types into two unique applications: Supply Fans in RTUs, Building Supply Fans, Chilled Water Pumps, and Condenser Water Pumps. Increasing the number of data points for these two basic equipment types increases the potential for accurate load of all four equipment types.
3. We will conduct multiple stages of sampling.
    - The first stage of sampling will be at the project level. We will draw this sample from all projects occurring between 2010 and 2012 in order to maximize the size of the pool of potential study participants. Project-level sampling will be stratified by project size (annual kWh savings) and weather region to ensure representation with respect to these variables

and program administrators. Weather region definitions will match those used in NEEP's 2011 C&I Unitary HVAC Loadshape Project Final Report.

- In the second stage of sampling, we will select specific VSDs for metering within each sampled project. If a sampled project includes the installation of multiple VFDs, then up to four VFDs within each project may be metered. If the project has fewer than four drives, then those drives will all be metered. If it includes multiple equipment types, then the number of equipment types metered will be maximized before multiple meters are installed on any single equipment type. If these rules do not uniquely determine all of the equipment to be metered at a given site, then VSDs will be selected randomly within the site as needed. (This random selection will be weighted according to equipment-type sampling targets; see Table 6.) For each VSD selected through randomization, we will record the within-site sampling probability for use in constructing sample weights. (These weights will be used in the data analysis.)

Table 16 describes the sampling targets for each equipment type as developed in our sample framework. Due to the limited equipment type information in the tracking data, we noted that our ability to achieve these targets is dependent on the existence of these equipment types within study population.

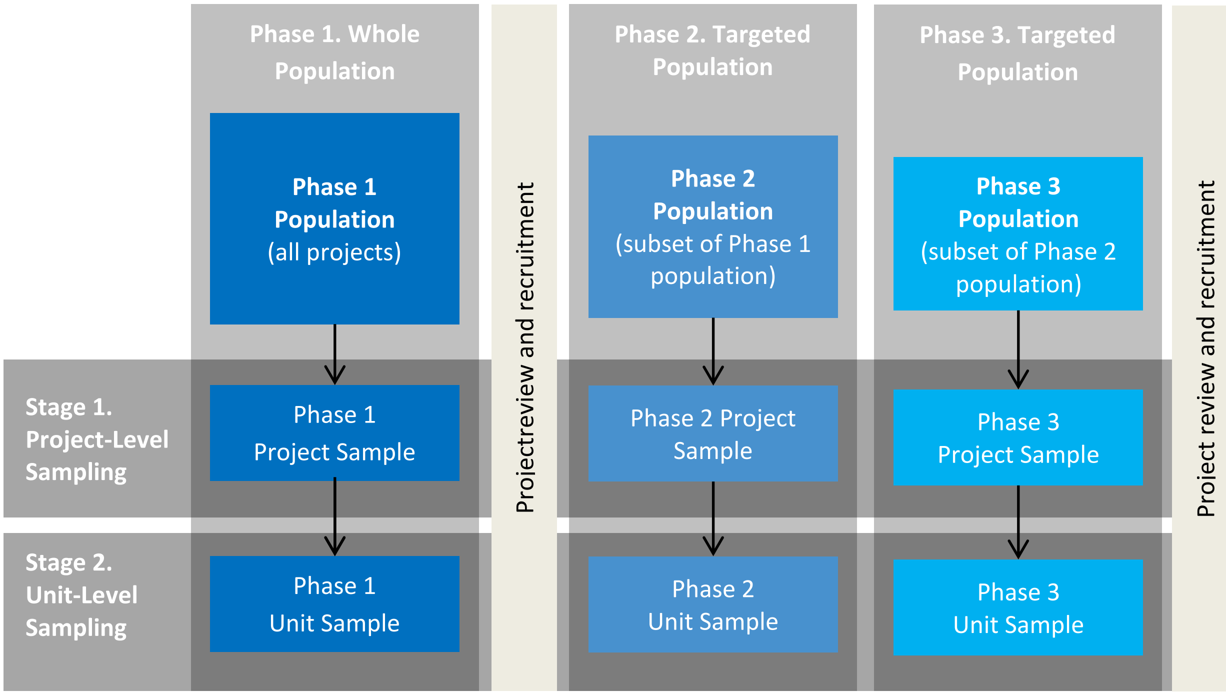
Table 16. Meter Installation Targets by Equipment Type

Equipment Type	Meter Installation Target
Cooling Water Pump (CWP)	102
Supply Air Fan (SAF)	102
Hot Water Pump (HWP)	72
Water Source Heat Pump Circulation Pump (WHP)	72
Return Air Fan (RAF)	72
Total	**420**

2.1.3 Develop Sampling Strategy

Figure 7 shows a diagram of our multi-stage, multi-phase sampling strategy to achieve the defined sample targets. The figure illustrates our method of performing two sampling *stages* within each of three sampling *phases*. After the first phase of sampling, we reviewed project documents and recruited customers to determine our targeted population for the next sampling phases. After the last sampling phase, we reviewed project documents and recruited customers to determine our final study sample.

Figure 7. Diagram of Multi-Stage, Multi-Phase Sample Strategy



Sample Stages

The study required two *stages* of sampling in order to select units within each equipment type category which were also distributed across various project sizes, weather regions, and study Sponsors.

- **Stage 1.** The first stage of sampling selected *projects*. We sampled projects among the population of all projects that occurred between 2010 and 2012 in order to maximize the size of the pool of potential study participants. We stratified the population by project size[11] and weather region[12] to ensure representation with respect to these variables and the study Sponsors.
- **Stage 2**. The second stage of sampling selected *units* within each sampled project. For sampled projects with four or fewer VSDs, we selected all units for the sample. For sampled projects with more than four VSDs, we sampled units to maximize the number of equipment types.

Sample Phases

The study required multiple *phases* of sampling in order to prevent oversampling the most common equipment types (supply fans and cooling water pumps). Since project equipment types were often

[11] We define the project size as the total annual kWh savings for the project in Sponsors' tracking data.
[12] Weather region definitions match those used in NEEP's 2011 C&I Unitary HVAC Load Shape Project Final Report.

unknown until samples were collected, sampling in multiple phases allowed us to update the targeted equipment types in the next phase to ensure coverage of the five equipment types of interest.

- **Phase 1**. We designed the first phase to select about two-thirds of the expected total project sample. We sampled projects randomly within each stratum without regard to the equipment types.
- **Phases 2+**. We designed the additional phases of sampling to improve control of the distribution of equipment types in the final unit sample. These additional phases allowed us to adjust the sampling population to target equipment types that were under-sampled in previous phases and to minimize the addition of equipment types that we over-sampled in previous phase(s).

Stratification by Project Size (Annual kWh Savings)

The team divided the population of projects into four project size categories such that each category represented 25% of the population's total savings. Table 17 shows the size boundaries, number of projects in the population, and total stated annual energy savings for each size category

Table 17. Stratification by Project Size (Annual kWh)

Project Size Category	Minimum Project Savings (kWh)	Maximum Project Savings (kWh)	Number of Projects	Stated Annual Savings (kWh)	Percent of Savings
1	679,638	5,938,500	23	37,018,663	25%
2	253,616	660,311	98	36,325,018	25%
3	100,533	248,270	230	36,725,299	25%
4	0	99,447	1,058	36,594,130	25%
Total	**NA**	**NA**	**1,049**	**146,663,110**	**100%**

Table 18 shows optimal sample sizes within each size category, as well as the expected numbers of meter installations, both in total and on average per project. We calculated the expected numbers of meter installations per project based on available data.

Table 18. Stratification by Project Size (Annual kWh)

Project Size Category	Sample Target	Expected Meter Installations	
		(per project)	(Total)
1	10	3.63	36
2	37	3.46	128
3	42	3.02	128
4	60	2.13	128
Total	**149**	**NA**	**420**

Stratification by Weather Region

The evaluation team assigned each project in the population to one of the following six weather regions:

- Mid-Atlantic (MAT)

- New England – North (NEN)
- New England – East (NEE)
- New England – South NES)
- New York – Inland (UNY)
- New York – Urban/Coastal (DNY)

These weather regions match those developed for NEEP's 2011 C&I Unitary HVAC Loadshape Project. A "◆" in the table indicates the weather region(s) to which each Sponsor's customers were assigned.

Table 19. Sponsors by Weather Region

Sponsor	DNY	MAT	NEE	NEN	NES	UNY
BG&E		◆				
CL&P					◆	
Con Edison	◆					
Efficiency Maine				◆		
Efficiency Vermont				◆		
First Energy		◆				
LIPA	◆					
National Grid*			◆ (NH)	◆ (MA)	◆ (RI)	
NU-NSTAR			◆			
NYSERDA	◆					◆
Pepco		◆				
PSNH				◆		

*Since National Grid's projects included customers in three states (NH, MA, and RI), we assigned its customers to weather regions based on the customer's state.

Sample Size Targets

Table 20 shows the distribution of projects across project size categories and weather regions in the population.

Table 20. Project Population Sizes

Project Size	DNY	MAT	NEE	NEN	NES	UNY	Total
1	15	3	4	1	0	0	23
2	26	9	33	3	11	16	98
3	33	34	67	8	24	64	230
4	92	90	191	135	128	422	1,058
Total	**166**	**136**	**295**	**147**	**163**	**502**	**1,409**

We designed the stratified sampling sizes to balance representation by weather region, the available sampling population, and the number of projects supported annually by each administrator. Table 21 shows the target sample sizes in each stratum and the total number of expected meter installations for each project size category.

Table 21. Target Project Sample Sizes

Project Size	Projects							Meter Installations
	DNY	MAT	NEE	NEN	NES	UNY	Total	
1	7	1	2	0	0	0	10	36
2	10	5	11	2	4	4	36	124
3	7	7	10	3	6	9	42	126
4	6	6	10	14	10	17	63	134
Total	**30**	**19**	**33**	**19**	**20**	**30**	**151**	**422**

2.1.4 Sample Execution

The target sample sizes developed in the sample strategy represent a sample design centered around confidence and precision goals for estimates to be summarized across projects. The final goal, however, is to produce loadshape estimates at the unit level and summarize across unit-level estimates within each equipment types. The evaluation team could not design the sample around this goal due to lack of information on the distribution of units across the population.

To obtain sufficient information on each equipment type, we collected the sample using the multi-phase, multi-stage procedure discussed above. As stated in the original sampling memo, we expected to adjust the target sample sizes as actual sampling progressed in order to meet the meter installation targets for each equipment type. We sampled projects according to the target sample sizes described above, making refinements to the sampling that occurred after the first phase.

Sample Phase 1

In the first phase, we randomly sampled 107 projects[13] from the study population (Table 20) based on the target distribution across project size and weather region strata (Table 21). We then collected detailed project information about the equipment types included within each project from the Sponsors for the Phase 1 Project Sample.

Table 22 shows the distribution of sample sizes achieved in the Phase 1 Project Sample. The total sample size was 88 projects (compared to the target of 107) due to high non-response rates as well as ineligibility, verified using the detail project information collected during the first phase. Further, several sample projects were dropped during the site visits because the actual equipment type using the VSD did not match the documented equipment type and therefore the project was determined to be

[13] We drew an additional 53 back-up projects (50% of the target sample size) to replace any primary projects that were not available. If a primary project was unavailable, we replaced it with a back-up project, randomly selected among the available back-up projects in the same stratum as the non-response or dropout project. In the end, 43 (40%) of the 107 primary projects were dropped and replaced with back-up projects.

ineligible for the study. For each initially selected project that did not respond or dropped-out due to ineligibility, we attempted to identify a back-up project in the same stratum as the non-responder. However, we were not able to replace all non-responders or dropouts. Among projects selected as replacements, additional non-response and dropouts occurred.[14]

Table 22. Project Sample Sizes for Phase 1 by Weather Region[15]

Project Size	M	NEE	NEN	NES	UNY	DNY	Total
Phase 1							
1	2	1	0	0	0	4	7
2	4	5	1	3	2	7	22
3	7	7	3	3	6	5	31
4	5	7	8	3	5	0	28
Total	**18**	**20**	**12**	**9**	**13**	**16**	**88**

Table 23 shows the distribution of equipment types achieved in the Phase 1 Unit Sample. The distribution shows that the sample exceeded the meter installation target for supply fans, but did not meet the meter installation targets for the other four equipment types.

Table 23. Unit Sample Sizes for Phase 1

Phase	SF	RF	CWP	HWP	WHP	Total
1	118	38	65	30	5	256
Total Target	102	72	102	72	72	420
Pct. of Total Target	116%	53%	64%	42%	7%	61%

Sample Phase 2

After examining the equipment types achieved in the Phase 1 sample, we made two adjustments to the sample strategy for Phase 2:

- We designed the Phase 2 sample to minimize the inclusion of additional supply fans to the sample and to target the other four equipment types.
- We increased the expected total project sample size based on the observed average number of units per project collected in the Phase 1 sample.

Projects eligible for sampling in Phase 2 met the following criteria:

- We did not draw the project as either a primary for back-up project in Phase 1.

[14] It is important to note the high dropout rates for sampled projects in this study. The evaluation team removed projects from the sample for a number of reasons including: (1) ineligibility based on documented or actual equipment type, (2) requests from the Sponsors to remove a customer from the sample, (3) inability to contact the customer, or (4) customer declines to participate.

[15] Weather regions are defined in the "Definitions" section.

- *For project with equipment type tracking data*, the project included at least one VSD on one of the following equipment types: RF, CWP, HWP, and WHP. In other words, we marked any projects with VSDs only on supply fans as ineligible for Phase 2.
  - Projects with unknown equipment types were eligible to be included in the sample, however, if a sampled project was determined to have no eligible equipment types other than supply fans during the documentation review, recruitment phone call, or site visit, we replaced the project with a back-up project from the same stratum when possible.

We initially sampled 45 projects during Phase 2. Table 24 shows the distribution of projects achieved in the Phase 2 Project Sample.

Table 24. Project Sample for Phase 2

Project Size	MAT	NEE	NEN	NES	UNY	DNY	Total
PHASE 2							
1	0	2	0	0	0	0	**2**
2	0	11	0	0	1	0	**12**
3	5	8	1	0	3	2	**19**
4	0	0	2	0	2	0	**4**
Total	**5**	**21**	**3**	**0**	**6**	**2**	**37**

Table 25 shows the distribution of equipment types included in the unit sample resulting from both Phase 1 and Phase 2. The distribution shows that the total sample exceeded the meter installation target for supply fans and was close to meeting the target for cooling water pumps. However, sample sizes for RF, HWP, and WHP were still below 90% of the targeted sample sizes though, so we proceeded to Phase 3 sampling.

Table 25. Unit Sample for Phases 1 and 2 Combined

Phase	SF*	RF	CWP	HWP	WHP	Total
1	118	38	65	30	5	256
2	17	20	31	15	10	93
1+2	135	58	96	45	15	349
Target	102	72	102	72	72	420
Percent of Target	132%	81%	94%	63%	21%	83%

* Although Phase 2 made ineligible any projects that had only supply fans, some projects had supply fans in addition to other eligible equipment types. Supply fans added to the unit sample in Phase 2 are units included in these eligible, sampled Phase 2 projects.

Sample Phase 3

We performed a third phase of sampling to target the three equipment types with the smallest presence in the population: RFs, HWP, and WSHPs. We reduced the Phase 3 population to projects that met the following criteria:

- We did not draw the project as either a primary for back-up project in Phase 1 or Phase 2.

- *For projects with equipment type tracking data*, the project included at least one of the following equipment types: RF, HWP, WHP. That is, we marked any projects that included only SFs or CWPs as ineligible for Phase 3.

We sampled 40 projects from the Phase 3 population. Table 26 shows the distribution of projects achieved in the Phase 3 Project Sample.

Table 26. Project Sample for Phase 3

Project Size	MAT	NEE	NEN	NES	UNY	DNY	Total
PHASE 3							
1	0	0	0	0	0	0	0
2	0	1	0	0	0	0	1
3	2	9	0	1	0	1	13
4	1	13	4	9	0	0	27
Total	**3**	**23**	**4**	**10**	**0**	**1**	**41**

2.1.5 Final Sample for Data Collection

Table 27 shows the distribution of equipment types in the unit samples collected during each phase and resulting overall sample sizes. The distribution shows that the sample sizes exceeded the meter installation targets for supply fans, cooling water pumps, and hot water pumps and reached 90% of the meter installation target for return fans.

Table 27. Phase 1+2+3 Unit Sample by Equipment Type

Phase	SF	RF	CWP	HWP	WHP	Total
1	118	38	65	30	5	256
2	17	20	31	15	10	93
3	2	7	22	38	3	72
Total	**137**	**65**	**118**	**83**	**18**	**421**
Target	102	72	102	72	72	420
Pct. of Target	134%	90%	116%	115%	25%	100%

The final sample includes 166 projects and 421 units across the project size and weather region strata. Table 28 shows the distribution of projects sampled in each stratum. For each of the 166 sampled projects, we installed power meters on up to four units (on average, we metered 2.5 units per project).

Table 28. Final Sample of Projects by Weather Region and Project Size

Project Size	MAT	NEE	NEN	NES	UNY	DNY	Total
1	2	3	0	0	0	4	**9**
2	4	18	1	2	3	7	**35**
3	14	24	4	4	9	8	**63**
4	6	21	14	11	7	0	**59**
Total	**26**	**66**	**19**	**17**	**19**	**19**	**166**
Pct. of Total	16%	40%	11%	10%	11%	11%	100%

Table 29 shows the distribution of units by equipment type and weather region.

Table 29. Final Sample of Equipment Type by Weather Region

Equipment Type	MAT	NEE	NEN	NES	UNY	DNY	Total
Supply Fan	22	22	23	9	35	26	**137**
Return Fan	14	20	3	3	10	15	**65**
Cooling Water Pump	25	54	5	8	4	22	**118**
Hot Water Pump	3	46	11	12	5	6	**83**
WSHP Circulation Pump	1	10	4	0	3	0	**18**
Total	**65**	**152**	**46**	**32**	**57**	**69**	**421**
Pct. of Total	15%	36%	11%	8%	14%	16%	100%

Table 30 shows the distribution of units by equipment type category, weather region, and project size.

Table 30. Final Unit Sample by Equipment Type, Weather Region, and Project Size

Project Size	MAT	NEE	NEN	NES	UNY	DNY	Total
Supply Fans							
1	0	4	0	0	0	8	**12**
2	8	4	1	2	4	8	**27**
3	6	6	6	7	17	10	**52**
4	8	8	16	0	14	0	**46**
Total	**22**	**22**	**23**	**9**	**35**	**26**	**137**
Return Fans							
1	0	8	0	0	0	8	**16**
2	0	7	1	1	2	3	**14**
3	7	3	0	2	8	4	**24**
4	7	2	2	0	0	0	**11**
Total	**14**	**20**	**3**	**3**	**10**	**15**	**65**
Cooling Water Pumps							
1	7	0	0	0	0	0	**7**
2	5	27	2	2	1	11	**48**
3	12	18	1	2	2	11	**46**
4	1	9	2	4	1	0	**17**
Total	**25**	**54**	**5**	**8**	**4**	**22**	**118**
Hot Water Pumps							
1	0	0	0	0	0	0	**0**
2	0	8	0	0	4	2	**14**
3	3	21	0	0	1	4	**29**
4	0	17	11	12	0	0	**40**
Total	**3**	**46**	**11**	**12**	**5**	**6**	**83**
WSHP Circulation Pumps							
1	0	0	0	0	0	0	**0**
2	0	4	0	0	0	0	**4**
3	1	4	4	0	2	0	**11**
4	0	2	0	0	1	0	**3**
Total	**1**	**10**	**4**	**0**	**3**	**0**	**1**
All Equipment Types							
Total	**65**	**152**	**46**	**32**	**57**	**69**	**421**

2.2 Sample Draw and Project Recruitment

Due to the multi-phased sampling method that required the results of one sampling phase to inform the next sampled phase, we performed the sample draw and recruitment as integrated activities. For example, we completed for projects sampled in Phase 1 to determine the population parameters for sampling Phase 2.

Figure 8 describes our recruitment process to engage sampled projects for this loadshape study.

Figure 8. Review Recruitment Process for Sampled Projects

1. Submit Project Sample to Sponsors for Approval and to Collect Project Documents
2. Review Project Documentation to Determine Eligibility
3. Recruit Customer by E-mail/Phone and Conduct Initial Survey
4. Conduct Site Visit to Verify Equipment Type, Determine Unit Sample (Stage 2), and Install Metering

Step 1. Submit Project Sample for Approval

Upon creating a Stage 1 project sample, we submitted the list of sampled projects—including primary and back-up projects—to each Sponsor for review and approval. We also requested that the Sponsors provide the project documentation for each sampled project.

Sponsors reviewed these sampled projects and provided the project documents as requested. In some cases, a Sponsor requested to remove a project from the sample. The reasons to remove projects included:

- The Sponsor indicated that we should not contact the customer for participation in this or other evaluation studies.
- The Sponsor indicated that the project is currently or was recently part of another evaluation project, so the Sponsor wants to minimize burden on the customer.
- The Sponsor indicated that the project did not meet the “HVAC” criteria for this study.

Although this step allows for some level of bias by allowing Sponsors to remove sampled projects, obtaining Sponsor approval is important for maintaining customer satisfaction in the Sponsors’ territories.

Step 2. Review Project Eligibility

Upon approval of the sample projects and receipt of project documents, the evaluation team reviewed all available project data to determine customer contact information, building location, customer or building type, and total number and type of units with installed VSDs.

During this review, we determined whether the project was eligible for this study or should be dropped. In this step, we replaced projects that met any of the following criteria:

- The project VSD(s) did not serve any of the five equipment types.

- The project VSD(s) did not serve HVAC loads.

If we could not determine the equipment type or VSD applications from the project documents, we kept the project in the sample.

Step 3. Recruit Customer and Conduct Screening Survey

We contacted customers for recruitment and scheduling only after Sponsor approval and our review of the project documents (Steps 1 and 2 above). For those customers with e-mail contact information, we preceded our phone calls with a notification letter that described the purpose of the study and requirements of participation. We then called customers to confirm details of the VSD projects, request their participation, and schedule our initial site visit.

We dropped projects in this step for several reasons, including:

- The customer declined to participate.
- We determined during the phone survey that the VSD-controlled equipment did not match the study's target equipment types.
- After four contact attempts, including e-mails and phone calls, we could not make contact with the customer.

Step 4. Conduct Site Visit

During these site visits, we verified the documented VSD installations and completed the Stage 2 sampling to determine which units to meter. We marked sites as fully recruited only after installing our power-metering equipment.

In some cases, we had to drop projects in this last step if we found that the installed VSD(s) did not meet the equipment type boundaries for this study.

Replacing Dropped Projects

If we had to drop a project at any stage during the recruitment process, we replaced that project with an approved back-up project matching the same project size stratum and weather region. If possible, we also matched the project Sponsor in order to maintain representation of all study Sponsors.

2.3 Data Collection

The team collected both primary and secondary data to support this loadshape study. Table 31 summarizes the data collection activities we completed between June 2012 and September 2013.

Table 31. Data Collection Activities

Activity	Description
Primary Data	
Sponsor Tracking Data	The evaluation team collected and reviewed the tracking data for VSD installations completed through the Sponsor's programs. We used these data to define the study population and design the study sample. For sampled projects, we also reviewed all available project documents to determine the number, type, and location of installed VSDs within the sampled project.
On-Site Survey and Metering	***Equipment Inspection and Survey*** The team surveyed facility staff for sampled projects to collect information about normal facility and equipment operation and baseline conditions. We used these data to develop our models for both VSD and baseline loadshapes.
	Metering The team installed power-metering equipment on sampled units to measure the energy consumption of VSD-controlled equipment throughout the year between August 2012 and September 2013. We used these data to model the hourly operation and electric demand of VSD-controlled units.
Secondary Data	
Existing Savings Values, Methods or Assumptions for VSDs	***TRM Review*** The team reviewed the existing savings methods and assumption in the Sponsors' Technical Reference Manuals. We used this information to compare the results of our study to existing savings claims.
	Review of Existing VSD Savings Methods The team reviewed common methods for estimating energy and demand savings from VSD installations. We used this information to develop our baseline demand model.
	Massachusetts Pre/Post Metering Study The team reviewed the meter data and analysis results from the Massachusetts Pre/Post VSD Study. We used these data and findings to develop and verify our baseline demand model.
Historical and Actual Weather Data	The team collected historical and TMY hourly weather data for the Northeast weather regions. We used historical actual data to examine relationships between VSD power and ambient weather conditions. We applied those relationships to TMY data to predict VSD power during typical weather years.

2.3.1 Sponsor Tracking Data

As described in the Sample Design section (Section 2.1) we collected and reviewed Sponsor tracking data to define the study population and sample design. For projects in the final sample, we also reviewed all available project documents to verify the number, type, and location of installed VSDs within the sampled project.

2.3.2 On-Site Survey and Metering

We visited sites for sampled projects two to three times to conduct the initial survey and install data loggers, replace the data loggers for continued monitoring (as necessary), and to remove the data loggers.

- **Logger Installation**: The first site visit included the majority of the on-site data collection activity, including a survey of the building and baseline operational practices, inspection of the project installation and verification of project data, equipment measurements and installation of the long-term monitoring equipment, and procurement of any EMS trend data.
- **Interim Replacement:** Some sites received an additional interim site visit for interim data collection with the loggers left in place through August 2013 [16.]. These sites included motor types with summer operation, such as cooling water pumps where the installed logger did not have sufficient data or battery capacity to capture the extended period.
- **Logger Removal**: The second site visit included collection of all data monitoring equipment and a brief survey with the facility manager to review operational information, discuss whether there were any significant changes at the facility, and answer any questions about the observed data[17] to date.

Equipment Inspection and Survey

During the first site visits, we surveyed the available facility staff member(s) to collect information to characterize typical building and HVAC system operation for both the existing (with VSD) and pre-retrofit (baseline) conditions. We created an iPad-based data collection form to guide these interviews and compile all data for quality control reviews.

In some cases, the ideal site contact was either not available or not knowledgeable enough to answer all survey questions. When possible, our field engineers collected additional contact information to follow up on remaining questions after completing the site visit.

[16] The Sponsors may opt to extend the data collection period for installations that have a strong weather dependence in order to capture additional cooled season data and equipment operation during the hottest hours of the year. With this option, data loggers will be downloaded at the end of the regular logging period (February 2013) and left through July 2013.

[17] For sites with the cellular enabled (U30) data logger, analysts will review the power data before the loggers are collected and may have questions about abnormalities in the data or any observed changes in operational patterns. For all sites, we may have more specific questions about why the equipment is operated a certain way (e.g., constant speed). We want to understand why so many VSD installations are completed this way, but will ask at the end of data collection so these discussions will not influence changes in operation for the data collection period.

Building Information

We started each on-site survey with a series of questions about typical annual building operations. We designed these questions to support our modeling of annual operations and to provide explanatory information for any unexpected data. Our questions probed the following building characteristics:

- Building type (using the standard list Table 32);
- Seasonal building operating calendar, including observed holidays and typical shut-down periods;
- Typical daily and weekend occupancy schedules;
- Description of HVAC systems;
- Seasonal operating calendar for HVAC systems, including whether systems operate all year or when the facility brings systems on/offline; and
- Typical daily and weekly HVAC system operating schedules.

Table 32 shows the standard list categories we used to assign each building type.

Table 32. Building Types

Building Types	
Office	K-12
Restaurant	Warehouse
College/University (Nonresidential)	Grocery
Industrial/Manufacturing	Multifamily/Dormitory
Retail	Hotel/Motel/Lodging
Hospital	Other

Unit Operation with VSDs

After completing our question about the general building and HVAC system, we focused on information about the sampled VSD units. For each unit, we asked a series of questions to examine the unit's purpose, control settings, and typical annual operation.

Unit Operating in the Pre-Retrofit Condition

For each sampled unit, we also asked questions about how the customer operated the equipment before installed the new VSDs.

We used the survey responses, our review of the Sponsor tracking data, and our on-site inspection to classify the pre- and post-retrofit systems into one of the categories in Table 33. In some cases, we documented pre-retrofit systems that were not included in the listed operational strategies (e.g., constant volume supply/return fan VSD control based on ambient temperature).

Table 33. VSD and Baseline Operational Categories

Category	Equipment Type				
	SF	RF	CWP	HWP	WHP
VSD Control Categories					
Auto-Fan: Modulate speed to maintain static pressure setpoint	◆	◆			
Auto-Fan: Modulate speed to match the supply fan		◆			
Auto-Pump: Modulate speed to maintain loop differential pressure setpoint			◆	◆	◆
Auto: Modulate speed to maintain other setpoint (specify)	◆	◆	◆	◆	◆
Hand/Manual: Speed maintained at setpoint	◆	◆	◆	◆	◆
Off: VSD Equipment is turned off and not controlling the associated motor	◆	◆	◆	◆	◆
Pre-Retrofit Control Categories					
Constant speed (100%)	◆	◆			
Constant speed with 2-way valve			◆	◆	◆
Constant speed with 3-way valve			◆	◆	◆
Inlet guide vanes	◆	◆			
Eddy current drive	◆	◆	◆	◆	◆
Older VSD (failed)	◆	◆	◆	◆	◆
Older VSD (non-failed)	◆	◆	◆	◆	◆

Power Metering

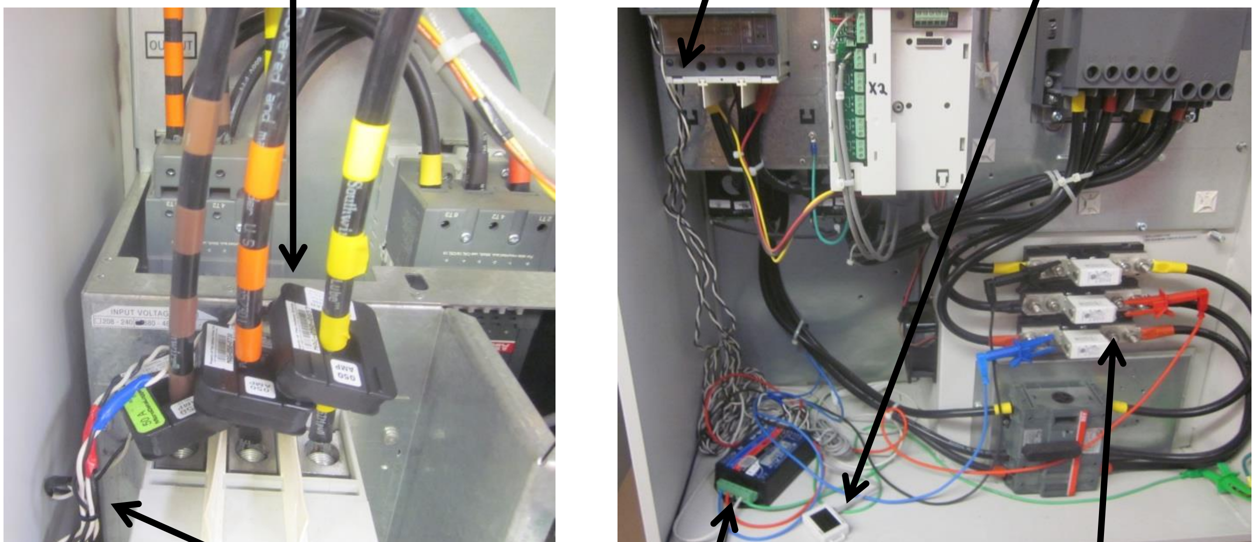
We installed power-metering kits on all sampled units to record the electric power consumed by each VSD throughout the data collection period. Each power-metering kit typically includes the following equipment:

- Three current transformers (size TBD) to measure the current for each phase;
- A set of 1,000-volt rated voltage clips to measure the voltage for each phase with fourth voltage clip connected to ground;
- One 480-volt (primary) or 208-volt (secondary) Watt Node;
- One data logger to record all measured data at pre-determined intervals; and
- One pulse adaptor to connect the WattNode to the data logger (if necessary).[18]

Figure 9 shows an example of power-metering equipment installed in an electrical panel.

[18] In cases where we used a UX90 logger, the pulse input adaptor is built in and an external adaptor was not necessary.

Figure 9. Example of Installed Power-Metering Kit



The image on the left shows the three current transducers (CTs) measuring current through the wires for each phase of the motor. These CTs are connected to the WattNode shown in the image on the right. The WattNode is also connected to three voltage clips that measure the voltage of each phased of the motor. The WattNode collects and send these current and voltage data to a data logger that records the measures values at specified intervals.

The team used the four different types of data loggers listed in Table 34.

Table 34. Power Logging Equipment

Parameter	Logging Equipment	Logging Frequency
kW	HOBO Energy Logger (H22-001)	5-min average
kW	HOBO Micro Station Data Logger (H21-002)	5-min average
kW	HOBO U30 Cellular Data Logger (U30-GSM)	5-min average
kW	HOBO UX90 State Logger (UX90-001)	5-min average

All set-ups include power factor measurement and satisfy the ISO New England measurement and verification requirements.

2.3.3 Existing Values, Methods, and Assumptions for VSDs

The evaluation team reviewed multiple sources of existing savings values, methods, and assumptions for VSD installations. These sources included the technical reference manuals used by study Sponsors or other program administrators, other existing VSD savings models or evaluation protocols, and the results from previous VSD evaluations.

Massachusetts Pre/Post Metering Study

Of particular interest among secondary data sources was the Massachusetts Pre/Post VSD Study. For this study, DMI—a partner in the NEEP Loadshape study—performed up to six months of pre-retrofit and post-retrofit metering for 22 VSD retrofit installations in Massachusetts. Cadmus, DMI, and the NEEP Technical Committee discussed key findings from this study to shape and verify our approach for estimating pre-retrofit power.

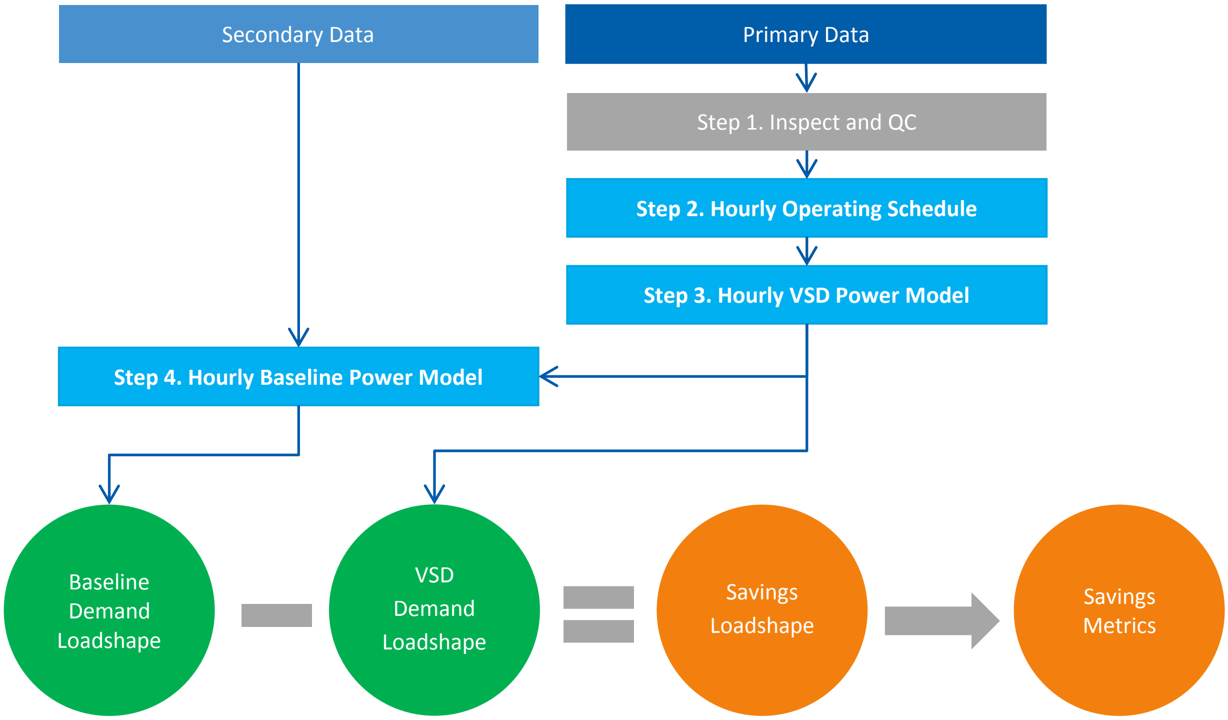
2.3.4 Weather Data

The evaluation team collected historical and TMY hourly weather data for the Northeast weather regions. We matched the six weather regions used in NEEP's 2011 C&I Unitary HVAC Loadshape Project Final Report. We used historical actual to examine relationships between VSD power and ambient weather conditions. We applied those relationships to TMY3 weather data to predict VSD power during typical weather years.

2.4 Data Analysis

The evaluation team used primary and secondary data to develop estimates of the savings loadshapes and savings metrics for each sampled unit. We used these data to develop models that estimate hourly operation and power for both the pre- and post-retrofit conditions. We then applied these hourly models to typical weather and calendar years to estimate demand and savings loadshapes for each unit. Figure 10 demonstrates our process to develop these unit-level savings results.

Figure 10. Process for Estimating Unit-Level Savings Loadshapes and Metrics



As the figure indicates, we first performed a preliminary analysis to conduct a quality inspection of the metered and survey data. We then created the following models for each unit:

1. The **hourly operating schedule** indicates the percentage of time in each hour that unit is expected to operate in a typical year. The evaluation team developed the operating schedules based on observed post-retrofit operating patterns during the data collection periods.
2. The **hourly VSD power model** estimates the electric demand required by the unit when *on* and operating with the connected VSD. The evaluation team used the metered on survey data to develop hourly VSD power models for each unit.
3. The **hourly baseline power model** estimates the electric demand that the unit would have required when operating in the pre-retrofit condition. In addition to the primary data, we used secondary data to guide and verify our approach for estimating pre-retrofit operating power. The evaluation team used secondary data to create a baseline modeling approach and combined this approach with metered and survey data to develop hourly baseline power models for each unit.

We used these unit-level schedules and operating power models to calculate the baseline demand loadshape, the VSD demand loadshape, savings loadshape, and savings metrics for each unit in a typical year.

The following sections outline the methods for each step in our data analysis.

2.4.1 Inspect and Perform Quality Control of Primary Data

During the initial download and inspection of meter data, we performed both a quality check and a preliminary analysis of the meter and survey data. In this review, we observed general trends in the data, such as seasonal operation, regularity of operating schedules, maximum observed power, and magnitude of power variations.

Data Download and Quality Control

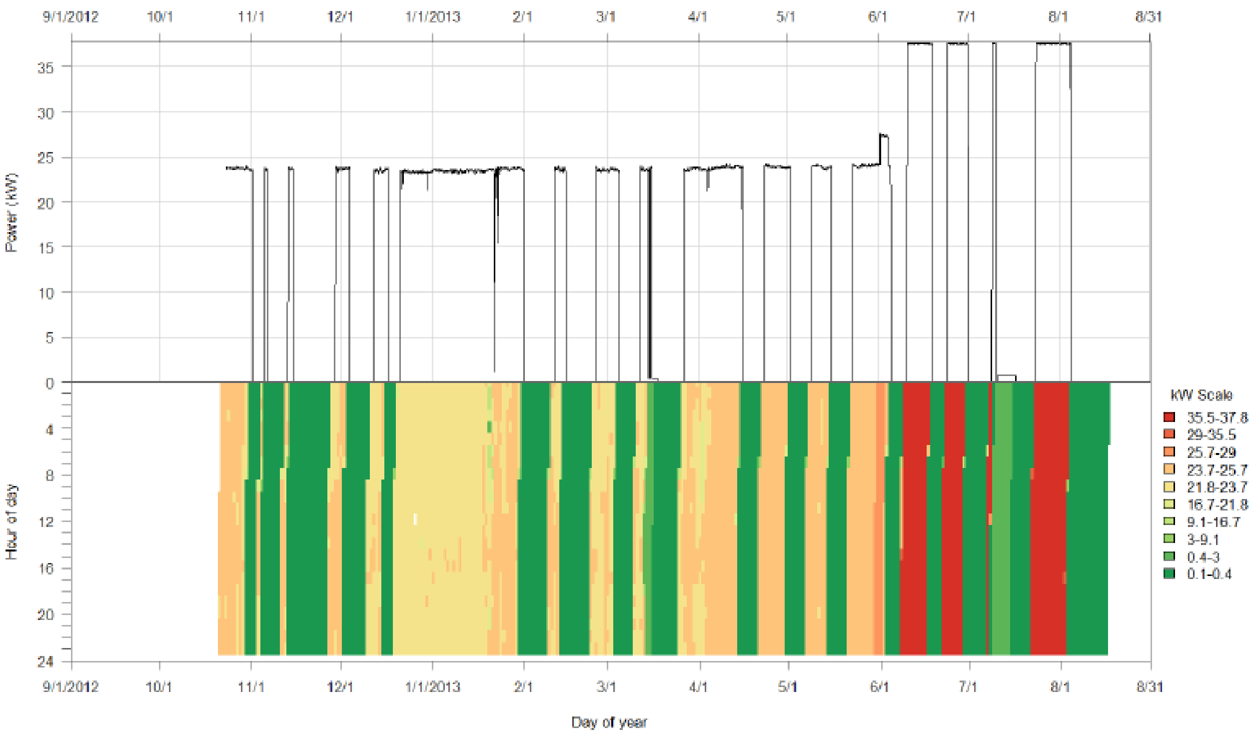
As we retrieved data loggers, we downloaded and compiled the raw meter data.[19] During this process, the evaluation team removed loggers with data errors (as noted by field technicians) and flagged loggers that indicated no unit operation. Next, we removed any data recorded before or on the date of installation, after or on the date of removal, and during the date of the interim visit (if applicable). We used the remaining data to develop hourly average status and power datasets for the period from September 1, 2012, through August 31, 2013.

Preliminary Analysis

We created time series and "power map" figures for each unit to conduct visual inspections of the meter data. The time series chart shows the average hourly power during the data collection period. The power map is similar to a topographical map and illustrates variation in power demand across hours in the day (y-axis) and days (x-axis) during the data collection period.

[19] Due to the long metered periods (exceeding 12 months in some cases), we had multiple data files for each unit. We compiled these multiple data files into a single dataset that included all data for the complete data collection period.

Figure 11. Example of Preliminary Data Review



We used these data graphics to complete the following steps in our quality control reviews and preliminary analysis:

- Identified any gaps or anomalous data and removed from the dataset (if appropriate).
  - We define "gaps" in the data as any periods between the installation and removal dates during which no data were recorded (e.g., the period between a logger stoppage and logger replacement).[20]
  - We defined "anomalous" data as any data that do not represent the normal operation of the unit (e.g., equipment not operating during period of interrupted electric service after Hurricane Sandy).
  - We determined that it is appropriate to remove data when we can confirm that the data does not represent normal unit operation for that period in a typical year.
- Identified any changes in system operation during the data collection period, and use these to define operating season(s). Compare these data observations to operating information collected from on-site surveys.

[20] A logger stoppage may be due to movement of the logging equipment by site personnel, logger reaching its memory capacity, or a failed battery.

- We defined an operating season as a period during which the unit exhibits a regular operating pattern. For example, a supply fan at a school may exhibit one pattern from September through May (when school is in session) and a different pattern from June through August (when the school is closed). These periods indicate distinct operating seasons.
- Operating information collected during the on-site surveys includes anecdotal information provided by the site staff about seasonal equipment-control strategies.

2.4.2 Hourly Operating Schedule

The hourly operating schedule indicates the percentage of time in each hour of the year that we expect the unit to operate. For example, a supply fan may operate continuously (8,760 hours per year) or on a fixed schedule (e.g., weekdays from 6:00 a.m. to 6:00 p.m.). The sum of all hours that the unit is operating in the unit's operating schedule indicates the expected annual operating hours.

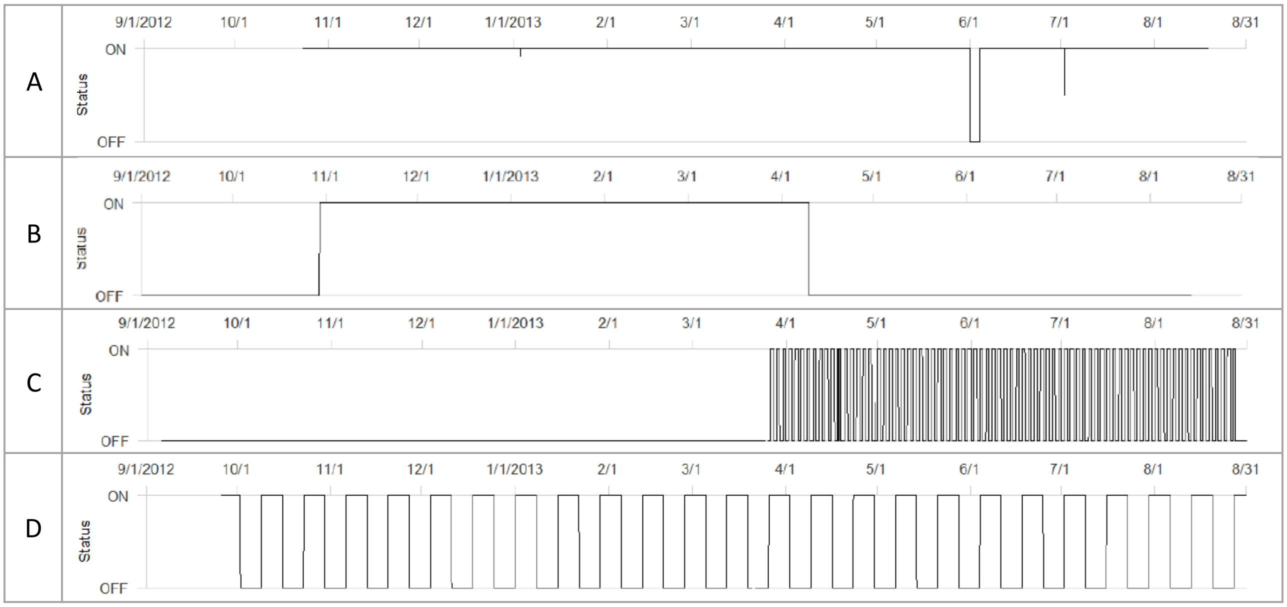
Post-Retrofit (VSD) Operating Schedule

We used our meter and survey data to develop the post-retrofit operating schedule for each unit. In this process, we considered the following operating characteristics:

- **Operating season(s)**. The operating season(s) defines the date range during which we expect the unit to operate in a typical year. For example, a fan in a commercial building will typically have an operating season that includes the entire calendar year. However, a fan in a school may operate only from September through May. We used both meter data and results of our on-site interviews to determine the operating season(s) for each unit. We indicated multiple operating seasons if meter data indicate multiple distinct operating patterns.
- **Operating pattern(s)**. The operating pattern describes the expected hourly operation within the defined operating seasons. We categorize each unit into one of these three patterns:
  - Continuous operation indicates that the unit operated continuously within its operating season.
  - Scheduled operation indicates that the unit operated on a regular schedule (e.g., on weekdays from 6:00 a.m. to 6:00 p.m.) within its operating season.
  - Irregular operation indicates that the unit demonstrated no regular operating patterns. This irregularity is typically due to the role of the unit as back-up or lead-lag equipment.
- **Rotating units**. Rotating units operate in a team of similar units to serve the same load. Facility operators rotate units to lengthen the lifetime of equipment and to provide redundancy in case of failure. Since rotating units take turns serving the designated load, each unit operates for only a fraction of the team's overall schedule.

These different operating characteristics all contribute to the unit's typical annual schedule. Figure 12 demonstrates the variety of operating schedules we observed. Each chart shows the operating status—*on* or *off*—throughout the data collection period.

Figure 12. Example of Unit Operating Schedule



Unit A operated continuously throughout the 10-month data collection period. We modeled this unit's schedule to operate continuously throughout the year. Although the data indicate a short period of inactivity at the beginning of June, we confirmed that this was a maintenance period that does not represent normal operation.

Unit B operates continuously only during the heating season. We modeled this unit's schedule to operate continuously during the heating season and remain *off* otherwise. In general, we defined the range of dates for heating, cooling, and other operating seasons by the dates indicated in the metered and survey data.

Unit C operates on a regular schedule and only during the cooling season. We modeled this unit's schedule to operate according to the observed average weekly schedule during the cooling season and to remain *off* outside of the cooling season.

Unit D is a rotating unit that operates with one other unit to serve a continuous and year-round load. We modeled this unit's schedule to operate only 50% of the time throughout the year.

Pre-Retrofit (Baseline) Operating Schedule

In this study, we assume that the pre-retrofit (baseline) operating schedule is the same as the observed post-retrofit (VSD) operating schedule. This assumption implies that the implementation of a VSD has no effect on the equipment operating hours, so that total operating hours are equivalent with or without a VSD. Although a VSD could influence both the operating power and the operating hours of the connected equipment, we determined that this study would focus only on the savings achieved by power reductions during post-retrofit operating hours.

Through discussions with the NEEP Technical Committee and the EM&V Forum, we agreed on this conservative assumption for the following reasons:

- Any survey data that we collected about baseline operation are anecdotal and rely on information provided by facility site staff during logger installation/removals. Due to the timing and post-installation focus of this study, we could not verify the baseline schedules for any equipment.
- We have baseline operating information only for a small fraction of the sampled equipment. For the majority of the units, the facility staff did not recall or could not report information about the baseline equipment or operation.
- We could also attribute adjustments to equipment operating schedules resulting in reduced operating hours to retro-commissioning or other energy management system upgrades.

2.4.3 Hourly VSD Power Model

The hourly VSD power model estimates the electric demand required by the unit when operating with the connected VSD. We analyzed relationships between measured operating power and the auxiliary variables that may influence that power. We produced a set of hourly models for each unit that predict the unit hourly operating power during specific operating seasons, day types, hours, and weather conditions. By combining this power model with the unit's operating schedule, we can predict the unit's hourly demand for a typical weather and calendar year.

In this section, we describe our approach to develop these hourly power models and calculate the expected hourly VSD power for a typical weather year.

Determine Modeling Approach

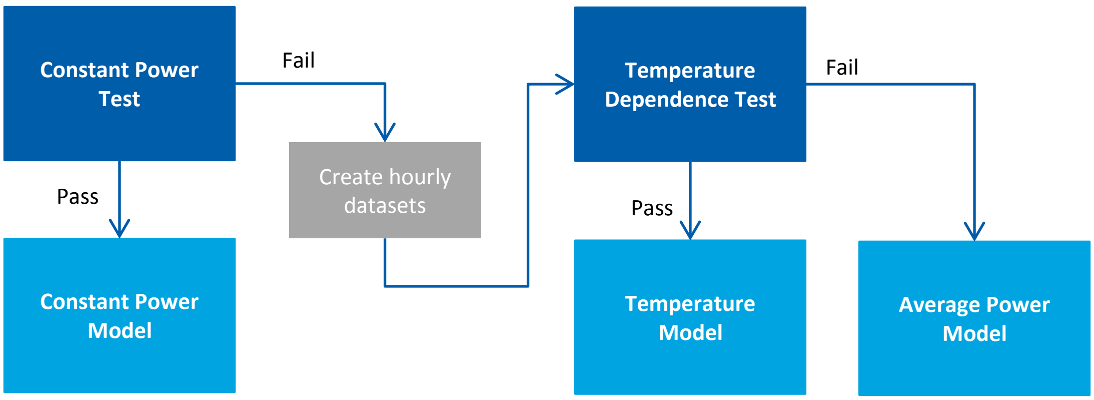
As previously noted, we observed a variety of operating patterns among the studied units. We noted that some units operated at constant power throughout the data collection period or within specific seasons, some units showed distinct power adjustments for different seasons, and some units operated with variable power throughout the year or within a specific season. Based on these observations, we developed three modeling approaches to predict the VSD operating power:

- ***Constant Power Model:*** For units that demonstrated constant operating power during the data collection period, this model applies the observed operating power value regardless of temperature or any other variable.
- ***Temperature Model***: For units that demonstrated variable power correlated with temperature, this model uses the observed hourly correlation between temperature and power to predict operating power using typical weather data.
- ***Average Power Model:*** For units that demonstrated variable power but showed no relationship between power and outside temperature, this model applies the measured average operating power for each combination of operating season, day type, and hour.

The Average Power Model is mathematically very similar to the constant power model for units that exhibit constant operating power. The Constant Power Model and the Average Power Models would produce very similar, if not identical, results for constant power units.

Figure 13 depicts our process for determining the modeling approach for each unit.

Figure 13. Process to Determine VSD Power Model



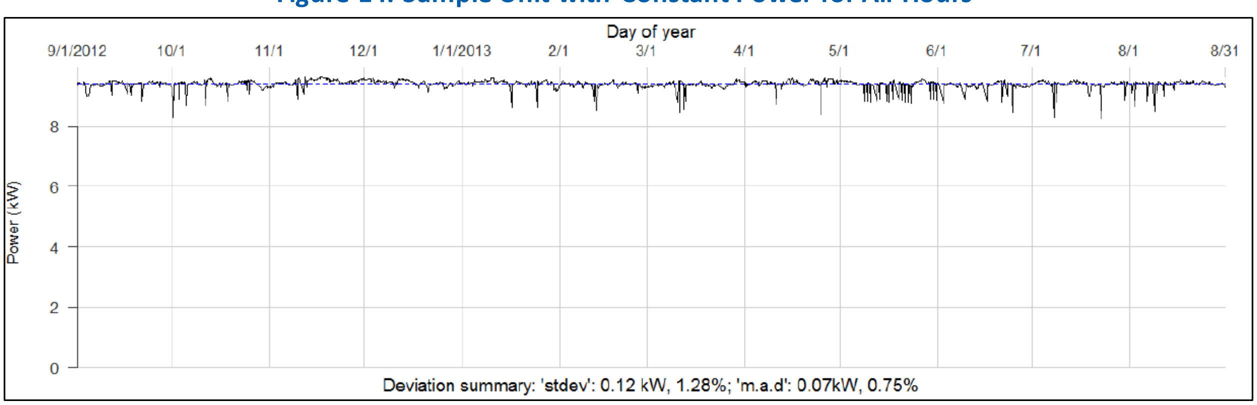
Constant Power Test

During the data collection phase, we observed that a large number of units operated at constant power during periods of scheduled operation throughout the data collection period. We performed this first test to identify the units that always operated at constant power.

We calculated the average operating power—the expected power when the unit is *on*—for all hours in the data collection period and the standard deviation on that average. Units pass this constant power test if the ratio of the standard deviation to the average power was less than 5%, indicating minimal variation in operating power throughout the data collection period.

Figure 14 shows the raw time-series power data for a unit that passed this constant power test.

Figure 14. Sample Unit with Constant Power for All Hours



Using this method, we identified 83 of 392 units (21%) that operated at a single constant power during hours of scheduled operation throughout the data collection period. It is worth noting that a number of other units seemed to operate at distinct constant power for different operating seasons (e.g., one constant power for heating season and a different constant power for cooling season), but because of the change in power during the data collection period, those units did not pass this initial screen. (These units would also fail the temperature screen and default to the Average Power Model.)

Identify Auxiliary Variables

Units that did not pass the constant power test have some level of variation in operating power during the data collection period. To analyze patterns in that variation, we reviewed the key variables that may influence changes in a unit's operating power. Since all the equipment in this study served HVAC loads, we expected the variables to be:

1. Season (heating vs. cooling, academic year vs. summer session, etc.);
2. Day type (weekday or weekend);
3. Time of day (occupied vs. unoccupied); and
4. Ambient weather conditions.

Although other variables—such as static pressure in supply air ducts, differential pressure in a chilled-water loop, or CO2 levels in a conference room—are typically the driving variables for VSD control, we limited our list of driving variables to those for which we have measured data for all buildings and for all hours in a typical weather year. This approach allows us develop useful models to predict operation for a normalized year. For example, we could analyze the relationship between duct static pressure and VSD-controlled fan speeds, but we could not use that relationship to model the fan speed in for a normal weather year or in another weather region without also knowing what the hourly duct status pressure would be in those scenarios.

Create Hourly Datasets

We separated the meter data for each unit into hourly datasets, or unique combinations of operating season, day type, and hour. This disaggregation of the data allowed us to separate the influences of each of these variables both from each other and from the influences of weather (tested in the next step). For example, we could separately model the unit's response to temperature at noon on a weekday and at 8:00 p.m. on a weekday. Similarly, we could separately model the temperature response at noon on a weekday in the winter, at noon and a weekday in the summer, and at noon on a weekend day.

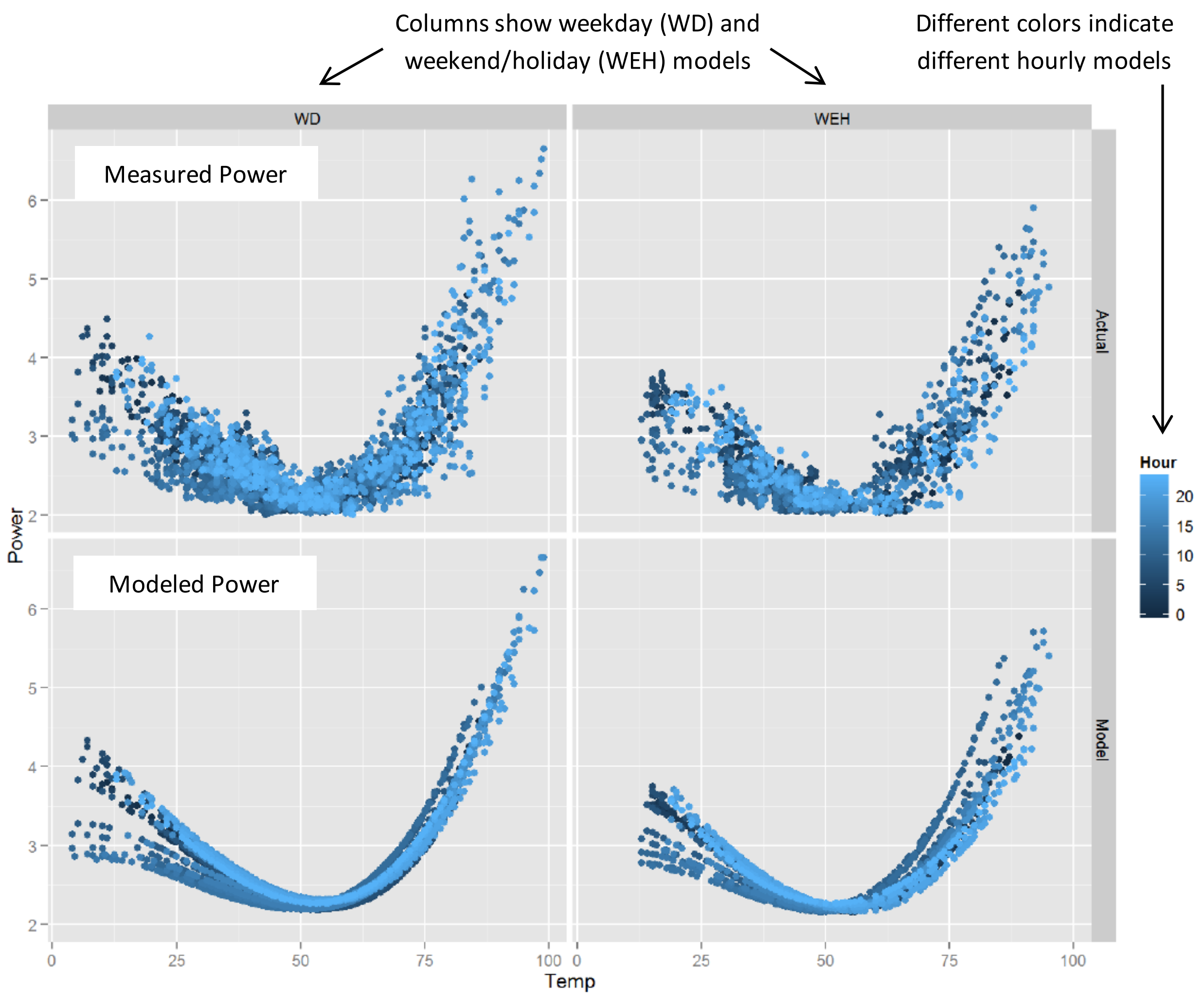
We often use this hourly modeling approach in loadshape analyses to capture the important influences of season, day type, and time on overall system demand. The next two sections describe how we apply this hourly modeling approach to capture those important influences on VSD operating power.

Temperature Dependence Test

For the temperature dependence test, we compared the hourly datasets to corresponding historical weather data to assess any correlation between operating power and outside temperature. We performed multiple regressions and recorded the R-squared and p-values of the estimated temperature coefficients for each. Any hourly model passed this test if the p-value of the temperature coefficient with the highest R-squared value was less than 0.1. These rules indicate that the temperature has a significant effect on the operating power of a unit, and we refer to this in the following sections as passing the temperature dependence test.

Figure 15 shows examples of the hourly models for a temperature-dependent unit with the results of our hourly modeling based on temperature regressions.

Figure 15. Examples of Hourly Models for Temperature-Dependent Units



For hourly models that passed the temperature dependence test, we recorded the model type and regression coefficients to define the hourly temperature model.

Average Power Model

For hourly models that failed the temperature dependence test, we assigned the average power model. For these units, the hourly power may have varied during our data collection period, but we could not correlate that variation with an auxiliary variable such as ambient temperature. For these units, the VSD is likely more influenced by internal building factors—such as occupancy—than by outside weather conditions.

It is important to note that our method of developing hourly models may results in multiple model types for a single unit. For example, a supply fan may exhibit temperature-dependent variable power during normal working hours but a constant power overnight and on weekends.

Estimate Hourly VSD Operating Power

For each unit, we used the set of hourly models defined in the previous steps to predict the hourly VSD operating power for a typical weather and calendar year.

For all temperature-independent (TI) units—units for which none of the hourly models passed the temperature dependence test—we created a single demand loadshape for the 2012 calendar year. For all temperature-dependent (TD) units—units for which at least one hourly model indicated temperature dependence—we created a demand loadshape for each of the six weather regions.

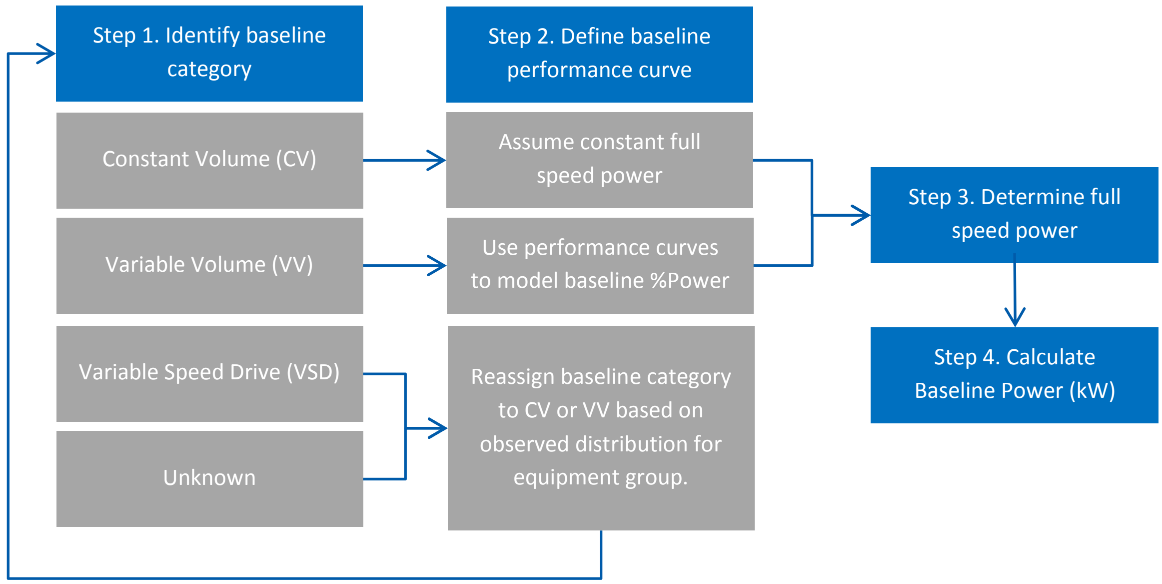
2.4.4 Hourly Baseline Operating Power

Because this study did not include pre-installation measurements, we used a combination of primary and secondary data to develop a baseline model and estimate the hourly operating power for a typical weather year.

Baseline Power Model

The baseline power model describes our approach to estimate the hourly demand of each unit in the pre-retrofit condition. Figure 16 illustrates our baseline modeling approach and is followed by a description for each step.

Figure 16. Process for Estimating Baseline Demand Loadshapes



Step 1. Identify Baseline Category

Since this study focused on VSD projects completed at least one year before our evaluation, we relied on survey data and on-site inspections to determine the baseline category for each unit. Using the data we collected during the site visits, we assigned each unit to one of the following baseline categories:

- **Constant volume (CV)**: A constant-volume system provides a constant volume of air or water when operating. CV systems may include distribution equipment that varies the volume of air or water that is supplied to the conditioned spaces or downstream HVAC equipment, but they still provide a constant volume at the primary piece of equipment.
- **Variable volume not including VSD (VV)**: A variable-volume system modulates the flow in response to downstream indicators (e.g., duct static pressure for a supply fan or loop differential pressure for a distribution pump in a hydronic heating/cooling system).
- **Variable Speed Drive (VSD)**: VSDs are a subset of the VV category, enabling variable flow by controlling the speed of the connected motor. We flagged all units for which the site contact reported that the new VSDs replaced existing VSDs. In these cases, the customers used program incentives to replace the old VSDs. Since VSD baselines are ineligible in all Sponsor programs, we did not include VSD baselines in the final analysis.
- **Unknown**: If the site contact could not describe how the pre-retrofit equipment was controlled and the field technician could not determine the pre-retrofit system through inspection, we recorded the baseline type as “unknown.”

For units in the VSD or unknown baseline categories, we assigned a “CV” or “VV” baseline type using the distribution of known baselines within that equipment type. Table 35 shows the initial and adjusted distributions of baseline categories for each equipment type.

Table 35. Reported Baseline (Pre-Retrofit) Category

Baseline Category	SF	RF	CWP	HWP	WHP	All
sample	n = 131	n = 60	n = 109	n = 77	n = 15	n = 392
Initial Distribution						
Constant volume	31%	42%	35%	25%	40%	33%
Variable volume	1%	6%	0%	0%	0%	2%
Variable speed drive	1%	2%	0%	0%	0%	1%
Unknown*	66%	50%	65%	75%	60%	65%
Adjusted Distribution**						
Constant volume	97%	92%	100%	100%	100%	98%
Variable volume	3%	8%	0%	0%	0%	2%

* The high percentage of units with unknown baselines is due to the elapsed time (minimum of one year) since the site installed the VSDs.
** We reassigned all equipment with VSD or unknown baselines using the observed distribution of CV and VV baselines within the same equipment type category.

The high percentage of units assigned to the CV category is consistent with our expectations and observations for HVAC systems in existing buildings.

Step 2. Define Baseline Performance Curve

The baseline category determines the baseline performance curve. Table 36 shows the loadshape approach for the two baseline system types and expected percentage of units for each baseline system type.

Table 36. Baseline Model Approach on Baseline System Type

Baseline Category	Expected Power Performance	Approach for Estimating the Baseline Performance Curve
Constant Volume (CV)	Constant kW	Assume that the baseline equipment will operate at constant power (100% FLP) during all operating hours.
Variable Volume (VV)	Variable kW	Assume that the baseline equipment operates at same flow rate as measured post-retrofit equipment. Use DOE.2 eQUEST performance curves to estimate hourly baseline %FLP based on observed hourly post-retrofit %FLP.

Constant Volume (CV) Baseline

For baseline CV systems, which provide a constant volume of air or water through the distribution network, we assumed that the baseline equipment operates at 100% of full load power. The pre-retrofit metering from the Massachusetts Pre/Post VSD Study supports this assumption. In that study, the pre-retrofit metering showed that the pre-retrofit operating power was constant for all studied units.

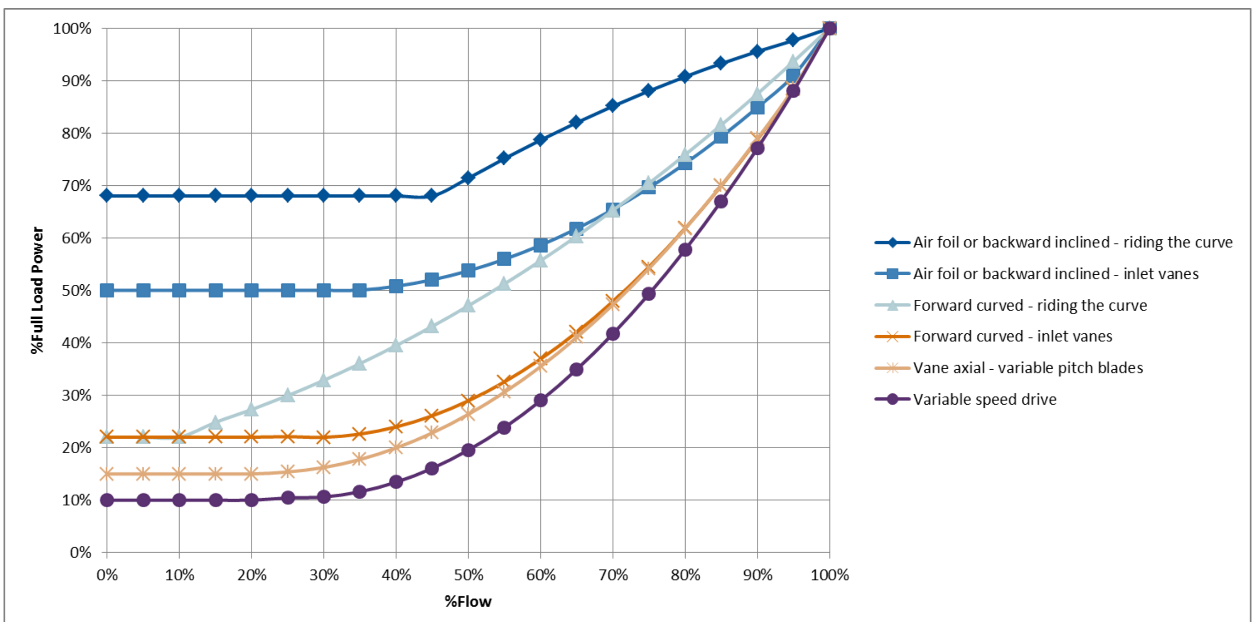
Variable Volume (VV) Baseline

For VV systems, we developed the baseline loadshape using the observed performance of the VSD system and system performance curves from the DOE eQUEST building energy simulation tool shown in the following figures. This approach has two built0in assumptions:

- *The downstream system dynamics that drive the variable flow—such as the operation of terminal box dampers—are the same in the baseline and VSD scenarios.* This assumption implies that the pre- and post- retrofit equipment serve the same building loads (a standard assumption for impact evaluations), and therefore, the baseline VV equipment will provide the same flow rates as the VSD equipment.
- *Unless otherwise specified by the site staff, the baseline VV system is operational*. Due to the post-installation focus of this study, we could not inspect or conduct measurements of the actual baseline systems. We had to rely on interviews with the staff to determine whether the baseline equipment was operating as designed. Based on our experience with such HVAC distribution systems in existing buildings and the fact that the facilities were investing in a system upgrade with the VSD retrofit, it is likely that a number of these VV systems were not operational and acted more like a CV than a VV system. However, in the absence of data—either anecdotal or physical—to quantify the percentage of non-operational systems, we defaulted to the conservative assumption that baseline VV systems operated as designed.

We model the energy performance of baseline VV systems using standard performance curves that describe how these systems respond to variations in flow. Figure 17 shows the relationship between power and flow for various VV fan systems, including a VSD system.

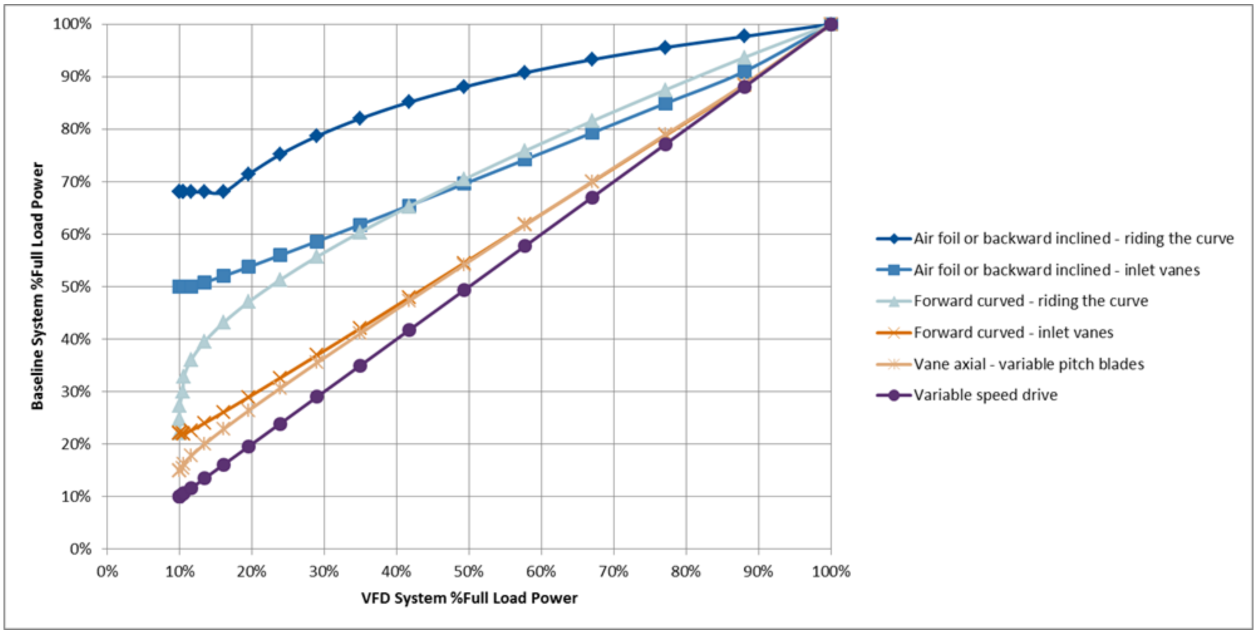
Figure 17. eQUEST Fan System Power-Flow Performance Curves



The performance curves demonstrate how the power, represented as the percentage of full load power (%FLP), for each system type responds to different volumes of flow.

We use these power-flow performance curves to develop relationships between VV system power and VSD system power for each of the fan system types.

Figure 18. Fan Systems Normalized to VFD (shown as y=x)



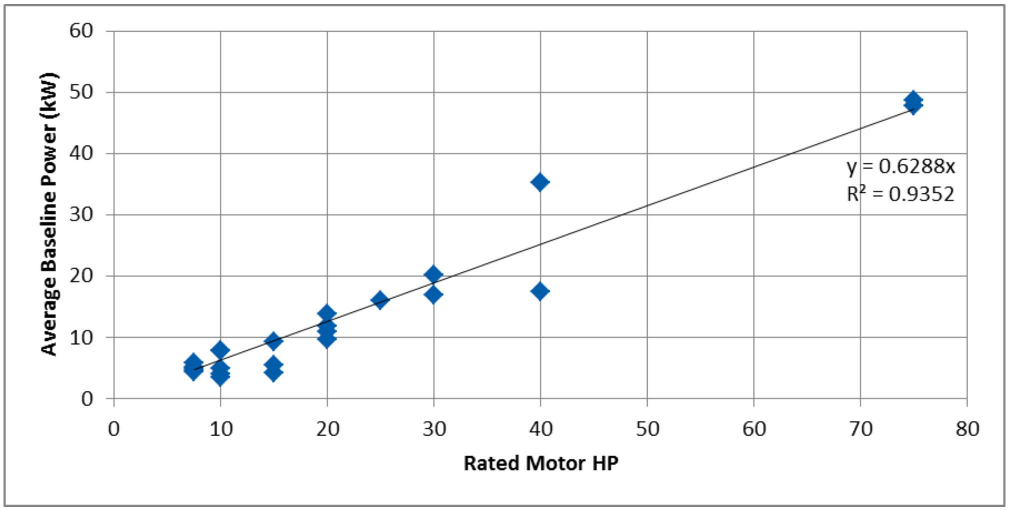
We used these relationships (Figure 18) to estimate the baseline %FLP given our hourly models of VSD %FLP.

$$Estimated\ Baseline\ \%FLP_h = Measured\ VSD\ \%FLP_h \times \frac{Model\ VV\ \%FLP}{Model\ VSD\ \%FLP}$$

Step 3. Determine Full Speed Power

We define the full load power (FLP) as the power demand when the motor is operating at full volume in the baseline case without a VSD. We used the relationship between rated horsepower and measured average pre-retrofit power from the Massachusetts Pre/Post Study to estimate the FLP for each unit in this study. Figure 19 shows these data from the Massachusetts Pre/Post VSD Study.

Figure 19. Average Pre-Installation Power from Massachusetts Pre/Post Study Metering



The data are based on pre-installation power metering of 23 units ranging in size from 7.5 to 75 hp. The equipment types in this study encompassed five cooling water pumps, four heating hot water pumps, 12 supply fans, one return fan, and one water source heat pump circulation pump.

We used this relationship to estimate the pre-retrofit full load power using the verified rated horsepower for each unit and the following formula:

$$Full\ Load\ Power\ (kW) = Rated\ Motor\ hp \times 0.6288\ kW/hp$$

Step 4. Calculate Baseline Power (kW)

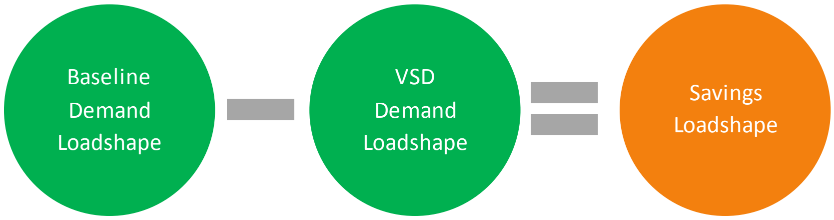
Finally, we used the assigned baseline model, baseline performance curve, and full speed power estimate to calculate the hourly baseline power for a typical weather and calendar year.

As we did for the VSD power model, we used the 2012 calendar year to create a single power loadshape for all temperature-independent units and weather region data to create region-specific hourly demand for all temperature-dependent units.

2.4.5 Unit-Level VSD Loadshapes

We use the loadshape components—unit operating schedule, VSD operating power, and baseline operating power—to calculate the baseline, VSD, and savings loadshapes for each unit.

Figure 20. Calculation for the Unit-Level Savings Loadshape



Baseline Demand Loadshape

We calculated the hourly baseline demand for each unit by multiplying the hourly baseline operating power by the hourly operating schedule. This baseline demand loadshape estimated the electric energy consumed by the unit for a typical weather year without the installed VSD.

VSD Demand Loadshape

Similarly, we calculated the hourly VSD demand, or the VSD demand loadshape, for each unit by multiplying the hourly VSD operating power by the hourly operating schedule. This VSD demand loadshape estimates the electric energy consumed by the unit for a typical weather year with the installed VSD.

Savings Loadshape

As indicated in Figure 20, we took the difference between the baseline demand loadshape and the VSD demand loadshape to calculate the hourly demand savings. This unit savings loadshape represents the expected demand savings of the VSD-controlled unit compared to its pre-retrofit condition.

2.4.6 Unit-Level Savings Metrics

Finally, we used hourly demand savings values in the unit-level savings loadshape to calculate the savings metrics listed and defined in Table 37.

Table 37. Definitions of Savings Metrics

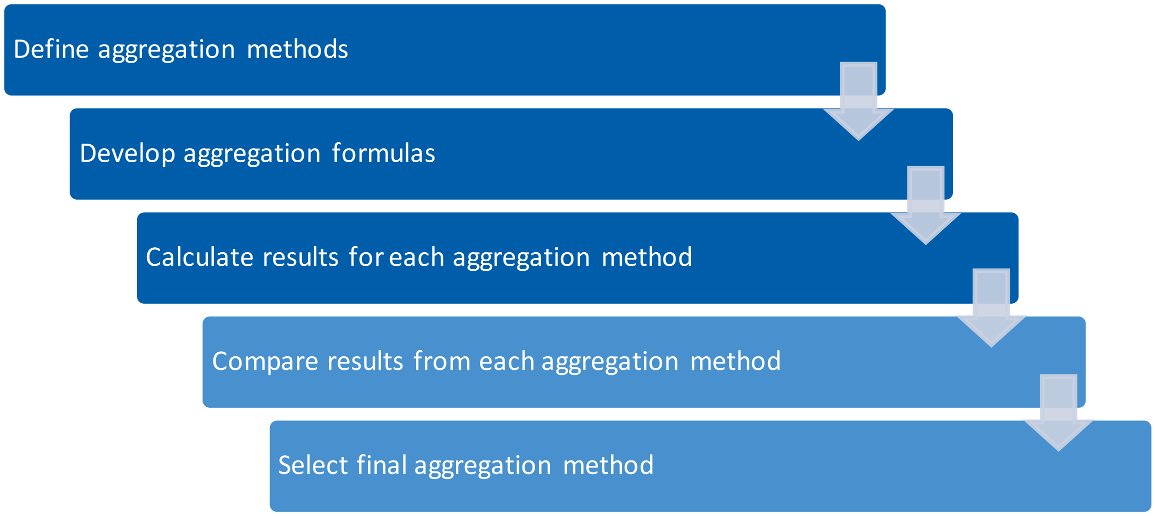
Savings Metrics	Units	Definition
Annual energy savings	kWh/year	Total kWh savings across all hours in a typical year
Annual operating hours	hours/year	Total hours that the unit operates during a typical year
Annual energy savings by energy period	kWh/year	Total kWh savings for all hours in each of four energy periods
ISO-NE summer on-peak demand reduction	kW	Average demand reduction for all hours in the ISO-NE summer on-peak demand period
ISO-NE winter on-peak demand reduction	kW	Average demand reduction for all hours in the ISO-NE winter on-peak demand period
PJM summer peak demand reduction	kW	*For temperature-independent units:* Average demand reduction across all hours in the PJM summer peak demand period *For temperature-dependent units:* Expected demand reduction when the daily WTHI is 83.1* modeled using a correlation between daily WTH and daily demand reduction for summer weekdays.

* PJM Manual 18B: Energy Efficiency Measurement and Verification

2.5 Sample Analysis

Sample analysis involves using the unit-level results from the study sample to make observations about the study population. For this study, we developed the sample analysis based on our observations from the unit-level data. Figure 21 shows our process for developing the sample analysis method.

Figure 21. Process for Defining the Sample Analysis Method



In this section, we describe the first three steps in this process. We describe the final two steps—which involve examination of the calculated results—in the Results chapter (Section 3).

2.5.1 Define Aggregation Methods

In this section of the report, we discuss aggregation as the method used to estimate population results based on sampled unit-level data. In a typical evaluation study, the aggregation method is predefined based on the sample design and is a straightforward weighted average of all sampled units to develop results for a single population. In this study, due to the observed variation in unit-level operation and distinct populations of temperature-dependent and temperature-independent units, we expanded the aggregation analysis to compare the results for different methods of aggregation.

In the following subsections, we describe the methods of aggregation that we explored, formulas for the aggregation analysis, comparison of the population results using these methods, and our final selection of the aggregation method used to arrive at the results reported for this study.

2.5.1.1 Aggregation Options

We worked with the NEEP Technical Committee to develop four methods as options for aggregating the unit-level data into population results. Each method is based on a different combination of unit-level data to develop the loadshapes for each equipment type. The different methods represent trade-offs between sharing data across weather regions and sample size.

Table 38 describes each method and the specific treatment for temperature-dependent and temperature-independent units.

Table 38. Aggregation Methods for Population Results

Method	Description	Temperature-Dependent (TD) Units	Temperature Independent (TI) Units
A	Create loadshapes for each weather region using only units located in that region.	Include only units from the weather region of interest Unit savings modeled based on unit weather region	Include only units from the weather region of interest Unit savings modeled based on unit weather region*
B	Create loadshapes for each weather region using all temperature-independent units (regardless of region) but only temperature-dependent units that are located in that region.	Include only units from the weather region of interest Unit savings modeled based on unit weather region	Include units from all weather regions Unit savings modeled based on unit weather region*
C	Create loadshapes for each weather region using all units from all regions. (For temperature-dependent units outside of the loadshape region, model the unit loadshape using the in-region typical weather).	Include units from all weather regions Unit savings modeled based on weather region of interest regardless of unit region	Include units from all weather regions Unit savings modeled based on unit weather region*
D	Create a single combined loadshape for the northeast using all units. For temperature-dependent units, each unit is modeled using typical weather from the region in which that unit is located.	Include units from all weather regions Unit savings modeled based on unit weather region	Include units from all weather regions Unit savings modeled based on unit weather region*

* For temperature-independent units, models based on unit weather region omit weather data since the units are temperature-independent.

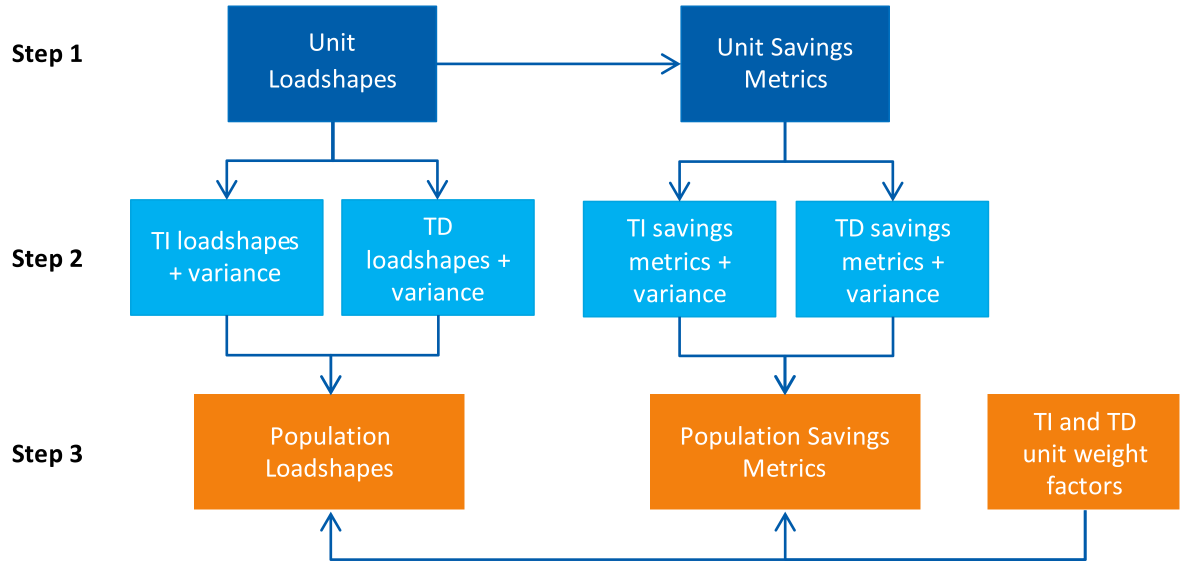
The first three aggregation methods (Methods A, B, and C) use the specified combinations of TI and TD units to develop loadshapes for each of the five equipment types in each of the six weather regions.

- Method A creates equipment loadshapes for each weather region using only units that are located in that region.
- Method B creates equipment loadshapes for each weather region using TD units from within the region only, but including TI units from all regions.
- Method C creates equipment loadshapes for each weather region units all units from all regions, with the TD units modeled for the region of interest (using TMY3 weather data) regardless of the unit's actual location.
- Method D combines all unit-level data to develop loadshapes for each equipment type across the entire northeast region (e.g., all Sponsor territories).

2.5.2 Develop Aggregation Formulas

Figure 22 shows the progression of calculations to develop the population loadshapes and savings metrics for each combination of equipment type, weather region of interest, and aggregation method.

Figure 22. Calculation Steps for Population Analysis



In Section 2.4, we described the calculation of unit-level loadshapes and savings metrics based on the metered data and baseline model (Step 1). In Step 2, we combined the unit-level results into totals for the TD and TI subpopulations or "domains." In Step 3, we combined the TD and TI domain results to develop total population results.

We provide the key formulas for these calculations below. The descriptions in Table 39 provide guidance to interpret the formulas. Please see Appendix A for the derivation and detailed discussion of these formulas.

Table 39. Definitions for Aggregation Formulas

Symbol	Description
Y, y	Population (upper-case) or unit (lower-case) demand savings
X, x	Population (upper-case) or unit (lower-case) horsepower
R	Population ratio estimate
R	Population ratio estimate
K	Domain (e.g., weather sensitive or non-weather-sensitive)
L	Stratum that is defined by a unique combination of project size and weather region
I	Identifier for *project* in the evaluation sample
J	Identifier for *unit* in the evaluation sample
M, m	Number of units in the population (upper-case) or evaluation sample (lower-case)
N, n	Number of projects in the population (upper-case) or evaluation sample (lower-case)

Step 1. Calculate Unit-Level Savings Loadshapes and Metrics

In Section 2.4, we described our methods for calculating the unit-level hourly savings loadshapes and savings metrics.

Step 2: Combine Unit-Level Results into Domain Totals

Our next step is to combine these data according to each aggregation method.

Results and Variance for TD and TI Domains

We first combine the unit-level results into totals for the TD and TI subpopulations or "domains." We calculate results for each domain using the following formulas:

- Estimated average per-unit savings for all units in the domain:

$$\hat{\hat{Y}}_k = \frac{1}{\hat{M}_k} \sum_{l=1}^{L} \frac{N_k}{n_l} \sum_{i=1}^{n_l} \frac{M_{il}}{m_{il}} \sum_{j=1}^{m_{ilk}} y_{ijlk}$$

- Estimated average per-unit horsepower for all units in the domain:

$$\hat{\hat{X}}_k = \frac{1}{\hat{M}_k} \sum_{l=1}^{L} \frac{N_l}{n_l} \sum_{i=1}^{n_l} \frac{M_{il}}{m_{il}} \sum_{j=1}^{m_{ilk}} x_{ijlk}$$

- Estimated variance of the total domain savings:

$$Var\left(\hat{Y}_{k\ (\hat{R}_k)}\right) = \sum_{l=1}^{L} \left[\frac{N_l^2}{n_l}\left(1-\frac{n_l}{N_l}\right) \sum_{i=1}^{n_l} \frac{1}{n_l-1}\left[\left(\hat{Y}_{ilk} - \hat{R}_k \cdot \hat{X}_{ilk}\right) - \left(\bar{Y}_{lk} - \hat{R}_k \cdot \bar{X}_{lk}\right)\right]^2 + \frac{N_l}{n_l} \sum_{i=1}^{n_l} \frac{{M_{il}}^2}{m_{il}}\left(1-\frac{m_{il}}{M_{il}}\right) \sum_{j=1}^{m_{ilk}} \frac{1}{(m_{ilk}-1)}\left[\left(y_{jilk} - \hat{R}_k \cdot x_{jilk}\right) - \left(\bar{Y}_{ilk} - \hat{R}_k \cdot \bar{X}_{ilk}\right)\right]^2\right]$$

Population Weights for TD and TI Domains

The various combinations of TI and TD results for the aggregation methods A through D described above require appropriate weighting of the observed occurrence of TI and TD units in each region. The following formulas describe how we develop these regional weighting factors for the TI and TD subpopulations.

- Estimated total number of units in the domain for all regions analyzed (as defined by the aggregation option):

$$\widehat{M}_k = \sum_{l=1}^{L} \frac{N_l}{n_l} \sum_{i=1}^{n_l} \frac{M_{il}}{m_{il}} m_{ilk}$$

- Estimated total number of units in the domain for the weather region of interest (as defined by the aggregation option):

$$\widehat{M'}_k = \sum_{l=1}^{L'} \frac{N_l}{n_l} \sum_{i=1}^{n_l} \frac{M_{il}}{m_{il}} m_{ilk}$$

Table 40 describes the comparison between the estimated number of domain units in the aggregation ($\widehat{\mathrm{M}}_{\mathrm{k}}$) and the estimated number of domain units in the weather region of interest ($\widehat{M'}_k$). We use the ratio of these two values to ensure that the total population result represents the observed ratio of TD and TI units for each weather region.

Table 40. Domain Weighting Factors by Aggregation Method

Method	Region of Interest	TD Units (k=1)	TI Units (k=2)
A	Each weather region	$\frac{\widehat{M'}_{k=1}}{\widehat{M}_{k=1}} = 1$	$\frac{\widehat{M'}_{k=2}}{\widehat{M}_{k=2}} = 1$
B	Each weather region	$\frac{\widehat{M'}_{k=1}}{\widehat{M}_{k=1}} = 1$	$\frac{\widehat{M'}_{k=2}}{\widehat{M}_{k=2}} < 1$
C	Each weather region	$\frac{\widehat{M'}_{k=1}}{\widehat{M}_{k=1}} < 1$	$\frac{\widehat{M'}_{k=2}}{\widehat{M}_{k=2}} < 1$
D	Northeast region combined	$\frac{\widehat{M'}_{k=1}}{\widehat{M}_{k=1}} = 1$	$\frac{\widehat{M'}_{k=2}}{\widehat{M}_{k=2}} = 1$

Step 3: Combine Domain Results into Population Totals

We then combine the TD and TI domain results to develop total population results, using the following formulas:

- Estimated total savings for all units in the complete population:

$$\hat{Y}. = \widehat{M'}_{k=1}\hat{\hat{Y}}_{k=1} + \widehat{M'}_{k=2}\hat{\hat{Y}}_{k=2}$$

- Estimated total horsepower of all units in the complete population:

$$\hat{X}. = \widehat{M'}_{k=1}\hat{\hat{X}}_{k=1} + \widehat{M'}_{k=2}\hat{\hat{X}}_{k=2}$$

- Ratio estimate, or estimated average per-unit savings for the complete population:

$$\hat{R}. = \frac{\hat{Y}.}{\hat{X}.} = \frac{\widehat{M'}_{k=1}\hat{\hat{Y}}_{k=1} + \widehat{M'}_{k=2}\hat{\hat{Y}}_{k=2}}{\widehat{M'}_{k=1}\hat{\hat{X}}_{k=1} + \widehat{M'}_{k=2}\hat{\hat{X}}_{k=2}}$$

- Variance of the ratio estimate:

$$Var\left(\hat{R}_{.}\right) = \frac{\left(\frac{\widehat{M'}_{k=1}}{\widehat{M}_{k=1}}\right)^2 Var\left(\hat{Y}_{k=1(\hat{R}_k)}\right) + \left(\frac{\widehat{M'}_{k=2}}{\widehat{M}_{k=2}}\right)^2 Var\left(\hat{Y}_{k=2(\hat{R}_k)}\right)}{\left[\left(\frac{\widehat{M'}_{k=1}}{\widehat{M}_{k=1}}\right)\hat{X}_{k=1} + \left(\frac{\widehat{M'}_{k=2}}{\widehat{M}_{k=2}}\right)\hat{X}_{k=2}\right]^2}$$

2.5.3 Calculate Results for Aggregation Methods

Due to the volume of data and number of calculations, we developed code using the R programming platform to perform the calculations. We performed quality control reviews and manual spot-checks for each sequence of code to ensure that our program performed the calculations correctly.

3 Results

While the focus of this loadshape project was to develop savings loadshapes for VSDs on the selected commercial HVAC equipment type, the analysis of collected tracking, survey, and meter data uncovered many unexpected results. This chapter discusses the final data sample, the evaluation team's observations on the varied operating patterns for VSDs, and the final savings loadshapes and metrics.

3.1 Final Study Sample

Table 41 shows the final sample of metered units by equipment type and weather region.

Table 41. Final Sample of Equipment Type by Weather Region

Equipment Type	DNY	MAT	NEE	NEN	NES	UNY	Total	Pct. of Total
Supply Fans (SF)	35	24	21	23	20	8	131	33%
Return Fans (RF)	9	15	13	17	4	2	60	15%
Cooling Water Pumps (CWP)	4	20	22	53	3	7	109	28%
Hot Water Pumps (HWP)	5	6	3	40	11	12	77	20%
WSHP Circulation Pumps (WHP)	3	0	1	8	3	0	15	4%
Total	56	65	60	141	41	29	392	100%
Percent of Total	14%	17%	15%	36%	10%	7%	100%	NA

3.1.1 Units Removed from the Dataset

We removed 29 units from the dataset for the following reasons:

- Data logger not recovered from site (7)
- Error in logger data or logger indicated no operation but customer did not confirm (15)
- Data collection period missing critical seasons (7)

3.1.2 Units with no Operation

The meter data for 52 units indicated no operation or very low operating hours during the data collection period. The team reviewed the survey data and contacted customers to confirm that the non-operation indicated by the meter data was accurate for that unit. These units typically represent lag units that only operate during periods of exceptionally high demand, or back-up units that operate only during rare periods when primary units are unavailable.

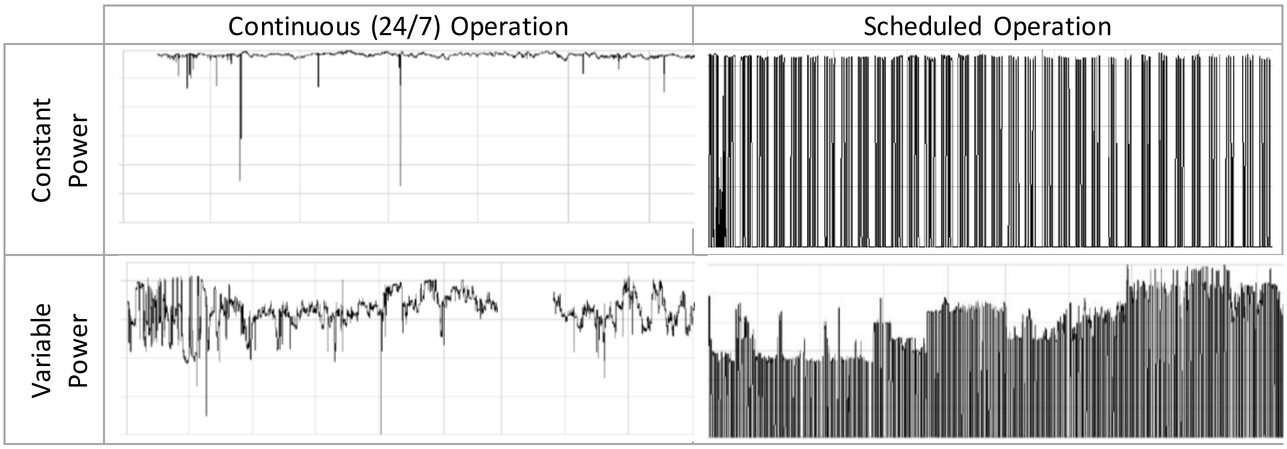
Through discussion with the Technical Committee, the evaluation team agreed to keep these non-operating units in the study sample.

3.2 Observations on VSD Operation

The metering data showed varied operating patterns for VSD-controlled units, even within the same equipment type and site. We used the project data and a combination of visual and analytical tests to characterize each unit by Unit Type, Seasonality, Operating Pattern, and Operation Power.

Each of these characteristics affects the unit's savings loadshape over the course of the year, influencing both whether the unit is *on* or *off*, and the expected electric demand and savings. The variety of characteristics across equipment types may be expected. However, the variety *within* each equipment type category causes wide variations in the hourly VSD savings results.

Figure 23. Examples of Observed Variation in VSD Operation



3.2.1 Motor Configuration

The motor configuration indicates the unit's role in serving its designated HVAC load. The evaluation team used the on-site survey and meter data results to assign each unit to one of the following configurations:

- **Primary** units operate as the primary, or lead, equipment to serve the designated load. When there is a call for heating, cooling, or ventilation, the primary unit will respond to meet the load requirements.
- **Lag** units assist primary, or lead, equipment when the lead equipment reaches its maximum capacity or a maximum setting. In these scenarios, the lag units will respond to serve any load beyond what is served by the lead unit. Because the primary equipment usually serves the full HVAC load, lag units typically operate only when the loads are unusually high.
- **Rotating** units operate in teams of like units to serve the same load. A team of rotating units will rotate the operating unit to serve the load while the other units "rest." Teams are typically two to three units and the rotation may be automated (e.g., through the facility EMS) or manual (e.g., by facility manager). The rotation intervals vary from weekly to multiple months, depending on the facility policy and attention of facility manager.
- **Back-up** units rarely operate and are in place to provide redundancy for primary or rotating units. Back-up units typically operate only when the other equipment malfunctions or is turned off for regular maintenance activities.

Sponsor data collection forms do not collect information on the unit type, but do require that equipment operates for a minimum of 2,000 hours per year to receive a VSD rebate.

3.2.2 Operating Pattern

The evaluation team reviewed metered data for each unit to characterize its operating pattern. The operating pattern indicates when the unit is on or off during its typical operating period.

- **Continuous** operation indicates that the unit operates during all hours in its operating season. Continuous operation is common for HVAC equipment serving continuous loads (e.g., a 24/7 retail space).
- **Scheduled** operation indicates that the unit operates on an hourly schedule such that the frequency of operation varies across the hours in a day. Scheduled operation is common for HVAC equipment serving spaces with regular occupancy schedules (e.g., office space).
- **Irregular** operation indicates that the unit operates with no clear pattern. Irregular operation typically indicates that the unit responds to an irregular variable or infrequent event, such as exceptionally high loads. These exceptions may be caused by extreme weather or by unusual activity in the conditioned space.
- **None** indicates those units that did not operate during the data collection period, and for which we confirmed with the customer that that logger data is accurate.

Table 42 shows the distribution of unit operating patterns within each equipment type.

Table 42. Unit Operating Pattern by Equipment Type

Operation	SF	RF	CWP	HWP	WHP	All
sample	(n = 133)	(n = 60)	(n = 103)	(n = 73)	(n = 15)	(n = 384)
Continuous	37%	25%	44%	55%	80%	42%
Scheduled*	55%	63%	42%	33%	7%	47%
Irregular	4%	5%	4%	5%	7%	4%
None	5%	7%	11%	7%	7%	7%

The data indicate that the majority of units across all equipment types operate continuously or on an hourly schedule. Across all equipment types, only 11% either did not operate or operated irregularly.

- Supply and return more frequently operated on an hourly schedule.
- Cooling water pumps were equally likely to operate on a continuous or scheduled pattern.
- Hot water pumps more frequently operated continuously.
- Although the sample size is small for WSHP circulation pumps, 80% operate continuously.

Sponsor data collection forms do not collect information on unit operating patterns, but do require that equipment operate for a minimum of 2,000 hours per year to receive a VSD rebate.

3.2.3 Seasonality

The team analyzed the survey data and meter data to indicate whether each unit was seasonal or non-seasonal.

- **Seasonal** units operate only for some portion of the calendar year. A seasonal unit may be a heating hot water pump that is turned off when the heating season is over, or a supply fan at an elementary school that is shut down during summer vacation.
- **Non-seasonal** units operate throughout the calendar year. Non-seasonal units may serve loads that persist throughout the year (e.g., ventilation) or may switch functions to serve different loads during the year (e.g., a dual heating/cooling pump in a two-pipe system).

Table 43 compares the seasonal and non-seasonal operation within each equipment type.

Table 43. Unit Seasonality by Equipment Type

Seasonality	SF	RF	CWP	HWP	WHP	All
sample*	(n = 127)	(n = 56)	(n = 95)	(n = 70)	(n = 14)	(n = 362)
Seasonal	0%	2%	22%	50%	0%	16%
Non-Seasonal	100%	98%	78%	50%	100%	84%

* Sample does not include units that indicated no operation

The data are consistent with our expectations for each equipment type.

- The majority of supply fans, return fans, and WSHP circulation pumps are non-seasonal. Since these equipment types typically serve both heating and cooling loads, they must operate throughout the year.
- Less than one quarter of cooling water pumps are seasonal, with 78% of CWPs indicating operation throughout the year. Although we expect CWPs to operate only during the cooling season, many spaces (e.g., restaurants, gymnasiums, and core spaces in a large office building) have year-round cooling loads. The cooling equipment serving these spaces must also operate throughout the year.
- Hot water pumps are evenly divided between seasonal and non-seasonal operation. Although we expect hot water pumps to operate only during the heating season, there are two primary reasons for non-seasonal operation:
    - Hot water pumps often also serve domestic hot water (DHW) loads. Since DHW loads are typically non-seasonal, these pumps will operate throughout the year.
    - Many of the units reported as HWPs are actually dual hot/cold water pumps in two-pipe distribution systems. At the end of the heating season, facility operators switch the units into cooling mode and continue to operate throughout the year.

Sponsor data collection forms do not collect information on the unit seasonality.

3.2.4 Operating Power

The unit operating power indicates the unit electric demand (kW) during operation. Typically, the unit size (horsepower), the designated HVAC load, and the VSD control settings affect the operating power. In our review of the meter data, we observed a variety of operating patterns from constant power throughout all operating hours to large fluctuations in operating power across hours and seasons. We categorized the operating power for each unit into one of the following categories:

- **Constant-Single** indicates that the unit operates at a constant operating power throughout its operating season.
- **Constant-Multiple** indicates that the unit operates at constant power.
- **Variable-Single** indicates that the unit operating power varies during operation and exhibits a single pattern throughout its operating months.
- **Variable-Multiple** indicates that the unit operating power varies during operation and exhibits multiple operation seasons.

Table 44 shows the distribution of unit operating power categories within each equipment type.

Table 44. Unit Operating Power by Equipment Type

Operating Power	SF	RF	CWP	HWP	WHP	All
sample*	(n = 133)	(n = 60)	(n = 103)	(n = 73)	(n = 15)	(n = 384)
Constant Single	12%	23%	31%	27%	50%	23%
Constant Multiple	10%	7%	8%	7%	0%	8%
Variable Single	61%	68%	47%	59%	29%	57%
Variable Multiple	17%	2%	14%	7%	21%	12%

*sample does not include units that indicated no operation

For prescriptive VSD rebates, the Sponsors do not collect any data on the unit operating power. Instead, they model the expected savings based on the unit size (horsepower) and equipment type.

3.3 Pre-Retrofit Operation

Section 2.4.4 described our methods to estimate pre-retrofit operating power. Based on the results of the Massachusetts Pre/Post VSD Study and discussions with NEEP's EM&V Technical Committee, we created pre-retrofit operating models for these two baseline categories: (1) constant volume and (2) variable volume (not including VSDs). Since the loadshape study focused on VSD projects completed at least one year before metering, we relied on survey data and on-site inspections to determine the baseline category for each unit.

Table 45 shows the distribution of baseline categories for each equipment type, based on customer reports during our on-site inspections or follow-up phone calls. We used the survey information to develop an initial distribution of baseline categories, then re-assigned any VSD or unknown baseline categories to develop the adjusted distribution for the savings analysis.

Table 45. Reported Pre-Retrofit Category

Baseline Category	SF	RF	CWP	HWP	WHP	All
sample	n = 131	n = 60	n = 109	n = 77	n = 15	n = 392
Initial Distribution						
Constant volume (CV)	31%	42%	35%	25%	40%	33%
Variable volume (VV)	1%	6%	0%	0%	0%	2%
Variable speed drive*	1%	2%	0%	0%	0%	1%
Unknown**	66%	50%	65%	75%	60%	65%
Adjusted Distribution* **						
Constant volume	97%	92%	100%	100%	100%	98%
Variable volume	3%	8%	0%	0%	0%	2%

* Based on discussions with the NEEP Technical Committee, we reassigned VSD baselines to either CV or VV. Since VSDs are not an eligible baseline or any Sponsor programs, the team elected to remove this baseline category from the final analysis.
** The high percentage of units with unknown baselines is due to the elapsed time (minimum of one year) since the site installed the VSDs.
*** We assigned all equipment with VSD or unknown baselines by randomly assigning the unit to a CV or VV baseline based on the probably of those baselines occurring in the initial, or "known" distribution.

The initial distribution shows that facility staff could not define the baseline system for almost two-thirds of the studied units. This inability to report on the baseline conditions was prevalent for the majority of sampled units across all equipment types. This is not surprising for a data collection effort conducted a minimum of one year after the customer installed the VSD equipment.

Among those staff members who could recall the baseline system type and operation, the majority indicated that the equipment operated at constant speed and power before the customer installed the rebated VSDs. Among these, some staff indicated that although variable volume equipment existed, the site was installing VSDs because the existing variable volume equipment was not in working condition. We classified these cases in the constant volume category.

To estimate the adjusted distributions, the evaluation team reassigned the baseline category for units with an unknown or VSD baseline in the initial distribution based on the observed distribution of CV and VV baselines among the known baseline categories within each equipment group. In other words, we randomly assigned each "unknown" or "VSD" baseline from the initial distribution to either the CV or VV baseline category using the probability of CV or VV from the initial baselines.

The final distribution demonstrates our estimate that almost all systems operated as constant volume prior to the VSD retrofit. Although contrary to many TRM approaches that assume a higher fraction of variable volume baselines, we confirmed through multiple discussions with the NEEP Technical Committee and building commissioning engineers that this high percentage of systems operating at constant volume is consistent with field observations across existing buildings and with the pre-installation findings from the MA VSD Pre/Post study. The following points support this finding:

- The CV baseline category includes systems that were designed as VV but operate as CV, because of improperly operating controls, broken equipment, etc.
- The program population of buildings does not include the full C&I building stock. Rather, the population includes only those existing buildings that participated in one of the Sponsors' VSD retrofit programs. Existing buildings with working variable volume systems are less likely to participate in the programs since there is no need to replace the working VV equipment.
- Eligibility requirements for several Sponsor VSD programs do not allow rebates for existing VV systems in working condition. This filter likely further reduces the number VV baselines among the participant population.
- Our commissioning engineers agree that based on their experience in existing buildings, it is becoming less and less common to see non-VSD VV systems in working condition. Frequently, they will find evidence that these VV systems were part of the original design, but noted that they are often not working. For example, we see guide vanes that are locked in place so they effectively operate as constant volume systems.
- For pumping systems, pumps without VSD controls are typically constant volume by design. There are systems that use variable volume distribution in the building (e.g. two-way valves at the coils), but they are typically configured using bypass valves at the plant so the primary loop pump would still operate at full, constant volume.
- Although the sample was small, the pre-retrofit metering results from the Massachusetts Pre/Post VSD study are consistent with these assumptions. For that study, the field team observed and metered the equipment up to a year before the VSD was installed. They identified a couple systems that were designed as VV, but the meter data showed constant power on those fans.

As described in Section 2.4, the evaluation team used a combination of project tracking data, meter data, standard system curves based on the assigned baseline category, and results of the Massachusetts Pre/Post Study data to estimate the hourly pre-retrofit demand for each unit.

3.4 Savings Results

The evaluation team aggregated the unit results to calculate population average loadshapes for each equipment type and weather region.

3.4.1 Key Assumptions

During the sampling, data collection, and analysis tasks, the evaluation team discussed methods and findings with NEEP's EM&V Technical Committee. This group made several key decisions to complete the savings loadshape analysis. Although thoroughly described in Chapter 2 (Methods), we summarize these decisions below since they affect the study results.

- **Pre-Retrofit Schedule**. Due to the post-installation focus of the study, the evaluation team could not monitor the pre-retrofit operating schedule. We assumed the pre-retrofit operating schedule was the same as the post-retrofit operating schedule. (See Section 2.4.2 for more details.)

- **Pre-Retrofit Operating Power**. Due to the post-installation focus of the study, the evaluation team could not measure pre-retrofit operating power. We modeled pre-retrofit power based on a combination of the unit rated horsepower, metered post-installation power, and results of the Massachusetts Pre/Post metering study. (See Section 2.4.4 for more details.)
- **Units with Baseline VSD**. A small number of interviewed site staff said the new VSDs replaced existing VSDs. Since replacement of existing VSDs is not eligible in the Sponsor's programs, we modeled these units as if they had been new VFD installations instead of replacement of existing VFDs by assigning assigned a new baseline category for these units based on the observed distribution of known baseline categories for units of the same equipment type.
- **Non-Operating Units**. Our metering and on-site data collection indicated that 52 of 392 (<14%) units have low operating hours due to rotating, lead-lag, or back-up control strategies. We retained these units in the study sample to represent these occurrences as we observed them in the study population (see Section 3.1 for more details).

3.4.2 Selection of Aggregation Method

The team used these aggregation formulas to calculate the population savings results and precision for each combination of equipment type, region of interest, and aggregation method. Due to the volume of data and number of calculations, we developed code using the R programming platform to perform the calculations. We performed quality control reviews and manual spot-checks for each sequence of code to ensure that our program performed the calculations correctly.

Review and Comparison of Aggregation Method Results

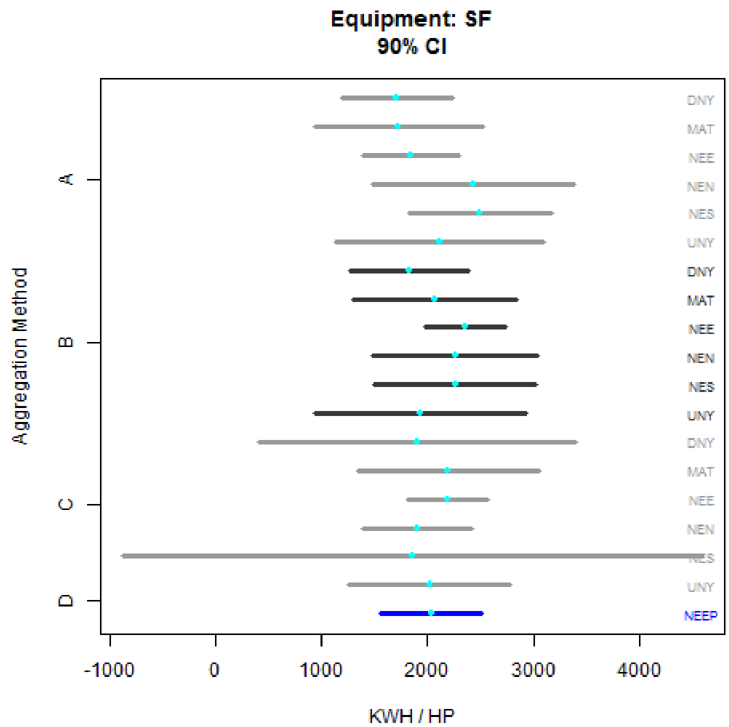
Once we completed the calculations for each aggregation method, we examined the results to determine their interpretability, consistency, and overall value to NEEP members. We reviewed these results with the NEEP Technical Committee to determine the most appropriate set of savings results for the Sponsors. During this review, we:

- Determined whether the results could be interpreted based on the characteristics of each equipment type and expectations about savings within each geographic region;
- Created summary information to review mean values and confidence intervals for each combination of aggregation method, weather region, and equipment type to support our discussions;
- Examined the consistency between results calculated using each aggregation method within each equipment type and across regions; and
- Compared our findings to existing savings assumptions in the Sponsor's technical reference manuals.

In our discussions with the NEEP Technical Committee, we combined these observations with practical considerations—such as maintaining consistency in aggregation methods across equipment types—to determine the value of results to NEEP members. With the guidance of the NEEP Technical Committee, we selected a single aggregation method for the study.

Figure 24 shows the population results for annual energy savings (kwp/hp) for supply fans as an example displaying results using the four aggregation methods.

Figure 24. Population Results for Supply Fans by Aggregation Method (SF)



The horizontal axis represents annual energy savings (annual ΔkWh per horsepower). We present the regional-level results as confidence intervals with points that represent estimated mean savings in the center of the bar that spans the 90% confidence interval. The results are displayed from top to bottom in groups according to the aggregation method. Results for Method A, which utilizes regional units only, is displayed at the top of the plot. Methods B and C, which combine units across regions depending on temperature dependence/independence, are next. Finally, the combined northeast ("NEEP") estimate, calculated using Method D, is provided at the bottom of the plot. The column on the right side of each figure indicates the region corresponding to each confidence interval.

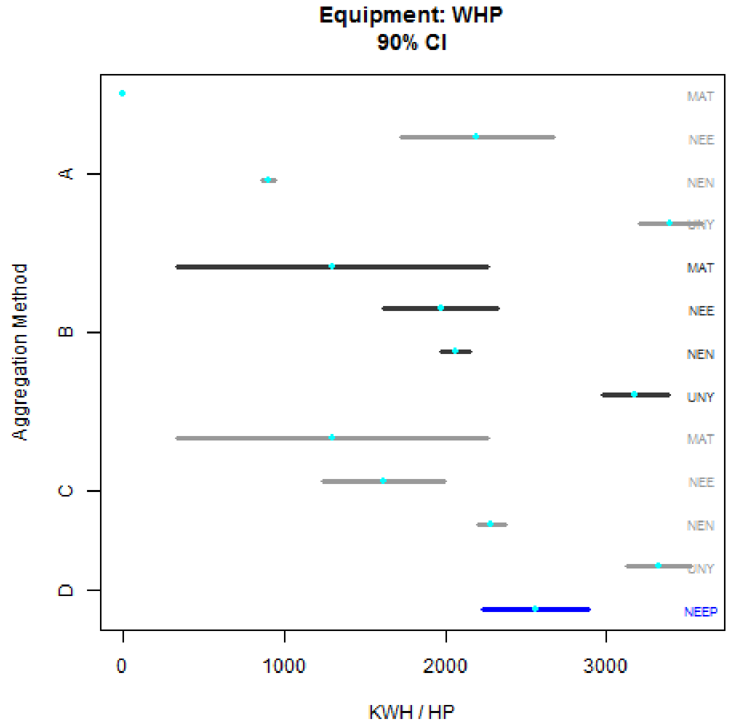
The plot helps us to compare results for a single equipment type. Each interval can be interpreted as follows: we are 90% confident that the interval covers the true mean loadshape. Although we have calculated a point estimate, we know that it is not equal to the true mean, but create the confidence interval to give an idea of the range of values the true mean is likely to take, based on the variance of observed values and the sampling uncertainty.

The bottom interval in Figure 24 shows that we are 90% confident that the interval from 1,500 to 2,500 kWh/HP covers the population mean SF loadshape for the entire NEEP region. Similarly, using Method C, we are 90% confident that the interval ranging from 1,200 to 2,800 kWh/HP covers the UNY mean loadshape estimated using Method C. The wider interval for UNY in Method C results from higher variance in the unit-level observations. Each confidence interval provides us with the range of plausible values that the true loadshape mean could take. In cases where we calculate confidence intervals for independent samples, such as in Method A, overlapping confidence intervals indicate that a statistical test would conclude that the means are not significantly different from one another. The estimates from one method to the other are not independent (the same data were used to estimate the interval in Method A UNY as in the NEEP interval), so we cannot make this strong an assertion. However, the intervals do give an indication of the range of values that the mean loadshape could take. We compare them and the extent of their overlap to get an idea of how similar or different the mean resulting from each aggregation method could be.

As illustrated in Figure 24, the confidence intervals within aggregation Method A, B, and C are overlapping, indicating that the mean loadshape values among the regions could lie in the same range. Further, the estimates are similar across aggregation methods. The NEEP confidence interval generated using Method D for the savings that encompasses all units from all regions covers a range that lies within the other regional intervals but provides a narrower margin of error around the mean since all unit-level observations were used to estimate the mean and standard error for the NEEP region. We observe similar results for the other equipment types and metrics (kWh/HP, SPkW/HP, and WPkW/HP).

A few exceptions did occur. Most notably, the results in Figure 25 illustrate that the WHP confidence intervals for average savings have little overlap between regions, indicating possibly significantly different mean savings for each region. For example, the estimated mean for Upstate New York (UNY) is notably higher than the other regions (Methods A, B, and C). However, we concluded that this result may be difficult to interpret and should not be solely attributed to regional differences.

Figure 25. Population Results for WSHP Circulation Pumps by Aggregation Method (WHP)



For other equipment types and savings metrics, the confidence intervals for some regions spanned zero but were positive for others. We did not believe in the interpretation of zero savings for a HWP in downstate New York (DNY) or the Mid-Atlantic (MAT), for example, but positive savings in other regions made sense based on physical characteristics of the units.

Aggregation Method Selection

As noted above, we explored multiple interpretations of the population results to determine the most appropriate aggregation method to develop final savings results for the NEEP Sponsors. In particular, we considered:

- Consistency among results where overlapping confidence intervals indicated that average savings loadshapes are not significantly different across regions for the majority of equipment types and metrics;
- Difficulty in attributing results to regional differences in cases where confidence intervals suggest the savings loadshapes are significantly different from region to region;
- Questionable findings in cases where confidence intervals contain zero, leading to the conclusion that the population savings is not significantly different from zero—when this occurs in one region but not another for the same equipment type; and
- Small sample sizes at the regional level and the observed variation in performance at the unit-level.

Based on our collaborative review with the NEEP Technical Committee, we concluded that aggregation method D—providing results at the regional level—would provide the most utility to NEEP members.

3.4.3 Savings Metrics

The team used the aggregation method and formulas described in the previous section to calculate population averages for the savings metrics defined in Section 2.4.6:

- Annual energy savings per unit horsepower (kWh/hp)
- Energy period savings per unit horsepower (kWh/hp)
- ISO-NE summer on-peak demand savings per unit horsepower (kW/hp)
- ISO-NE winter on-peak demand savings per unit horsepower (kW/hp)
- PJM summer peak demand savings per unit horsepower (kW/hp)

The following tables show the population savings estimates and associated relative precision (RP) values for each equipment type. Because the savings are based on an aggregation of all VSD units and projects across all Sponsor states (Aggregation Method D), the results represent the expected average across all Sponsor territories.

Table 46 shows the estimated annual energy savings per horsepower for units across the Northeast region. We present the annual energy savings in units of kWh per hp.

Table 46. Annual Energy Savings per Unit Horsepower

Equipment Type	kWh/hp	RP @ 90%	RP @ 80%
Supply Fans	2,033	23.5%	18.3%
Return Fans	1,788	13.8%	10.8%
Cooling Water Pumps	1,633	17.7%	13.8%
Hot Water Pumps	1,548	18.4%	14.3%
WSHP Circulation Pumps	2,562	12.8%	10.0%
* Results apply for all units across the northeast region.			

Table 47 shows the estimated allocation of annual energy savings for each energy period. We present the energy period savings in units of kWh per hp. The last column indicates that across all equipment types, about half of the annual energy savings occur in the winter on peak period and less than 12% of the annual energy savings occur in the summer off peak period.

Table 47. Energy Period Savings per Unit Horsepower

Equipment Type	Energy Period	kWh/hp	RP @ 90%	RP @ 80%	% Annual Energy Savings
Supply Fans	Summer On Peak	489	21.6%	16.8%	24%
	Summer Off Peak	187	29.4%	22.9%	9%
	Winter On Peak	982	21.6%	16.8%	48%
	Winter Off Peak	376	29.1%	22.7%	18%
Return Fans	Summer On Peak	469	13.9%	10.8%	26%
	Summer Off Peak	119	24.4%	19.0%	7%
	Winter On Peak	959	13.4%	10.5%	54%
	Winter Off Peak	241	24.4%	19.0%	13%
Cooling Water Pumps	Summer On Peak	363	16.9%	13.1%	22%
	Summer Off Peak	177	19.8%	15.4%	11%
	Winter On Peak	743	17.4%	13.5%	45%
	Winter Off Peak	350	19.8%	15.4%	21%
Hot Water Pumps	Summer On Peak	190	32.3%	25.2%	12%
	Summer Off Peak	91	32.6%	25.4%	6%
	Winter On Peak	850	20.5%	16.0%	55%
	Winter Off Peak	418	21.5%	16.8%	27%
WSHP Circulation Pumps	Summer On Peak	520	15.4%	12.0%	20%
	Summer Off Peak	285	12.8%	10.0%	11%
	Winter On Peak	1,166	12.4%	9.6%	46%
	Winter Off Peak	590	12.1%	9.5%	23%

Table 48 shows the estimated demand reduction value for the ISO-NE summer on-peak period. We present these summer demand savings in units of kW per hp.

Table 48. ISO-NE Summer On-Peak Demand Savings per Unit Horsepower

Equipment Type	kW/hp	RP @ 90%	RP @ 80%
Supply Fans	0.288	18.8%	14.6%
Return Fans	0.302	11.9%	9.3%
Cooling Water Pumps	0.183	16.7%	13.0%
Hot Water Pumps	0.096	34.1%	26.5%
WSHP Circulation Pumps	0.229	22.0%	17.1%

* Results apply for all units across the northeast region.

Table 49 shows the estimated demand reduction value for the ISO-NE winter on-peak period. We present these winter demand savings in units of kW per hp.

Table 49. ISO-NE Winter On-Peak Demand Savings per Unit Horsepower

Equipment Type	kW/hp	RP @ 90%	RP @ 80%
Supply Fans	0.265	21.5%	16.7%
Return Fans	0.274	15.3%	11.9%
Cooling Water Pumps	0.194	18.2%	14.1%
Hot Water Pumps	0.221	20.7%	16.1%
WSHP Circulation Pumps	0.297	12.4%	9.7%

* Results apply for all units across the northeast region.

Table 50 shows the estimated demand reduction value for the PJM summer peak period. We present these summer demand savings in units of kW per hp.

Table 50. PJM Summer Peak Demand Savings per Unit Horsepower

Equipment Type	kW/hp	RP @ 90%	RP @ 80%
Supply Fans	0.286	19.0%	14.8%
Return Fans	0.297	12.4%	9.7%
Cooling Water Pumps	0.185	16.7%	13.0%
Hot Water Pumps	0.096	34.3%	26.7%
WSHP Circulation Pumps	0.234	20.6%	16.0%

* Results apply for all units across the northeast region.

Comparison to TRM and Other Studies

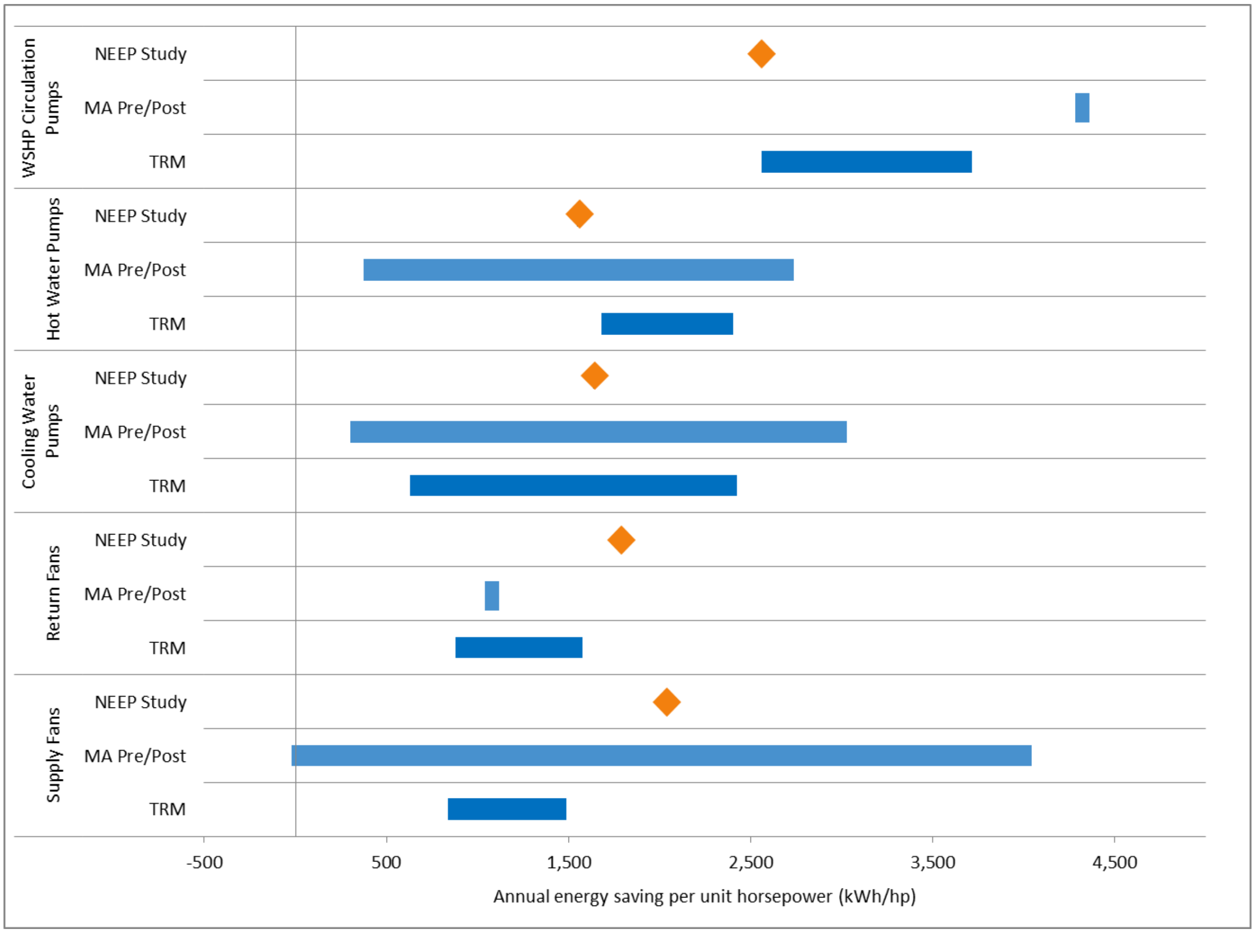
The evaluation team compared the population results from this study to assumptions in existing technical reference manuals and the results of the Massachusetts Pre/Post Study. We referenced the following documents for our comparison:

- Existing technical reference manuals:
  - New York Standard Approach for Estimating Energy Savings from Energy Efficiency Programs ("TRM")
  - Massachusetts Technical Reference Manual for Estimating Energy Savings from Energy Efficiency Measures, 2013-2015 Program Years – Plan Version ("TRM")
- Evaluation Studies:
  - Impact Evaluation of 2011-2012 Prescriptive VSDs (2013) ("Pre/Post Study")

In the following figures, we compare the NEEP study results for each equipment type to the range of values observed in the referenced documents. For the TRM values, the range is defined by the savings values for different buildings types. For the Massachusetts Pre/Post Study, the range is defined by the minimum and maximum evaluated savings for all units in the study.

Figure 26 shows this comparison for annual energy savings per horsepower.

Figure 26. Comparison of Results by Equipment Type, Annual Energy Savings

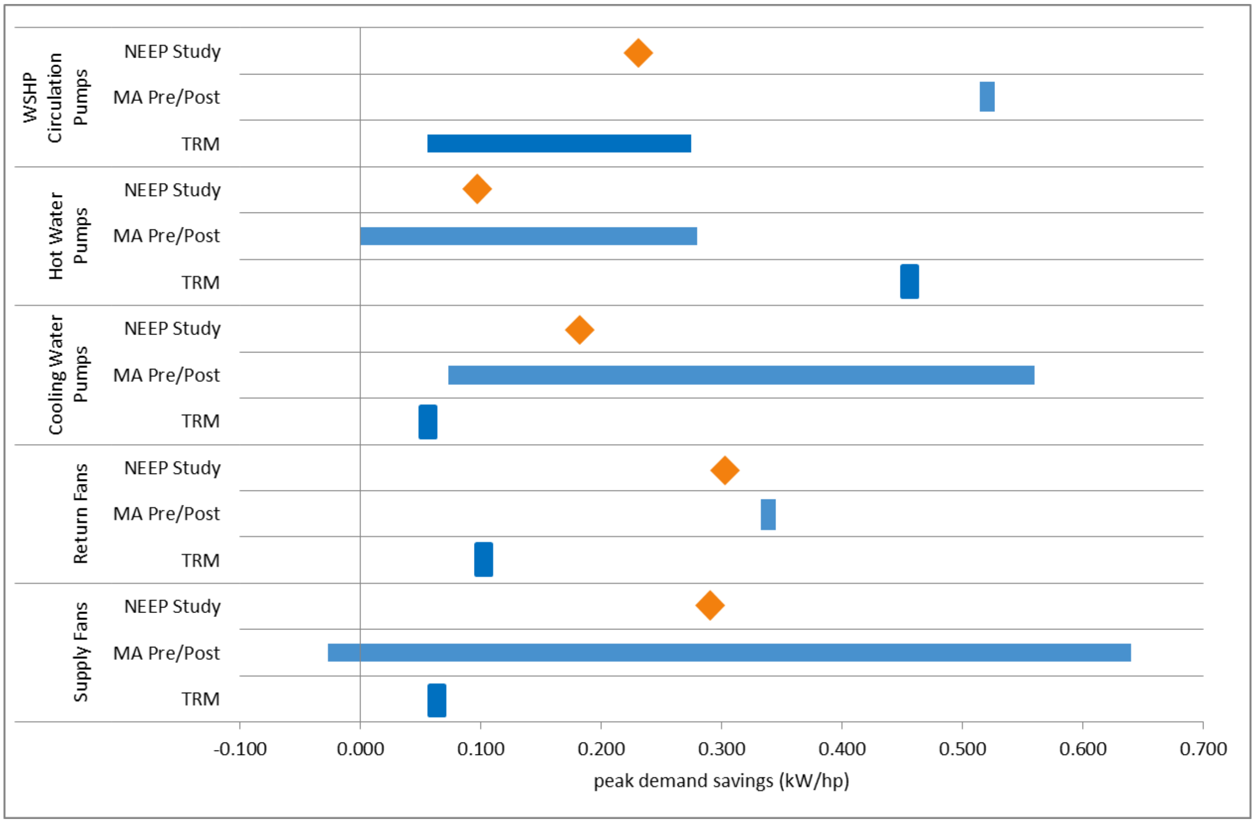


Comparison for annual energy savings:

- **Pre/Post Study:** For the equipment types for which the Pre/Post Study included more than one unit, the NEEP study results are within the range of values observed in the Massachusetts Pre/Post Study.
- **TRM:** The NEEP study results are higher than the existing TRM assumptions for supply fans and return fans, within the TRM range for cooling water pumps, and lower than the TRM range for hot water pumps and WSHP circulation pumps.

Figure 27 shows the comparison for summer demand reduction per horsepower.

Figure 27. Comparison of Results by Equipment Type, ISO-NE Summer On-Peak Savings

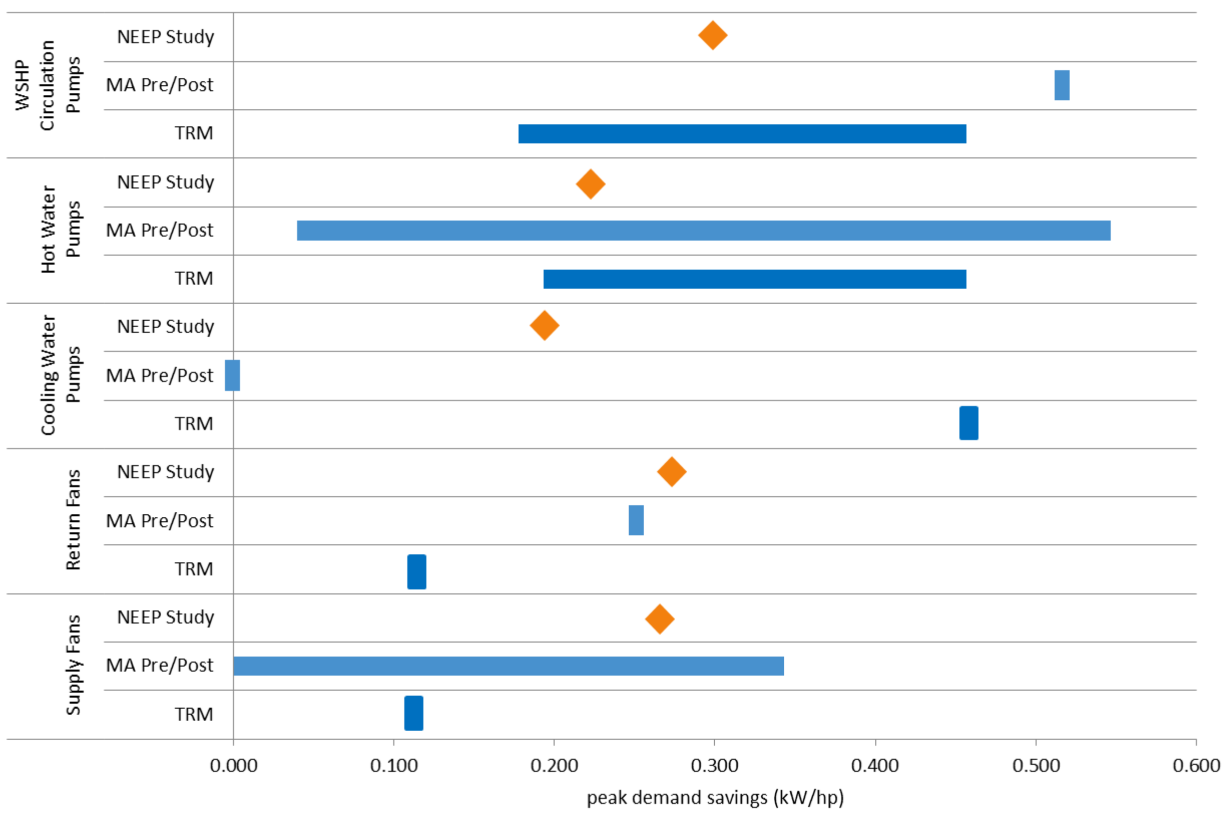


Comparison for ISO-NE summer on-peak savings:

- **Pre/Post Study:** For the equipment types for which the Pre/Post Study included more than one unit, the NEEP study results are within the range of values observed in the Massachusetts Pre/Post Study.
- **TRM:** For WSHP circulation pumps, the NEEP study value is within the range of TRM assumptions. For the other equipment types, the TRM provides a single savings value across all building types. For hot water pumps, the NEEP savings are lower than the TRM estimate. For all other equipment—supply fans, return fans, and cooling water pumps—the NEEP savings are higher than the TRM estimate.

Figure 28 shows the comparison for winter demand reduction per horsepower.

Figure 28. Comparison of Results by Equipment Type, ISO-NE Winter On-Peak Savings



Comparison for ISO-NE winter on-peak savings:

- **Pre/Post Study**:
  - For hot water pumps and supply fans, the NEEP study results are within the range of values observed in the Massachusetts Pre/Post Study.
  - None of the cooling water pumps in the Pre/Post Study produce winter peak savings because they did not operate during the winter season; however, the NEEP Study indicate savings for a fraction of CWPs that operate year-round.
  - The Pre/Post Study had only one sample point for WSHP circulation pumps and return fans. The NEEP Study average savings for WSHP are lower than observed in the Pre/Post and the NEEP Study average savings for return fans are similar to the observed value in the Pre/Post Study.
- **TRM:** The NEEP study results are within the TRM range for hot water pumps and WSHP circulation pumps. The NEEP average for cooling water pumps is lower than the TRM value. The NEEP average for supply and return fans is higher than the TRM values.

3.4.4 Key Findings that Explain the Results

We uncovered multiple important findings that guided our analysis approach and dictated our recommendation for a single set of savings results averaged across the NEEP region.

Variable speed drives frequently operate at constant speed.

Our on-site observations and metering data showed that customers operated at least one third of VSD-controlled motors at a constant speed (typically less than full speed) during the nine- to 12-month data collection period. Similarly, the Massachusetts Pre/Post VSD Study found that customers operated more than two-thirds of the metered VSDs at constant speed. When we discussed this operating strategy during our on-site interviews,[21] some facility operators indicated that they intended this constant speed operation while others indicated that they had not fully commissioned the VSD equipment. Although we expect VSDs to vary the motor speed depending on load conditions, the observed constant speed operation may result in higher energy savings during peak demand periods compared to when standard savings assumptions that VSD-controlled motors operate at or close to full speed during peak conditions.

Operators may select constant speed operation over variable speed operation.

Although we expect operators to use new variable speed drives to vary the operating speed of the motor, we found that it is not uncommon for operators to choose to operate the motor at a constant speed setting. Through discussions with facility staff in this study and our building commissioning engineers, we identified several reasons an operator may choose to use a VSD to operate a motor at constant speed:

- Operators may use a VSD to dial in on a reduced constant flow requirements. Reduced constant flow could also be achieved by using a valve or damper to throttle the flow or for certain pumping applications modifications could be made to the pump impellers. Compared to the throttling option, the VSD substantially reduces power requirements, energy consumption, and energy costs. Compared to the impeller modification option, the VSD allows the operator to keep the existing equipment in place and retains the flexibility of increasing speed (and capacity) if needed in the future.
- Operators may forgo the cost of implementing the controls for variable speed operation and instead settle on a reduced constant speed that is acceptable. Implementing controls may require installing new flow or pressure sensors, connecting those sensors and the VSD to a central EMS, programming controls sequences, and commissioning the system to ensure that the controls work correctly. Due to the cost and time requirements, operators may prefer to operate the equipment at a constant speed that meets the generally meets flow requirements. This constant speed may be higher than the necessary for periods of low load, but still reduces energy consumption and costs compared to constant speed. The installation of

[21] We asked these questions during removals at the end of our data collection period to minimize any influence on the facility's typical operation.

the VSD allows them to take advantage of further operational modifications if the controls are updated in the future.

Variable speed drive performance often does not track outside temperature.

In addition to a large percentage of VSDs that operated at a constant speed setting (discussed above), our unit-level data analysis demonstrated that the operating power for more than half of the units did not correlate with ambient temperature. Unlike larger equipment that operates to meet whole-building HVAC loads, internal variables such as occupancy or occupant activity may be more influential to VSD performance than external variables such as ambient temperature.

The savings estimates for each weather region are similar and similarly diverse.

In our aggregation analysis, we calculated average savings for each weather region and compared savings estimates between regions as well as to the average across all regions combined (NEEP region). The comparison showed that the confidence intervals for the regions overlap in most cases, suggesting that the average results are not very different from region to region. The confidence interval for the combined NEEP region covered a range that lies within the other regional intervals but provided a narrower margin of error around the mean. Further, we found that the variation in operation was similar from region to region, which provided another indication that regional differences were small. Due to these findings, we present average savings across all six weather regions.

Most pre-retrofit equipment operates at constant power.

The evaluation team's on-site survey and secondary data review indicated that a majority of pre-retrofit equipment operated at constant power. As indicated in Table 5, we modeled 98% of the pre-retrofit systems at constant power (after removing several occurrences of VSD baselines from the sample). Although standard VSD assumptions often model other variable flow systems as the baseline for VSD retrofit project, our research suggests that even when these variable flow systems exist they are not in working condition. Our research is supported by the Massachusetts Pre/Post VSD Study, which demonstrated constant power operation for 100% of the pre-retrofit systems.

3.4.5 Application of Results

Implementers in the Northeast and Mid-Atlantic states may use these results to estimate the savings for VSD installations that meet the following characteristics:

- The VSD is retrofitted on HVAC equipment in an existing nonresidential building and does not replace an existing, working VSD.
- The VSD controls a motor no larger than 200 horsepower.
- The VSD controls a motor driving one of these equipment types: (1) supply fans, (2) return fans, (3) chilled water plant distribution pumps, (4) hot water distribution pumps, and (5) water source heat pump distribution pumps.
- The controlled equipment serves an HVAC load.

When using these results, the implementer should calculate the desired savings parameter by multiplying the rated horsepower of the motor or total horsepower of the population of motors by the appropriate savings factor from the tables above. For example, to estimate the annual energy savings for a VSD retrofit project on a 50-hp supply fan, the implementer should multiply 50 (the rated horsepower of the existing motor) by the appropriate savings factor from Table 6. Similarly, the Sponsor may estimate the ISO-NE on-peak demand reduction by multiplying 50 (the rated horsepower) by the appropriate demand savings factor from Table 7.

Dissimilar to many TRM savings approaches that provide savings factors by building type or that use engineering algorithms to estimate savings using project-specific input parameters, the results of this study are averaged savings that account for the varied performance of VSD installations across building types and weather regions in the Northeast and mid-Atlantic states. This study does not deny the influence of building operating hours or ambient temperature on VSD performance; however, the diversity of equipment performance demonstrated in this study indicates that these two variables are not reliable predictors for VSD performance. As discussed in this report, many other factors such as equipment operating schedules, motor configuration, and VSD control strategy also influence VSD performance and savings estimates.

These study results are based on direct and long-term measurements of nearly 400 VSD installations and account for the diversity of motor sizes, building types, HVAC loads, and operating strategies, and seasonal differences across the northeast. The results also account for recent, measured findings about pre-retrofit performance.

4 Recommendations

The evaluation team offers the following recommendations for implementers and evaluators of VSD projects to improve the energy savings of VSD installations and the effectiveness of VSD programs.

Recommendations for Implementers

- Continue to promote the installation of VSD on existing equipment.
  - VSD retrofit projects are achieving significant energy and demand savings across the Northeast and Mid-Atlantic regions.
- To ensure that VSDs operate as intended to achieve energy and demand savings, Program Administrators should integrate VSD control and commissioning requirements into program implementation activities. Application forms should require specification of the intended control strategy, and post-installation inspection should include verification of commissioned VSD control sequences.
  - We observed, during the site visits and in our reviews of the metered data, that many customers operate their VSDs at constant speed. In some cases, customers intend to operate VSDs at constant speed, but for many customers this constant speed operation is due to incomplete project commissioning. In addition, we found that a larger percentage of VSDs operated at constant power in the Massachusetts Pre/Post VSD Study (conducted immediately before and after VSD installation) compared to the NEEP Study (conducted at least one year after installation). We assume that the lower percentage of constant speed units observed in this study is due to the longer period of elapsed time after the VSD installation allowing more customers to complete commissioning.
  - As VSDs saturate the existing building stock, the Program Administrators should take more care in screening project eligibility.
  - For several sampled projects, the rebated VSD units replaced existing VSD units at the end of their useful lives. Although we did not include those baseline occurrences in this study, these observations are evidence of projects receiving program incentives despite ineligibility.
- To support future evaluation efforts, the Program Administrators should add pre-retrofit data collection requirements to program application forms. At minimum, the PAs should require customers to specify the baseline system type and working condition of that system and operating schedule for the baseline equipment.
  - Information about baseline operation is limited in Sponsor tracking data and difficult to collect after customers complete VSD projects. Since baseline operation is a critical component for estimating energy and peak demand savings, it is important for the programs to record the working condition of baseline systems as well as the existing operating strategy and schedule.

Recommendations for Evaluators

- The timing of the post-installation inspection and metering is important. Our findings suggest the customers may take a year or longer installing the VSD to set up the controls and fully commission the system. Performing evaluation activities within a year of installation will provide accurate first-year results but may not accurately reflect VSD performance in the following years.
- When metering VSD power for energy analyses, the evaluator should examine seasonal operation defined for each facility. Seasons may be associated with changes in equipment purpose (e.g., heating or cooling), occupancy patterns (e.g., academic year vs. vacation periods), or other parameter such as control strategy (e.g., constant vs. variable speed).
    - Customers use HVAC motors differently throughout the year. This is especially true for equipment in seasonal facilities and for equipment that serve both heating and cooling loads.